Proceedings of the
Sixteenth International
TOVS Study Conference

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7-13 May 2008

Sharing ideas, plans and
techniques to study
the earth’s weather and climate
using space-based observations
FOREWORD

The International TOVS Working Group (ITWG) is convened as a sub-group of the International Radiation Commission (IRC) of the International Association of Meteorology and Atmospheric Physics (IAMAP). The ITWG continues to organise International TOVS Study Conferences (ITSCs) which have met approximately every 18 months since 1983. Through this forum, operational and research users of TIROS Operational Vertical Sounder (TOVS), Advanced TOVS (ATOVS) and other atmospheric sounding data have exchanged information on data processing methods, derived products, and the impacts of radiances and inferred atmospheric temperature, moisture, and cloud fields on numerical weather prediction (NWP) and climate studies.

These Technical Proceedings provided on CD bring together the papers of the scientific presentations and posters from the Sixteenth International TOVS Study Conference (ITSC-XVI) hosted by Centro de Previsão de Tempo e Estudos Climáticos, National Institute for Space Research (CPTEC/INPE) at the Hotel do Frade near Angra dos Reis from 6-13 May 2008. The ITSC-XVI conference report is also available which summarises the scientific exchanges and outcomes of the meeting. The ITWG web site contains electronic versions of the conference presentations, posters and publications which can be downloaded (http://cimss.ssec.wisc.edu/itwg/). Together, these documents and Web pages reflect a highly successful meeting in Angra. An active and mature community of TOVS and ATOVS data users exists, and considerable progress and positive results were reported at ITSC-XVI in a number of areas, including many related to the ATOVS system, use of IASI and AIRS measurements, and to the other current and impending advanced sounders.

ITSC-XVI was sponsored by industry, government agencies and a university, including Petrobras, INPE, SBMET, VCS Engineering, CNES, Kongsberg Spacetec AS, ABB, ITT Industries, the Met Office, the University of Wisconsin-Madison Space Science and Engineering Center, EUMETSAT, NOAA/NESDIS, CPTEC, Sea Space, NASA, NPOESS and the NSMC. The support of these groups is gratefully acknowledged. We wish to thank the local organising committee from the INPE/CPTEC, located in Cachoeira Paulista, SP, Brazil, especially to Dr. Dirceu Herdies, Dr. Rodrigo Souza and Dr. Simone da Costa for their exceptional effort and talent in leading the local organization and to Carine Previatti and Marcelo Acquaviva of Acquaviva Produções e Promoções for their enthusiastic support to the CPTEC team.

Details of Reports and Proceedings from previous conferences are also available from the web site. If you require a copy of the ITSC-XV report or CDs of the proceedings please contact the Working Group Co-Chairs at the co-ordinates below.

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Table of Contents

Papers from Presentations

Session 1: Guy Rochard session on direct broadcast packages, preprocessing, calibration and frequency protection

Kathleen Strabala....................................................................................................................... 2
*IMAPP: Software to Transform EOS Direct Broadcast Data into Science Products (Abstract only)*

John Overton.............................................................................................................................. 3
*International Polar Orbiter Processing Package (IPOPP) (Abstract only)*

Nigel Atkinson........................................................................................................................... 4
*AAPP developments and experiences with processing MetOp data (Abstract only)*

Liam Gumley ............................................................................................................................. 5
*EOS Direct Broadcast Real-Time Products for the US National Weather Service (Abstract only)*

Thomas Achtor........................................................................................................................... 6
*McIDAS-V - An open source data analysis and visualization tool for multi and hyperspectral satellite data*

Jean Pla .................................................................................................................................... 12
*Passive microwave protection: results of WRC-07 and future work plan (Abstract only)*

Richard Kelley ......................................................................................................................... 14
*3rd Annual Passive Sensing Microwave Workshop Proceedings/Summary (Abstract only)*

Steve Swadley.......................................................................................................................... 15
*SSMIS Calibration Anomalies:Observed F-16 and F-17 Anomalies, Detailed Analysis of the Root Causes, and the Path Forward (Abstract only)*

Session 2: The Infrared Atmospheric Sounding Interferometer

Denis Blumstein.......................................................................................................................... 17
*IASI Performances on MetOp-A after one year in orbit (Abstract only)*

Lars Fiedler .............................................................................................................................. 18
*IASI L1 data quality and NRT monitoring at EUMETSAT (Abstract only)*

Peter Schlüssel .......................................................................................................................... 19
*IASI Level-2 Product Processing at EUMETSAT (Abstract only)*

Nicole Jacquinet-Husson ......................................................................................................... 21
*Spectroscopic database GEISA-2008 edition: content description and assessment through IASI/MetOp flight data (Abstract only)*
William Smith
Joint Airborne IASI Validation Experiment (JAIVEx) - An Overview

Daniel Zhou
Retrievals with the Infrared Atmospheric Sounding Interferometer and validation during JAIVEx (Abstract only)

Paolo Antonelli
Using JAIVEX data to evaluate the impact of PCA Noise Filtering on the High Spectral Resolution Physical Retrieval Algorithm (Abstract only)

Stuart Newman
Direct radiance validation of IASI - results from JAIVEx

Xu Liu
Retrieval algorithm using superchannels (Abstract only)

Nikita Pougatchev
Error Assessment and Validation of the IASI Temperature and Water Vapor Profile Retrievals (Abstract only)

Fiona Hilton
Assimilation of IASI Radiances at the Met Office

Andrew Collard
Monitoring and Assimilation of IASI Radiances at ECMWF (Abstract only)

Marc Schwärz
Assimilation of IASI Data into the Regional NWP Model COSMO-EU: Status and Perspectives

Cathy Clerbaux
Atmospheric Chemistry using IASI / MetOp: Overview of initial results (Abstract only)

Session 3: Atmospheric radiative transfer

Paul van Delst
Community Radiative Transfer Model (CRTM) Status (Abstract only)

Roger Saunders
What can RTTOV-9 do for me?

Marco Matricardi
An assessment of the accuracy of the RTTOV fast radiative transfer model using IASI data

Thomas Kleespies
Microwave Radiative Transfer at the Sub-Field-of-View Resolution
Error analysis about using CO2-absorbing band for temperature retrieval (Abstract only)

Fast Forward Modeling in Scattering Atmospheres with Optimum Spectral Sampling (Abstract only)

Development of the Multilayer Cloudy Radiative Transfer Model for the GOES-R Advanced Baseline Imager (Abstract only)

Session 4: Surface emission and scattering

Retrieval of Global Hyperspectral Surface Emissivity Spectra from Advanced Infrared (Abstract only)

Using Hyperspectral IR Sounder Data Over Land - PC radiative transfer and 1d-Var (Abstract only)

Infrared continental surface emissivity spectra retrieved from IASI observations (Abstract only)

Recent updates of the UW/CIMSS high spectral resolution global land surface infrared emissivity database (Abstract only)

Session 5: Climate Studies

Upper tropospheric humidity data set from operational microwave sounders (Abstract only)

Intersatellite Calibrated HIRS Upper Tropospheric Water Vapor

Long-term application and evaluation of IAPP using global radiosonde and CHAMP (Abstract only)

AIRS in Atmospheric and Climate Research (Abstract only)

The Frequency of Severe Storms in the Tropical Zone and Global Warming
Session 6: Current use in NWP

John Derber

NCEP: Progress and Plans for the use of radiance data in the NCEP global and regional data assimilation systems (Abstract only)

Brett Candy

Met Office: An Update on the Operational Use of Satellite Sounding Data at the Met Office (Abstract only)

Florence Rabier

MeteoFrance: Recent advances in the use of satellite data in the French NWP models (Abstract only)

Nicolas Wagneur

Inclusion of new data types in the Canadian data assimilation system (Abstract only)

Qifeng Lu

CMA/NSMC Satellite Data Assimilation Activities: Uses of ATOVS and Fengyun VASS Data in WRF

Kozo Okamoto

JMA: Assimilation of radiance data at JMA: recent developments and prospective plans

Zhiquan Liu

WRF: Direct Radiance Assimilation for WRF: Implementation and Initial Results (Abstract only)

Martin Stengel

HIRLAM (SMHI): The Assimilation of Clear-Sky Infrared Radiances in the HIRLAM Model (Abstract only)

Session 7: Developments in use of sounding data in NWP and Environmental Prediction

Niels Bormann

Recent developments in the use of ATOVS data at ECMWF

William Bell

A Comparison of IASI water Vapour and SSMIS window channel impacts on NWP analyses and forecasts

Louis Garand

Impact of combined AIRS and GPS-RO data in the new version of the Canadian global forecast model

Martin Stengel

The Assimilation of Cloudy Infrared Radiances in the HIRLAM Model: Initial Experiences (Abstract only)
Gang Ma.......................................................... 180
Impact of VASS radiance of FY3 assimilation on numerical typhoon prediction (Abstract only)

Brett Harris.......................................................... 181
An Information Based Radiance Data Selection Scheme for Efficient Use of a Multi-Satellite Constellation

Benjamin Ruston..................................................... 187
Use of Hyperspectral IR Data in 4D Assimilation at NRL (Abstract only)

Banghua Yan.......................................................... 188
Intercomparison of the Cross-Track and Conical Scanning (Abstract only)

Thomas Auligne..................................................... 189
Impact of AIRS and AMSU-A data in regional data assimilation over the Antarctic (Abstract only)

Session 8: Cloud Studies

William Blackwell .................................................. 190
Neural Network Estimation of Atmospheric Profiles Using AIRS/IASI/AMSU Data in the Presence of Clouds (Abstract only)

Lydie Lavanant ..................................................... 192
Using AVHRR radiances analysis for retrieving atmospheric profiles with IASI in cloudy conditions (Abstract only)

Arlindo Arriaga..................................................... 193
CO2 Slicing Method for IASI (Abstract only)

Session 9: Developments in assimilation of sounding data in NWP in cloud regions

Remi Montroty.................................................... 194
Impact of rain-affected microwave data assimilation on the analyses and forecasts of tropical cyclones (Abstract only)

Peiming Dong.................................................... 195
Experiment of the Use of Satellite Microwave Data Affected by Cloud in Numerical Prediction

Min-Jeong Kim................................................... 205
The inclusion of cloudy radiances in the NCEP GSI analysis system (Abstract only)

John Le Marshall.................................................. 206
Using Clear and Cloudy AIRS Data in Numerical Weather Prediction
Session 10: Other applications of sounder data

Jie Zhang................................................................................................................................ 216
Effect and Improvement of Aerosol on Temperature Profile from MODIS (Abstract only)

Ninghai Sun ........................................................................................................................... 217
Evaluation of Special Sensor Microwave Imager and Sounder (SSMIS) Environmental Data Records

Laure Chaumat....................................................................................................................... 233
Potential of CO2 Retrieval from IASI (Abstract only)

Filomena Romano.................................................................................................................. 234
Analysis of Arctic clouds by means of hyper-spectral satellite

Tony Reale............................................................................................................................. 242
NOAA Products Integrated Validation Dataset / Database (Abstract only)

Cyril Crevoisier...................................................................................................................... 243
Midtropospheric CO2 Concentration derived from infrared and microwave sounders. Application to the TOVS, AIRS/AMSU, and IASI/AMSU instruments (Abstract only)

Anton Kaifel........................................................................................................................... 244
NNORSY-GOME Ozone Profile Retrieval Products and Climatology (Abstract only)

Ramesh Singh ........................................................................................................................ 246
Pronounced Changes in Water Vapor, Ozone and Metrological Parameters Associated with Dust Storms Using MULTI SENSOR Data (Abstract only)

Timothy Schmit ..................................................................................................................... 247
Advanced Infrared Sounding System for Future Geostationary Satellites (Abstract only)

S. Peyridieu........................................................................................................................... 248
Dust aerosol layer altitude from AIRS (01/2003 to 11/2007) and from Calipso (06/2006 to 11/2007): a comparison (Abstract only)

Session 11: Climate Studies

John Eyre ............................................................................................................................... 249
Evolution of the Global Observing System (Abstract only)

David Griersmith ................................................................................................................... 250
Status report on the Global RARS initiative (Abstract only)

Dieter Klaes ........................................................................................................................... 251
EUMETSAT Plans
Session 12: Climate Studies

Peter Wilczynski .......................................................... 262
The National Polar-Orbiting Operational Environmental Satellite System (NPOESS) and the NPOESS Preparatory Project (NPP) – Program status and international initiatives status (Abstract only)

Stephen Mango ......................................................... 263
The Joint Capabilities and Opportunities of Advanced Sounders on MetOp and NPOESS for NWP and Climate Monitoring In a GEOSS Era (Abstract only)

Papers from Posters

Fuzhong Weng .......................................................... 266
Radiative transfer in vertically layered soil (Abstract only)

Stephen Tjemkes ....................................................... 267
A clear sky radiative transfer model for MTG-IRS (Abstract only)

Stephen Tjemkes ....................................................... 268
Scenes Analysis for the Meteosat Third Generation Infrared Sounder Observations (Abstract only)

Fiona Hilton ............................................................ 269
Comparison of IASI radiances with models from seven operational centres (Abstract only)

Allen Larar .............................................................. 270
IASI Validation Studies using Airborne Field Campaign Data (Abstract only)

Stuart Newman ......................................................... 271
Identification of biases in the modelling of high peaking water vapour channels from IASI

Simone Costa .......................................................... 283
The water vapor continuum effect on the surface transmitted irradiance at 8 – 12 \mu m atmospheric window (Abstract only)

Yong Han ................................................................. 284
The effect of Doppler shift due to Earth’s spin on SSMIS UAS channels

Yong Han ................................................................. 293
A fast radiative transfer model for AMSU-A channel 14 with the inclusion of the Zeeman-splitting effect

Philippe Marguinaud ................................................. 302
A graphical user interface for RTTOV (Abstract only)
Laure Chaumat....................................................................................................................... 303
4A/OP: An operational fast and accurate radiative transfer model for the infrared (Abstract
only)

Xiaoqing Li ............................................................................................................................ 304
Forward Simulation for FY-3 MWHS using RTTOV-7 (Abstract only)

Fanny Duffourg...................................................................................................................... 305
Convective-scale data assimilation of satellite infrared radiances over the Mediterranean:
adaptation of the observation operator to the high-resolution

Steve Swadley........................................................................................................................ 315
SSMIS Upper Atmosphere Radiance Assimilation: Preprocessing Requirements and
Preliminary Results (Abstract only)

Carlos Bastarz ........................................................................................................................ 316
Evaluating the impact of the geopotential height profile data assimilation deriving from the
AIRS/AQUA sensor by the CPTEC’s RPSAS assimilation model (Abstract only)

Jairo Gomes Junior ................................................................................................................ 317
Impact of ATOVS geopotential heights retrievals over analyses generated by RPSAS

Roger Randriamampianina .................................................................................................... 324
Investigating the assimilation of IASI data in a limited area model (Abstract only)

Brett Candy ............................................................................................................................ 325
Does the ATOVS RARS Network Matter for Global NWP?

Aurélie Bouchard................................................................................................................... 332
Satellite Data Assimilation over Antarctica: The Concordiasi Field Experiment

Yann Michel........................................................................................................................... 342
Case studies of 4D-Var assimilation of potential vorticity observations derived from image
processing (Abstract only)

James Cameron...................................................................................................................... 343
Impact of variable O3 and CO2 on assimilation of high spectral resolution sounder data
(Abstract only)

Luiz Sapucci........................................................................................................................... 344
Impact analysis of assimilation of integrated water vapor estimates from AIRS/AMSU over
Amazonian region (Abstract only)

Blazej Krzeminski.................................................................................................................. 345
Towards better usage of AMSU observations over land at ECMWF (Abstract only)

Rita Valéria Andreoli............................................................................................................. 346
The relative contributions of the various observing systems in the CPTEC global data
assimilation/forecast system (Abstract only)
Thomas Pangaud .................................................................................................................... 347
Assimilation of cloudy AIRS observations in the French global atmospheric model ARPEGE

Qifeng Lu ............................................................................................................................... 358
Data assimilation and use of EOS data in land surface model (Abstract only)

Ricardo Todling ..................................................................................................................... 359
The GMAO 4d-Var System (Abstract only)

Nancy Baker ........................................................................................................................... 360
NRL:Implementing Radiance Assimilation in NAVDAS-AR: Lessons Learned (Abstract only)

Michael Uddstrom ................................................................................................................. 362
Environmental Forecasting at NIWA:A Progress Report (Abstract only)

Paolo Antonelli ...................................................................................................................... 363
Fostering a new generation of Remote Sensing Scientists (Abstract only)

Allen Huang ........................................................................................................................... 364
Processing Package and Remote Sensing Training Workshops for International Direct Broadcast Users (Abstract only)

Thierry Phulpin ...................................................................................................................... 365
Report on the first International IASI Conference (Abstract only)

Pascal Prunet .......................................................................................................................... 366
Synergy between IASI sounding and AVHRR imagery for the processing of IASI data in non-uniform scenes (Abstract only)

David Tobin ........................................................................................................................... 367
Validation of IASI spectral radiances using aircraft underflight data collected during JAIVEx (Abstract only)

David Tobin ........................................................................................................................... 368
Principal component analysis of IASI spectra with a focus on non-uniform scene effects on the ILS (Abstract only)

David Tobin ........................................................................................................................... 369
Evaluation of IASI and AIRS spectral radiances using Simultaneous Nadir Overpasses (Abstract only)

Zhaohui Cheng ....................................................................................................................... 370
The use of principal component analysis in monitoring IASI radiances and diagnosing climate anomaly (Abstract only)

Nathalie Selbach .................................................................................................................... 371
Operational Processing of ATOVS data at the Satellite Application Facility on Climate monitoring (Abstract only)
Validation of level 1b/1c LEO instruments in synergy with LEO/GEO companion instruments or in stand alone mode: Application to AIRS/Aqua, IIR/Calipso, IASI/Metop (Abstract only)

Cloud properties from AIRS and evaluation with Calipso (Abstract only)

A quantitative link between CO2 emissions from tropical vegetation fires and the daily tropospheric excess (DTE) of CO2 seen by NOAA-10 (1987-1991) (Abstract only)

SIFTI: A Static Infrared Fourier Transform Interferometer dedicated to ozone and CO pollution monitoring

Derivation of tropospheric carbon dioxide and methane concentrations in the boreal zone from satellite-based hyper-spectral infrared sounders data

Total ozone depletion due to tropical cyclones over Indian Ocean (Abstract only)

From TOVS to ATOVS based ozone monitoring – implication for the quality and homogeneity

Preliminary comparisons between the CO retrievals from AIRS and the CO CATT-BRAMS model estimations over the Amazon region during the 2002 dry-to-wet season (Abstract only)

Multi-satellite observation on upwelling after the passage of typhoon Hai-Tang in the southern East China Sea (Abstract only)

Retrieval of atmospheric water vapour profile using the Megha-Tropiques (Abstract only)

The use of HSB to derive the integrated water vapor content: an example using the RACCI/LBA experiment (Abstract only)

High-Resolution Passive Millimeter-wave Measurements from Aircraft: Validation of Satellite Observations and Radiative Transfer Modeling (Abstract only)

Synergetic Operational Earth observations with Metop-A instruments (Abstract only)

Australian Bureau of Meteorology Satellite Data Exchange and Use (Abstract only)
Simon Elliot ........................................................................................................................... 409
Operational dissemination of IASI data using principle component compression (Abstract only)

A. K. Sharma.......................................................................................................................... 410
NOAA/NESDIS Updates on Operational Sounding Data Products and Services (Abstract only)

Limin Zhao............................................................................................................................. 411
Operational Implementation of Integrated Microwave Retrieval System (Abstract only)

Lihang Zhou........................................................................................................................... 412
Enhancements of the AIRS Eigenvector Regression Algorithm (Abstract only)

Sid Boukabara........................................................................................................................ 413
Global Coverage of Total Precipitable Water using the Microwave Integrated Retrieval System (MIRS) (Abstract only)

Haibing Sun ........................................................................................................................... 414
CrIS Radiance Simulations in Preparation for Near Real-Time Data Distribution (Abstract only)

Thomas Kleespies .................................................................................................................. 415
Serendipitious Characterization of the Microwave Sounding Unit during an Accidental Spacecraft Tumble

Bjorn Lambrigtsen ................................................................................................................. 421
A Geostationary Microwave Sounder for NASA and NOAA

Louis Garand.......................................................................................................................... 427
A Canadian satellite mission for continuous imaging of the northern latitudes (Abstract only)

Thomas Achtor....................................................................................................................... 428
Examining the mid winter severe weather outbreak of 7 January 2008 using high resolution data with McIDAS-V (Abstract only)

Norman Grant ........................................................................................................................ 429
Sub-mm Wave Micromachined Free-Standing Frequency Selective Surfaces (Abstract only)

Author Index .......................................................................................................................... 430
PAPERS FROM
ORAL PRESENTATIONS
**IMAPP: Software to Transform EOS Direct Broadcast Data into Science Products**

Kathleen Strabala, Liam Gumley, Allen Huang, Elisabeth Weisz, and Jun Huang

The International Moderate Resolution Imaging Spectroradiometer / Atmospheric Infrared Sounder (MODIS/AIRS) Processing Package (IMAPP) provides users with EOS satellite Terra and Aqua direct broadcast antennae the capability to create environmental products from the downlinked raw data. This effort is funded by NASA and freely distributed by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison. This presentation will include a description of the current suite of MODIS, AMSR-E and AIRS science product software packages concentrating on the recent release of a completely repackaged MODIS Level 2 suite as well as a number of IMAPP product applications. Funding for this effort has been renewed through 2010; a number of new products including synergistic MODIS/AIRS retrieval algorithms and numerical weather prediction models that assimilate IMAPP products will be included in future package releases.
International Polar Orbiter Processing Package (IPOPP)

John Overton, Bill Thomas, Patrick Coronado, Kelvin Brentzel, Liam Gumley, Allen Huang

The International Polar Orbiter Processing Package is a software package that is critical to the Direct Broadcast (DB) user community throughout its transition from EOS to NPOESS. IPOPP is the primary processing package that will enable the DB community to process, visualize, and evaluate NPOESS Preparatory Project (NPP) Sensor and Environmental Data Records

Why is IPOPP Needed?

- Meets high expectations by DB community for mission continuity from EOS to NPOESS
- Integrates Multi-disciplined science processing packages such as IMAPP (Atmosphere), SeaDAS (Ocean) and MODIS Land Rapid Response (Land)
- Provides DB community with user friendly processing packages for global as well as regional optimized value added applications
- Enables global feedback loop for NPP CAL/VAL campaigns
- Enable DB users to contribute their regional validated processing approaches/products to assist and improve global CAL/VAL efforts
- Initiates role of research to operations provider for Direct Readout Mission
- Facilitates the adoption/adaptation of DB regional optimized research/unique processing approaches to enhance functionality and capability
- Enables industry to productize government provided algorithms into commercial product lines which offer choice to all users

Who is the DB Community?

AAPP developments and experiences with processing MetOp data

Nigel Atkinson, Pascal Brunel, Philippe Marguinaud and Tiphaine Labrot

Version 6 of the ATOVS and AVHRR Preprocessing Package (AAPP) was released in October 2006, shortly before the launch of the MetOp-A satellite. The talk will describe the capabilities of the software and give examples of its use in an operational context. Data types now processed by AAPP include: - direct broadcast HRPT from NOAA satellites - Level 0 files from MetOp AHRPT (AMSU, MHS, HIRS, AVHRR, IASI) - global level 1b ATOVS data from NOAA - global ATOVS and IASI data from EUMETSAT (BUFR format) - global MetOp and NOAA-18 AVHRR data from EUMETSAT (EPS format) - regional ATOVS data (BUFR format - e.g. EARS and RARS) During the commissioning phase of MetOp-A the Level 0 processing capabilities of AAPP were fully tested, including the IASI local processor OPS-LRS. Unfortunately the MetOp-A AHRPT primary transmitter failed on 4th July 2007, so there has been no Level 0 data since then. At the Met Office, assimilation of IASI data became operational in November 2007. This is using an AAPP-based preprocessor in which AMSU is mapped to the IASI grid and the IASI data are thinned spatially and spectrally via a channel selection. Principal Components compression is also available, and to support this an updated set of eigenvectors has been made available to users, based on 6 months of IASI data. The talk will describe the properties of these eigenvectors. Another activity in which AAPP is a key component is the WMO initiative to develop Regional ATOVS Retransmission Services (RARS). Two networks have come on-line during 2007 - the Asia-Pacific RARS and the South American RARS. These complement the EARS network established by EUMETSAT in 2002. RARS data have been operationally assimilated at the Met Office since November 2007. Also the data quality is monitored routinely by the NWP SAF and a selection of results are made available on the NWP SAF web site. Finally, the next major release of AAPP is planned to coincide with the launch of NPP (late 2009). AAPP will not process the direct broadcast data directly but the intention is that it will be able to read the level 1 ATMS/CrIS/VIIRS products from IPOPP (being developed by NASA and the University of Wisconsin), as well as the global ATMS/CrIS radiances to be distributed by NOAA.
The Space Science and Engineering Center (SSEC) at the University of Wisconsin-Madison operates an EOS Direct Broadcast ground station which receives data in real time from the Terra and Aqua spacecraft. Data from the MODIS, AIRS, AMSU, and AMSR-E instruments are processed in real time to create a range of products. Recently, the National Weather Service (NWS) in the US Central Region has started to use several of the real time MODIS products from SSEC in their forecast operations. In addition, the NWS office at Kennedy Space Center is now using real-time products to support NASA Space Shuttle launch, abort, and landing operations. This presentation will provide an overview of the DB processing infrastructure at SSEC, starting from acquisition of raw satellite data, through product generation on a cluster computing system, to product dissemination via the NWS Advanced Weather Interactive Processing System (AWIPS) at NWS forecast offices. Examples of NWS applications for EOS real-time products will be presented, including nighttime fog detection, daytime high temperature forecasting, and precipitation type and duration forecasting.
McIDAS-V - A powerful data analysis and visualization tool for multi and hyperspectral environmental satellite data *

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ABSTRACT
The Man-computer Interactive Data Access System (McIDAS) project began over 30 years ago at the University of Wisconsin-Madison to analyze and visualize data from the first generation of geostationary weather satellites. McIDAS continues to provide a strong data analysis and visualization capability for the current environmental satellites. However, the next generation of operational remote sensing instruments under development for the NPOESS and GOES-R programs require software tools with expanded capability and performance to support innovative techniques for developing algorithms, visualizing data and products, and evaluating results. A project is underway at SSEC to develop the fifth generation of McIDAS, a java-based, open-source system for multispectral and hyperspectral researchers and algorithm developers that will provide powerful new data manipulation and visualization tools to work in this data rich environment. NASA EOS MODIS and AIRS data as well as MSG SEVER1 and METOP IASI data are now being used in conjunction with in situ and gridded data to develop new analysis and product validation techniques in the McIDAS-V environment. This new data analysis and visualization system will support both researchers and operational users of the current and advanced measurement systems on environmental satellites.

INTRODUCTION
The Man-computer Interactive Data Access System (McIDAS) has its origins in the early 1970’s. The data analysis and visualization capabilities of this system are so powerful that even 35 years later, the software is used by many atmospheric scientists in research, operations and industry. Three years ago, scientists and programmers at SSEC formed a development team to bring the McIDAS concept to a modern and more versatile computing environment. Named McIDAS-V for the 5th generation of the McIDAS software, this evolutionary leap will provide powerful new capabilities for data analysis and visualization to support scientists developing products for the next generation of environmental satellites.

The requirements for McIDAS-V include full support for current generation McIDAS users, easy installation, an easy to use interface, powerful data analysis tools, access to a wide array of weather satellite and other environmental data, and high quality documentation and training materials. The software is open source and freely available. The development path of McIDAS-V integrates the following software tools and new ideas into its’ environment.

VisAD – Visualization for Algorithm Development
IDV – Integrated Data Viewer
HYDRA - HYperspectral-viewer for Development of Research Applications
McIDAS-X to -V Bridge – moving output to the new McIDAS environment
New Development – building new tools for researchers

The following paragraphs provide information and references on each McIDAS-V component.

* This article was modified (3/09) to bring the information up to date.
VisAD
The foundation of McIDAS-V is the Visualization for Algorithm Development (VisAD), an open source, Java™ library for building interactive and collaborative data analysis and visualization tools. Developed by Bill Hibbard at UW-Madison/SSEC in the 1990’s, VisAD (http://www.ssec.wisc.edu/~billh/visad.html) is used by a wide variety of scientists and others seeking a powerful data analysis software tool. VisAD combines several important attributes, including
* the use of Java for platform independence,
* a powerful mathematical data model that embraces virtually any numerical data set
* a general display model that supports 2-D and 3-D displays, including multiple data views with direct manipulation
* metadata that is integrated into each data object
* adapters for multiple data formats (netCDF, HDF-5, FITS, HDF-EOS, McIDAS, Vis5D, etc.)
and access to remote data servers through HTTP, FTP, DODS/OPeNDAP, and OPENADDE protocols

IDV
The Integrated Data Viewer (IDV) is also an open source, Java based software framework developed at Unidata that builds upon the VisAD library to provide a versatile data analysis and visualization toolkit for geoscience data. The IDV brings together the ability to display and work with satellite observations, surface and upper air (radiosonde) observations, gridded data, and radar and profiler data, all within a unified interface. The VisAD/IDV visualization capability provides 3-D views of the atmosphere and allows users to interactively slice and probe the data, creating cross-sections, profiles, animations and value read-outs of multi-dimensional data sets. The software is freely available from Unidata (http://www.unidata.ucar.edu/software/idv/) under the terms of the GNU Lesser General Public License. Figure 1 shows an example of a 3 dimensional rendering of temperature and wind fields over the U.S., while Figure 2 shows an IDV display of data from consecutive overpasses of A-Train instruments MODIS and CALIPSO.

Figure 1: IDV rendering of color enhanced 850mb temperature field with 3D wind field greater than 50 kts.
HYDRA

The Hyperspectral Data Research Application (HYDRA), is a powerful software toolkit developed by SSEC scientists to interrogate multi and hyper spectral satellite data. This tool allows scientists to interactively work with the data, displaying radiance spectra, multi-band imagery, scatter plots and transects. HYDRA was developed for scientist use with aircraft Scanning HIS and EOS AIRS observations, and has also been applied to EOS MODIS, MSG SEVIRI, and METOP IASI data. With the forthcoming NPP/NPOESS and GOES-R programs in the U.S., the HYDRA data interrogation capability is a key feature to add to McIDAS-V. Integration of HYDRA functionality into McIDAS-V was recently completed. Two examples of HYDRA capabilities are shown below. In Figure 3, the McIDAS-V HYDRA display shows the user has selected a METOP IASI granule (top), and the user has selected two locations on the image to display the full IASI spectra (bottom). The user can move the slider bar on the spectra display to change the image in the top display, thereby allowing powerful user interaction with the entire IASI granule data.
Figure 3: McIDAS-V HYDRA displays of a METOP IASI granule window channel image (top) and user selected locations for display of the associated spectra for that field of view.

In Figure 4 simulated data from the forthcoming GOES-R Advanced Baseline Imager (ABI) is displayed. The simulated data sets help algorithm developers to develop products for immediate use upon launch and operational deployment of space-based instruments. The left panel of this McIDAS-V display shows an image from the ABI band 14 (11 um); the center panel shows an image of the differences between band 14 and band 11 (8.5 um) and the right panel shows a scatter plot from the two images; the X-axis is the 11 um brightness temperature and the Y-axis is the difference between band 14 and band 11 (BT14-BT11). Differencing these two channels enables the scientist to separate water cloud from ice cloud. The McIDAS-V user can use the cursor to draw a rubber band box over a region, such as off the west cost of California, to display those pixels in the scatter plot corresponding
to those within the box. The user can also draw a rubber band box in the scatter plot and colorize the pixels in the image. This type of data interrogation tools allows users to interactively examine single pixel brightness temperature values for a spectral band or combination of spectral bands.

These types of display demonstrate how HYDRA capabilities in McIDAS-V can assist scientists in interrogating data and in developing useful products from current and forthcoming advanced remote sensing instruments. Integrating HYDRA into McIDAS-V will connect this powerful interrogation tool with the many features of the VisAD/IDV.

Figure 4: The user has selected two GOES-R ABI spectral bands (left and center) and displayed a scatter plot of the channel differences vs. one channel brightness temperature. The user can identify a group of pixels with the cursor and color enhance those pixels on the imagery or within the scatter plot, thereby identifying specific features from the data.

The X TO V BRIDGE

An additional and crucial part of the McIDAS-V development is how to support the current McIDAS-X user community in their migration to McIDAS-V. McIDAS-X, the 4th generation, was created in the early 1990’s to operate on computers running the uni’X’ operating system. McIDAS-X contains over 1 million lines of software, written primarily in the Fortran and C programming languages, that produces a tremendous amount of functionality. Many McIDAS-X users have developed their own software that adds additional functionality to meet their specific needs. In developing McIDAS-V it was evident that all this code and all the functionality could not be rewritten in Java … there would need to be another solution. That solution was a two-way communication between McIDAS-V and a session that was running McIDAS-X. The ‘Bridge’ between -X and -V includes a data chooser that communicates with a McIDAS-X “listener”, providing a bridge between the two systems. Commands initiated from within McIDAS-V are run in McIDAS-X and the results are visualized in the McIDAS-V environment. This allows sites to continue to use McIDAS-X (including locally developed code) while transitioning to McIDAS-V.

The McIDAS-X listener allows outside clients to communicate with a running McIDAS-X session via an arbitrarily assigned network port. Text commands are executed as if they were typed into the McIDAS-X command window and frame contents are returned as either GIF89a formatted images or as raw pixel values. Raw binary data (frame data, words from shared memory and files in MCPATH) can be requested as well.

Figure 5 shows a McIDAS-V session running on the top of the screen, and a McIDAS-X session running on the bottom. Using the Listener, a GOES image in native resolution is brought into –V, the projection was changed to account for the GOES E-W oversampling and the Milwaukee Sullivan
level 2 radar was overlaid. This figure demonstrates the ability to bring an –X image and data into –V and the powerful new capabilities of –V to add 3-dimensional information.

Figure 5: McIDAS-V session on top and McIDAS-X session on bottom. The GOES image from McIDAS-X is acquired by the McIDAS-V session through the “Bridge” and displayed with coordinate transformation and level 2 radar data.

SUMMARY AND FUTURE WORK
McIDAS-V is a software ensemble containing many features. It builds upon 10+ years of VisAD and several years of IDV development to enhance functionality. McIDAS-V will integrate the multi and hyperspectral satellite data capabilities from HYDRA and allow a two-way dialog with a McIDAS-X session to make available those data and products. On top of these powerful attributes are improved data and server management, and a friendly and user configurable interface. Finally, since the software is freely available and open source, we will add our own and our collaborators improvements to continue to evolve the capabilities of the software.

At the annual American Meteorological Society (AMS) meeting in January 2009, a beta version of McIDAS-V was released and demonstrated to the general public. Several new features in McIDAS-V include increased HYDRA functionality and capability with additional data types, a new chooser layout updated for consistency, and additional local image servers. The beta version of the McIDAS-V User’s Guide has been released, as well as the introduction of a support forum. The initial full version release of McIDAS-V is scheduled for summer 2009. Check the McIDAS-V web page for information regarding the release and the McIDAS-V support forum (http://www.ssec.wisc.edu/mcidas/software/v/).
Passive Microwave Protection: Results of WRC-07 and Future Work Plan

Jean Pla

The microwave passive frequency bands that are essential for the retrieval of physical parameters such as soil moisture, ocean salinity, water vapour content, temperature from the ground up to the atmosphere or Earth’s surface are divided into two categories of frequency bands according to the international regulation (Radio Regulation or RR) and fall within the category of Earth Exploration Satellite Service or EESS (passive). These data are collected through the use of passive radiometers mounted on satellite platforms. Purely exclusive frequency bands are dedicated to passive services only: in those bands, sharing is not possible since “all emissions are prohibited”. Shared frequency bands have the characteristics to have both passive services and active services. The last World Radio Conference took place in November 2007 (WRC-2007) and essential results have been obtained concerning the protection of some passive bands: limits and levels for in band sharing for the shared frequency bands 10.6-10.68 and 36-37 GHz with Fixed and Mobile Service, limits and levels for out of band emissions for exclusive passive frequency bands (1400-1427 MHz, 23.6-24 GHz, 31.3-31.5 GHz and 50.2-50.4 GHz). The paper will explain the main results obtained at the last WRC-07 concerning those frequency bands. The last WRC-2007 conference also provided the agenda for the next WRC-2011. Two items will need to be discussed at the next ITSC Conference. Agenda item 1.8 deals with regulatory issues relative to the fixed service between 71 and 238 GHz. The protection of the passive bands within this frequency range will be addressed. The first frequency band that is under consideration is the 86-92 GHz exclusive band that is widely used by many passive sensors. Technical compatibility activity with nearby active services are currently on going. However, in addition to this essential activity, it is necessary to answer the following question: if the proposed limits, which are based on international agreed recommendations for the protection of microwave passive sensors, are exceeded, what are the actual consequences in terms of reliability of the weather forecasting, climatology and monitoring of the environment? Preliminary work has been done in some cases, but it will be necessary to draft a precise future workplan, with a focus on some frequency bands, especially for example the 86-92 GHz band which is under consideration within ITU-R. Other frequency bands will also be discussed. Agenda 1.6 will address the passive bands between 275 GHz and 3000 GHz. Space and meteorological agencies are invited to provide all elements concerning their future needs and usage.
about these frequencies. Passive bands need to be reviewed and clearly identified, without any firm allocation.
The efforts of the (international) Space Frequency Coordination Group (SFCG) and International Telecommunications Union-Radio (ITU-R) prompted the conduct of a NOAA Passive Sensing Workshop last year. The workshop’s objective was to finalize the results of two previous workshops. It also focused on the introduction and discussion of technical papers on the identification, evaluation and utilization of particular passive sensing microwave bands, emphasizing bands above 275 GHz. This paper summarizes the workshop and provides a table which is an initial guide for updating ITU-R recommendations RS.515, RS.1028, and RS.1029. Workshop attendees recommended several changes and some additions to the existing table. Variables addressed were vegetation biomass, cirrus cloud, ice water path, cloud ice, cloud liquid water, height and depth of melting layer, precipitation, soil moisture, and the water vapor profile. Observations of these variables spanned the range of 1.37 to 882 GHz. It is hoped that the presentation of these workshop results will lead to discussions of needs for additional table entries as the changes to the ITU-R recommendations go forward.
SSMIS Calibration Anomalies: Observed F-16 and F-17
Anomalies, Detailed Analysis of the Root Causes, and the
Path Forward

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and D. Boucher

Detailed descriptions and comparisons of the observed F-16 and F-17 SSMIS
radiometric calibration anomalies uncovered during the Calibration and Validation
(Cal/Val) efforts are presented. As previously described for F-16, two principal
anomalies were detected: an intermittent solar intrusion to the warm load calibration
target; and reflector emission due to solar heating of the reflector face itself. The
solar intrusion anomaly is readily evident in the time series of the individual channel
radiometer gains, and can result in as much a 1.5 K peak depression in the observed
scene temperatures. A Fourier based filtering mitigation strategy has been
implemented to perform the gain filtering in the SSMIS ground processing software
for the sensor data records (SDRs). Performance of the F-17 hardware modifications
designed to inhibit the direct solar intrusions is presented. The reflector emission bias
is a function of both the frequency dependent reflector emissivity and the difference
between the reflector face and Earth scene temperatures. Warm biases of 1-2.5 K in
the 50-60 GHz channels and up to 5 K in the high frequency channels (150-183 GHz)
are observed. These anomalies correspond to reflector emissivities of ~0.015 at 50
GHz to as high as 0.07 at 183 GHz. For F-16 the reflector thermal cycle and resulting
emission anomaly is driven by earth and/or spacecraft shadow, and is a maximum
when the reflector face is directly illuminated by the sun. F-17 is in the terminator
orbit configuration and shading due to the solar panel array dominates the thermal
cycle of the SSMIS main reflector. Investigations were performed to directly measure
the effective surface electrical conductivity of the main reflectors to determine the
root-cause of the apparent high emissivities. Techniques were developed to perform
laboratory measurements of the remaining SSMIS flight-unit reflectors have indicated
the feasibility of low surface electrical conductivities of the F-16 and F-17 reflectors
(i.e. less than 1.0 MS/m) compared with pure aluminum (36 MS/m). Low
conductivities were also evident on the reflectors intended for use on other precision
space-based microwave radiometer systems. Procedures to determine the electrical
conductivity of the reflectors are now part of the pre-flight analysis for future SSMIS
instruments. Methods have also been developed to strip existing coatings and re-
coat the reflectors to meet the necessary electrical conductivity criteria (~18 MS/m)
for a negligibly emissive reflector. The main reflector of the third SSMIS instrument
(F-18) scheduled for launch in mid 2008 has been replaced with a spare reflector having significantly higher conductivity (17-18.5 MS/m) is expected to reduce the on-orbit reflector emission to a negligible level.
IASI Performances on MetOp-A after one year in orbit

Denis Blumstein, Eric Péquignot, Bernard Tournier, Roger Fjortoft, Lars Fiedler, Ines Gaudel, Claire Baque, Laurence Buffet, Thierry Phulpin, Carole Larigauderie

The Infrared Atmospheric Sounding Interferometer (IASI) is a key element of the payload embarked on METOP series of European meteorological polar-orbit satellites. IASI provides very accurate information about the atmosphere, land and oceans for weather predictions, climate and atmospheric chemistry studies. IASI measurements is designed to retrieve temperature and humidity profiles with a vertical resolution of one kilometer and an average accuracy of one Kelvin and 10 %, respectively. The IASI measurement technique is based on passive IR remote sensing using a precisely calibrated Fourier Transform Spectrometer operating in the 3.7 – 15.5 \(\mu\)m range and an associated infrared imager operating in the 10.3-12.5 \(\mu\)m range. The optical configuration of the sounder is based on a Michelson interferometer. Interferograms are processed by the onboard digital processing subsystem which performs the inverse Fourier Transform and the radiometric calibration. The integrated infrared imager allows the coregistration of the IASI soundings with the AVHRR imager onboard METOP. The first METOP satellite was successfully launched on the 19th of October 2006. The first interferogram was received at the CNES IASI TEC on the 27th of November 2006 and the first spectra were produced on board 2 days later. Dissemination of the data by Eumetsat began on the 24th of May 2007 in trial dissemination mode and was declared operational the 26th of July 2007 by Eumetsat and CNES. This paper provides an overview of the status of the instrument after 18 months in orbit and summarises the radiometric, spectral and geometric performances of the IASI instrument observed during this period. The spectral calibration is better than 2.10^{-6} and the radiometric absolute calibration is better than 0.5 K at 280K. There is no detectable evolution of these performances with time. In addition to the planned long term availability of the measurements (more than 15 years), this stability shows that IASI data are very well suited to calibrate other sensors and a reliable source of information for climate monitoring. Some slight evolutions of the Level 1 processing algorithms are nevertheless proposed for day 2 following some recommendations provided by the users, in particular at the Anglet Conference, and to facilitate the monitoring of the IASI performances by the TEC. An overview of these evolutions is provided. A companion paper presents the Near Real Time monitoring of the Level 1 IASI products at EUMETSAT and the anticipated improvements of these products for day 2.
The Infrared Atmospheric Sounding Interferometer (IASI) is part of the payload of Metop-A, the first of three satellites of the EUMETSAT Polar System (EPS). METOP-A was launched on 19th of October 2006. The IASI instrument has been switched on the 26th of October 2006 and generated the first interferogram on the 27th of November 2006. EUMSTAT started the trial dissemination of IASI L1 products on the 24th of May 2007. The IASI L1 products have been declared operational at the 26th of July 2007 by EUMETSAT and CNES after intensive evaluation during the Cal/Val period. The product quality of IASI L0 and L1 products are monitored in near real time (NRT) at EUMETSAT. This paper gives an overview of the NRT monitoring concept. Results from the first 9 month of IASI L1 operational data processing and NRT monitoring at EUMETSAT are presented. Results from radiance monitoring based on the RTIASI model using NWP forecast data as input are given. EUMETSAT and CNES are currently preparing the so-called Day 2 products content for the IASI L1 products. It is foreseen to start operational processing of Day 2 IASI L1 products at EUMETSAT in 2009. The anticipated improvements of the IASI L1 products will be presented.
IASI Level-2 Product Processing at EUMETSAT

Peter Schlüssel, Thomas August, Arlindo Arriaga, Xavier Calbet, Tim Hultberg, Olusoji Odeleye

The IASI (Infrared Atmospheric Sounding Interferometer) Level 1C data are processed in near real time to Level 2 (geophysical products) in the EUMETSAT Polar System's Core ground segment and disseminated to the users via the EUMETCast system. The Level-2 processor ingests the IASI data along with information from the companion instruments AVHRR (Advanced Very High Resolution Radiometer), AMSU-A (Advanced Microwave Sounding Unit A), and MHS (Microwave Humidity Sounder). The processor functionality can be broadly broken down into three parts, the pre-processing, the cloud-detection, and the retrieval step. The level 2 processing starts with a pre-processing. The processing options are read from a user-configurable auxiliary data set. All necessary data are accepted from the input streams and are checked for availability, validated against thresholds, and co-located on IASI footprints by interpolation or nearest match-up. A radiance tuning is applied to the IASI spectra to account for biases between the natural and the modelled radiative transfer. A number of cloud detection tests are executed, based on IASI data alone, or using IASI in combination with AVHRR and/or ATOVS. The AVHRR scenes analysis is used to determine cloud amount, cloud height distribution, and the number of cloud formations within an IASI field of view. If clouds are detected, a CO2 slicing method, adapted for the use with interferometric data, is applied to determine cloud height and amount. The cloud phase is determined by applying thresholds on brightness-temperature differences in the infrared window. Flags are generated or updated to reflect the cloud situation and to modify the choice of the retrieval method accounting for the actual cloud condition. Different retrieval types are utilised, chosen according to data availability and cloud conditions. In the cloud-free case the parameters to be derived are temperature and water-vapour profiles, ozone amounts in deep layers, columnar amounts of carbon monoxide, methane, and nitrous oxide, surface temperature, and surface emissivity at different wavelengths. In cloudy situations, the number of retrieved parameters can change according to cloud amount and user choice. It is foreseen that parameters are derived above clouds only or in case of low cloud amounts, that a cloudy retrieval is performed. The retrieval techniques implemented are statistical retrievals based on EOF regression and artificial neural network methods for the first retrieval, and a variational Marquardt-Levenberg method employing a sub-set of IASI channels. It is possible that different choices can be made depending on the parameter to be
derived and on cloud condition. The processor is being optimised and validated with data from short-range NWP forecast and dedicated field campaigns.
Spectroscopic database GEISA-2008 edition: content description and assessment through IASI/MetOp flight data

N. Jacquinet-Husson, V. Capelle, L. Crépeau, N.A. Scott, R. Armante, and A. Chédin

The principal purpose of spectroscopic parameter compilations, in spectroscopic databases, is to provide the necessary molecular absorption input for transmission and radiance codes. In this context, GEISA (Gestion et Etude des Informations Spectroscopiques Atmosphériques: Management and Study of Spectroscopic Information), initiated in 1976, is a computer-accessible spectroscopic database, designed to facilitate accurate forward radiative transfer calculations using a line-by-line and layer-by-layer approach. Remote sensing of the terrestrial atmosphere has advanced significantly in recent years, and this has placed greater demands on the compilations in terms of accuracy, additional species, and spectral coverage. Actually, the performance of instruments like AIRS (Atmospheric Infrared Sounder - http://www-airs.jpl.nasa.gov/), in the USA, and IASI (Infrared Atmospheric Sounding Interferometer -http://earth-sciences.cnes.fr/IASI/) in Europe, which have a better vertical resolution and accuracy, compared to the previous satellite infrared vertical sounders, is directly related to the quality of the spectroscopic parameters of the optically active gases, since these are essential input in the forward models used to simulate recorded radiance spectra. Currently, GEISA is involved in activities related to the assessment of the capabilities of IASI through the GEISA/IASI database derived from GEISA. Since the Metop (http://www.eumetsat.int) launch (October 19th 2006), GEISA/IASI is the reference spectroscopic database for the validation of the level-1 IASI data, using the 4A radiative transfer model (4A/LMD http://ara.lmd.polytechnique.fr; 4A/OP co-developed by LMD and NOVELTIS - http://www.noveltis.fr/) with the support of CNES (2006). The updated 2008 edition of GEISA (GEISA-08), a system comprising three independent sub-databases devoted, respectively, to line transition parameters, infrared and ultraviolet/visible absorption cross-sections, microphysical and optical properties of atmospheric aerosols, will be described with special emphasize given to GEISA/IASI. Results of critical assessments of the spectroscopic databases such as GEISA, HITRAN and MIPAS, in terms of spectroscopic line parameters archived will be presented. Spectroscopic parameters quality requirement will be discussed in the context of comparisons between observed or simulated Earth’s atmosphere spectra. GEISA is implemented on the CNES/CNRS Ether Products and Services Centre WEB site.
(http://ether.ipsl.jussieu.fr), where all archived spectroscopic data can be handled through general and user friendly associated management software facilities. More than 350 researchers are registered for on line use of GEISA.

References:


Joint Airborne IASI Validation Experiment (JAIVEx) - An Overview


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Abstract:
The Joint Airborne IASI Validation Experiment (JAIVEx) was held during April and May 2007. Seven days of coincident MetOp satellite IASI and WB-57 aircraft NAST-I/S-HIS interferometer data were obtained over the DoE ARM CART-site and the Gulf of Mexico. Under flights of the NASA A-train of satellites were conducted on five of the mission days. Coincident dropsondes and remote sensing surface and atmospheric data were provided by the UK BAe-146 aircraft, which under flew the MetOp, A-train, and WB-57. An overview of the JAIVEx field program, and an example use of the JAIVEx data set, is presented.

1. Introduction

Airborne field campaigns are essential for the calibration validation of new satellite sounding systems, which have very high radiometric and geophysical product accuracy requirements. It is only through aircraft missions that near time and geographical location coincidence can be achieved with the spatial resolution of the satellite measurements to be validated. The aircraft payload must consist of well-validated and SI-traceable “state-of-the-art” remote sensing spectrometer and in-situ vertical profile measurement systems in order to validate the satellite radiance measurements, and the geophysical products derived from them, to within the satellite measurement resolution and accuracy objectives.

The specific objectives of airborne calibration validation campaigns are: (1) radiometric and spectral calibration of satellite sensors, (2) cross-validation of sensors in different orbit, (3) validation of forward radiative transfer models used for retrieval of geophysical variables, and (4) the provision of accurate in-situ and well calibrated ground-based, airborne and satellite radiance data sets. The airborne campaign data sets are crucial for the achievement of objectives 1,2, and 3 above, as well as for conducting studies to define limitations of current sensing techniques and to define more optimal sensing approaches. The campaign data sets can also be used to simulate instrument measurements and validate processing algorithms intended for future satellite systems. Regional Observing System Experiments (OSEs), conducted to define NWP impact of current and simulated future satellite systems, can also be performed with these airborne calibration validation campaign data sets.

The unique contribution of the airborne component of these campaigns is that it provides simultaneous, independent, and SI traceable, radiance measurements for absolute radiometric and spectral calibration validation of satellite sensors. The airborne radiance measurement data can also be used as a transfer standard for cross-validation of sensors in different orbits at more than a very limited number of polar latitudes. The aircraft sensors and flight patterns...
enable near simultaneous in-situ and remotely sensed geophysical variables that characterize the entire footprint of the satellite sounder as needed for the validation of satellite products and the forward radiative transfer models used for their derivation. In summary, the high spatial resolution, coupled with the high spectral resolution, of the aircraft interferometer radiance measurements enable a complete characterization of the satellite radiance measurement characteristics and their impact on the accuracy and spatial resolution of the derived products.

2. Joint Airborne IASI Validation Campaign (JAIVEx)

The Joint Airborne IASI Validation Experiment was a joint USA and European calibration validation campaign in support of the NPOESS and MetOp series of operational satellites. Although all measurements on the MetOp-A and A-train satellites are of interest, the focus of JAIVEx was on the validation of radiance observations and meteorological products from the Infrared Atmospheric Sounding Interferometer, IASI. Launched on MetOp-A on 19 October 2006, IASI is the first of the advanced ultra-spectral resolution temperature, humidity, and trace gas sounding instruments to be flown as a component of the Joint Polar System (JPS) of NPOESS and MetOp operational satellites. The objective of the JPS is improved weather, climate, and air quality observation and forecasting. IASI measures radiation emission from the surface and atmosphere in the 645 – 2760 cm\(^{-1}\) (i.e., 3.6-15.5 µm) spectral band with high spectral resolution (i.e., 8461 spectral channels with a spacing of 0.25 cm\(^{-1}\)). As MetOp-A orbits overhead, IASI scans the Earth between ± 49° providing a swath of data across the Earth of 2132 km. The scan swaths are made with a frequency to provide contiguous coverage across the Earth’s surface as the satellite orbits overhead. Seven consecutive orbits, each with a 101 minute period, provides total Earth coverage every twelve hours. The aircraft employed for the JAIVEx were the NASA WB-57 and the FAAM BAe-146. The primary sensors on board the WB-57 were the NPOESS Airborne Sounding Testbed - Interferometer (NAST-I) and the Scanning High resolution Interferometer Sounder (S-HIS) spectrometers. The spatially scanning NAST-I has a spectral resolution and spectral coverage similar to the IASI, as described above, but with a horizontal resolution of 2 km from the WB-57 flight altitude. The S-HIS has approximately the same spectral coverage as IASI and spatial resolution of NAST-I but with a spectral resolution of 50% of that of IASI and NAST-I. The aircraft base location, dates of the experiment, satellite, airborne, and surface resources being used for JAIVEx, participants, and sponsors in figure 1.

Figure 1: An overview of the JAIVEx resources, participants, and sponsors. A more complete description of the sensors can be found in the publication describing the European AQUA Thermodynamic Experiment (EAQUATE).
3. Flight Missions

The surface targets of the calibration validation flight missions were the U.S. Department of Energy (DoE) Southern Great Plans (SGP) Atmospheric Radiation Measurement (ARM) facility in north central Oklahoma and the Gulf of Mexico. The ARM facility is well instrumented with in-situ and ground based remote sensors, as desired for meteorological product validation, while the Gulf of Mexico provides a relatively uniform surface background, as desired for spectral radiance measurement validation. One important goal of the JAIVEx was to inter-compare MetOp-A operational measurement capability with that provided by the A-train of advanced NASA research satellites. (The A-train consists of the Aqua, Aura, Parasol, OCO, CALIPSO, and CloudSat satellites). Although the orbits of the MetOp and the A-Train are about four hours apart (MetOp-A being in a 09:30 descending orbit and the A-train being in a 13:30 ascending orbit), the aircraft missions were of a long enough duration to permit under flights of both the MetOp satellite and the A-train. The aircraft sensors were used as a relative calibration transfer reference for each of the satellite systems (e.g., the difference between MetOp and aircraft measurements being compared to the difference between A-train and aircraft measurements) in order to account for space and time difference between the measurements from the two satellite systems. This capability was particularly useful for characterizing the differences between the spectral radiance measurements and derived products from the Aqua AIRS and the MetOp IASI advanced sounding instruments. The figure below shows the flight tracks of the WB-57 aircraft during the JAIVEx missions. As can be seen, there were four flights over the ARM-site, 2 daytime and 2 nighttime, and three flights over the Gulf of Mexico, 2 daytime and 1 nighttime. There were a total of five joint MetOp and A-train under flights, 3-day time and 2-night time.

![Flight Tracks](image)

Figure 2. JAIVEx WB-57 flight tracks.

4. Radiometric and Spectral Calibration Validation of Satellite Sensors

The University of Wisconsin external blackbody used for the absolute calibration of the internal blackbodies of the S-HIS has been referenced to the International System of Units (SI) traceable National Institute of Standards and Technology (NIST) blackbody. Subsequently, the NAST-I internal blackbodies have been referenced to the NIST traceable UW external blackbody. Thus, inter-comparisons of the radiances measured with these
instruments with those measured with a satellite instrument provide an SI-traceable validation of the satellite observations.

Figure 3 below shows the intercomparison of the entire spectrum measured by the MetOp IASI with the radiances measured simultaneously by the NAST-I and S-HIS instruments over the SGP ARM-site on April 19, 2007. The spectral resolution of the IASI (0.25 cm⁻¹) and NAST-I (0.25 cm⁻¹) instruments was reduced to that of the lower resolution S-HIS (0.5 cm⁻¹) so that all three observations could be placed on a common spectral scale with a common Instrument Line Shape (ILS). As shown there is little difference between the three observations. The only significant differences shown are between the IASI and the aircraft measurements in spectral regions where there is a significant radiance contribution of the atmosphere above the aircraft flight level (~ 18 km) to the satellite measurements.

Figure 3. Comparison between time and space coincident IASI (black), NAST-I (blue), and S-HIS (red) radiance spectra, observed over the SGP ARM-site on April 19, 2007, processed to match SHIS spectral resolution. Discrepancies are due to radiance contributions to the IASI satellite measurements from the atmosphere above the NAST-I and SHIS aircraft altitude (~ 18 km).

The radiance contribution from the atmosphere above the aircraft can be accounted for using a Line By Line Radiative Transfer Model (LBLRTM) calculation based on two near simultaneous radiosonde observations, one launched one-hour before and the other at the time of the satellite overpass. The one-hour before launch enables coincidence between the balloon measurements and the satellite measurements in the upper atmosphere near the time of the overpass. By producing a calculated radiance spectrum for both the aircraft and satellite measurement levels, the difference between observation and calculation for both the satellite measurements and the aircraft measurements can be inter-compared. The difference between the satellite “observed minus calculation” and the aircraft “observed minus calculation” (i.e., the double difference) alleviates the influence of the atmosphere above the aircraft level on the intercomparison.

Figure 4 shows the result of this aircraft validation of satellite radiance measurement technique for a longwave spectral region. As shown, there is little difference between the IASI and the aircraft observations. The double differences were averaged over 50 cm⁻¹ intervals to minimize the effects of measurement noise in trying to establish the absolute accuracy of the IASI measurements. It is clearly seen that the absolute accuracy of the IASI measurements must be very good in order for their reduced spectral resolution values to agree to within 0.2 K of those observed by both the NAST-I and S-HIS instruments. Similar close
agreement (not shown here) was obtained throughout the remainder of the infrared spectrum measured by the satellite IASI and airborne NAST-I and S-HIS instruments.

Figure 4. Spectra showing the close correspondence between satellite and aircraft interferometer measurements corresponding to the longwave spectral band. The numbers are the mean differences over 50 cm⁻¹ wavenumber intervals.

2. Transfer Standard for Cross-Validation of Sensors in Different Orbits

The airborne spectral radiance data during JAIVEx was used to cross-validate MetOp IASI and Aqua AIRS radiances and derived sounding products. This cross-validation is otherwise difficult because of the four-hour time separation between the MetOp and Aqua orbits. However, with the aircraft interferometers, when the orbits nearly overlap geographically, the time variation of atmospheric radiance between orbits can be accounted for by inter-comparing the products from each satellite to aircraft observations of the same product obtained from time synchronized aircraft observations made over the same geographical regions of the satellite overpasses. As was noted earlier, there were a total of five joint under flights of the MetOp and the Aqua satellite.

Figure 5 below shows an example cross-validation of the MetOp IASI and Aqua AIRS radiances⁷. This figure shows false color latitude (25.5-27.5 N) cross-section of water vapor brightness temperature spectra (1540-1610 cm⁻¹), obtained near 90 W Longitude on April 29, 2007. The temporal variations indicated by the MetOp IASI (1550 GMT) and the Aqua AIRS (1919 GMT) observations are validated by the NAST-I radiance measurements obtained over exactly the same geographical regions sampled by each instrument nearly coincident with the overpass times of the Metop and Aqua satellites.
Figure 5. NAST-I, IASI, and AIRS False color latitude (25.5-27.5 N) cross-section of water vapor brightness temperature spectra (1540-1610 cm⁻¹) obtained near 90 W Longitude on April 29, 2007.

3. Validation of Forward Radiative Transfer Models

For the retrieval of atmospheric soundings from satellite radiance measurements the forward radiative transfer model used for this process plays a crucial role in that its accuracy limits the vertical resolution and absolute accuracy of the derived product. A “Fast-Forward Radiative Transfer Model (FFRTM) is generally used for the routine operational retrieval process in order for the processing to keep up with the real-time acquisition of the satellite data⁸.

Although there are many FFRTMs, many of them are based on a library of radiance spectra simulated using the Line By Line Radiative Transfer Model (LBLRTM)⁹, radio soundings, and the satellite Instrument Line Shape (ILS). Thus, it is important to validate the accuracy of the LBLRTM using the satellite data for which it is to be used.

Figure 6 shows the result of a validation recently performed¹⁰ using the April 19, 2007 JAIEx SGP ARM-site radiosondes and corresponding IASI radiance measurements. Two radiosondes, one launched 1-hour before the satellite overpass and one launch at the time of the satellite overpass, were blended together to portray the atmospheric state at the time of the satellite measurements. Small adjustments in surface skin temperature and emissivity, and a climate estimate of the ozone profile were made to eliminate obvious systematic differences between the observed and calculated radiance spectra due to uncertainties in these surface and atmospheric state parameters. As can be seen, the agreement between the calculation and the observation of the brightness temperature spectrum is exceptional, with the differences generally being less than 0.5 K. Relatively large, and spectrally random, differences occur in the shortest wavelength (i.e., longest wavenumber) region of the spectrum due to the increased IASI radiance measurement noise level in this particular region of the spectrum. This result provides confidence in both the accuracy of the IASI instrument radiance measurements and the fundamental radiative transfer models used to derive geophysical products from these measurements.

The JAIVEx data set is ideal for the validation of satellite profile retrieval techniques and the resulting satellite data product vertical resolution and accuracy. As an example, figure 7 shows retrievals produced from the JAIVEx data for the April 19, 2007 SGP ARM-site overpass data compared with the two radiosondes, one launched one hour before the satellite overpass time and the other at the time of the satellite overpass. The retrieval solution is the one-dimensional variational physical solution, using an initial profile produced by the EOF (i.e., empirical orthogonal function) regression methodology. A similar approach is used for the operational production of soundings from these data. The radiative transfer model used was LBLRTM, as validated above, and no bias corrections were used in the production of the sounding product. It is apparent that the expectation to be able to resolve fine scale vertical structure, including temperature and moisture inversions, with the ultra-spectral sounder (i.e., IASI), is fulfilled.
Figure 7. Comparison of a MetOp IASI retrieval with two ARM-site radiosondes, one released one hour before and the other at the time of the MetOp satellite overpass.

Another JAIVEx case, April 29, 2007 demonstrates that mesoscale spatial resolution atmospheric temperature and moisture features can be resolved with the IASI ultra-spectral resolution data. Figure 8 shows the mesoscale sounding area (delineated by the red box) over the Gulf of Mexico for which fine scale atmospheric structure, obtained from the encircled 96 IASI Field of View (FOV) radiance spectra, is shown as eight North to South cross-sections shown in figure 9. Each North – South cross-section (arranged to be from the left to right on each color insert of figure 9) was constructed from the 12 soundings obtained along each of the NNW to SSE lines of radiance spectra. In figure 9, the cross-sections are arranged in a West to East fashion so as to provide a three dimensional view of the atmosphere as observed by the IASI instrument. The panels on the far right of the IASI temperature and moisture cross-sections are cross-sections obtained from the Dropsondes launched from the BAe-146 aircraft, which were obtained within a one hour time period centered on the MetOp satellite overpass time. Although the cross-section for the closely spaced dropsonde data cuts across four of the IASI cross-sections (i.e., is not aligned with any one of the IASI cross-sections shown), it serves to validate the North to South variations retrieved from the IASI data below the aircraft flight level pressure altitude of 400 mb. As expected, the dropsonde cross-sections display somewhat smaller vertical scale features of the atmosphere than do the IASI retrievals, but the general correspondence between the fine scale spatial features is striking, particularly for moisture, considering the very small region of atmospheric variability being observed. For temperature, there appears to be more spatial coherence in the small scale spatial variability retrieved from the lower spatial resolution IASI spectra than can be deduced from the spatially independent point measurements of the dropsondes for this very small range of atmospheric temperature variation.
Figure 8. IASI footprints superimposed over a 10-12 μm infrared image showing the retrieval locations over the Gulf of Mexico on April 29, 2007 at 15:50 UTC. WB-57 aircraft flight track and BAe-146 Dropsonde locations are also shown.

Figure 9. Eight adjacent 3-degree (333km) North-South cross-sections of temperature (deviation from the mean for each pressure level) and relative humidity obtained near 91 W longitude over the Gulf of Mexico on 29 April 2007 (see figure 8). The West to East spacing of the NNE to SSE oriented cross-sections is approximately 25 km.

Finally, figure 10 shows the radiance measurement and retrieval residual characteristics associated with the 96 IASI spectra analyzed for this case. These retrievals result from a three-step process in which an eigenvector (EOF) regression retrieval (Regr.Retr.) is used as an initial profile for a two-step variational inverse physical solution of the radiative transfer equation for the temperature and moisture profile. The procedure is similar to that which has used for trace gas (e.g., CO) profile retrieval from NAST-I data\textsuperscript{12}. The first physical retrieval (Phys.Retr.-I) is obtained by solving for a water vapor profile perturbation of the EOF regression solution from the residuals of radiance calculated from the EOF regression retrieval, and that observed by IASI, by excluding uniformly mixed gas (e.g., CO\textsubscript{2} spectral channels from the retrieval process. The second, and final, physical retrieval (Phys.Retr.-II) is
obtained by solving simultaneously for both the temperature and water vapor profile perturbations from the EOF regression temperature profile and Phys.Reetr.-I water vapor profile using the entire spectrum (CO₂, “window”, and H₂O channels) of residuals between the calculated and observed radiances. The purpose of the three-step process is to alleviate the errors, which would otherwise result, from the highly non-linear nature of the water vapor inverse solution of the radiative transfer equation (i.e., the accuracy of the water vapor solution being highly dependent on the accuracy of the temperature profile solution). As can be seen, this procedure produces retrievals that minimize the retrieval radiance residuals to a level very close to the random error level of the measurements.

**Figure 10.** IASI radiance and retrieval residual statistics for the 96 retrievals used to produce the mesoscale sounding results shown in figure 9.

5. **Summary and Conclusion**

The JAIVEx was a very successful airborne calibration validation campaign. A unique collection of simultaneous satellite, surface-based, and aircraft in-situ and remote sensing measurements were acquired which can be used for the calibration validation of radiances and
derived products obtained from a large family of satellites in orbit and viewing the JAIVEx campaign measurement region (e.g., MetOp, A-train, and GOES).

Results from two of the seven JAIVEx observation days were shown as examples of how the data can be used for validation of observed and forward radiative transfer model calculated radiances and the geophysical products derived from them. It is concluded that the IASI radiance measurements are well within an absolute radiometric accuracy of 0.5K, as demonstrated through inter-comparisons with two independent airborne interferometer spectrometer systems SI traceable through their reference to a NIST standard calibration blackbody. It is also shown that the airborne interferometer spectrometer measurements can serve as a reference for the cross-validation of sensors in different orbits (e.g., IASI on MetOp and AIRS on Aqua). Near-simultaneous atmospheric profile measurements from radiosondes launched one-hour before and at the MetOp satellite overpass time have been used to validate the accuracy of the LBLRTM calculations relative to measurements from the IASI. The results indicate that the error resulting in LBLRTM calculations are close to the single sample random error level of the satellite measurements. Finally, the unique combination of JAIVEx radiosonde and dropsonde data has been used to demonstrate the fine scale vertical and horizontal atmospheric measurement capability of ultra-spectral sounding systems, such as the IASI validated here.

The JAIVEx data set is now available on two web-sites (http://cimss.ssec.wisc.edu/jaivex/ and http://badc.nerc.ac.uk/data/jaivex/). A DVD of data sets for five case study days (19, 28, 29, 30 April and 4 May, 2007) has been put together by the UK Met Office participants in the JAIVEx and is available, upon request, from Jonathan Taylor (jonathan.p.taylor@metoffice.gov.uk).

6. References


10. Clough, S.A. and his associates at the AER, (personal communication).


Retrievals with the Infrared Atmospheric Sounding Interferometer and validation during JAIVEx


The Joint Airborne IASI Validation Experiment (JAIVEx) was conducted during April 2007 mainly for validation of the IASI on the MetOp satellite. IASI possesses an ultra-spectral resolution of 0.25 cm⁻¹ and a spectral coverage from 645 to 2760 cm⁻¹. Ultra-spectral resolution infrared spectral radiance obtained from near nadir observations provide atmospheric, surface, and cloud property information. An advanced retrieval algorithm with a fast radiative transfer model, including cloud effects, is used for atmospheric profile and cloud parameter retrieval. This physical inversion scheme has been developed, dealing with cloudy as well as cloud-free radiance observed with ultraspectral infrared sounders, to simultaneously retrieve surface, atmospheric thermodynamic, and cloud microphysical parameters. A fast radiative transfer model, which applies to the cloud-free and/or clouded atmosphere, is used for atmospheric profile and cloud parameter retrieval. A one-dimensional (1-d) variational multi-variable inversion solution is used to improve an iterative background state defined by an eigenvector-regression-retrieval. The solution is iterated in order to account for non-linearity in the 1-d variational solution. It is shown that relatively accurate temperature and moisture retrievals can be achieved below optically thin clouds. For optically thick clouds, accurate temperature and moisture profiles down to cloud top level are obtained. For both optically thin and thick cloud situations, the cloud top height can be retrieved with relatively high accuracy (i.e., error < 1 km). Preliminary retrievals of atmospheric soundings, surface properties, and cloud optical/microphysical properties with the IASI observations are obtained and presented. These retrievals are further inter-compared with those obtained from airborne FTS system, such as the NPOESS Airborne Sounder Testbed – Interferometer (NAST-I), dedicated dropsondes, radiosondes, and ground based Raman Lidar. The capabilities of satellite ultra-spectral sounder such as the IASI are investigated.
Using JAVIEX data to evaluate the impact of PCA Noise Filtering on the High Spectral Resolution Physical Retrieval Algorithm

Paolo Antonelli, Dave Tobin, Bob Knuteson, Steve Dutcher, and Hank Revercomb

PCA has been demonstrated to be a powerful approach to characterize and reduce the random component of the instrument noise for high spectral resolution Grating and FTS infrared instruments. While the impact of a PCA based noise filter at radiometric level has been investigated quite extensively, its impact of the accuracy of the retrieved atmospheric variables is still unclear and not widely tested. By using S-HIS and IASI data collected during the JAVIEX field campaign, this work aims to evaluate the impact of the PCA-based noise filter on the accuracy of the Physical Retrieval Algorithm used to invert the radiances into the atmospheric variable space.
The Joint Airborne IASI Validation Experiment (JAIVEx) was based in Houston, Texas during April and May 2007. This dataset, combining collocated hyperspectral infrared radiance measurements and in situ sampling of the atmospheric state, has been used to validate IASI radiances and identify sources of error in the radiative transfer modelling. The calibration accuracy of IASI radiances is shown to be valid to within 0.2 – 0.3 K. Characterisation of surface emissivity and skin temperature is shown to be important for accurate radiative transfer modelling of IASI spectra over land. This dataset is available to the wider community for investigations into the exploitation of IASI data in numerical weather prediction.

1. Description of the campaign

The methodology underpinning airborne research studies into satellite calibration and validation is to characterise rigorously both the absolute upwelling atmospheric radiance and the state of the atmosphere (in particular fields of temperature and humidity). Temporal and spatial collocation of these measurements is important to minimise representivity errors. Airborne hyperspectral sounders have been demonstrated to be of particular benefit in constraining calibration errors and developing algorithms for retrieval of atmospheric state vectors (Taylor et al., 2008; Tobin et al., 2006).

The Joint Airborne IASI Validation Experiment (JAIVEx) brought together the UK Facility for Airborne Atmospheric Measurements (FAAM) BAe 146 aircraft and the NASA WB-57 high altitude research aircraft. Both are comprehensively instrumented airborne research platforms, well suited to satellite cal/val exercises of this kind. Flights of the two aircraft were coordinated with overpasses of IASI on the MetOp-A satellite. The campaign was based in Houston, Texas during April and May 2007, with sorties conducted over ocean (Gulf of Mexico) and over land (ARM Southern Great Plains facility, Oklahoma). This dataset can be exploited to test the absolute radiative accuracy of IASI and hyperspectral retrieval algorithms over different surfaces.
The FAAM aircraft instrument capabilities include:

- Airborne Research Interferometer Evaluation System (ARIES) measuring upwelling and downwelling infrared radiances at 1 cm\(^{-1}\) spectral resolution;
- Heimann broadband infrared radiometer for mapping surface temperatures;
- AVAPS dropsonde system, allowing profiles of temperature and humidity below the aircraft to be sampled at high spatial resolution;
- Onboard temperature and humidity probes for measuring in situ atmospheric conditions, and aerosol and cloud probes for measuring particulates;
- Onboard chemistry probes for measuring in situ atmospheric concentrations of trace gases such as ozone and carbon monoxide.

The WB-57 aircraft carries two state-of-the-art interferometers:

- Scanning High-resolution Interferometer Sounder (S-HIS) measuring upwelling and downwelling infrared radiances at 1 cm\(^{-1}\) spectral resolution;
- National Polar-orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounder Testbed – Interferometer (NAST-I) measuring upwelling radiances at 0.5 cm\(^{-1}\) spectral resolution (comparable to IASI).

Both of these interferometers are scanning cross-track, i.e. measure a swath below the aircraft in a similar way to IASI on MetOp. For flights over the Oklahoma ARM site there was additional profile information through the launch of radiosondes and ground-based lidar and interferometer measurements.

In the case studies described here only measurements within the same geographic area and small time window have been considered, to give maximum confidence that all measurements relate to the same atmospheric airmass. Exclusively clear sky fields of view for radiometric measurements have been analysed, as determined from onboard observations and MetOp AVHRR imagery.

### 2. Line-by-line simulations

Atmospheric profiles for input to a line-by-line radiative transfer code, representative of the observed radiances, were constructed in the following way:

1. The nearest collocated dropsonde profile was used for temperature and humidity below the FAAM 146 altitude (typically around 10 km);
2. Trace gas profiles for ozone and carbon monoxide were derived for this lower atmosphere range from in situ aircraft probes;
3. In the absence of closely coincident radiosonde observations, temperature and humidity for the upper atmosphere (above around 10 km) were derived from operational NWP model fields. Fields were available from both the Met Office and ECMWF global model forecast (run from the closest previous analysis). Ozone was available as a variable parameter from the ECMWF model.

4. The surface skin temperature was derived from Heimann radiometer measurements, coupled with spot retrievals of temperature and emissivity using ARIES hyperspectral radiances.

GENLN2 (Edwards, 1992) was used as the line-by-line code. Recent updates to spectroscopic parameters (HITRAN 2004) and the water vapour continuum (MT_CKD_1.0) were implemented in the simulations.

3. Gulf of Mexico case study 30 April 2007

A coordinated BAe 146 and WB-57 flight on 30 April 2007 was conducted over the Gulf of Mexico, with a coincident MetOp overpass at 1529 UTC. Figure 1 shows that the southwestern portion of the flight track was clear of cloud (confirmed by onboard observations), and the case study fields of view (FOVs) have been confined to this geographic area.

Figure 1: AVHRR channel 1 image (580-680 nm) from MetOp pass on 30 April 2007, overlaid with FAAM BAe 146 flight track and (white asterisks) selected clear IASI FOVs. The brightest parts of the AVHRR image show the presence of clouds due to solar reflection.
The FAAM BAe 146 launched several dropsondes in close time and space coincidence with the MetOp overpass. Figure 2 shows collocation of IASI and ARIES footprints in the clear air region together with four dropsonde profiles (all launched between 1519 and 1527 UTC, i.e. all were in the air during the overpass).

**Figure 2:** Collocation of observations during the measurement period. The diamond symbols denote (the centres of) individual instrument footprints on the ground, while crosses show the launch and splash coordinates of dropsondes, see legend.

Having carefully selected clear sky observations and collocated profile measurements, GENLN2 simulations were run for each of the four profiles (topped up with model fields); each interferometer field of view (FOV) was then matched to the nearest profile/simulation, and observed – calculated residuals computed. The average residuals are plotted in Figure 3 for the longwave spectral region. There are a number of points to note:

1. Due to the different altitudes of ARIES (around 10 km) and IASI (on MetOp) only IASI is sensitive to the upper atmosphere. There are therefore significant differences in the average spectra, particularly in bands sensitive to CO₂ and ozone.

2. The residuals generally lie within the ± 1 K level. Exceptions to this include the region above 1200 cm⁻¹ where the spectra are sensitive to methane (not measured during the campaign) and for IASI in the ozone band 1000-1100 cm⁻¹ which relies on
ozone concentrations from NWP models. The Met Office fields do not include variable ozone, hence climatological values have been used.

3. Apart from the ozone band, the Met Office and ECMWF fields used to “top-up” the tropospheric profiles derived from dropsondes give very similar results in the residuals plot for IASI in this spectral region.

4. Excluding the ozone band, the residuals in the 800-1200 cm\(^{-1}\) atmospheric window (sensitive mainly to sea surface emission and tropospheric water vapour continuum) are very small, on average \(-0.2\) K.

5. The window region residuals for ARIES and IASI differ by less than 0.1 K, giving confidence in the absolute calibration accuracy.

6. Larger residual errors in the modelling of IASI data are found in other spectral regions, e.g. the strong water vapour band around 1400-1800 cm\(^{-1}\). The reasons for this, related to the accuracy of model field data for the upper atmosphere, are discussed in detail in Newman et al., 2008.

Figure 3: (Upper panel) IASI and ARIES clear-sky upwelling brightness temperature spectra recorded on 30 April 2007. (Lower panel) residual differences (observed – calculated GENLN2 spectrum) for both Met Office and ECMWF upper atmosphere fields, see legend.

The good level of agreement between observed and calculated radiances in Figure 3 can be attributed to a well constrained atmospheric profile and surface characteristics coupled with good calibration performance of the interferometers. It remains to test whether the results are sensitive to the line-by-line code used. Figure 4 compares the GENLN2 with results generated
with the LBLRTM code (Clough, 2005). LBLRTM contains more recent updates to some key spectroscopic parameters, particularly CO\(_2\) line mixing. Figure 4 appears to show that LBLRTM is more successful than GENLN2 at reducing the size of residuals in the CO\(_2\) band between 700-770 cm\(^{-1}\). Other parts of the spectrum such as weak water vapour lines above 800 cm\(^{-1}\) are much less affected (similar HITRAN line parameters were used in both codes). In the remainder of this paper the GENLN2 code has been used for simulations; Figure 4 suggests that the performance of this code is sufficient for drawing conclusions about radiometric accuracy, e.g. in the atmospheric window region.

![Figure 4: (Upper panel) IASI clear-sky upwelling brightness temperature spectrum for 30 April 2007. (Lower panel) residual differences (observed – calculated) for GENLN2 and LBLRTM (see legend) using ECMWF reference profile for the upper atmosphere.](image)

### 4. Oklahoma case study 19 April 2007

A night-time flight was conducted on 19 April 2007 over the Oklahoma ARM CART site, with a coincident MetOp overpass at 0335 UTC. A north-south flight track was followed (Figure 5), and all available observations indicated that the atmosphere was clear of cloud at all levels. As in the previous case study, coincident interferometer and profile measurements were selected to obtain a self-consistent dataset for validation. Figure 6 summarises the observations for this case, with three dropsondes launched between 0320 and 0333 UTC. A radiosonde ascent from the ARM site at 0541 UTC was also available for independent profile information, albeit separated from the other measurements by two hours.
Figure 5: MetOp IASI radiances at channel 900 cm$^{-1}$ overlaid with FAAM BAe 146 flight track and (black asterisks) selected clear IASI FOVs. The position of the ARM CART site central facility is shown as the open circle. The variations in radiances are due to surface temperature and emissivity differences between FOVs.
Figure 6: Collocation of observations during the measurement period. The diamond symbols denote (the centres of) individual instrument footprints on the ground, while crosses show the launch and terminating coordinates of dropsondes and radiosonde, see legend.

The FAAM BAe 146 completed two runs at 1 km altitude either side of high level (8-9 km) measurements to coincide with the MetOp overpass. These low level runs are invaluable for retrieval of surface properties to be used as boundary conditions for line-by-line simulations. The methodology used to retrieve surface skin temperatures and spectral emissivity from ARIES observations is described in detail in Newman et al. (2005).

Briefly, a combination of upwelling and downwelling ARIES spectra are used to differentiate between the spectrally structured downwelling radiance and (assumed) spectrally smooth surface emission. The fraction of downwelling radiance reflected at the surface (and thereby present in the upwelling radiance) is retrieved over spectral bands in the 800-1200 cm$^{-1}$ region. This gives a coarse-resolution emissivity spectrum and simultaneously an estimate of surface skin temperature for each band. The average retrieved skin temperature is then used to derive an emissivity spectrum at full ARIES resolution.

Figure 7 shows the results of emissivity retrievals from the low level runs over the atmospheric window region. Note that principal component noise reduction has been applied to the ARIES radiances to facilitate the retrieval. There is a very broad spread of spectra, indicative of a mix of surface types in the Oklahoma region around the ARM site (largely arable land, a mix of vegetation and bare soil). The shape of the emissivity spectra with the lowest values, with an emissivity minimum around 1100 cm$^{-1}$, is characteristic of a
contribution by minerals in soil (R. Knuteson, private communication). Conversely, the ARIES footprints with a high fraction of vegetation exhibit a spectrally flat emissivity with values close to 1.0.

![Graph of emissivity retrievals from 4222 upwelling ARIES radiance spectra.](image)

**Figure 7:** Individual emissivity retrievals from 4222 upwelling ARIES radiance spectra. The superimposed black line gives the average emissivity over this set. The outliers with low emissivity values around 900 cm$^{-1}$ are believed to be real, consistent with artificial structures and buildings seen in the FAAM 146 downward-facing video footage.

The 800-1200 cm$^{-1}$ region is best suited to emissivity retrieval due to a combination of high instrument signal-to-noise and high atmospheric transmittance. It is possible also to retrieve emissivity in other spectral regions, though with noisier results. Figure 8 shows the average emissivity retrieved from the ARIES low level data, including regions beyond 2000 cm$^{-1}$. There is a signal for a lower emissivity at 2500 cm$^{-1}$ than at 1200 cm$^{-1}$.

Retrieval of surface skin temperature accompany those of emissivity (see Figure 9). There is a trend of decreasing temperature during the night, plausibly due to the effects of radiative cooling in clear sky conditions. In order to arrive at an average surface temperature value to be used in line-by-line simulations of interferometer radiances at the MetOp overpass time, the temperatures have been interpolated assuming a linear trend. This gives a representative surface skin temperature of 284.7 K. It should be noted that the standard deviation of the retrievals during each run is approximately 1.5 K; this may well be due to real variations in surface temperature, but underlines the uncertainties in this retrieved parameter.
Figure 8: Average emissivity retrieval from 4222 upwelling ARIES radiances, covering spectral regions with sufficiently high atmospheric transmittance for retrieval.

Figure 9: Retrieved surface temperature from ARIES data for 19 April 2007 case. Data for the two low level runs are interpolated to the overpass time of 0335 UTC.
Having characterised the land surface properties for this case study, line-by-line simulations have been run for the selected FOVs in a similar way as in Section 3. Figure 10 displays the average residuals over all FOVs for the longwave spectral region. The inclusion of the retrieved surface temperature and emissivity in the simulations is shown to restrict the obs - calc residuals to within ± 1 K over much of the atmospheric window.

**Figure 10:** (Upper panel) IASI and ARIES clear-sky upwelling brightness temperature spectra recorded on 19 April 2007. (Lower panel) residual differences (observed – calculated GENLN2 spectrum) for both Met Office and ECMWF upper atmosphere fields, see legend.

To gauge the improvement over the assumption of a spectrally constant emissivity, Figure 11 compares simulations including a fixed emissivity of 0.98. Whereas with a retrieved spectral emissivity the residuals are generally within ± 0.5 K, with a (higher) fixed emissivity there is a bias of approximately −1 K across the spectrum. This shows the importance of including a realistic surface emissivity in the forward modelling of IASI spectra over land.
Figure 11: Comparison of simulations with differing surface emissivity assumptions. The upper panels show the average IASI brightness temperature over longwave and shortwave spectral regions. The lower panels show obs – calc residuals, using both ARIES retrieved and fixed (0.98) emissivity values.

5. Gulf of Mexico case study 29 April 2007

The final case study discussed here concerns a coordinated BAe 146 and WB-57 flight on 29 April 2007, conducted over the Gulf of Mexico with a MetOp overpass at 1550 UTC. This case study is particularly advantageous for studying instrument inter-calibrations because all four interferometers on the FAAM BAe 146, WB-57 and MetOp were operational on this day. Figure 12 shows that the northern portion of the flight track was clear of cloud, and again the case study instrument FOVs have been confined to this geographic area. Figure 13 shows the measurement collocations in more detail. Dropsondes were launched in close proximity to the overpass time (1531 and 1540 UTC).

Since the two aircraft and MetOp operate at different altitudes, their respective interferometers are sensitive to different parts of the atmosphere, at least over those spectral regions with transmittances significantly less than unity. However, in microwindows in the 800-1200 cm\(^{-1}\) region the upwelling radiances are dominated by surface emission and the water vapour self-broadened continuum which is overwhelmingly dependent on the concentration of lower-tropospheric water vapour. Hence, it is possible to compare directly radiances from the four instruments to test their respective calibration accuracies. Note that the satellite zenith angle for the IASI footprints does not exceed 2.6\(^\circ\) for the selected FOVs, so it is legitimate to compare these data with directly upwelling radiances recorded by the other interferometers.
Figure 12: MetOp AVHRR channel 1 image (580-680 nm) overlaid with FAAM BAe 146 flight track and (white asterisks) selected clear IASI FOVs. The brightest parts of the AVHRR image show the presence of clouds due to solar reflection. Note that sun glint contaminates this image.

Figure 14 compares the average brightness temperatures for IASI, NAST-1, S-HIS and ARIES. Their respective sensitivity to progressively warmer parts of the atmosphere is seen in the trend of brightness temperatures, e.g. below 700 cm$^{-1}$ in the longwave CO$_2$ band. However, all instruments record very similar brightness temperatures in parts of the atmospheric window region. Figure 15 shows the same information, but expanded in a small part of the window region; also an apodisation function has been applied to the spectra to standardise their effective spectral resolutions and aid direct comparison. In microwindows insensitive to the upper atmosphere the level of agreement between all four instruments is striking, with only 0.3 K separating these independent measurements. Thus, it can be claimed with confidence that the radiometric accuracy of IASI is within 0.3 K, a statement that is corroborated by results from the other case studies (see Figure 3).
Figure 13: Collocation of observations on 29 April 2007. The diamond symbols denote (the centres of) individual instrument footprints on the ground, while crosses show the launch and terminating coordinates of dropsondes, see legend.
Figure 14: Comparison of average brightness temperatures from four interferometers, measured on 29 April 2007.

Figure 15: As Figure 14, but over a reduced spectral range.
6. Summary

The JAIVEX campaign, bringing together hyperspectral radiance measurements with high-density collocated observations of the atmospheric state, has produced a valuable dataset for validation of satellite calibration accuracy and retrieval algorithms.

Three case studies described here have been used to test the absolute calibration accuracy of IASI. Line-by-line simulations of radiances measured over ocean match the observations to within 0.2 K over the 800-1200 cm\(^{-1}\) region, and within 1.0 K over much of the rest of the spectrum. Allied with agreement of four independent interferometer measurements to within 0.3 K, it can be concluded that the calibration accuracy of IASI is, at worst, a few tenths of a degree. The importance of constraining the surface emissivity and temperature characteristics is demonstrated for IASI data over land.

The JAIVEx dataset is freely available for academic research, contact stu.newman@metoffice.gov.uk for more information.

Acknowledgements

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Retrieval algorithm using superchannels

Xu Liu, Dan Zhou, Allen Larar, Bill Smith, Peter Schlüssel

Recent progress in using PCRTM super channel retrieval methodology will be discussed. Results applying the retrieval algorithm to IASI and NAST-I will be shown.
Error Assessment and Validation of the IASI Temperature and Water Vapor Profile Retrievals

Nikita Pougatchev, T. August, X. Calbet, T. Hultberg, P. Schlüssel, and B. Stiller

The Infrared Atmospheric Sounding Interferometer (IASI) Level 2 products generated by Product Processing Facility (PPF) at EUMETSAT comprise retrievals of vertical profiles of temperature and water vapor. The L2 data were validated through assessment of their error covariances and biases using radiosonde data for the reference. The reference radiosonde data set includes dedicated launches as well as the ones performed at regular synoptic times. For optimal error estimate the linear statistical Validation Assessment Model (VAM) was used. The model establishes relation between the compared satellite and reference measurements based on their relations to the true atmospheric state. The VAM utilizes IASI averaging kernels and statistical characteristics of the ensembles of the reference data to allow for finite vertical resolution of the retrievals and temporal non-coincidence. The paper presents the validation results for different geographical locations and discusses potential use of the VAM estimated error covariances and biases for applications such as NWP, satellite intercalibration, and Earth System studies.
Assimilation of IASI at the Met Office and assessment of its impact through observing system experiments

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Data from the Infrared Atmospheric Sounding Interferometer (IASI) onboard MetOp has been assimilated at the Met Office in both Global and North Atlantic and European (NAE) model configurations since November 2007. It has been a considerable challenge to reduce data volumes to a manageable level within the constraints of the forecast system and this paper will summarise the processing methodology employed.

Pre-operational trials of IASI assimilation in the Global model delivered a positive impact on forecasts approximately twice as large as that shown by AIRS. A series of observing system experiments confirms the relative performance of IASI and AIRS, and shows that impact from IASI is equivalent to a single AMSU-A+MHS.

Analysis of a second season Global model IASI assimilation trial indicates that the measurement of impact is strongly affected by variations in performance of the control forecast. Furthermore, the impact of IASI is strongly dependent on the variables and methods chosen for verification: although improvements to the large scale fields (e.g. mean sea-level pressure and geopotential height) were also seen in the NAE configuration, no forecast impact was seen for variables such as visibility and rain-rate.

1. Selection, preprocessing and assimilation of IASI data

Data selection

For a six-hour assimilation cycle, 324,000 IASI spectra each consisting of 8461 channels are processed. This equates to $2.7 \times 10^9$ channel observations per cycle, in comparison with approximately $0.04 \times 10^9$ channel observations for ATOVS data from five satellites. One of the greatest difficulties in the use of IASI data is therefore to extract detailed atmospheric information as efficiently as possible to enable assimilation within the current computing constraints of our operational numerical weather prediction (NWP) system.

The approach taken to enable fast delivery of benefit from IASI was to perform spatial and spectral reduction at the earliest possible opportunity in the data processing chain. The 8461 channels are reduced to 314 using the 300-channel selection proposed by Collard (2007) – which selects the channels with the greatest information content for a variety of meteorological situations – and adding in 14 extra monitoring channels chosen by the Centre National d’Etudes Spatiales (CNES; Blumstein, pers. comm.). The observations are thinned spatially to 1 pixel from 4 in each field of view using the IASI L1c AVHRR cluster information to select the most homogeneous field of view. This is carried out in AAPP (Atkinson et al., 2006) before data storage.
This spatial and spectral data reduction approach is a rather blunt instrument, but it is anticipated that in future we may be able to dispense with the spatial thinning and use principal component scores to compress information from the whole spectrum into a relatively few pieces of information which can be assimilated efficiently.

Following data reduction, for the Global model, we process a maximum of 81,000 observations (0.025x10^9 channel observations) for each six-hour assimilation cycle. These are further reduced to around 3,000 observations for assimilation through rejection of observations during preprocessing, details of which follow in the next section. For the NAE model, the data coverage is highly variable, but between 200 and 800 observations are typically assimilated in each six-hour 4D-Var cycle.

**Preprocessing**

Before assimilation, the IASI data are passed through a 1D-Var and quality control stage known as the Observation Processing System (OPS) where the observations are compared with forward-modelled atmospheric columns constructed from model fields. The process consists of several steps including bias correction, surface type assignment, cloud detection, channel selection and 1D-Var.

At the Met Office a static bias correction scheme is used rather than variational bias correction. This correction consists of a different constant offset for each channel and each scan angle plus a linear function of the 850-300 hPa thickness and 200-50 hPa thickness, with different coefficients for each channel.

The Met Office model has a land/sea mask and also a sea ice fraction which are used to assign a surface type to the observation. The model surface type is used in conjunction with a surface type determined from AMSU observations which are mapped to the IASI footprints in AAPP (English et al., 1997). The AMSU data is tested for consistency with eight different surface types and an optimal estimation method is used to match each observation to the best-fitting surface type.

Four cloud detection tests are employed. The first two which are taken from Cheng et al. (2006) and are carried out in AAPP. The standard deviation of the four IASI pixels in one field of view at 2390 cm\(^{-1}\) is compared with NE\(\Delta T\) for the channel: if it is greater than 3x NE\(\Delta T\) the pixel is cloudy. The second test predicts IASI BT at 2390 cm\(^{-1}\) from AMSU 4, 5 and 6. If (AMSU – IASI) > 2K the pixel is cloudy. The third test also runs in AAPP and is a by-product of the AMSU surface type test mentioned above: if the fit to all possible surface types is poor, the pixel is declared “microwave cloudy”. The final infrared cloud test follows the Bayesian methodology of English et al. (1999): a cloud cost is computed taking into account information from the observation and the model profile and this cost function is tested in conjunction with a window channel observation-background (O-B) check at 810.25 cm\(^{-1}\). No IASI data are assimilated where an infrared cloud test is failed.

Not all of the 314 channels are used during preprocessing and assimilation. In OPS, channels in the 8\(\mu\)m ozone band, all channels in Band 3, and several other channels which seem to cause problems in the 1D-Var minimisation (for example, the very highest peaking channels)
are rejected. Only water vapour channels peaking below 520hPa (from their temperature Jacobians for the US standard atmosphere) are used – this leaves 31 water vapour channels in the minimisation. For observations over land or where the microwave cloud test is failed, channels peaking below 400hPa (for the US standard atmosphere) which may be sensitive to the surface emission are rejected. No water vapour channels are used over land. Figure 1 shows a typical IASI spectrum with the channels from the 314 set marked according to their usage. 183 channels are used in 1D-Var. No IASI data are assimilated over sea ice.

![IASI Spectrum, US Standard Atmosphere](image)

**Figure 1:** 314 channel set marked on a typical IASI spectrum. Red lines mark the channels used in all conditions; yellow lines mark channels used only in clear conditions over the sea. Blue lines mark channels used in all conditions in OPS, but rejected in 4D-Var. Cyan, lime and green channels are not used at all.

The radiative transfer model used to forward-model the atmospheric columns is RTTOV7 (Saunders et al., 2002) with coefficients based on kCARTA (Strow et al., 1998). In OPS, the standard deviation of the observation errors are set to the instrument noise measured during thermal vacuum testing (Phulpin, pers. comm.) plus 0.2K assumed forward model error.

**Assimilation**

Channels peaking above 50hPa are used in OPS but are not assimilated via 4D-Var because the increments they generate exhibit stratospheric ringing. In total, 138 channels can be assimilated depending on the cloud conditions and surface type (see Figure 1). The observations are thinned to one in every 154km box to ensure that there are no correlations between observations.
For 4D-Var, the errors are inflated in line with those for other radiance data to compensate for lack of off-diagonal elements in the covariance matrix: the standard deviations of error are inflated to 0.5K for the 15μm CO₂ band, 1K for window channels and 4K for water vapour channels. These values were chosen to maximise the weight given to IASI without allowing the fit to other satellite sounders to deteriorate significantly. In particular, the large errors assumed in the water vapour band help to compensate for lack of inclusion of any correlated error.

2. Global Model Assimilation Trials

June 2007

A series of assimilation trials where IASI was included on top of the current operational satellite data usage were run for the period 24th May – 24th June 2007. The trials tested assimilation under a range of conditions: with and without water vapour channels; with 0.5K and 1K observation errors for the temperature sounding channels; at different horizontal resolutions; and with different model physics configurations.

Forecast impact at the Met Office is measured by use of a score called the NWP Index (see Annex A for detail) which combines improvements in forecast skill in a number of atmospheric parameters. Assuming one knows the persistence error perfectly (a reasonable assumption in comparison with the forecast error), over a one-month trial where the impact is reasonably consistent in time and across the components of the Index (also reasonable in this case), using the standard error as a measure of forecast error, an improvement in the Index of 0.5 points is considered to be significant.

The results of all trials run were very consistently positive, and the inclusion of water vapour channels and use of 0.5K observation errors for the temperature sounding channels produced the largest positive impact of 1.2 points verified against observations and 0.8 points against analyses – 1.0 points overall.

The largest impacts seen were in the tropical and northern hemisphere geopotential height forecasts against analyses; and against observations in the wind fields and 500hPa height in the tropics and southern hemisphere, and 500hPa height and PMSL in the northern hemisphere. Figure 2 shows the improvement to the bias in the T+24 height forecast in the southern hemisphere.

The NWP Index was improved for most days of the forecast trial period against both observations and analyses except for a few days towards the end (Figure 3). Interestingly, the impact of AIRS for this trial period was significantly less than IASI, 0.6 against observations and 0.1 against analyses. Previous AIRS assimilation trials have shown overall impact of about 0.5 Index points (Cameron et al., 2005; Hilton et al., 2006). It is likely that the larger number of IASI channels employed and the greater weight given to the temperature sounding channels of IASI contributed to this difference (AIRS is assimilated with a 1K error in the 15μm CO₂ band).
The strong performance of IASI leading to marked improvements in forecast skill are particularly impressive considering that IASI has been added to a system already assimilating sounding data from ATOVS on three NOAA satellites and on MetOp (whose observations are coincident with IASI), AIRS on EOS Aqua, and SSMIS on DMSP F16. This result suggests that new information is being added by the assimilation of IASI. Bell et al. (2008) compare humidity increments for IASI and SSMIS and show that using the 31 water vapour channels that were tested in the trial, 1D-Var specific humidity increments from IASI span the troposphere where SSMIS increments are concentrated in the lower troposphere.

Figure 2: Mean forecast error in geopotential height at T+24 for the southern hemisphere verified against radiosondes. The red line is the control and the blue line is the IASI assimilation trial.

Figure 3: Daily change in NWP Index for the June 2007 IASI assimilation trial. The black line shows the running mean of the Index, which at the end of the period is the value of the Index for the experiment. The left panel is verified against observations, the right against analyses.
A second season of assimilation experiments was run for the period 12th December 2007 to 12th January 2008 after IASI assimilation became operational. The first of these removed IASI data from the assimilation system. Removing IASI had negative impact, but not as significant as over the summer period: a degradation of 0.4 verified against observations and 0.6 against analyses (0.5 overall).

A time series of the trial period (Figure 4) shows that whilst for the majority of days the removal of IASI data degraded the forecast, forecasts verifying against observations on December 29th showed an improvement from the removal of IASI data. The period from 30th December to 8th January showed almost no impact from IASI. No investigation has been done into why the forecasts for December 29th were degraded by assimilation of IASI, but further observing system experiments indicate that the impact of other satellite radiance data types was also reduced during the end of December and the beginning of January relative to the first two weeks of the trial period.

Figure 4: Daily change in NWP Index for the December 2007 IASI assimilation trial. The black line shows the running mean of the Index, which at the end of the period is the value of the Index for the experiment. The left panel is verified against observations, the right against analyses.

Although the positive impact seen from IASI assimilation was smaller for the winter period, the verification of particular forecast parameters was broadly consistent between the two periods (Figure 5) with the exception of the southern hemisphere 500hPa geopotential height and short range PMSL, and tropical 850hPa winds at short forecast range.

The difference in NWP Index scores can be attributed to the way the forecasts are verified and the change in performance of the control between the two periods. The skill scores used to calculate the NWP Index compare the performance of the trial relative to persistence with the performance of the control relative to persistence. In the northern hemisphere, persistence is much poorer as a forecast during winter than summer, and the control therefore exhibits much greater skill during the winter 2007 trial period (Figure 6). Although the reduction in RMS error in the northern hemisphere from the assimilation of IASI is quite constant between
summer and winter trial periods, the reduction in RMS error of the control is an order of magnitude larger.

Figure 5: Comparison of percentage change in forecast RMS error verified against observations for June 2007 and December 2007 trial periods.

Figure 5 also indicates that during the summer trial IASI performed strongly for the 850hPa wind forecasts in the tropics, variables to which the NWP index calculation is particularly sensitive. Figure 6 shows that the skill of the control forecast was increased by 20-35% during the winter trial period for the 850hPa wind forecasts (in this case the increased skill could not be attributed to persistence being a poorer forecast in the winter period).

3. Global Model Observing System Experiments

A series of observing system experiments were run for a slightly shortened winter trial period of 12th December 2007 to 4th January 2008 where individual satellite sounding instruments were tested on top of a no-satellite-sounding baseline. Five experiments were run:

- No satellite sounding – AMSU, MHS, HIRS, AIRS, IASI and SSMIS excluded
- IASI only
- AIRS only
- MetOp AMSU-A+MHS only
- MetOp HIRS only

The verification of these trials was performed against observations only. Verifying against radiosondes obviously has drawbacks, not least from the point of view of the spatial variability of the network – in particular the sparseness of the verifying observations in the southern hemisphere is of concern given that satellite data have traditionally shown greater...
impact here but at least the verification is consistent across the experiments. Verifying against analyses would probably favour either the control or the experiment for such a data-poor experimental set up.

Figure 6: Percentage change in weighted skill relative to persistence of the control runs used for IASI assimilation experiments in December and June: a positive value indicates that the December control showed more skill relative to persistence than the June control.

Figure 7 shows the NWP index scores for this series of experiments. The no-satellite-sounding trial demonstrated a 4-point degradation. IASI provides about as much forecast impact as MetOp AMSU-A+MHS, restoring about half the skill of the whole system. AIRS and HIRS provide a smaller positive impact on the forecasts. Although each IASI observation has many more assimilated channels than each AMSU-A+MHS observation, the impact of the latter is enhanced by its ability to be used in cloudy areas, providing better global coverage and data in meteorologically active areas. The relative performance of AIRS and IASI has not been investigated but it is possible that the difference in impact results from the fact that around twice as many IASI channels are assimilated as AIRS channels, and the 15\(\mu\)m CO\(_2\) band channels on IASI are given twice as much weight.

A time series of the daily Index change shows that in general the satellite sounding observations are all showing similar patterns of impact in terms of day-to-day variability (Figure 8). There is a reduction in the impact of the satellite data during the last few days in December and the first few days in January, as also seen in the experiment removing IASI from the full assimilation system.
Figure 7: Change in NWP Index verified against observations for addition of individual satellite data sources over a no-satellite-sounding baseline. AMSU/MHS and HIRS are from MetOp only.

Figure 8: Daily change in NWP Index verified against observations for addition of individual satellite data sources over a no-satellite-sounding baseline. Red=IASI, Blue=AIRS, Green=AMSU/MHS, Yellow=HIRS. AMSU/MHS and HIRS are from MetOp only.

It is extremely encouraging that assimilation of IASI in clear areas only is providing similar forecast benefit to the assimilation of ATOVS data in both clear and cloudy conditions. The relative performance of IASI and AIRS in the assimilation system demonstrates that more information can be extracted from hyperspectral infrared sounders when data with low radiometric noise are given appropriate weight in the assimilation system.
4. North Atlantic and European Model Assimilation Trial

An IASI assimilation trial for the period 24th May to 24th June was also run for the NAE model configuration. Despite extremely positive results in the global model, IASI showed neutral impact in the NAE, in common with previous satellite data assimilation trials for AIRS (Hilton et al., 2006) and AMSU (Candy et al., 2003).

Verification for the NAE is very different from the global model. A UK NWP Index is calculated from six weighted forecast variables: surface visibility, six hour precipitation accumulations, total cloud amount, cloud base height, surface temperature and surface wind verified against observations. Annex B describes the calculation of the UK Index.

Satellite radiances typically show little impact on these “weather” variables, despite providing benefit in the upper air fields for the NAE model. Table 1 shows the change in scores for the IASI trial for the largest and smallest verification domains, which showed respectively the best and worst Index changes.

<table>
<thead>
<tr>
<th>Weighted ETS difference</th>
<th>Full NAE Area</th>
<th>UK Index List Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Visibility</td>
<td>-0.016</td>
<td>0.032</td>
</tr>
<tr>
<td>6hr Precip Accum</td>
<td>0.032</td>
<td>0.035</td>
</tr>
<tr>
<td>Total Cloud Amount</td>
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<td>-0.034</td>
</tr>
<tr>
<td>Cloud Base Height</td>
<td>-0.011</td>
<td>-0.017</td>
</tr>
</tbody>
</table>

| Weighted Skill difference        |                |                    |
| Surface Temp                     | 0.013          | -0.080             |
| Surface Wind                     | 0.022          | 0.031              |
| Overall Change in Index          | 0.12%          | -0.08%             |

Table 1: Change in UK Index score components for the NAE model configuration IASI assimilation trial. A change of about 0.3% overall would have been significant.

The highest impact (for the full NAE domain) was +0.12%. No objective significance testing has been applied to this result. However, the operational change procedure at the Met Office considers a change of 0.3% to be a small but significant impact, particularly if this impact was shown to be consistent in time and across different verification areas. Therefore, whilst this is a subjective significance test, 0.12% is unlikely to be a significant change.

In contrast, Figure 9 shows the benefit of assimilation of IASI on the 1000hPa geopotential height forecast: there are reductions in the forecast bias and RMS error at longer forecast ranges. Other fields showing benefit from assimilation of IASI were relative humidity and temperature below 500hPa; pressure at mean sea level and winds at 250hPa.

The verification results for the upper air and large-scale fields are in keeping with the results from the global model trials. This suggests that the negligible impact seen when adding satellite data into Met Office limited area models may be partly due to the way in which the model is verified, but also that the improvements seen in the large-scale model fields are disconnected from changes in the surface weather variables which make up the UK Index.
Figure 9: Change in mean and RMS forecast error for 1000hPa geopotential height against forecast range verified over the old mesoscale model area. The red line is the control and the blue line is for the IASI assimilation trial. Other verification areas show similar benefit from IASI assimilation.

5. Conclusion

Experiments have shown that assimilation of IASI in the Met Office Global model provides significant forecast benefit on top of a system which already makes use of ATOVS, AIRS and SSMIS data. Observing system experiments testing individual satellite instruments on top of a no-satellite-sounding baseline suggest that IASI provides a similar level of improvement in forecast skill to AMSU-A+MHS, and significantly more than current implementations of AIRS and HIRS. The benefit seen in the North Atlantic and European model is negligible for the forecast variables which are used for the verification of Met Office limited area models, suggesting that benefits in large-scale fields such as geopotential height and PMSL do not feed into surface weather variables.

The considerable improvement in the global forecast was achieved with a simple assimilation scheme treating IASI in the same way as the previous generation of sounding instruments. There is much more information to be extracted from IASI, and future work will focus on using the spectral information more effectively to allow us to increase the amount of data assimilated and thus improve forecasts further. This could be through spectral compression, or using more channels over land and over cloud (Pavelin, 2006).
Acknowledgements

The authors are extremely grateful for the assistance of Andrew Collard (ECMWF), Steve English, John Eyre, Roger Saunders, James Cameron and Brett Candy, for reviewing the assimilation scheme and providing advice; Mike Thurlow, Mark Naylor and Adam Maycock for assistance with testing and trialling of IASI assimilation and Pascal Brunel (Météo-France) for provision of RTTOV-7 coefficient files.

References


Annex A: The Met Office Global NWP Index

In order to provide an objective global assessment of data assimilation or model changes the Met Office uses a basket of forecast verification scores. Each score is weighted against its perceived importance to create a global index. Whilst this index is not sufficient to judge any change it can be a useful objective way to compare a number of changes without subjectively selecting a particular verification score which favours one change above another. The index has risen by 25% over 10 years so the importance of new changes can be judged against past performance.

The Index is compiled from mean sea-level pressure (PMSL), 500 hPa height (H500), 850 hPa wind (W850) and 250 hPa wind (W250). It is verified over the following areas: Northern Hemisphere 20N-90N (NH), Tropics 20N-20S (TR) and Southern Hemisphere 20S-90S (SH) and at forecast ranges from T+24 to T+120. The weight given to each verification field is shown in Table A.1. The change in weighted skill scores is measured using both conventional observations and analyses as verification and the two results are averaged to give the NWP Index.

The skill score is calculated from the forecast and persistence root mean square errors for each combination of parameter, area and forecast range. This is defined in terms of reduction of variance, i.e.

\[ S = 1 - \frac{r_f^2}{r_p^2} \]

where \( r_f \) is the RMS forecast error and \( r_p \) is the RMS persistence error.

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<th>T+120</th>
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<td>6</td>
<td>4</td>
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<td></td>
<td>6</td>
<td>4</td>
<td>2</td>
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<td></td>
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<tr>
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<td></td>
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<td></td>
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<tr>
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</table>

*Table A.1:* Weights given to each forecast parameter in Met Office global NWP index.
Annex B: The Met Office U.K. NWP Index

The UK index is based on forecasts of selected parameters currently out to 48 hours ahead for a selected set of positions verified by comparison with station observations and is based on 36 months of data. A score is calculated for each parameter included in the Index. The individual scores are then combined in a weighted average to form a single value.

The Index is compiled from the following parameters:

- Near-surface (1.5m) temperature
- Near-surface (10m) wind speed & direction
- Precipitation yes/no (equal to or greater than 0.2, 1.0 and 4.0 mm over the preceding 6 hours)
- Total cloud amount yes/no (equal to or greater than 2.5, 4.5 and 6.5 oktas)
- Cloud base height given at least 2.5 oktas yes/no (equal to or less than 100, 500 and 1000 m above ground)
- Near-surface visibility yes/no (equal to or less than 200, 1000 and 4000 m)

verified at quality controlled station positions across the UK and at the following forecast ranges: T+6, T+12, T+18, T+24, T+30, T+36, T+42 and T+48

The UK Index is calculated verifying forecasts against observations from all the WMO Block 03 stations across the UK including the Channel Islands and the Isle of Man. This includes Northern Ireland, but excludes the Republic of Ireland.

However, for experimental analysis, the index can be calculated over different domains, typically: the full NAE model area, the old mesoscale model area (UK and Ireland), the WMO Block 03 stations and the “UK Index List” – quality controlled radiosonde stations in the UK. These domains are successively smaller in size and therefore each contains fewer verification points, but also become successively more trustworthy in the quality of the data used for verification.

Verification of temperature and wind

Temperature and wind forecast accuracy at each forecast range is measured using a skill score, defined in terms of Reduction of Variance, i.e.

\[ S = 1 - \frac{r_f^2}{r_p^2} \]

where \( r_f \) is the RMS forecast error and \( r_p \) is the RMS persistence error.

The smaller the ratio between forecast and persistence errors, the closer the skill score will be to 1 (perfection). If the forecast error is greater (worse) than the persistence error, then the skill score will be negative and is in fact unbounded.
Verification of precipitation, total cloud amount, cloud base height and visibility

The Equitable Threat Score is used as the basis for the precipitation, total cloud amount, cloud base height and visibility components of the Index, the definition being:

\[ ETS = \frac{(R - \text{“chance”})}{(T - \text{“chance”})} \]

Where \( R \) is the number of observed events which were correctly forecast and \( T \) is the total number of events which were either observed or forecast. Subtraction of "chance" from the numerator and denominator removes those observed events which are expected to be correctly forecast by chance. It is given by:

\[ \text{“chance”} = \frac{F \times O}{N} \]

Where \( F \) is the number of events forecast, \( O \) is the number of events observed, \( N \) is the total number of events plus non-events.

This score has properties similar to the rms-based score, i.e. it takes the value of 1 for a perfect forecast, and is negative if the forecast is worse than chance, although in this case there is a lower limit of \(-1/3\).

Compilation of the Index

A simple weighted average, \( S \), of all the individual scores (eight forecast ranges and six variables (four of which have three thresholds) is calculated. The weighting factors are chosen to give equal overall weighting to each of the 5 components (wind, temperature, precipitation, cloud and visibility), so total cloud amount and cloud base height get lower individual weighting than precipitation and visibility (Table B.1).

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</tr>
<tr>
<td>Wind</td>
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<tr>
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<td>Cloud Base Height</td>
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<td>Visibility</td>
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Table B.1: Weights given to each forecast parameter in Met Office UK NWP index.
Monitoring and Assimilation of IASI Radiances at ECMW

Andrew Collard and Tony McNally

IASI data at full spatial and spectral resolution have been arriving in near real time at ECMWF via the EUMETSAT EUMETCAST system since February 2007. Real time monitoring of a subset 366 channels commenced on 8th March 2007. Monitoring of radiance departures indicates that IASI data quality is good with biases and standard deviations comparable with or better than AIRS in the longwave temperature sounding band. An initial assimilation trial with 168 channels in the 15micron CO2 band (a region considered particularly important following experience with AIRS) has yielded significant positive impact on forecast scores. Following this result the assimilation of these IASI channels became operational at ECMWF on 12th June 2007. Enhancements on this initial system including the use of the water vapour channels will be discussed.
Assimilation of IASI Data into the Regional NWP Model COSMO-EU: Status and Perspectives

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Abstract

This work will present a first setup of the assimilation of IASI data into the regional NWP model COSMO-EU of "Deutscher Wetterdienst" (DWD). The assimilation scheme is a combination of Nudging with a 1D-VAR step (utilizing the EUMETSAT NWP SAF 1D-VAR software package). The combination of these procedures should test and demonstrate the possible usage of observations which are connected to the model variables by non-linear operators (as IASI data are). The work will present the initial setup of the assimilation scheme for IASI data. The implementation of the bias correction scheme after Harris and Kelly (2001) is described, using two different layer thicknesses of the model, the total column water vapor, and the surface temperature as bias predictors. As forward model for the 1D-VAR step the new version of RTTOV (RTTOV-9-beta) was implemented. The work will show first impact experiments based on the described scheme focused on the used channel sets. Finally, the optimization of the used nudging weights and the inclusion of cloudy and partly cloudy measurements, respectively, the next steps planned, are addressed.

Introduction

The Infrared Atmospheric Sounding Interferometer (IASI), which is part of the core payload of the METOP series of polar orbiting operational meteorological satellites which are operated by EUMETSAT (first satellite METOP-A was successfully launched on Oct. 19, 2006), is providing a further significant improvement of vertical resolution of the state of temperature and humidity compared to existing operational satellites via a very high spectral resolution. Furthermore it will deliver ozone profiles and surface skin temperature as well as cloud parameters and column amounts of nitrous oxide (N$_2$O), methane (CH$_4$), and carbon monoxide (CO).

IASI is a Michelson type Fourier transform interferometer, which samples a part of the infrared (IR) spectrum contiguously from 645 cm$^{-1}$ to 2760 cm$^{-1}$ (15.5 $\mu$m – 3.6 $\mu$m) with an unapodized spectral resolution of about 0.5 cm$^{-1}$. The acquisition of information about the surface and the atmosphere is based on detection, recording, and analysis of electromagnetic (EM) radiation emitted by the earth mainly in the infrared range of the EM spectrum. The characteristics of the modification of radiation when passing through the atmosphere depends on the amount and properties of the atmospheric constituents. Therefore the information about the state of the atmosphere stored in the detected radiation may be retrieved from the measured spectrum.

Temperature profiles are obtained from observations in the absorption bands of carbon dioxide (CO$_2$), which is a relatively abundant trace gas of known and uniform distribution. Other atmospheric constituents absorbing in the thermal IR are H$_2$O (water vapor and temperature sounding), ozone (O$_3$ – ozone profiling), N$_2$O, CH$_4$, and CO (trace gas column amounts). The atmospheric window regions, where attenuation is minimal, are used to obtain surface and cloud properties. With the opportunity of
a very high spectral resolution at several wavelengths, the possibility of observing different layers can be established by taking into account that radiances measured in the center of an absorption band arise from the upper atmospheric layers, while measurements at the wings of a band will sense deeper into the atmosphere.

One of the primary objectives of the IASI instrument, according to the IASI science plan (Camy-Peyret and Eyre (1998)), is the improvement of the vertical resolution of temperature and water vapor profiles to about 1 km in the middle and lower troposphere as well as improving the retrieval accuracy to within 1 K in temperature and ~10% in humidity. This level of performance is greatly assisting numerical weather prediction (NWP) in delivering accurate and frequent temperature and humidity profiles for operational and research needs shown at the first IASI Conference (c. f. Phulpin and Klaes (2007)) and it will supply more accurate quantifications of climate variability, particularly contributing to our knowledge of the climate of the upper troposphere.

The main goal of this report is the presentation of the first setup of the assimilation of IASI data into the regional NWP model COSMO-EU of the German Weather Service (DWD). We are describing the preparation and preprocessing of the data for utilizing it in the COSMO-EU model. Then a short description of the optimal fusion of the data with the model output, i. e., the used forward model, the minimization scheme, as well as the two-step assimilation framework – 1DVar followed by nudging is given. The next section provides some very preliminary comparison results between the routine-run of COSMO-EU at DWD and an experiment where IASI data were assimilated. Finally, a short outline of the planned activities for a first tuning campaign of the described setup is provided.

**Data Preparation and Preprocessing**

In comparison to conventional infrared (IR) and microwave (MW) nadir looking sounder data like data from HIRS (20 channels) or AMSU-A/B (20 channels) the full IASI spectrum contains 8461 channels. Hence, it is clear that the current data preparation and preprocessing setup of the COSMO-EU satellite data assimilation system has to be changed essentially. Here we have to attach importance to an intelligent design of the processing steps as well as on an effective and robust channel selection scheme.

**Data Preparation and Preprocessing outside COSMO-EU**

Data preparation and preprocessing outside the COSMO-EU model contains the following steps:

- The data conversion from the BUFR format to netCDF format. This is provided by an external program since DWD decided to transfer the handling of observational data from the BUFR format to netCDF to get the possibility to out-source work resulting from e. g., changes in the BUFR format.

- A rough quality control step where the different IASI quality flags provided by the IASI level 1c data are used in a first implementation.

- The selection of observed IASI data according to the COSMO-EU region. This selection implies that the assimilation of data from the IASI instrument or more general of data from the METOP satellite can only be used in the 0:00 UTC and 12:00 UTC assimilation run (except some observations near the North Pole which lie inside the COSMO-EU domain). This is due to the fact that METOP is in a sun-synchronous orbit and crosses the equator at 9:30 local time at the ascending node.

- The deselection of IASI measurements over land using the land-sea mask of the COSMO-EU model to avoid the not yet solved problem of land surface emissivities.
The selection of an optimal subset of channels which is sufficiently sensitive to the retrieved variables.

The last point is crucial due to the fact that the conversion of the radiances (distributed by EUMETSAT) to brightness temperatures has a high computational cost. At this initial setup the implementation of this last point was performed by selecting only those channels which are distributed via the GTS system too. The selected subset was obtained by applying the information content theory (c. f. Rodgers (2000)) to different spectral regions to get a well distributed subset of channels for each atmospheric constituent (e. g., CO$_2$, H$_2$O) and for all atmospheric variables of interest (e. g., temperature, water vapor, or surface skin temperature), respectively (Collard and Matricardi (2005)).

Preprocessing inside COSMO-EU

Since the following preprocessing steps will need information from the state of the model itself, i. e. a first guess of the atmospheric state obtained from the model is needed, these steps have to be integrated directly into the COSMO code:

- The setup of a cloud detection scheme: Since currently no IR data are assimilated at DWD a new cloud detection scheme for IR data has to be implemented. As a first step the IASI Level 2 cloud flags are used. Since they are currently delivered only for each second IFOV of the overall 120 IFOV’s of one IASI scan line only each second measurement can be qualified. Of course this reduces the number of selectable IFOV’s per EFOV by two. Hence, as a second step currently the cloud detection algorithm of McNally and Watts (2003) has been integrated into the COSMO-EU code. It is provided as a stand alone package by NWP-SAF Collard (2006). This scheme has been implemented but is currently not used. Initially, only cloud-free pixels will be used. As a second step, the usage of all channels which are sensitive at heights above the cloud top is planned.

- The implementation of a new, more general bias correction scheme: The implementation of the bias correction scheme for ATOVS data is based on the scheme of Eyre (1992) and uses AMSU-A channel 4 and 9 as predictors. We decided to implement the bias correction scheme based on Harris and Kelly (2001) which uses predefined model parameter as bias predictors. Hence, the calculation of the bias correction coefficient and the bias correction itself were generalized to an arbitrary number of predictors. Figure 1 shows a first preliminary plot of bias corrected radiances. The first guess statistics for the bias prediction coefficients used to correct the bias for the radiances shown in this plot were quite small. We have chosen a period between January 10 2008 and February 1 2008 to calculate them. For the computation only those measurements were taken into account which were specified as cloud free by the IASI Level 2 cloud flags. The usage of the IASI Level 2 cloud flags reduces the number of iterations in obtaining meaningful bias correction coefficients. Unfortunately, the chosen period was quite cloudy over Europe (at least for infrared instruments) one can see from the plot that the bias correction coefficients are usable in this first preliminary setup except for some channels (dark) which could not be corrected well.

- The implementation of a quality control scheme which exploit the difference in brightness temperature between the bias-corrected measurements and the first guess. This has to be tuned to get an optimal state for the finally resulting analysis field. Due to the fact that is not clear how good the IASI Level 2 cloud flags are and how good the bias correction is working the maximal difference value is currently set to the very conservative value of 5 K difference in brightness temperature.
Figure 1: Observed minus bias corrected measurements for about one month of IASI data and all monitored channels. One can see that for those channels currently used in the minimization process (lower third of the channels) the bias correction works more or less well whereas for the humidity and surface channels this cannot be said. (Hence, the bias correction coefficients have to be updated.)

**Nudging and 1DVar – "NudgeVar"**

**Nudging**

In general, Nudging or Newtonian relaxation denotes the adjustment of the prognostic variables of a model towards prescribed values within a given time window. This technique can be found in detail in e. g., *Anthes* (1974), *Davies and Turner* (1977), or *Stauffer and Seaman* (1990). The adaption of the nudging technique to the COSMO model is described in *Schraff and Hess* (2002).

Nudging means the introduction of a relaxation term into the model equations, i.e., the time dependency of the prognostic variables are given by:

\[
\frac{\partial}{\partial t} \Psi (x, t) = F (\Psi, x, t) + G_{\Psi} \sum_{k_{\text{obs}}} W_k (x, t) \left[ \Psi_{\text{obs}, k} - \Psi (x_k, t) \right],
\]

where \( F \) denotes the dynamics and physical parameterization of the model, \( \Psi_{\text{obs}, k} \) the value of the \( k \)th observation influencing the grid point \( x \) at time \( t \), and \( x_k \) the location of the observation. \( G_{\Psi} \) is a constant which is called the nudging coefficient, and \( W_k \) is an observation dependent weight which in almost all cases takes values between 0 and 1. The difference \( \left[ \Psi_{\text{obs}, k} - \Psi (x_k, t) \right] \) between observed and model value is called observation increment. The complete additional term is the so called nudging term determining the analysis increment, i.e., the impact of the measurement on the model state.

A single observation in the nudging process is not used at the correct observation time only, but it is used at regular intervals with an exponentially increasing impact starting from 1.5 h before observation time and exponentially decreasing impact until 0.5 h after the observation time for satellite data (c.f. Figure 2). Thus, equation 1, the so called nudging equation describes a continuous adaption of the state of the model towards the observations during the forward integration of the model which is illustrated in Figure 3).

**1DVar**

Since there is no possibility to directly use the radiance measurements of satellites in the nudging process a 1DVar assimilation step has to be performed prior to it to transform the radiances from measurement space into model space.
Figure 2: A single satellite observation is used at regular intervals with an exponentially increasing impact starting from 1.5 h before observation time and exponentially decreasing impact until 0.5 h after the observation time. Note that this means that during a 3 hours “NudgeVar” we have to account for observations which occur at most half an hour before the start of the assimilation and at most one and a half hour after it.

Figure 3: The Figure sketches the influence of the observations on a free forecast process. It illustrates the influence of the nudging term which forces the model trajectory towards the observations.

The 1DVar scheme is implemented in the following way:

- As forward model the new version of RTTOV, RTTOV-9.0 beta (c. f. Saunders and Matricardi (2007)), was implemented and will be replaced by the final version after it is released.

- The background errors are obtained by utilizing the NMC-method (c. f. Parish and Derber (1992)) and were calculated for the COSMO consortium by F. Di Giuseppe. This method derives the background error covariance matrices by analyzing the analysis minus forecast differences for different forecast times but for the same point in time.

- As mentioned above, the bias correction is applied after Harris and Kelly (2001) using total column water vapor, surface skin temperature (SST), and two different kinds of layer thicknesses (1000 hPa to 300 hPa and 200 hPa to 50 hPa) as predictors.
Since the radiative transfer calculation, i.e. RTTOV needs a meaningful state above the top of COSMO-EU currently IFS/ERA-40 climatological profiles (c.f. Uppala et al. (2005)) are appended. In the next few months it is planned to replace this scheme by using ECMWF analysis fields with a meaningful transition between these two models.

It has to be mentioned that in a first step satellite measurements will only be used if their ground pixels are over sea and if the cloud detection has flagged them as cloud free.

The minimization scheme utilized here is based on the M1QN3 algorithm (c.f. Gilbert and Lemarechal (1989)) as supplied by the NWP-SAF.

First preliminary experiment

The assimilation setup described above is currently tested for the period between January 10 2008 and February 10 2008 which has not been finished until now. Hence, only preliminary results can be shown here.

In order to show that the implementation works and that changes in the assimilation scheme are showing an – at least weak – impact in the forecast a one day case study from this experiment was extracted.

Figure 4: Analysis difference of 500 hPa temperature of the routine-run of COSMO-EU at DWD and the experiment where the IASI data were assimilated, after one day of assimilating IASI data, i.e. for January 12 2008.

Figure 4 shows the analysis difference in 500 hPa temperature of the routine-run of COSMO-EU at DWD and the experiment where the IASI data were assimilated after one day of assimilating IASI data, i.e. for January 12 2008. I have chosen this day for presenting the differences between routine and experiment since it gives us the opportunity to see the impact of the of the data on the forecasts without too much difference in the starting analysis fields. Those are still correlated since the assimilation of IASI data started a day ago only. Due to the fact that the period around January 10 was quite cloudy there were not many regions where IASI data were assimilated – only in the Bay of Biscay and in the West of Norway and Ireland.

The strong impact over the Iberian peninsula is not resulting from the assimilation of measurements over land but of the model since the assimilation window was 3 hours in this case. The other larger differences (orange and light blue spots) over land can also be explained by a drifting of the assimilated information via the model trajectory since the assimilation of IASI data already has started 24 hours ago, as mentioned above.
Figure 5: Difference between Analysis and 24 h forecast 500 hPa temperature of the routine-run of COSMO-EU at DWD.

Figure 6: Difference between Analysis and 24 h forecast 500 hPa temperature of the experiment where the IASI data were assimilated.

Figure 5 and 6 are showing the forecast minus analysis differences between the routine-run (Figure 5) and the experiment (Figure 6). This first view does not allow us to figure out the differences between the two forecasts although a more closer view (c. f. Figure 7) is showing them. Figure 7 shows the differences between the 24 h forecast started from the experiment, i. e. the analysis where the IASI data was assimilated and the forecast started from the analysis field obtained by the routine-run. We can see that there are point-wise differences west of the British Islands and that there is a wide area of forecast differences at the South-western Alps and the France and Corsica and Sardinia. But due to the fact that currently there are only three forecast runs ready there is no possibility to check whether the impact of the IASI data on the forecast quality is positive or negative at this first preliminary setup.
Summary and Outlook

Summarizing it can be said that the technical implementation of the 1DVar/nudging – the so called "NudgeVar" – scheme for the assimilation of IASI data within the COSMO model has been finished in its first setup. The following implementation steps have been performed until now:

- The data preparation and preprocessing outside the COSMO-EU model which contains the steps of data conversion from the BUFR format to netCDF format, the selection of the observed IASI data according to the COSMO-EU region, the deselection of IASI measurements which lie over land, as well as the selection of an optimal subset of channels which is sufficiently sensitive to the retrieved variables.

- The preprocessing inside COSMO-EU which contains the implementation of a cloud detection scheme (preliminary until now via the usage of the IASI Level 2 cloud flags), the implementation of a new, more general bias correction scheme, and the implementation of a quality control scheme which exploit the difference in brightness temperature between the bias-corrected measurements and the first guess.

- The generalization of the COSMO code to handle more than one instrument-set per satellite, which has been implemented partly, but has to be finished as a next step.

- The upgrade of RTTOV – from version 7 to the new version RTTOV-9 beta.

Currently a first test of this preliminary implementation scheme is in progress.

The remaining steps to declare the implementation of the usage of IASI data within the COSMO-EU model as complete (in its first setup) are the usage of the cloud detection algorithm of McNally and Watts (2003) (it has been implemented but is not used until now) and one or two further iterations in the determination of the bias correction coefficients.

As next steps the tuning of this initial setup of the currently described assimilation scheme for the regional model COSMO-EU for IASI measurements is planned:

- The implementation of AAPP to get a more enhanced preprocessing (due to the fact that measurement information from other instruments on board of METOP scanning the same or at least
almost the same region on surface is taken into account too by AAPP) and a good cooperation of the different instruments on board of the METOP satellite during the assimilation.

- A tuning of the error model to get an optimal final state estimate which then can be nudged into the model.
- An optimal setup for the profiles added at above model top of COSMO-EU as well as an smooth transition between them and the COSMO-EU has to be found to minimize the impact of inconsistent stratospheric (and mesospheric) states on the troposphere.
- The selection of an optimal subset of channels of the IASI spectrum combining a possible seasonal dependency of the channel subset with a slightly modified selection procedure compared to that described above (c. f. Collard and Matricardi (2005)) has to be performed.
- In addition, a redefinition of the optimal nudging weights as well as of the used background covariance matrix should be investigated.

As mid- and long-term perspectives the comparison of the impact on COSMO-EU forecasts of the IASI Level2 Product with the 1DVar scheme described above is planned. In addition, the inclusion of cloudy observations is intended and the applicability of IASI measurements over land will be tested.

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List of References


MetOp, the first European meteorological platform on a polar orbit was launched on October 19, 2006. The platform carries a series of instruments, including IASI, the Infrared Atmospheric Sounding Interferometer designed and built by the French spatial agency CNES. IASI consists of a Fourier transform spectrometer, which measures radiance spectra of the Earth-atmosphere system between 645 and 2760 cm\(^{-1}\) in the thermal infrared, at a spectral resolution of 0.5 cm\(^{-1}\) (apodised). The nadir-looking geometry of IASI, combined with an across-track scanning mode reaching 48° on both sides, allows global coverage to be achieved in twelve hours. The first IASI spectra were delivered from mid July 2007. This work exhibits the first results acquired by analyses of IASI spectra, using retrieval tools dedicated both to operational and scientific processing, analysis of peculiar spectra in calibration mode, or images. We show that the extended spectral coverage of IASI provides unique information on the concentration distribution of numerous tropospheric species, impacting on climate (H\(_2\)O, CO\(_2\), N\(_2\)O, CH\(_4\), CFCs) or on chemistry (O\(_3\), CO, HNO\(_3\)). For most of these gases we demonstrate that vertical profiling is possible. IASI is showed to be very useful to monitor volcanic SO\(_2\). The emphasis of this work is put on preliminary analyses of O\(_3\), CO, CH\(_4\) distributions on local to global scales, acquired during the first months of IASI operation, and also on CFCs and SO\(_2\).
Community Radiative Transfer Model (CRTM) Status

Paul van Delst and Yong Han

The Community Radiative Transfer Model (CRTM) is the operational model developed jointly by the partners of the US Joint Center for Satellite Data Assimilation (JCSDA) and JCSDA-funded research groups. This talk will discuss the current status and future development plans for the CRTM. The current implementation includes modules to compute atmospheric transmittances, optical parameters for several cloud and aerosol types, surface emissivity and reflectivity for ocean, land, ice and snow surface types, and a multiple stream radiative transfer solution. The current CRTM supports many infrared and microwave sensors, including hyperspectral sensors such as AIRS and IASI. The ongoing and planned development of the CRTM includes the implementation of a transmittance model for SSU that takes the leakage of the CO2 cell pressure into account, improvements in the CompactOPTRAN transmittance model, implementation of multiple atmospheric transmittance algorithms such as those used in RTTOV and SARTA, implementation of an algorithm to add extra layers at the top-of-atmosphere (TOA) as required to prevent large valued temperature Jacobians at TOA, implementation of a new low-frequency microwave sea surface emissivity model, implementation of a fast radiative transfer model that takes the Zeeman effect into account, investigation of a new infrared land surface emissivity model from NRL, improvement of the computational efficiency of the current Advanced Doubling-Adding (ADA) radiative transfer solver, and implementation of the Successive Order of Interaction (SOI) radiative transfer solver developed at the University of Wisconsin.
What can RTTOV-9 do for me?

by
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Abstract
The development of the RTTOV fast radiative transfer model for nadir viewing atmospheric sounders and imagers has continued with the release of RTTOV-9 in March 2008. The new developments in RTTOV-9 are summarized here together with a documentation of the performance of the RTTOV model versions on several platforms. The plans for the next version of RTTOV are also outlined.

1. Status of RTTOV
The development of the fast Radiative Transfer for (A)TOVS (RTTOV) model has continued since the release of RTTOV-8 in Nov 2004. Around 313 users worldwide have received the RTTOV-8 code from the NWP-SAF to date and the code is used in a number of operational NWP centres and satellite agencies. This work is carried out within various EUMETSAT funded activities and is coordinated by the NWP Satellite Application Facility (SAF). Scientists from ECMWF, MeteoFrance and the Met Office all work on the development of the code and in addition visiting scientists from around the world have also provided useful contributions.

Over the last two years, more developments have been made to RTTOV-8, leading to the release of a new version of the model, RTTOV-9 (specifically v91), to users in March 2008. The number of users of this new version is 53 as of 1 May 2008. Users can request a free copy of RTTOV-9 by visiting \url{www.nwpsaf.org} and clicking on software requests and completing a licence form. All documentation and latest updates to the code for all supported versions are available at the website above in the radiative transfer area. Any comments on the models or suggestions for improvements should be submitted to the NWP SAF using the \texttt{nwpsaf@metoffice.gov.uk} email address or feedback form on the NWP SAF web site given above.

2. What is RTTOV-9?
RTTOV is a radiative transfer model to compute very rapid calculations of top of atmosphere radiances for a range of space-borne infrared and microwave radiometers viewing the Earth’s atmosphere and surface. The original basis for
the RTTOV fast computation of transmittances is described by Eyre and Woolf (1988). This was modified for later versions of RTTOV by Eyre (1991), Rayer (1995), Saunders et. al. (1999), Matricardi (2003) and Matricardi (2005). The performance of RTTOV-7 and RTTOV-8 for AIRS has been documented in Saunders et. al. (2007) by comparing with other fast and line-by-line radiative transfer models and AIRS observations. In summary, RTTOV-9 has the following attributes:

- It comprises forward, tangent linear, adjoint and K (full Jacobian matrices) versions of the model; the latter three modules for variational assimilation or retrieval applications
- Top-of-atmosphere radiances, brightness temperatures and layer-to-space plus surface-to-space transmittance for each channel are output for a given input atmospheric profile. There are also other layer-to-space and layer-to-surface radiances output for computing cloudy radiances
- It takes about 0.5ms to compute radiances for 20 HIRS channels for one profile on a Linux PC
- The input profile must have as a minimum temperature and water vapour concentration.
- It can compute sea-surface emissivity for each channel internally or use a value provided by the user. The ISEM-6 model (Sherlock, 1999) is used for the infrared. The FASTEM model (Deblonde and English, 2001) is used for the microwave. There are also very simplistic values provided over land for both wavelength regions
- Cloud-top pressure and effective cloud amount can be specified for simple, single-layer cloudy radiance calculations
- A full cloud water/ice profile can also be supplied for cloudy radiance simulation with various overlap assumptions
- A wrapper code allows RTTOV to be used to compute rain-affected microwave radiances (RTTOV_SCATT) as described by Bauer et. al. (2006)
- It supports all the sensors given in the Table 1 for all the platforms the sensor has flown on
- It is written in Fortran-90, and run under unix or linux
- It has been tested on a range of platforms including vector and scalar supercomputers and linux PCs. Some performance statistics are given below in section 5.

3. The differences between RTTOV-8 and RTTOV-9

This section summarises the main scientific and technical differences between RTTOV-8 and RTTOV-9. More details can be found in the RTTOV-9 users guide and science and validation plan both available on the web site given above. The main differences are:
• Now six variable gas profiles can be supplied to RTTOV (H₂O, O₃, CO₂, + N₂O, CO, CH₄) with only H₂O being mandatory
• Parameterised aerosol scattering for a range of user aerosol components for the infrared channels
• New cloud parameterised scattering for infrared sensors inside RTTOV
• Linear in optical depth approximation for the Planck function to improve the accuracy of the radiance computation
• Include reflected solar radiation for wavelengths below 5 microns.
• Further optimisation of optical depth computations for all gases for high resolution IR sensors (RTTOV-9 predictors)
• An altitude dependent variation of local zenith angle and optionally allow for atmospheric refraction to accurately compute the atmospheric path length
• Simplified interface to avoid the need to specify polarisation (NB microwave imager channel numbers are now different)
• The 2m surface humidity variable can now be an active variable in the state vector
• The Mie scattering tables have been extended to include the "total ice" hydrometeor type, as an alternative to separate "snow" and "cloud ice".
• The input profile levels can now be defined by the user and the layer radiances and transmittances output are on the same levels. This important new feature which allows better mapping of computed jacobians on to user levels, is described in more detail below.

Allowing user defined input and output levels for RTTOV has been a request from users, for some time, to avoid the need for interpolation of the input profiles to ‘RTTOV levels’ within their codes. In addition users of the adjoint or K codes were finding missing levels in the computed jacobians from RTTOV-8 when the number of user levels were greater than the number of RTTOV levels because of the ‘nearest neighbour’ approach of the interpolators used. For these interpolators the value for a variable on a given target level comes from an interpolation between values on the two nearest source levels above and below. Therefore, when the RTTOV adjoint/K code is run, the interpolator does not necessarily use all the source levels to estimate a variable on the output profile levels. The final Jacobian column on user levels, a channel sensitivity profile, can suffer significant distortion compared to the case where no interpolation has been performed.

The interpolator used in RTTOV-9 closely follows that described in Rochon et al. (2007), which has been designed to overcome this problem. It calculates a set of weights that, each time an interpolated value is required, will bring in all the source levels between the target level and its own neighbours above and below. Because it deals with triplets of target levels and the source levels used
each time enter in a weighted sum, the method used is one of a piecewise weighted integration. In Figure 1 the inputs and output user levels are 101 whereas the internal RTTOV optical depth calculations are on 43 levels. Figure 1 clearly demonstrates the improvement obtained in the Jacobians when the weighted average interpolator is used for this case.

![Figure 1. Temperature jacobians from RTTOV-9 for the case of nearest neighbour interpolation (red) and weighted interpolation (black) as in RTTOV-9.](image)

4. Sensors simulated by RTTOV-9
All supported versions of RTTOV (i.e. versions 7, 8 and 9) can simulate a range of different infrared and microwave sensors as listed in Table 1. This list is added to as required and plans are underway to include the NPOESS and Chinese FY-3 sensors during the next year. Note that only the infrared and microwave channels can be simulated at present. There is also a need to consider adding historical satellite sensors to the list for reanalyses and climate data record applications. Users can request new sensors to be added to the list supported by RTTOV. There have also been a number of studies where RTTOV has been used to simulate radiances from hypothetical sensors in order to evaluate their utility for atmospheric sounding.
<table>
<thead>
<tr>
<th>Platforms</th>
<th>Sensor</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIROS-N</td>
<td>HIRS, MSU, AHSU, AMSU-A</td>
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<td>1-3, 1-15</td>
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<td></td>
<td>SEVIRI</td>
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<tr>
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<td>ATSR</td>
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<td>Coriolis</td>
<td>WindSat</td>
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<tr>
<td>FY-1, FY-2</td>
<td>MVISR, VISSR</td>
<td>1-3, 2-4</td>
</tr>
</tbody>
</table>

Table 1. List of sensors and platforms supported by RTTOV as of May 2008.

5. Comparisons between RTTOV-7, RTTOV-8 and RTTOV-9 for ATOVS

The plot in Figure 2 below shows the standard deviation of the differences between line-by-line computed brightness temperatures and those computed by various versions of the RTTOV code using the same predictors for ATOVS. This verifies the correct implementation of the code and the performance for the original RTTOV-7 predictors which are still available in RTTOV-9. The computations were done for 117 diverse profiles and 5 different viewing angles. A fixed surface emissivity of 1 was assumed for all HIRS (channels 1-20) and 0.65 for AMSU (channels 21-40).
5. Performance of RTTOV-9

For every new version of RTTOV released the performance of the model in terms of speed and memory resources must be assessed before release to ensure it is not significantly slower or memory intensive without a good reason. Unfortunately this is not as simple as it appears because different computing platforms perform differently. Figure 3 shows the time required to compute 50,000 profiles for AMSU-A with no interpolation (tests 1 and 4), AMSU-A with interpolation (tests 2 and 5) and HIRS with no interpolation (tests 3 and 6). Tests 1 to 3 are for 50 profiles input to RTTOV for each call and tests 4 to 6 are for 1 profile input per call. Results for RTTOV-8, RTTOV-9 and various improved versions of RTTOV-9 are shown run on the Met Office NEC SX-6 supercomputer. There are a number of points that can be made from Figure 3.

- For a vector machine like the SX6 it is more efficient to call RTTOV with many profiles at a time (factor of 2 improvement in speed). This is not the case for a scalar machine like the IBM.
- The interpolation in RTTOV has a significant cost (more than a factor of 2).
- On the SX6 for single profiles per call RTTOV-9 is more expensive than RTTOV-8 whereas for many profiles per call the opposite is true. For scalar machines (not shown) RTTOV-9 is always faster than RTTOV-8.
- A newer optimized version of RTTOV-9 has significantly improved the performance for single profile calls making it close to RTTOV-8 performance.
It should also be noted that RTTOV-9 can be run on a multiprocessor environment allowing run times to be reduced accordingly. In terms of memory resources both RTTOV-8 and RTTOV-9 use the same resources but note if the full IASI spectrum is computed then a large memory resource is required.

6. Future Plans for RTTOV-9 and RTTOV-10

Plans are now underway to develop enhancements to the RTTOV-9 model. These include the following:

- Include Zeeman splitting for AMSU-A (channel 14) and SSMIS (channels 19-22), see paper from Yong Han in these proceedings.
- Provide new LBLRTM based coefficients for AIRS/IASI and CrIS
- Add Non-LTE using SARTA or similar approach
- Rewrite coefficient generation software and make available to users
- Upgrade FASTEM-3 microwave ocean surface emissivity
- Upgrade FASTEM-3 over land for lower frequencies (SMOS, AMSR-E, TMI)
- Make ‘hidden’ top layer to be defined by user
- Add new SSU predictors for improving simulation of SSU radiances for reanalyses
- Formulate design for including PCRTM capability to allow more efficient calculation of IASI spectrum
- *Add simple VIS/NIR optical depth and scattering calculations*

The items in italics are planned but are subject to external factors.
7. Acknowledgements

The authors acknowledge the support of EUMETSAT for RTTOV development and Yves Rochon of Environment Canada for providing the interpolator incorporated into RTTOV.

8. References


Matricardi, M. 2005. The inclusion of aerosols and clouds in RTIASI, the ECMWF fast radiative transfer model for the infrared atmospheric sounding interferometer. *ECMWF Research Dept. Tech. Memo.* 474. [http://www.ecmwf.int/publications](http://www.ecmwf.int/publications)


An assessment of the accuracy of the RTTOV fast radiative transfer model using IASI data

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Abstract
IASI measurements of spectral radiances made the 1st April 2008 are compared with simulations performed using the RTTOV fast radiative transfer model utilizing regression coefficients based on different line-by-line models. The comparisons are performed within the framework of the European Centre for Medium-Range Weather Forecasts Integrated Forecasting System using fields of temperature, water vapour and ozone obtained from very short range forecasts. Simulations are performed in controlled conditions to study the behaviour of the different line-by-line models and spectroscopic parameters on which the RTTOV coefficients are based.

Introduction
The exploitation of satellite radiance data for numerical weather prediction (NWP) requires the use of a fast radiative transfer (RT) model to simulate radiances from an input atmospheric profile. The variational approach to the assimilation of data into a NWP system involves the definition of the observation-error covariance matrix that is used to specify errors associated with radiance data. The observation-error covariance matrix is the sum of the instrumental-error covariance matrix and the forward-model-error covariance matrix which is based on the estimation of errors associated with fast RT models. RT errors are therefore an important consideration in the definition of the observation-error covariance matrix and consequently must be properly evaluated and fully understood.

The fast RT model used operationally at ECMWF is the Radiative transfer model for TOVS (RTTOV) (Matricardi et al. 2004). RTTOV is a regression based fast RT model on fixed pressure levels. It can be used in conjunction with a number of regression coefficients generated using different line-by-line (LBL) models. Regression coefficients for IASI are available based on the GENLN2 (Edwards 1994), LBLRTM (Clough et al.1992) and kCARTA (Strow et al. 1998) LBL models. In this paper we study the accuracy of the RTTOV computations by running four Integrated Forecast System (IFS) monitoring experiments where we compare the simulated spectra with spectra measured by IASI during the 1st April 2008. Results presented in this paper are very preliminary since spectra could only be processed over a limited time period due to the late implementation of the latest version of RTTOV into the Integrated Forecasting System (IFS).

The monitoring experiments
Four monitoring experiments have been run using cycle 33R1 of the IFS at the T799 full horizontal resolution (~25 km). A feature of cycle 33R1 is a vertical discretization of the atmosphere into a grid of 91 pressure levels. The spacing of the grid follows the horography of the terrain while the top level is fixed at 0.01 hPa. The state vector variables used in the RTTOV simulations are forecast fields of temperature, humidity and ozone. IASI data within a 12-hour 4D-VAR window are grouped into 30 minutes time slots. A T799 high resolution forecast is then run every 30 minutes from the previous analysis and observation minus model differences are computed for IASI soundings that, within a time slot, fall inside a 15 minute interval either side of the forecast time. This sequence is
then repeated for each 12-hour 4D-VAR window. In this study we consider IASI data inside two 4D-VAR windows on the 1st April 2008.

Each monitoring experiment is based on a different RTTOV coefficient file as shown in Table 1.

Table 1: the regression coefficients used for the RTTOV simulations

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Continuum</th>
<th>CO₂ line mixing</th>
<th>Molecular database</th>
</tr>
</thead>
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<td>Line-by-line model:</td>
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<td></td>
<td></td>
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<tr>
<td>kCARTA</td>
<td>MTK_CKD_v1.1_UMBC</td>
<td>P/Q/R branch (ν2 and ν3 band)</td>
<td>HITRAN_2000</td>
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<tr>
<td>Number of vertical levels:</td>
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<td></td>
<td></td>
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<tr>
<td>Training set:</td>
<td>52 profile training set</td>
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<td>Line-by-line model:</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>GENLN2</td>
<td>CKD_2.1</td>
<td>Q branch (ν2 and ν3 band)</td>
<td>HITRAN_1996</td>
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<tr>
<td>Number of vertical levels:</td>
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<td></td>
<td></td>
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<tr>
<td>Training set:</td>
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<tr>
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<td>Training set:</td>
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<td>Line-by-line model:</td>
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<tr>
<td>LBLRTM</td>
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<td>Training set:</td>
<td>83 profile training set</td>
<td></td>
<td>HITRAN_2004/06, GEISA_2003</td>
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</table>

From Table 1 it can be seen that the regression coefficients have been generated using the kCARTA, GENLN2 and LBLRTM LBL models. Important differences also exit between the water vapour continuum model, the CO₂ line mixing model and the molecular database used in each LBL computation. Table 1 also shows that regression coefficients are generated using various profile training sets and for different numbers of vertical pressure levels. Regarding the pressure levels, it should be noted that although RTTOV computes optical depths on the levels specified in the coefficient files, the integration of the RT equation is performed on the 91 IFS levels using the internal interpolation routine implemented in the latest version of RTTOV. Note how the GENLN2 model includes the effects of CO₂ line coupling only for the CO₂ Q branches (Strow et al. 1994) whereas kCARTA and LBLRTM include the effects of line mixing also for the P and R branches using the models by Strow et al. (2003) and Niro et al. (2005) respectively. The self- and foreign-broadened water vapour continuum absorption is included in all computations using different versions of the CKD and MTK_CKD model (Clough et al. 1989). In particular, kCARTA features a revised version on the MTK_CKD model based on the use of AIRS clear sky data and radiosondes at the ARM sites (Machado 2008). Figures 1 and 2 show the water vapour broadening coefficients for some of the models used in this study (self broadening is the dominant source of continuum in the window regions whereas foreign broadening dominates in the water vapour band) As Figure 1 shows, in the 10 μm window region MTK_CKD_UMBC self broadening coefficients are smaller than CKD_2.4 and MTK_CKD_v1.1 coefficients. In the centre of the water vapour band around 1600 cm⁻¹ the CKD_2.4 foreign broadening coefficients are smaller that MTK_CKD_UMBC and MTK_CKD_v1.1
coefficients whereas for larger wave numbers MTK_CKD UMBC foreign broadening coefficients are larger than CKD_2.4 and MTK_CKD_v1.1 coefficients (Figure 2).

Finally, note how for the LBLRTM computations we use molecular database that is the blend of molecular parameters from HITRAN_2000 (Rothman et. al 2003), HITRAN_2004/06 (Rothman et. al 2005) and GEISA_2003 (Husson et al. 2005)

Figure 1: spectral density function for the water vapour self broadening coefficients at 300K and 1013 hPa.

Figure 2: spectral density function for the water vapour foreign broadening coefficients at 300K and 1013 hPa.
The IASI spectra used in our experiments are measured over the sea and only channels detected as clear by the ECMWF cloud detection algorithm are processed. Since the ECMWF cloud detection algorithm (McNally and Watts 2003) finds clear channels rather than clear locations, the size of sample varies with the sensitivity of the channel to surface emitted radiance: i.e. channels characterized by weighting functions that peak at high altitudes are less sensitive to clouds than channels with weighting functions that peak at low altitudes or at surface. To illustrate this we show in Figures 3 and 4 the number of clear radiances for a surface channels and for a stratospheric channels respectively. It can be clearly seen that the number of clear radiances detected for the stratospheric channels outnumber by far the clear radiances detected for the surface channel.

Figure 3: the clear radiances detected for a surface channel.

Figure 4: the clear radiances detected for a stratospheric channel.
The size of the sample for each channel is shown in Figure 5 for the tropical latitude band (30°S - 30°N). It can be clearly seen that the size of the sample amount to thousands of spectra for the channels peaking at middle and high altitudes whereas the sample for channels peaking at low altitudes or at surface amounts to hundreds of spectra.

![Number of samples](image)

**Figure 5: the size of the sample for the tropical latitude band.**

In our RTTOV computations the state vector includes profiles of temperature, water vapour and ozone, surface parameters (e.g. skin temperature and surface pressure) and a wave number dependent value of the sea surface emissivity that includes the dependence on the viewing geometry. In addition to the profiles of temperature, water vapour and ozone, the experiments that use RTTOV coefficients on 100 vertical levels also require input profiles of CO₂, CO, N₂O and CH₄. This is not the case for the 43 level coefficients where constant climatological values are assumed in the LBL computations used to train the fast model. Since profiles for trace gases are not prognostic variables in the ECMWF model we had to fix the trace gas profiles in the 100 level experiments. To this end we have chosen the values assumed in the LBL computation used to train kCARTA. The rationale behind this choice is that at present kCARTA coefficients are used operationally at ECMWF and we want to use the kCARTA spectra as benchmark in our comparisons.

**Results**

In Figure 6 we show the mean value of the difference (bias) in units of brightness temperature for the latitude band between 30° N and 90° N. The top panel show results for the GENLN2 and kCARTA 43 level experiments (henceforth GENLN2_43 and kCARTA_43) whereas in the middle and bottom panel the GENLN2 and LBLRTM 100 level experiments (henceforth GENLN2_100 and LBLRTM_100) are superimposed to the kCARTA_43 experiment. Note how results are only shown for IASI band 1 and 2. At the time the experiments were carried out we were not sure about the correct implementation into the IFS...
of the 100 level regression coefficients in IASI band 3 and consequently have decided not to show the results for this band until the issue is fully resolved.

Figure 6 shows that for all experiments biases are generally below 1 K in all spectral regions. The only exception is the ozone band at 9.8 μm where biases are consistently larger that 1 K probably reflecting some intrinsic weakness of the ozone assimilation system. Of particular interest are the result in 15 μm temperature sounding region. It can be clearly seen that all the experiments based on GENLN2 show larger biases between 700 cm$^{-1}$ and 750 cm$^{-1}$. We attribute this feature to the fact that GENLN2 does not feature CO$_2$ P/R branch line mixing in this region. For the experiments that feature CO$_2$ P/R branch line mixing (kCARTA_43 and LBLRTM_100) biases are within 0.5 K and between 645 cm$^{-1}$ and 720 cm$^{-1}$ the experiments on 101 levels exhibits biases that are remarkably below 0.2 K. In the window region the GENLN2_43 experiment shows larger biases probably due to the use of an early version of the water continuum model. All the experiments give very similar results between 900 cm$^{-1}$ and 1200 cm$^{-1}$. Most of the differences between kCARTA_43 and GENLN2_43 in the CH$_4$ band (top panel, 1200 cm$^{-1}$ - 1400 cm$^{-1}$ region) can be attributed to the fact that the concentration used in the underlying LBL computations is different (and cannot be changed). It should also be noted that some of the differences in this spectral region can be attributed to the water vapour molecular parameters used in GENLN2_43. As discussed previously, the CH$_4$ concentration can be changed in the 100 level experiments and we have fixed it to the value assumed in kCARTA. This is reflected in the middle and bottom panel where GENLN2_100 and LBLRTM_100 biases are much closer to kCARTA_43 biases. It should be noted however that since the CH$_4$ variability is not reflected in the RTTOV computations, a portion of the bias seen in all the experiments the CH$_4$ band can be attributed to this factor. An interesting feature of Figure 6 is the behaviour of GENLN2 around 1600 cm$^{-1}$. The larger biases seen for the GENLN2 experiments around this wave number reflect, in our opinion, the difference between the water vapour continua models. In other regions of the water vapour band differences are not so obvious to interpret. The fact that the GENLN2_43 and kCARTA_43 spectra shown in the top panel are in good agreement (note how the two experiments use different molecular databases) hints to the fact that differences seen in the middle and bottom panel can be partially attributed to the number of levels on which the regression coefficients are provided although the impact of differences between water vapour continuum models cannot be completely ruled out.

Standard deviations are shown in Figure 7. They are comparable to biases in the window regions and in the temperature sounding region whereas they tend to be larger than biases in the ozone sounding region and in the water vapour band. Some larger values of the standard deviation in the water vapour band can be attributed to the instrument noise as well as in the region between 645 cm$^{-1}$ and 670 cm$^{-1}$. 
Figure 6: the mean value of the difference between observed and computed brightness temperatures for the northern hemisphere.

Figure 7: the standard deviation of the difference between observed and computed brightness temperatures for the northern hemisphere.
Results for the tropical band (30° S - 30° N) are shown in Figures 8 and 9. It is evident how biased have increased above all in the regions dominated by water vapour absorption although in most of the spectral regions biases are still within ± 1K. Biases in the ozone sounding band are smaller that biases observed in the northern hemisphere and biases in the 15 μm sounding region are now within ±0.5 K compared to ±0.2 K observed in the northern hemisphere. CO₂ P/R branch line mixing still has a very significant impact on the spectra and improvements in the water vapour molecular parameters are very evident when the GENLN2_43 biases between 750 cm⁻¹ and 1350 cm⁻¹ are compared to the GENLN2_100, kCARTA_43 and LBLRTM_100 biases: i.e. the conspicuous absence of spikes in the latter experiments. The comparison between the GENLN2_100 and LBLRTM_100 experiments also provides, in our view, some evidence of the fact that results are clearly influenced by the water vapour continuum model. Noticeable in Figure 9 is the increase of the standard deviation in the water vapour band.

Finally, results for the southern hemisphere (30° S to 90° S) are shown in Figures 10 and 11. It is evident how biases have significantly decreased above all in the water vapour band. In general, conclusions drawn for the northern hemisphere can be applied to southern hemisphere as well with the exception of the fact that although biases in the water vapour band have decreased the maxim value of the standard deviation has actually increased and for a large number of channels values are comparable to those observed in the tropics. Most likely this is the combination of an increased instrument noise resulting from lower scene temperatures and a less robust assimilation of water vapour radiances in this hemisphere.

![Graph showing biases in brightness temperatures for the tropics](image)

Figure 8: the mean value of the difference between observed and computed brightness temperatures for the tropics.
Figure 9: the standard deviation of the difference between observed and computed brightness temperatures for the tropics.

Figure 10: the mean value of the difference between observed and computed brightness temperatures for the southern hemisphere.
Figure 11: the standard deviation of the difference between observed and computed brightness temperatures for the southern hemisphere.

Conclusions
Four monitoring experiments have been run to compare IASI observed radiances to radiances simulated using the RTTOV fast radiative transfer model using regression coefficients based on different LBL models and molecular parameters. Results obtained for the 1st April 2008 using spectra over the sea and selecting clear channels (i.e. channels not affected by clouds) show that in the northern hemisphere biases are typically within ±1K. This figure is only exceeded in the ozone sounding band. CO₂ P/R branch line mixing has a significant impact on the simulated radiances resulting in a reduction of the biases up to 1K. In the water vapour band the use of the latest version of the water vapour continuum model results in a reduction of the bias of typically 1K in the region around 1600 cm⁻¹. The use of regression coefficients computed on a different number of pressure levels has an impact on the biases as well as the use of different water vapour continuum models. Biases in the tropics are typically larger than biases in the northern hemisphere although this is not the case in the ozone band where smaller biases are observed. However, in general, biases are still within ±1K in most of the spectral regions. The inclusion of CO₂ P/R branch line mixing is still effective in significantly reduce biases between 700 cm⁻¹ and 750 cm⁻¹ and there is evidence that the use of the latest version of the water vapour continuum model results in smaller biases. It should be noted however that these are very preliminary results. For practical and operational reasons the experiment were run over a very limited time period and the conclusions drawn in this paper could be affected by the availability of a larger sample of spectra. For this reason we are planning to run a further number of experiments over a much longer time period to accumulate a more robust statistics. Within this framework we want include experiments with kCARTA coefficients on 100 levels and a specification of the atmospheric state that reflects more realistically the concentration of the CO₂, CO, N₂O and CH₄ trace gas species.
Acknowledgements
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References


Microwave Radiative Transfer at the Sub-Field-of-View Resolution

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**Introduction**

Radiative transfer with channels that ‘see’ the surface is problematic because of emissivity and skin temperature uncertainties. This is especially true of inhomogeneous backgrounds, including coastlines, large rivers, mountainous regions, and even regions of high ocean temperature gradients (e.g. north wall of Gulf Stream). A possible solution might be the ability to integrate high resolution databases within a given field-of-view, and perform multiple radiative transfer within the field of view, weighed and integrated according to the antenna beam power.

**Methodology**

The AMSU antenna patterns were normalized by adding (negative) maximum value of each pattern to all values. All 10 channels were averaged for the 0 deg (crosstrack) and 90 deg (alongtrack) slices. The best fit to the eye was achieved with a 7th order polynomial. The 99% power level inside the field of view (fov) is at -20 dB. This is approximately 10 deg wide. Compared with 3.3 deg for the nominal 50% power of the AMSU fov, this is three times larger. Figure 1 gives the nominal AMSU fovs for a single scan, where the shading indicated the antenna power. Figure 2 shows the same AMSU fovs taken out to the 99% power level.

The GTOPO30 Digital Elevation Model (DEM) from the United States Geodetic Survey was used for this study. This model has a 0.008333° resolution, which translates to 0.93km at the equator. A single fov in the Philippines was selected. The nominal 50%, 95% and 99% power levels are shown in Figure 3. Figure 4 shows the same fov with the DEM warped according to the power fraction. This nominal land brightness temperature was 280K and the nominal ocean brightness temperature was 210K. Table 1 gives an example of integrated brightness temperature difference when the land/sea fraction was integrated according to the power fraction. For this example even going from 95% to 99% power levels yields almost a 1K difference.

**Summary**

A method has been presented to integrate land/sea fraction with antenna power fraction within the AMSU fov. If such a method is used to perform radiative transfer over inhomogeneous terrain, care must be taken to include as much of the actual fov as can be afforded computationally, lest unacceptable errors occur from truncation of the antenna power function.
Figure 1. Nominal 50% power AMSU fovs. The gray scale indicates the relative power.

Figure 2. AMSU fovs at 99% power. The gray scale indicates the relative power.

Table 1. Simulated brightness temperature computed from nominal land brightness temperature of 280 K and nominal ocean brightness temperature of 210 K for the 50%, 95% and 99% fov sizes, weighted according to antenna power.

<table>
<thead>
<tr>
<th>Land Fraction</th>
<th>Sea Fraction</th>
<th>Land Power Fraction</th>
<th>Sea Power Fraction</th>
<th>Tb</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>0.480</td>
<td>0.488</td>
<td>0.512</td>
<td>244.16</td>
</tr>
<tr>
<td>95%</td>
<td>0.301</td>
<td>0.371</td>
<td>0.628</td>
<td>236.01</td>
</tr>
<tr>
<td>99%</td>
<td>0.238</td>
<td>0.358</td>
<td>0.641</td>
<td>235.13</td>
</tr>
</tbody>
</table>
Figure 3. Nominal 50% power AMSU fov (inner) with 95% and 99% power fov over the Philippines.

Figure 4. AMSU fov at the 99% power level, with DEM warped over the relative antenna power.
Error analysis about using CO2-absorbing band for temperature retrieval

Qi Chengli, Ma Gang, Liu Hui, Zhang Peng

In the past more than 30 years, the traditional temperature retrieval method is using the infrared channels on CO2-absorbing band, meanwhile in the current several decades, the column contents of CO2 have noticeably increased. So in the retrieval method it is no more accurate for the forward calculation that generate fast transmittance coefficients using fixed content CO2 column contents. Using the updated CO2 column contents to calculate fast transmittance coefficients and perform the bias estimation of simulated satellite observed measurements, and derive the temperature retrieval results. Comparison between the traditional temperature retrieval results and that with adjusted satellite observed brightness temperature show the error results.
Assimilation of cloudy radiances and retrieval of cloud properties require a radiative transfer method that is accurate and computationally fast. An efficient treatment of scattering is one necessary element of the modeling. Another requirement is an efficient method to represent the spectral response of a channel, without resorting to numerical integration over a fine grid of monochromatic points covering the channel response function. Optimum Spectral Sampling (OSS) has been established as a very accurate and fast method to handle the spectral response and radiative transfer in clear and cloudy atmospheres. This paper describes progress in development and testing of OSS extensions to cloudy atmospheres where scattering is significant. OSS computes the radiance for a channel as a weighted average of results from radiative transfer calculations at a relatively few monochromatic points, where the points and their weights are determined by optimization. The OSS optimal selection process can be performed in a localized manner, where the search for the optimal points is restricted to the spectral range of finite response for the channel. Another mode (described at ITSC-14) is the implementation of generalized training, where the search for optimal points for a channel is bounded only by the range of spectral response of all the channels together. A clustering approach makes the search process efficient. With generalized training, only ~250 spectral points are needed for the full AIRS channel set, which is an average of ~0.1 points per channel. For cloudy skies, OSS weights derived with generalized training from clear-sky optimization are not always accurate. The optical properties of clouds may vary substantially across the range of spectral points that contribute to a channel, and the properties will vary with the microphysical properties of the clouds and their spatial distribution. A variety of cloud conditions can be mixed into the training set, to seek spectral points and weights that are accurate for cloudy and clear atmospheres, but the performance in clear atmospheres tends to be degraded by the inclusion of cloudy atmospheres. Because cloud optical properties are spectrally smoother than molecular absorption, the cloudy profiles are less demanding, and a set of weights that achieves a specified accuracy overall will not necessarily achieve that accuracy for the clear-sky subset of training cases. To address this issue, we require that the accuracy threshold be met simultaneously for each subset (clear sky, ice cloud, liquid cloud, ice+liquid cloud). In addition, we have implemented a segmented version of generalized training by breaking the spectrum into intervals of ~20 cm-1 and applying the generalized training method to the channels in each interval independently. In such intervals, the variations in cloud properties have an impact on radiances that is quasi-linear. This capability was originally introduced for land applications to handle spectral variations of surface
emissivities, and for cloud it may well be that we could use wider intervals. This approach gives a lower computational gain than the fully generalized training, but gives increased robustness for clear and cloudy atmospheres. For AIRS, this method yields ~1 spectral point per channel. For an instrument with broader response functions, such as MODIS, the number of required nodes per channel can be up to about 25. In such cases, the radiative transfer integration becomes the dominant element of the computation time. An option for speeding up the OSS RT calculations in scattering atmospheres consists of predicting a multiple-scattering increment relative to non-scattering radiances. Under such a scheme, radiance calculations in non-scattering conditions (these include treatment of cloud absorption) are performed for all the nodes, which is fast, and the full scattering calculations are performed only for a few selected predictor nodes optimally selected among the original set of OSS nodes used by this channel. The difference between the monochromatic radiances obtained with scattering and without scattering for this selected subset of nodes is used to predict a scattering correction for the channel. In tests with MODIS thermal channels, the accuracy of this OSS approach can exceed the accuracy of the commonly used band-transmittance parameterization method with an average of 1.7 scattering calculations per MODIS channel. This OSS method is particularly advantageous for reflective surfaces with low optical depths. For mini-AIRS, it is expected that this approach, combined with the generalized training, may require much less than one multiple-scattering calculation per channel.
Surface, aircraft and satellite observations show that many cloud types can appear simultaneously at the same location but at different altitudes. Furthermore, clouds may be continuous or broken at a given cloud level within a sensor's field of view. Therefore, it is desirable that a general radiative transfer model can deal with multilayer cloudy atmospheres for remote sensing applications. Multilayer cloudy systems can be complicated even for a non-scattering atmosphere. It can be shown that forming a two- and three-layer cloud system yields 10, and 218 combinations, respectively. The satellite cloud detection or cloud property retrieval algorithms (e.g. the CO2-slicing method, the N* methods) which have been widely used for a single-layer or a simple two-layer overcast cloud system are not applicable to more complicated multilayer cloudy systems. In support of GOES-R Advanced Baseline Imager (ABI) for remote sensing of cloudy atmospheres, we develop a generalized multilayer cloudy radiative transfer model. The model is not too complicated that it makes the cloudy retrieval problems unmanageable, while generalized enough to handle multilayer clouds with the definition of the effective cloud emissivity to include the multiple scattering effects. The clear-sky atmosphere is a special case of this model where the cloud fractions are reduced to zero.
Retrieval of Global Hyperspectral Surface Emissivity Spectra from Advanced Infrared Sounder Radiance Measurements

Jun Li and Jinlong Li

Global hyperspectral surface emissivity map has been generated using Atmospheric InfraRed Sounder (AIRS) radiance measurements. Single field-of-view physical retrieval algorithm (Li et al. 2007: Geophysical Research Letters) was used for retrieving the global hyperspectral IR emissivity product. Collocated operational MODIS (Moderate Resolution Imaging Spectroradiometer) cloud mask product with 1 km spatial resolution is used for AIRS sub-pixel cloud detection (Li et al. 2004: Journal of Applied Meteorology); only AIRS radiances from clear skies are used for the IR surface emissivity retrieval. The 8-day (01 – 08 January 2004) composite of AIRS emissivity retrievals agrees well with the operational MODIS emissivity product at a few broad spectral bands. The spatial and spectral features of the derived emissivity spectra over desert and other regions well reflect the surface property and ecosystem conditions. The method can also be applied to process IASI (Infrared Atmospheric Sounding Interferometer) radiances with full IR spectral coverage. The global hyperspectral IR emissivity map is very important for assimilating radiances over land, retrieving other products such as dust properties and cloud properties using IR radiances.
Using Hyperspectral IR Sounder Data Over Land - PC radiative transfer and 1d-Var.

Jonathan P Taylor, Stephan Havemann, Jean-Claude Thelen

The Met Office started assimilating IASI data from the Metop platform in November 2007 and trials have shown it to have a big impact on NWP skill. However, current assimilation techniques only allow 183 of the 8461 available channels on IASI to be utilised and these are only assimilated in cloud free conditions. Over land the number of channels is reduced further to around 40 that have their peak sensitivity at altitudes above 400hPa. A novel new principal component radiative transfer scheme has been developed and coupled with a version of the UM 1d-Var code. Using this new technique we demonstrate the ability to use hyperspectral sounder data over all cloud free scenes including those over land. In this presentation results using around 4000 channels from the Airborne Research Interferometer Evaluation System (ARIES) on the FAAM BAe146 research aircraft will be presented showing the skill in retrieving temperature, water vapour and ozone profiles simultaneously with spectrally resolved land surface emissivity and land surface temperature all of which are required to utilise satellite data over land within an NWP environment. The presentation will conclude with a presentation on the future direction of this research which includes the simulation of cloud affected radiances using principal component radiative transfer.
**Infrared continental surface emissivity spectra retrieved from IASI observations**

E. Péquignot, A. Chédin, N. A. Scott

Infrared Atmospheric Sounding Interferometer (IASI) is a key element of the payload onboard METOP series of European meteorological polar-orbit satellites. The first METOP satellite was successfully launched on 19th of October 2006. In this paper, IASI observations over land are interpreted in terms of surface emissivity spectra at a resolution of 0.05 μm and skin temperature. For each IASI observation, an estimation of the atmospheric temperature and water vapor profiles is first obtained through a proximity recognition within the Thermodynamic Initial Guess Retrieval (TIGR) climatological library of about 2300 representative clear sky atmospheric situations. With this a priori information, all terms of the radiative transfer equation are calculated by using the 4A line-by-line radiative transfer model. Then, surface temperature is evaluated by using a single IASI channel (channel 699 at 12.203 μm) chosen for its almost constant emissivity with respect to soil type. Emissivity is then calculated for a set of 97 atmospheric windows (transmittance greater than 0.5) distributed over the IASI spectrum. The overall infrared emissivity spectrum at 0.05 μm resolution is finally derived from a combination of high spectral resolution laboratory measurements of various materials carefully selected within the MODIS/UCSB and ASTER/JPL emissivity libraries.
Recent updates of the UW/CIMSS high spectral resolution global land surface infrared emissivity database

Eva E. Borbas, Robert O. Knuteson, Suzanne W. Seemann, Elisabeth Weisz, Leslie Moy

An accurate infrared land surface emissivity product is critical for deriving accurate land surface temperatures, needed in studies of surface energy and water balance. Current sensors provide only limited information useful for deriving surface emissivity and researchers are required to use emissivity surrogates such as land-cover type or vegetation index in making rough estimates of emissivity. Inaccuracies in the emissivity assignment can have a significant effect on atmospheric temperature and moisture retrievals. To accurately retrieve atmospheric parameters, a global database of land surface emissivity with fine spectral resolution is required. An accurate emissivity is also required for any application involving calculations of brightness temperatures such as the assimilation of radiances into climate or weather models. At the Cooperative Institute of Meteorological Satellite Studies (CIMSS), University of Wisconsin, the so-called UW/CIMSS Baseline Fit (BF) global infrared land surface emissivity database was developed. The monthly, global database has been available since 2006 at the http://cimss.ssec.wisc.edu/iremis/ website and includes data for each month from October 2002 at ten wavelengths (3.6, 4.3, 5.0, 5.8, 7.6, 8.3, 9.3, 10.8, 12.1, and 14.3 microns) with 0.05 degree spatial resolution. The BF approach uses selected laboratory measurements of emissivity to derive a conceptual model, or baseline spectra, and then incorporates MODIS MYD11 measurements at six wavelengths to adjust the emissivity at 10 hinge points. These wavelengths were chosen to capture as much of the shape of the higher resolution emissivity spectra as possible between 3.6 and 14.3 microns. As a recent effort at the UW/CIMSS, an algorithm was developed to derive a high spectral resolution (HSR) IR land surface emissivity from a combination of HSR laboratory measurements of selected materials, and the UW/CIMSS Baseline Fit (BF) global infrared land surface emissivity database by using a principal component analysis (PCA) regression. The first Principal Components of 123 selected laboratory spectra (in this study the wavenumber resolution between 2-4cm-1, at 416 wavenumbers) were regressed against the 10 hinge points of the monthly UW/CIMSS BF emissivity. The algorithm to extract the high spectral resolution emissivity database from the UW/CIMSS BF emissivity dataset will be available in early 2008. In the presentation, after the introduction of the emissivity database, the impacts of varying the emissivity on the calculated top-of-atmosphere BT across the infrared spectral regions are examined, then an analysis of the effects of a change in emissivity on retrieved temperature and moisture profiles will be presented. At the end this MODIS-based emissivity database will be compared to the HSR emissivity database derived from AIRS measurements.
Upper tropospheric humidity data set from operational microwave sounders

V. O. John, S. A. Buehler, M. Kuvatov, M. Milz, B. J. Soden, and D. L. Jackson

Microwave radiation measured around 183.31 GHz by operational weather satellites can be used to derive Upper Tropospheric Humidity (UTH). This presentation gives details of a new UTH data set derived from Advanced Microwave Sounding Unit - B (AMSU-B) instruments on board NOAA (15, 16, and 17) satellites for 8 years (2000-2007). In contrast to UTH data sets derived from infrared measurements, the new data set is less affected by clouds. The maximum uncertainty due to clouds is estimated as 10 %RH in deep convective areas. We also show that the data from the three satellites are consistent with mean relative differences less than 4+/−7%. Comparisons with Radiosonde measurements and infrared UTH measurements show consistent results with previous studies.
Intersatellite Calibration of HIRS Upper Tropospheric Water Vapor

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Abstract

Intersatellite calibration is carried out for the upper tropospheric water vapor (UTWV) data from clear-sky HIRS channel 12 measurement. As the intersatellite biases are scene brightness temperature dependent, an algorithm is developed to account for the varying biases with respect to brightness temperature. The bias correction data are derived from overlaps of monthly means of each 10-degree latitude belt. For the colder temperature range, data from the simultaneous nadir overpass observations are incorporated. The HIRS measurements from the NOAA series of polar orbiting satellites are calibrated to a baseline satellite. The time series of the intersatellite calibrated HIRS UTWV data from late 1970s to present is constructed and anomaly data are computed. The anomaly time series is used to track tropical waves and variability. The HIRS UTWV anomaly data are particularly useful in monitoring the Madden-Julian oscillation and various equatorial waves.

Introduction

The High-Resolution Infrared Radiation Sounder (HIRS) has been on board the operational National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellite series (N#, where # is the satellite number) for nearly 30 years. Among the twenty channels in the HIRS instrument, channel 12 measures the upper tropospheric water vapor (UTWV). Due to the independence in the calibration based on individual HIRS instrument’s channel spectral response function along with other factors, biases exist from satellite to satellite. Fig. 1 shows monthly mean time series of limb-corrected clear-sky HIRS UTWV from each individual satellite of the NOAA polar orbiting satellite series between 30S and 30N. On a monthly basis, the upper tropospheric measurements from different overlapping satellites should reflect similar basic features. However, consistent biases are evident among satellites. For example, the averaged difference between N11 and N12 is -1.2 K. When the HIRS instrument switched from HIRS/2 to HIRS/3, the difference between N14 and N15 is about 8 K. These intersatellite biases have become a common source of uncertainty for long-term studies. The UTWV is a fundamental climate data record and is key to water vapor feedback, so it is important that the intersatellite biases are corrected.

Efforts were made in the past to adjust these HIRS inter-satellite biases. Bates et al. (1996) intercalibrated 13-years (1981-1993) of HIRS time series with an empirical method. In the analysis, the data were binned on 2.5 by 2.5 degree grids for 5-day averaged data. A 13-year mean for each location based on each pentad and each satellite was calculated. The anomaly relative to this mean was then computed for the dataset. The anomalies were compared empirically between two satellites for the same target assuming that the statistical distributions of anomalies were the same. Based on the comparison, the satellites were adjusted to a base satellite (N7) to produce a self-consistent dataset of global observations. Recently, Cao et al. (2005) used simultaneous nadir overpass (SNO) observations to inter-compare radiances measured by HIRS on board N15, N16, and N17. The SNO observations were taken from the same location at the satellite nadir within a few seconds. The method was developed to quantify the observed radiance
differences measured by HIRS on different satellites with little ambiguity. The study also provided extensive discussion on possible causes for HIRS radiance biases.

![Graph showing monthly mean time series of HIRS UTWV from each individual satellite, averaged from 30S to 30N latitudes.]

**Intersatellite Calibration Datasets**

The SNO observations provide inter-comparisons of overlapping satellite measurements. However, because the satellites intersect with each other in high latitudes, the data represent only a small portion of the dynamic ranges of global data. In the present study a new approach is developed to derive the clear-sky HIRS intersatellite biases based on matched-up zonal averages from the equator to the poles. On a monthly basis, the global HIRS clear-sky field exhibits distinct zonal features (Wu et al., 1993). We first divide the global data into 10-degree latitude belts from 85S to 85N. Monthly means of these latitude belts are computed. For the overlapping satellites, the differences (biases) of monthly means are obtained along with the monthly mean temperature to account for the temperature dependent features of the intersatellite biases.

The intersatellite biases of UTWV for TIROS-N, N6 to N17, and METOP-2 derived from overlaps of zonal monthly means are shown in Fig. 2. The biases are computed by subtracting the matched-up
brightness temperatures for a later satellite from those for the earlier satellite (for example, the bias between N16 and N17 is $T_b(N16) - T_b(N17)$). For every 2 degree temperature bin of the HIRS observation, the intersatellite biases are extracted and averaged. In the figure, each plot represents the averaged intersatellite bias for the scene temperature centered at the indicated value with the range of -1 and +1 degree K.

![Bias vs Temperature](image)

Fig. 2: Sequential intersatellite biases of UTWV for eleven pairs of satellites, as functions of the brightness temperature.

The bias values are very large between N14 and N15. This is caused by the channel frequency change from about 1480 cm$^{-1}$ on N14 and earlier satellites to 1530 cm$^{-1}$ on the KLM series of satellites starting with N15. Due to the frequency change, the sensors on N14 and N15 essentially observed water vapor at different heights, which lead to the large bias of more than 8 K. For other satellite pairs, the biases are within the range of $\pm0.8$ K. Many satellite pairs have bias variations of more than 0.5 K across the scene temperature ranges. Small bias values are found at the low brightness temperature range. Biases generally become larger with increasing brightness temperature.

This bias dataset covers a large range of the scene temperatures. However the monthly means do not cover data at the very low and very high temperatures of pixel observations. For the cooler temperatures,
measurement from SNO observation is used. The SNOs occur when two satellites paths intersect, generally at +70° to +80°, and -70° to -80° latitude zones. Detailed data processing procedure has been provided by Cao et al. (2005). At the high end of the temperature, examinations show that the bias tends to saturate to a constant value (Fig. 2). Therefore for the scene temperatures greater than the ranges in the zonal mean bias dataset, the bias values at the high temperature bound is assigned.

Intersatellite Calibrated UTWV Time Series

The HIRS data are first processed to clear cloudy pixels for the water vapor field. Limb correction is applied with a linear multi-variate regression algorithm using multiple HIRS channels (Jackson et al., 2003). Based on the intersatellite bias dataset, the HIRS channel 12 data from individual satellites are adjusted to N12 as a base satellite. The bias datasets derived from overlaps of zonal monthly means are applied to the scene temperatures except for the coldest scene temperatures, for which biases based on SNO are used. Because there is no overlap between N8 and N9, the intersatellite bias for UTWV between these two satellites are estimated by comparing the time series to the one using methods developed by Bates et al. (1996). An ad hoc bias value of -0.3 K is derived based on the comparison. These bias adjustments are applied to N6 through N17 for each pixel. The pixel data are then mapped to 2.5x2.5 degree grids, and the gridded daily and monthly means are computed.

The intersatellite calibration algorithm is designed to minimize the differences among different satellite measurements. Fig. 3 shows the intersatellite calibrated monthly mean time series of UTWV data from N6 through N17 from 1979 to 2007. A general agreement is found among multiple satellites for the periods that there are overlapping satellites. The large jumps from satellite to satellite displayed in Fig. 1 are removed. The data from the ATOVS satellites (N15 and after) are brought to the TOVS satellite level with similar overall variance between HIRS/2 and HIRS/3. The time series can continually be extended using this method. Comparison of this time series to the one generated based on the algorithm described in Bates et al. (1996) for 1979-1998 also reveals good agreement.

Detailed examination of the intercalibrated time series shows that small differences remain between overlapping satellites. Much of these differences can be explained by the nature of the clear-sky data. The cloudiness condition varies at different observation times of the different satellites. The monthly means for different satellites are thus often the averages of different days in a month, which lead to slight differences in monthly means. To quantify the remaining intersatellite differences that have not been removed by the intercalibration algorithm, the differences of intersatellite-calibrated monthly mean HIRS UTWV between the overlapping satellite pairs are shown in Fig. 4. In the figure each plotted value represents the average of gridded monthly mean differences from 30S to 30N. The difference is calculated by substracting the later satellite value from the earlier satellite value. Fig. 4 displays that the monthly differences of intercalibrated time series are mostly within ±0.2 K, and almost all the monthly differences are within ±0.4 K. The averages of these remaining differences for each pair of the satellites are presented in Table 1. The list shows that the averaged differences are all near zero, and none of the averaged differences is larger than 0.1 K. It is important that the difference clusters of individual pairs of satellites are all closely grouped around 0 K. This ensures that the discontinuities among the uncorrected individual satellite series are minimized in the intercalibrated satellite series.
Fig. 3: Interatellite calibrated monthly mean time series of HIRS UTWV from each individual satellite, averaged from 30S to 30N latitudes.

Fig. 4: Differences of intersatellite calibrated HIRS UTWV monthly mean between individual satellites, averaged from 30S to 30N latitudes.
Table 1: Averaged remaining differences (K) of intersatellite calibrated HIRS UTWV monthly mean between individual satellites for 30S to 30N latitudes.

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Fig. 5: Time-longitude section of clear-sky UTWV anomaly averaged from 7.5S to 7.5N. Shaded colors are the 3-day running mean anomalies calculated by subtracting the daily climatological mean based on the 1979 to 2007 period. The arrows are examples of propagating equatorial tropical waves.
A global UTWV anomaly dataset is developed based on the intersatellite calibrated daily time series. To track and monitor tropical waves, time-longitude section of UTWV data near the equator are examined. The analysis shows that UTWV data have the advantage of around-the-globe coverage of equatorial waves compared to the outgoing longwave radiation data that are currently used by numerical prediction centers. The outgoing longwave radiation analysis typically only captures the tropical waves over the eastern hemisphere. The UTWV provides a continuous observation across both eastern and western hemispheres. Fig. 5 shows a time-longitude section of clear-sky UTWV anomaly averaged from 7.5S to 7.5N for about five months of data. In the figure shaded colors are 3-day running mean anomalies calculated by subtracting the daily climatological mean based on the 1979 to 2007 period. As an example, the black arrows indicate the propagation of several eastward moving Madden-Julian Oscillations, and the green arrows show the westward propagating equatorial Rossby waves which are most significant over the western hemisphere (eastern Pacific Ocean, central America, and Atlantic Ocean). Such a diagram is useful in the continuous monitoring of the movement of Madden-Julian Oscillation and various equatorial waves.

Acknowledgments

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References

**Long-term application and evaluation of IAPP using global radiosonde and CHAMP measurements**

Marc Schröder, Jörg Schulz, Markus Jonas, and Ralf Lindau

The major objective of the Satellite Application Facility on Climate Monitoring (CM-SAF) is the exploitation of satellite observations to derive information on key climate variables of the Earth system. The CM-SAF focuses on the atmospheric part of the Essential Climate Variables defined within the framework of the Global Climate Observing System (GCOS). Among other methods the CM-SAF operationally applies the International ATOVS Processing Package (IAPP) to retrieve humidity and temperature profiles from ATOVS observations onboard NOAA-15, -16, and -18. A kriging routine is applied to the swath based retrievals in order to determine daily and monthly averages on a global grid. Furthermore, the profiles are vertically integrated and averaged to provide column integrated water vapour as well as humidity and temperature values for 5 layers and at 6 layer boundaries. Currently the years 2004-2007 had been processed, and a reprocessing event will go back to 1998 in the near future. The evaluation of temperature and humidity Climate Data Records (CDRs) for the period 2004-2007 is carried out using global radiosonde observations that meet the quality standards of the GCOS Upper Air Network (GUAN). The evaluation is extended by utilising CHAllenging Minisatellite Payload (CHAMP) observations for the years 2004 and 2005. The evaluation considers biases, RMSE, and mean absolute deviations and separates between global and zonal values. The maximum average bias of column integrated and layer integrated water vapour between ATOVS and GUAN radiosondes is 0.5 kg/m2 and 0.8 kg/m2 (850-700 hPa), respectively. For the layer averaged temperatures we find a maximum bias of -1.1 K (300-200 hPa). The RMSE of water vapour exhibits an annual cycle with a maximum in summer months and a maximum of zonal RMSE around the equator with some variation depending on the month. The exemplary comparison of ATOVS and CHAMP data confirms above findings. When future progress in inter-calibration efforts leads to improved homogenised radiances, reprocessing of ATOVS observations can be carried out easily and will lead to CDRs with at least the accuracy as presented above. Currently CM-SAF is working on an automated evaluation of temperature and humidity products with radiosonde profiles from reference stations.
**AIRS in Atmospheric and Climate Research**

**Bjorn Lambrigtsen, Mous Chahine, Tom Pagano, Eric Fetzer**

The Atmospheric Infrared Sounder (AIRS), the first of a new generation of hyperspectral infrared sounders, was launched on the NASA Aqua platform in 2002 and has operated flawlessly ever since. With its extremely high spectral resolution – 2378 channels between 3.7 and 15.4 microns – and very stable and accurate radiometric measurements it has been possible to produce atmospheric data sets of unprecedented coverage, accuracy and resolution. Assimilation of the observed radiances into numerical weather prediction models – now done on a routine basis at a number of the world’s major weather prediction centers – has already had a major impact on global weather forecast accuracy and range. Now, derived data sets are also beginning to play a major role in atmospheric research, ranging from process studies related to the hydrologic cycle to climate research related to greenhouse and other trace gases. These data sets, which include global 3-dimensional temperature and water vapor fields that are as accurate as can be obtained with the highest quality radiosondes – but with daily global coverage, are enabling studies that were previously not possible. The AIRS data sets are freely available from NASA and now cover the period from September 2002 to the present. A new version of the data processing system – V5 – was recently implemented and is now used to process all current and past data to the highest quality. We describe the data sets and results of efforts to validate them and discuss research problems that they can be used to address. The work reported on here was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.
Surface temperature dependence of the frequency of severe storms in the tropical oceans

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Abstract

The analysis of five years of data from the Atmospheric Infrared Sounder (AIRS) shows that the frequency of extreme Deep Convective Clouds (DCC) in the tropical oceans increases by about 50% per 1 K of warming of the zonal mean surface temperature. With the current 0.13K/decade rate of global warming, this implies a 6%/decade increase in the frequency of DCC and, through correlation, severe storms. Since we define extreme DCC as deep convective clouds with cloud top temperature of 210 K or colder, i.e. clouds which penetrate the tropopause and inject water vapor into the lower stratosphere, an increase in the frequency of DCC with global warming also increases the amount of water vapor in the stratosphere. This increase is consistent with observations over the past 50 years.

Key words: Deep Convective Clouds, Infrared temperature sounding hyper-spectral climate cloud feedback

Introduction

Higher temperatures of the oceans associated with global warming should result in an increase in the amount of water vapor, which should manifest itself as an increase in the fractional cloud cover. However, the analysis of 22 years of data from eleven HIRS instruments on the NOAA/ATOVS weather satellites between 1978 and 2003 revealed no significant trend in the low or high cloud fraction for the tropical oceans (Wylie et al. 2005). High clouds in that study were defined as cloud tops above 400 hP, which are referred to as Deep Convective Clouds (DCC) by Rong Fu et al. (1990) and correspond to cloud top temperatures colder than 240 K. Since no change is detectable in the frequency of 240 K cloud tops, we focused on cloud tops colder than 210 K. These clouds should be referred to as extreme DCC, but in the following we refer to them as just DCC. We treat the DCC as a process and analyze the temperature dependence of the frequency of this process in the tropical oceans.

Approach

The analysis used data from the first five years of the Atmospheric InfraRed Sounder (AIRS) (Chahine et al. 2006). AIRS is a infrared hyperspectral imager on the EOS Aqua spacecraft, which covers the 3.7-15.4 micron infrared spectral region with 13 km nadir footprints. AIRS was launched into polar 705 km altitude orbit on May 4, 2002 and has been in routine data gathering mode essentially uninterrupted since September 2002. Global coverage is achieved twice each day. The 1:30 PM ascending node and the altitude of the EOS Aqua orbit are

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accurately maintained to minimize confusion of diurnal variability with climate trends. Each day AIRS generates about 3.7 million spectra.

Results

Every spectrum over where the brightness temperature in the 1231 cm⁻¹ window channel is less than 210 K at non-frozen land or ocean position is identified as a DCC. The spectra selected with this simple threshold invariably show the very pronounced spectral characteristics of cirrus ice in the 11 micron window region (Aumann et al. 2006b). On average about six thousand DCC are identified globally each day, almost all within 30 degrees of the equators. While this seems like a large number, it corresponds to only about 0.5% of all spectra in the tropical ocean latitudes. The temperature of the southern and northern tropical oceans goes through a seasonal cycle between 294 K and 302.5 K. Correlated with this seasonal cycle is the frequency of DCC (Aumann et al. 2007). This correlation, shown in Figure 1 for the 0-30N oceans, is used to determine the temperature sensitivity of the DCC frequency.

![Figure 1. The strong correlation between the mean zonal SST (solid line) and the count of DCC (broken line) can be used to determine the temperature sensitivity of the DCC frequency.](image)

For each of the 1788 days between 2002/09/01, the first day of routine AIRS data availability, and 2007/08/31 we counted the DCC in four independent groups: The 0-30N and 0-30S tropical ocean zones, and for each zone we separate the day time overpasses (at 1:30 PM, ascending orbit) from a night time overpasses (at 1:30 AM local time, descending orbit). Figure 2 shows the correlation between the daily count of DCC for the night overpasses of the 0-30N latitude zone, and the mean SST in that zone. This is not the SST associated with the DCC, which is
considerably warmer than the zonal mean SST. A very similar high correlation between the zonal mean SST and the DCC count can be seen in the other three groups.

Inspection of Figure 2 shows that the typical count is 1500 and that the count increases by 2000 as the temperature increases by 3 K from 298 to 301K, i.e. about 670/K. The DCC count divided by the mean number of spectra is the DCC fractional frequency sensitivity, i.e. the back-of-the-envelope estimate results in a temperature sensitivity of 670/1500/K= 0.45/K. Table 1 summarizes the results for the four groups using linear regression. For the 0-30N night data this results in a sensitivity of 0.51/K, i.e. the frequency increases by 51% if the SST increases by 1 K in the 299 to 301 K range.

The correlation between the DCC count and the SST ranges from 0.57 to 0.62 for the four groups. Although the mean SST in the 0-30S zone is 0.4 K lower than 0-30N, there is no obvious N/S effect in the temperature sensitivity of the DCC frequency.

### Table 1. Summary of the DCC trends of the four tropical ocean groups including the TWP

<table>
<thead>
<tr>
<th>1788 day with TWP</th>
<th>DCC count / SST correlation</th>
<th>mean zonal SST</th>
<th>mean DCC count</th>
<th>sensitivity [fraction/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30N day</td>
<td>0.59</td>
<td>300.3</td>
<td>1113</td>
<td>0.58</td>
</tr>
<tr>
<td>night</td>
<td>0.62</td>
<td>300.2</td>
<td>1287</td>
<td>0.51</td>
</tr>
<tr>
<td>0-30S day</td>
<td>0.57</td>
<td>298.9</td>
<td>638</td>
<td>0.46</td>
</tr>
<tr>
<td>night</td>
<td>0.59</td>
<td>298.8</td>
<td>804</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Discussion

In our study we focused on extreme DCC with cloud tops colder than 210 K, corresponding to a pressure level of 150 hP and less. These high clouds are found in only about 0.5% of the spectra in the tropical ocean latitudes, while 35% of the tropical oceans are covered with clouds above 400 hP (Wylie et al. 2005). These extreme DCC penetrate the tropopause and inject water vapor into the lower stratosphere.
We have treated the DCC as a process, with a temperature dependent frequency. The derivation of a 0.5/K temperature sensitivity of the frequency of this process has implications in the context of long-term global warming. Using the nominal global warming rate of +0.13 K/decade (IPCC 2007), the frequency of DCC increases at the rate of 0.5/K*0.13K/decade= 6%/decade.

As the frequency of DCC increases by 6%/decade with global warming, the amount of water vapor injected into the stratosphere also increases. Assuming a linear correlation between the DCC frequency and the amount of water vapor injected into the stratosphere, a 6%/decade increase in the stratospheric water vapor would be expected. This is reasonably consistent with the observation by Rosenlof et al. (2001) that the stratospheric water vapor mixing ratio has increased steadily over the past half century at the rate of 10%/decade.

The association of cloud formations with cloud tops colder than 210 K with heavy rainfall, lightning, crop damaging hail and tornadoes goes back to Reynolds in 1980 and infrared data from the first geosynchronous satellites (Reynolds, D. W. 1980). Our finding suggests that the frequency of severe storms will increase with global warming at the rate of 6%/decade. A recent re-analysis of SSMI data (Wentz et al. 2007) shows that precipitation over the oceans has increased by 1.5% per decade during the past 19 years. The increase in the total precipitation may be associated with the increase in the frequency of DCC, but precipitation associated with DCC, while heavy, does not play a dominant role in the total precipitation.

Conclusions

Five years of data from the Atmospheric Infrared Sounder are used to argue that the frequency of Deep Convective Clouds in the +/-30 degree tropical zone increases by 50% per degree of increase in the zonal mean surface temperature from the current mean tropical ocean temperature. Assuming global warming at the 0.13 K/decade rate, the frequency of DCC, and by correlation the frequency of severe storms in the tropical oceans, will increase by 6% per decade. This rate is consistent with the observed increase in stratospheric water vapor.

Acknowledgements

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References


Chahine, Moustafa T, Thomas S. Pagano, Hartmut H. Aumann, Robert Atlas, Christopher Barnet, John Blaisdell, Luke Chen, Murty Divakarla, Eric J. Fetzer, Mitch Goldberg,


Progress and Plans for the use of radiance data in the NCEP global and regional data assimilation systems

J. Derber, R. Treadon, D. Kleist, M. Rancic

Significant changes in the use of radiance data at NCEP have been developed and are in the process of being implemented. These developments include the use of new satellite data (METOP, SSMIS), improvements in the bias correction and quality control, enhancements in the inclusion of the surface signal in the simulated radiances, the introduction of improved radiative transfer and advances in the data assimilation techniques. Details of some of these changes (e.g., new satellite data and improved radiative transfer) are covered in other talks at this meeting. This presentation will present an overview of the changes and present the impact of these changes on the overall data assimilation and forecast system. In addition, specific details of the enhancements to the bias correction technique, improvements in the incorporation of the surface signal and the significant changes in the data assimilation technique will be presented. Finally future plans for operation assimilation of satellite sounder data will be briefly discussed.
An Update on the Operational Use of Satellite Sounding Data at the Met Office

Brett Candy, Steve English, Fiona Hilton, James Cameron, Amy Doherty, T. R. Sreerekha, William Bell and Nigel Atkinson

This talk will give a snapshot of the sounding instruments used operationally in the Met Office global model. Since the last ITSC meeting a major forecast impact has come from the use of the instruments onboard METOP-A. However several other important updates have been introduced that increase the number of observations from existing instruments. These include the use of high peaking channels from AIRS over land and the reintroduction of the HIRS instruments on NOAAs 16 & 17 and AMSU-B on NOAA-17. Channel usage and observation errors have also had to be revised following very large analysis increments in the upper stratosphere around the winter pole.
Recent advances in the use of satellite data in the French NWP models


The use of satellite data in the French NWP models at global and regional scales is described. In the last year, a lot of effort had been dedicated to the assimilation of data from the MetOp satellite (ATOVS, ASCAT and IASI). The operational assimilation of ATOVS and ASCAT has been performed. The assimilation of IASI data and the more extensive use of AIRS data is currently pre-operational. Another major milestone has been the operational use of GPS radio-occultation data from the COSMIC, CHAMP and GRACE satellites mid-2007. METEOSAT CSR data are also being introduced in the global model (in the regional model ALADIN, a fine resolution radiance product provided by the CMS in Lannion is used instead). GPS ground-based data have been used in both models since 2006. In terms of algorithmic development, an improved parametrisation of microwave emissivity has allowed a better use of these data over land, as investigated in particular over Africa during the AMMA field experiment period. Another major development was the introduction of a variational bias correction algorithm based on the one developed at ECMWF, for radiance bias correction. This change was quite positive in terms of forecast scores in the global model.
Inclusion of new data types in the Canadian data assimilation system

Nicolas Wagneur, L. Garand, J. Aparicio, A. Beaulne, M. Buehner, J-M. Bélanger, D. Anselmo, G. Deblonde, J. Hallé, P. Koclas, R. Sarrazin, and G. Verner

The Canadian data assimilation system is now benefiting from several new data types: Quikscat oceanic winds, radiances from seven SSM/I channels, and 87 AIRS channels. Extreme scan angles from AMSU-A and AMSU-B are also assimilated, which increases by about 25% the volume of these data. In addition, the radiative transfer model was upgraded to RTTOV-8 along with a new vertical interpolator. The poster will present the impact of these new data as evaluated in a parallel run which was run from January to April 2008. At the time of this writing, results are clearly positive in the Southern hemisphere and closer to neutral in the Northern Hemisphere. In the Tropics, a large improvement in the geopotential bias is noted. It is planned to continue that parallel run with the inclusion of GPS radio-occultation data assimilated up to 30 km. Results on the impact of these data should be available at the time of the conference.
CMA/NSMC Satellite Data Assimilation Activities: Uses of ATOVS and Fengyun VASS Data in WRF

Lu Qifeng¹, Liu Zhiquan¹,², Wu Xuebao¹, Zhang Peng¹, Lu Naimeng¹, Zhang Fengying¹, Ma gang¹, Yang jun¹, Dong Chaohua¹, Tang shihao¹, Dale Barker²

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ABSTRACT
The regional ATOVS data received and preprocessed by National Satellite Meteorological Center of Chinese Meteorological Administration (NSMC/CMA) have been operationally assimilated (Liu, 2006) in NSMC/CMA using regional 3DVar data assimilation system (WRF/3DVar) by RTTOV8.7 model. Based on the WRF 3DVAR system of NCAR, some improvements were further done to put the satellite data into use in NWP model at NSMC/CMA. In this paper, the extensions on WRF 3DVAR for satellite data assimilation at NSMC/CMA were introduced; the assimilation application of ATOVS data in the typhoon track prediction and in emergency response to monitor the snow storm occurred in January 2008 over South China were demonstrated; further the potential of FY3 VASS data assimilated into NWP was analyzed; and finally the further work on the satellite data assimilation was delineated.

Key words: CMA/NSMC, Satellite Data Assimilation Activities, ATOVS, FENGYUN VASS

1 INTRODUCTION
The regional ATOVS data was received and preprocessed by National Satellite Meteorological Center of Chinese Meteorological Administration (NSMC/CMA) and the ATOVS radiances have been operationally assimilated (Liu, 2006) in NSMC/CMA using regional 3DVAR data assimilation system (WRF/3DVar, Barker, 2004, 2006) by RTTOV8.7 model (Eyre, 1991). WRF 3DVAR system was developed from MM5 3DVAR system, the more details on the WRF and WRF 3DVAR can be found in reference of WRF model guidance (Michalakes et. al., 1999; William et. al., 2006). Based on the WRF 3DVAR system of NCAR, the following works were further done to improve the satellite data application in NWP model at NSMC/CMA.

1). The satellite atmosphere data assimilate system was constructed based on WRFV2 forecast model and 3Dvar assimilation system, with the assimilation system forced by NCEP and T213 dataset, with 6-hour assimilation window at 00, 06, 12, 18UTC, corresponding to 21-03, 03-09, 09-15, 15-21UTC, and post-processed by NCAR-GRADS, and extends them as following[]
- With RTTOV8.7 for radiance assimilation[]
- Using Harris & Kelley Method (Eyre, 1992; Harris and Kelly, 2001) for bias correction[]
- Using NMC Method for background covariance[]
- Modifying land surface dataset for China surface complexity[]
- Using ATOVS data received, preprocessed by NSMC/CMA;
- With More reasonable algorithm to retrieve typhoon track
- With BE updated every 6 hour;
- With corresponding physics schemes selected to depict the snow information
- With FY3/VASS instruments added into WRF/3Dvar;
- With METOP/IASI instrument added into WRF/3Dvar.

2). Tentatively build the operational procedure of assimilation and prediction for typhoon utilizing the assimilation system already set up, with some valuable results obtained.

3). Develop the preliminary emergency service procedure to monitor snow storm based on ATOVS assimilation, which has been applied to monitor the snow storm occurred in South China in JAN 2008.

4). Tentatively set up the satellite assimilate procedure for FY3/VASS data.

WRF model is executed daily at NSMC/CMA, providing forecasts over China, with initial data taken from T213 global model, kindly provided by the National Meteorological Center of Chinese Meteorological Administration (NMC/CMA). WRF updates 4 times per day and produce forecast for 48 hours to the future. Forecasts include wind speed and direction, wind gusts, temperature, total cloud cover and precipitation etc.

In this study, the data assimilation experiments were conducted before and after the operational use of ATOVS radiances to demonstrate significant impacts on forecasts and analyses of typhoon track and the application case of assimilating ATOVS to monitor the snow storm occurred in January 2008 were demonstrated, finally the application potential of FY3 VASS in typhoon track prediction was analyzed.

## 2 ATOVS ASSIMILATION AND ITS APPLICATION IN TYPHOON TRACK PREDICTION

### 2.1 Bias correction

The statistical feature of scan angle bias in all channels of ATOVS/NOHAA18 HIRS4, AMSU-A and MHS has been statistically analyzed, as showing in Fig 2 with the scan angle bias of channel 1-15 of ASMU-A varying along scan position, revealing that the scan angle bias generally increase with the scan position far away from the nadir, but not increase strict-progressively; the scan angle bias of some channel take on opposite change tendency of scan angle bias at the both sides of nadir. All this further verify the importance of scan angle bias correction.

![Fig 1 the scan angle bias of AMSU-A](image)

The correction coefficients calculated from statistical samples of some time before always are utilized to correct the brightness temperature biases at the nest time, further used into the radiance assimilation system. In this study the correction coefficients were calculated from statistical samples from 10 July to 10 August 2007 to correct brightness temperature bias after 10 August, with the brightness temperature bias before correction and after at 0600UTC 15 August plotted in Fig4, indicating that the results of bias correction is encouraging, the statistical distribution of brightness temperature bias after correction locates mostly in the vicinity of zero, with the more Gaussian distribution, especially obvious for the some “bad ” channel, such as 1-3, and 13-15. The bias correction was not always perfect, such as, for channel 11 and 12 with asymmetric distribution, and for
channel 13 and 14 with bimodal distribution structure, which maybe resulted from the error of channel itself, and could not be dispelled through bias correction itself.

The results of brightness temperature bias correction of HIRS and MHS were similar to AMSU-A, no more details were given here due to the limited space.

2.2 Assimilating ATOVS data

It could be seen from Fig 3 that the predicted typhoon track without the ATOVS assimilation leans more northwards than the observed one, while the predicted typhoon track with the ATOVS assimilation was adjusted southwards, with better agreement with the observed one, but during the period at the initial stage and after the landfall of typhoon, the typhoon track with ATOVS assimilation and without all could not be simulated well.

The reasons may be that, at initial stage, because there exist large area of positive scattered vorticity, the typhoon track retrieval algorithm used here can not find and discriminate the correct track from so many positive vorticity; after landfall, due to the complexity of land surface characteristic, which will inspire some meso- or small-scale convection weather system, and because the landfall system would be reduced fast, it is difficult to distinguish the landfall system from the inspired system using the minimum vorticity method, leading to less accuracy for the typhoon track retrieval.

3 ATOVS ASSIMILATION TO MONITOR 2008 SNOW STORM IN SOUTH CHINA

In the middle and last ten days of January 2008, the southern area of China was attacked by the snow storm,
leading to paralysis of traffic and communication, which make the rescue work more difficult. At the critical time to rescue, observation information from the surface radar and surface station could not be provided for sufficient data or was delayed due to the snow storm, though the snow cover information can be obtained from satellite observation in visible and infrared spectral channel, quantitative snow information to monitor snow storm still rely on the observation from the microwave sensor, such as SSM/I or SMMR, however, during the snow storm in January 2008, this observation could be obtained in real-time, leading to no real-time effect snow information provided from this datasets. The ATOVS data was received and preprocessed by NSMC/CMA in real-time, with no more than half an hour from receiving to preprocessing, which make it possible to provide the snow disaster information controlled by the weather background at regional scale. In this study the ATOVS data was assimilated to provide more accurate snow information, by carefully selecting physical schemes, with the NOAH land surface sub-model selected to delineate the physics mechanism of snow-frozen and snow-melting.

In the figure of geo-potential height and temperature at 500hPa on 0600UTC 28 January 2008, there clearly existed one steady block high pressure in the vicinity of Ural mountain, and one horizontal trough at southern side of Baikal, with -42°C as its corresponding temperature, and the dry and cold air current after trough flows southwards along the small fluctuation of middle latitudes at south side of block high pressure, with straight circulation of middle latitudes and prevailing westward wind; at the same time, there exist one trough eastward near 96°E, with the temperature trough lagging behind the atmospheric pressure trough, and there is obvious cold laminar flow after the trough; The powerful northwest pacific subtropical high over southeast of China makes the southward current of blocky high, trough current and subtropical high form tripartite equilibrium situation over south area of China, with heavy snowfall weather course over the interface region of the three.

![Geopotential height at 500hPa on 00728 JAN 2008](image1.png) ![Temperature at 500hPa on 00728 JAN 2008](image2.png)
It could be seen from the figure of wind field and water vapor field at 700hPa that the strong air current from Europe-Atlantic Ocean was divided into two pieces of north and south, with north piece northward into the polar region of high latitude, invading China with colder momentum, leading to the stronger northwest monsoon, and with south piece southward into Central Asia forming the low vortex, with the air current at the side of low vortex moving round Qinghai-Tibet Plateau into Bay of Bengal and further into China border, leading to the more violent warm-wet current invaded from south and with a water vapor transportation zone along Northeast-Southwest direction formed over the South China.

Fig 5 demonstrate the corresponding relations between the observed snow depth over snow storm area of South China and the observed brightness temperature at channel 5 of ATOVS/NOAA18-MHS on 0600UTC 28 January 2008, with the brightness temperature at channel 5 reflecting the characteristics of water vapor transportation and functionally weighted at 700hPa as background, and in the figure, the green triangle stands for the station with snow depth more than 12cm observed on 0600UTC 28 January 2008, while the red dot for the station with snow depth less than 12cm.
It can be seen from the Fig 5 that there exist cold zone in Southwest-Northeast direction from along Yunnan-Guizhou to Changjiang-Huaihe, which corresponds to the water vapor transportation zone at 700hPa from Indian ocean to Bay of Bengal into South China; The cold area in the background of observed brightness temperature correlates well to the area of heavy snowfall observation, with lower brightness temperature over the area of Changjiang-Huaihe corresponding to the more heavy snowfall; at the same time, the brightness temperature decreases over large area from Gansu-Shanxi to North China caused by the invasion of colder air current from Siberia into China, with the heavy snowfall over large area actually observed. The comparison analysis between brightness temperature in channel 5 of ATOVS/NOAA18-MHS and snow depth observation demonstrate that: the information on temperature decrease and snowfall was contained in the satellite-observed ATOVS data, with one confirming another well. The forecast system simulates and predicts the spatial-temporal development of weather situation based on dynamics mechanism, and theoretically the more accurate snowfall information such as snow depth and snow water equivalence could be simulated by assimilating the ATOVS data containing the snowfall information and under full consideration of the physical process of snow-freezing and snow melting.
The variable in Fig 6 stands for the snow water equivalent change in 6 hours at 00-06, 06-12, 12-18, and 18-24 UTC (Unit: kg/m²), with positive value for snow-precipitating in 6 hours and with negative value for snow-melting in 6 hours. As the lower trough at 500hPa move eastwards and colder air current after the trough move southwards, the strong shear line has been formed, moving east-southwards, leading to the snowfall area to move east-southwards gradually too. The results from Fig 4 delineate this evolution tendency, which demonstrates that this snowfall event was caused by the weather process and the change tendency of snow water equivalent in 6 hours could reflect the moving track of weather process.

4 FY3-VASS DATA ASSIMILATION AND ITS RELATED

The FY3 will be launched soon (at the end of May 2008), with vertical atmospheric sounder system (VASS) on-boarded, including InfRared Atmospheric Sounder (IRAS), Microwave humidity sounder (MWHS), and Microwave temperature sounder (MWTS). These instruments are similar to ATOVS instrument of NOAA series and the instrument IRAS, MWTS and MWHS of FY3 VASS, theirs Passband Characteristic and theirs counterparts in NOAA ATOVS are shown in Table 1, 2, 3. Before FY3 launched, we adopt the similar channels of NOAA ATOVS to carry on research.

<table>
<thead>
<tr>
<th>FY3-IRAS</th>
<th>NOAA-18-HRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>center number (cm²)</td>
<td>center number (cm²)</td>
</tr>
<tr>
<td>1 669</td>
<td>1 669</td>
</tr>
<tr>
<td>Chan num</td>
<td>680</td>
</tr>
<tr>
<td>---------</td>
<td>-----</td>
</tr>
<tr>
<td>3</td>
<td>690</td>
</tr>
<tr>
<td>4</td>
<td>703</td>
</tr>
<tr>
<td>5</td>
<td>716</td>
</tr>
<tr>
<td>6</td>
<td>733</td>
</tr>
<tr>
<td>7</td>
<td>749</td>
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<td>802</td>
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<td>1365</td>
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<td>13</td>
<td>1533</td>
</tr>
<tr>
<td>14</td>
<td>2188</td>
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<td>18</td>
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<tr>
<td>19</td>
<td>2515</td>
</tr>
<tr>
<td>20</td>
<td>2660</td>
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</tbody>
</table>

Table 2 FY3 MWTS Channels, Its Passband Characteristic and Its counterparts in NOAA18

<table>
<thead>
<tr>
<th>FY3-MWTS</th>
<th>NOAA-18-AMSSA</th>
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</thead>
<tbody>
<tr>
<td>Chan num</td>
<td>Center freq (GHz)</td>
</tr>
<tr>
<td>1</td>
<td>50.30</td>
</tr>
<tr>
<td>2</td>
<td>53.596± 0.115</td>
</tr>
<tr>
<td>3</td>
<td>54.94</td>
</tr>
<tr>
<td>4</td>
<td>57.290</td>
</tr>
</tbody>
</table>

Table 3 FY3 MWHS Channels, Its Passband Characteristic and Its counterparts in NOAA16

<table>
<thead>
<tr>
<th>FY3-MWHS</th>
<th>NOAA-16-AMSLB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chan num</td>
<td>Center freq (GHz)</td>
</tr>
<tr>
<td>1</td>
<td>150(V)</td>
</tr>
</tbody>
</table>
Fig 4 showed that by adopting the bias correction of Harris and Kelly, the statistical distribution of brightness temperature bias after correction locates mostly in the vicinity of zero, with the more Gaussian distribution.

<p>| | | | | | | |</p>
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<tr>
<td>2</td>
<td>150(H)</td>
<td>2</td>
<td>150.00(H)</td>
<td>1000</td>
<td>window</td>
<td>surface</td>
</tr>
<tr>
<td>3</td>
<td>183.31±1</td>
<td>3</td>
<td>183.31±1</td>
<td>500</td>
<td>H2O</td>
<td>350 hPa</td>
</tr>
<tr>
<td>4</td>
<td>183.31±3</td>
<td>4</td>
<td>183.31±3</td>
<td>1000</td>
<td>H2O</td>
<td>500 hPa</td>
</tr>
<tr>
<td>5</td>
<td>183.31±7</td>
<td>5</td>
<td>183.31±7</td>
<td>2000</td>
<td>H2O</td>
<td>650 hPa</td>
</tr>
</tbody>
</table>

The observed geo-potential height at 500hPa and the difference of geo-potential height at 500hPa after and before assimilating FY3 VASS at 500hPa were demonstrated in Fig 8 and Fig 9 respectively. In Fig 9, the green contour line was utilized to indicate the simulated geo-potential height at 500hPa without assimilating FY3 VASS data, to clearly display the effect of assimilating the FY3 VASS data, the difference between geo-potential height at 500hPa after and before assimilating FY3 VASS was drawn, with the blue dotted line standing for negative difference between the two, and with the filled area for positive difference between the two.

Comparison of the simulated geo-potential height at 500hPa without assimilating FY3 VASS data in Fig 9 with observed one in Fig 8 demonstrate that the trough in the Northwestern China was overestimated, with shallower trough predicted and the ridge in the Southeast China was underestimated, with weaker ridge predicted. It can be seen from the difference between geo-potential height at 500hPa after and before assimilating FY3 VASS in Fig 9 that after assimilating FY3 VASS, the deeper trough and the stronger ridge was simulated than before assimilating FY3 VASS, in better agreement with the observed one.
5 CONCLUSION AND FUTURE WORK

In this study, the extensions to the WRF 3DVAR system done at NSMC/CMA for the better using satellite data into NWP was overviewed, the ATOVS assimilation application in typhoon track prediction and in emergency response to monitor the snow storm occurred in January 2008 over South China were demonstrated, indicating that by assimilating ATOVS data, the prediction skill can be improved well and more accurate information can be provided to monitor disaster. The preliminary results of FY3 VASS data assimilation based on NOAA ATOVS suggest that the simulation could be improved by
assimilating the FY3 VASS data and the potential of FY3 VASS application in NWP model is great. Although the frame of satellite data assimilation has been established and the preliminary results are inspiring, there are still many detail questions needed to solve, such as the inaccuracy of emissivity leads to discard so many radiance, especially in Tibet Plateau region and cloudy contamination reduce the effect information into the assimilation system. To solve these questions, the future work will focus on the following:

- **The core work on satellite data assimilation of NSMC/CMA orientate on quality control and bias correction.**
- **Directly assimilate the radiance** by RTTOV and CRTM fast radiative transfer model; Assimilate the atmospheric profile of temperature and moisture from FY3A, cloud track wind, and ocean surface wind by the interpolation algorithms; provide the input for fast radiative transfer model by setting up the dynamic O3 datasets.
- **The inaccuracy of land surface emissivity** leads to less radiance data assimilated into in Plateau region of China and discarding the radiance in the window channel, to solve this, the following scheme was adopted: For the infrared spectral region, the land surface emissivity needed by HIRS data assimilation was convolved from the one of high spectrum; For the microwave spectral region, the 1DVAR method can be used to obtain land surface emissivity.
- **Assimilating the radiance in the cloudy region**: a. The radiance always was discarded in infrared spectral region due to the cloudy contamination during radiance assimilation, however, the radiance in the cloudy region contain some atmospheric information on the cloud, so it is valuable to assimilate the infrared radiance in the cloudy region, implementing as following: First of all, compare the cloud physical schemes to select the prefect one, by which (provide the cloud parameters needed by RTTOV) the RTTOV will simulate the radiance, with smallest error comparing between observed radiance and simulated one; Utilize LAPS cloud analysis scheme to obtain more accurate cloud top emissivity and cloud parameters needed by RTTOV to simulate cloudy radiance, and then assimilate the cloudy radiance by fast radiative transfer model. b. For precipitating cloud radiance, assimilate the cloudy radiance derived by scatter module in fast radiative transfer model using the cloud top emissivity and cloud parameters above.

**ACKNOWLEDGMENTS**

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**REFERENCE**


Assimilation of radiance data at JMA: recent developments and prospective plans

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Abstract
Recent developments on the satellite data assimilation at JMA, especially regarding radiance data, are presented. After the last conference in October 2006, JMA introduced various data into its operational global 4D-Var data assimilation system. The data include: AP-RARS/EARS ATOVS radiances, ATOVS radiances onboard NOAA18 and Metop, MTSAT-1R water vapor clear sky radiances (WV-CSRs), and refractivities of CHAMP GPS radio occultation. Above all, Metop ATOVS (AMSU-A and MHS) gave the greatest positive impact on forecasts, especially of geopotential height, in our data assimilation experiments. AIRS radiance assimilation is under development: The evaluation of cloud detection scheme against CloudSat and that of analysis against radiosondes was encouraging but, at the time of writing, the forecast skill was degraded due to the discrepancy between the model trend and AIRS impact. The improvement of a cloud screening and bias correction for SSMI, TMI and AMSR-E and the inclusion of SSMIS radiances at window channels were evaluated. Appropriate usage of frequent measurements of WV-CSRs from five geostationary satellites generated greater positive impact on forecast than from MTSAT-1R only.

Outline of JMA NWP system
JMA operates two deterministic forecast models: the global spectral model (GSM) and mesoscale model (MSM, Japan Meteorological Agency 2007). GSM was significantly upgraded in November 2007. The resolution was upgraded from TL319L40 to TL959L60 (roughly 20 km in horizontal resolution) and model top height was raised from 0.4 hPa to 0.1 hPa. This upgrade improved forecast of severe precipitation and various synoptic fields including 500 hPa geopotential height (Z500) and wind speed at 250 and 850 hPa in the extra-tropics and tropics.

The global data assimilation system is based on incremental 4D-Var with the resolution of TL319L40/T106L40 to TL959L60/T159L60 in the outer/inner loop. 6-hour assimilation window is divided into six time slots of about 1-hour. The early and delayed (cycle) global analysis are operated in JMA. Data cut-off time is set to 2h25m for the early analysis, and 5h35m and 11h35m for the cycle analysis at 00/12 UTC and 06/18 UTC, respectively. The early analysis is followed by 84-h forecast at 00, 06 and 18 UTC and 192-h forecast at 12 UTC. Variational Bias Correction (VarBC, Derber and Wu 1998; Dee 2004) is applied for all radiance data assimilated in the global 4D-Var.
MSM aims at providing the disaster prevention information such as heavy rain prediction around Japan. It is a non-hydrostatic grid model with a horizontal resolution of 5 km and 50 vertical layers up to about 22 km (Saito et al. 2006). MSM operates every three hours and performs 15-h forecast at 00/06/12/18 UTC and 33-h forecast at 03/09/15/21 UTC. The assimilation system of MSM is an incremental 4D-Var method with the resolution of 10/20 km in the outer/inner loop. Assimilation window is six hours with six 1-hour time slots and data cut-off time is 50 minutes. While the global 4D-Var system assimilates radiances from various satellites, the meso 4D-Var system assimilates retrievals due to the smaller computational burden required for the strict operational time schedule. The radiance assimilation in the meso 4D-Var system is under development considering the availability of VarBC.

The satellite data operationally assimilated in the global (G) or meso (M) analysis systems are as follows (as of May 2008):

- NOAA15-18/AMSU-A, AMSU-B and MHS radiances (G)
- Metop/AMSU-A and MHS radiances (G)
- Aqua/AMSU-A radiances (G)
- NOAA15-18/ATOVS temperature retrievals, processed by NESDIS and Meteorological Satellite Center (MSC) of JMA (M)
- Metop/ATOVS temperature retrievals (M)
- DMSP-13,-14/SSMI radiances (G), and total column water vapor (TCWV) and rain rate (M)
- TRMM/TMI radiances (G), and TCWV and rain rate (M)
- Aqua/AMSR-E radiances (G), and TCWV and rain rate (M)
- MTSAT-1R, GOES-11,-12, and Meteosat-7,-9 AMV (G and M)
- Aqua/MODIS and Terra/MODIS AMV (G)
- QuikSCAT Sea surface winds (G and M)

The following sections are confined to the radiance assimilation in the global analysis.

**ATOVS radiance assimilation**

Changes in ATOVS radiance assimilation in the global analysis since the last TOVS conference in October 2006 are the addition of the Asia-Pacific Regional ATOVS Re-transmission System (AP-RARS) in February 2007, NOAA18 in April 2007, EUMETSAT Advanced Retransmission Service (EARS) in August 2007 and Metop in November 2007. We assimilate AP-RARS from 12 stations in Australia (5), China (4), Korea (1) and Japan (2), including Japan’s Syowa Station on the Antarctica, as of May 2008. The assimilations of Metop and RARS are shown in this section.

The level-1C data of AMSU-A and MHS on Metop from EUMETSAT via GTS became available at JMA on 7 February 2007. The stability and timeliness of the data dissemination, which are essential for an operational NWP system, have been entirely satisfactory. They are pre-processed and
assimilated as ATOVS radiances on NOAA satellites are done (Okamoto et al. 2006). The cycle experiments with Metop/ATOVS radiances showed substantial positive impacts on forecast at day 1 to day 3, especially for the geopotential height even in the presence of four NOAA satellites (NOAA15-18) and Aqua satellites (Fig.1).

The use of the early delivery ATOVS data from AP-RARS and EARS in the early global analysis makes the analysis closer to the cycle global analysis. The early analysis generating forecast products are not allowed to wait for sufficient satellite data coming in. In contrast, because the cycle analysis assimilates more satellite data due to longer data cut-off time length, it is generally more accurate than the early analysis. In order to assess impacts of AP-RARS and EARS individually, three one-month early analysis experiments were carried out: “EXP-NORARS” run where operational data configuration was used, “EXP-APRARS” run where AP-RARS ATOVS data were added to EXP-NORARS, and “EXP-EARS” run where EARS ATOVS data were added to EXP-NORARS.

Fig. 2: Difference between early analysis and cycle analysis for Z500 (left) without EARS ATOVS and (right) with EARS ATOVS at 12 UTC on 17 June 2007. Blue (red) shades depict positive (negative) value of the difference and contours indicate Z500. Outlines of ATOVS data coverage are plotted with dashed lines.
EXP-APRARS showed a better fit to cycle analysis with respect to the geopotential height mostly in the stratosphere around AP-RARS stations than in EXP-NORARS. Meanwhile, EXP-EARS showed much better agreement with the cycle analysis for Z500 in the mid- and high-latitudes of the Northern Hemisphere (Fig.2) and better forecasts in the Northern Hemisphere and Tropics than EXP-NORARS (not shown). The greater impact of EARS on forecast were due to the number of EARS ATOVS data available, which was generally three times more than that of AP-RARS ATOVS data.

**AIRS radiance assimilation**

The assimilation of the hyperspectral infrared sounder AIRS onboard Aqua is being developed. We are receiving AIRS warmest field of view (FOV) dataset with 324 channels from NESDIS. Clear radiances of 54 temperature sounding channels, which are chosen based on an entropy reduction method (Rodgers 2000), have been tested over the ocean. The data are thinned to one per a 180 x 180 km box by giving the priority to pixels closer to the center of the box and analysis time, and go to subsequent quality control (QC) and bias correction (BC) procedures. The primary QC procedure is the rejection of cloud-contaminated channels. The cloudy channel identification consists of two steps. First, completely clear pixels, of which no channels are contaminated by clouds, are identified with different approaches at daytime and nighttime. At daytime, pixels with cloud fraction less than 10% are determined to be completely clear. The cloud fraction is derived from the visible and near infrared channels and is included in the data. At nighttime pixels are flagged as completely clear on condition that 1) their brightness temperature (TB) differences between short wavelength channel and long wavelength channel are small (i.e. neither low clouds nor thin cirrus are present) and 2) sea surface temperature (SST) simulated from window channels is close to SST given by independent SST analysis (i.e. no thick clouds are present, Le Marshall et al 2006). Second, if the pixels are not completely clear, clear channels are determined using McNally and Watts (2003). Even clear pixels are removed when observation-minus-background (O-B) exceeds three times the observation errors predefined or any instrumental quality error flags included in the data are on. The BC scheme adopts the same method as ATOVS except VarBC predictors.

A cloud top height (CTH) can be estimated from cloudy channels identified with the altitude of their weighting functions. We verified the AIRS CTH with the Cloud Profiling Radar (CPR) on CloudSat satellite (Stephens et al. 2002). Figure 3 (a) shows frequency of CTH from CRR in 2B-GEOPROF dataset with cloud mask over 30 at every two pixels and that from QC-passed AIRS over the ocean. A population at 0.5 km height indicates clear pixels. The lower rate of low clouds at 1-2 km altitude in AIRS suggests that AIRS may miss those clouds because passive infrared instruments have difficulty distinguishing radiations from the ground and low clouds. In contrast, higher rate of mid-level clouds at 3-5 km from AIRS is evident. The reason is not clear but it may be associated with dry biases of the model because the current cloud detection algorithm is based on O-B variation with height.

Figure 3 (b) is a scatter plot of CTH from QC-passed AIRS and that from CPR closest to the center of
Fig. 3: (Left) Frequency of cloud top height from AIRS and CloudSat/CPR (2B-GEOPROF) from 1 to 7 2007. The frequency is normalized by their total number. (Right) Comparison of cloud top height from AIRS and that from CloudSat/CPR closest to the center of AIRS FOV from 1 to 7 2007.

the AIRS FOV. While some AIRS CTHs well agree with CPR CTHs, not a few AIRS CTHs are higher than CPR CTHs. This can be explained by the fact that AIRS is more sensitive to small cloud particles. Moreover, the figure shows that there are many pixels flagged as cloud for AIRS but as clear for CPR. This is probably because, in addition to the sensitivity difference, much smaller CPR FOV can spot a clear portion in a broken cloud area while AIRS radiances can be affected by partial clouds. From these comparisons, it is hard to conclude that AIRS CTH is accurate enough for a pure CTH retrieval purpose but the algorithm to identify cloudy channels is safer for removing cloud-affected channels in the data assimilation context of our target.

Fig. 4: Fit of analysis/first-guess to RAOBs with and without AIRS radiances assimilation for (a) the temperature in the Southern Hemisphere and (b) the relative humidity in the tropics over a month in August 2007.

AIRS radiances that underwent the QC and BC procedures were assimilated in the experimental global analysis system for 50 days from 20 July to 9 August in 2007 to evaluate their impacts on analysis and forecast. Because number of total channels of AIRS assimilated in each analysis is roughly three times more than that of AMSU-A on a single satellite, the assimilation made large changes to analyses. The large changes are found in the latitudes of 10S to 30N in the mid-troposphere and tropospheric temperature in the southern hemisphere and stratospheric temperature (not shown). Reflecting these changes, biases in the lower tropospheric temperature in the southern hemisphere and
mid-tropospheric humidity in the tropics verified against radiosonde observation (RAOB) are significantly reduced (Fig.4). However impacts on the day-1 forecast verified against their own initials are neutral for Z500 and negative for temperature at 850hPa (T850) (Fig. 5). Moreover, moistening the mid troposphere caused excessive precipitation in the tropics (not shown). These detrimental effects might be due to the conflict between model biases and analysis increment by AIRS. We are tackling this conflict by reviewing the bias correction procedure, re-estimation of observation errors as well as model physical process in the GSM.

**MicroWave Imager (MWI) radiance assimilation**

Less-cloud affected radiances from microwave imagers such as SSMI, TMI and AMSR-E have been assimilated over the ocean operationally since May 2005. Only vertical polarized channels are assimilated because we believe that there is little independent information in horizontal polarized channels in our system where no Jacobian with respect to the surface parameters, such as temperature or wind speed, is included. The removal of cloud affected radiances is implemented using three cloud-related indices of CWI, $S_{IDX}$ and $P_{IDX}$. CWI is calculated from TB at 19 and 37 GHz channels, SST and ocean surface emissivity (Takeuchi 2002). $S_{IDX}$ and $P_{IDX}$ are

\[
S_{IDX} = (T_{22V}-T_{37V}) - C_s(T_{22V}-T_{19V})
\]

\[
P_{IDX} = (T_{85H}/T_{85V}) - C_p(T_{22V}-T_{19V})
\]

where $TxV$ ($TxH$) is TB observed at vertically (horizontally) polarized channel at frequency $x$, and the coefficients $C_s$ and $C_p$ are estimated for each instrument. These indices go beyond certain ranges when rain or clouds are present. In addition to excluding cloudy radiances, data are screened out when O-B in TB is over three times the predefined observation error or O-B in TCWV is over 10 mm. Biases are corrected by VarBC with predictors of TCWV, sea surface temperature (SST), square of SST, ocean surface wind speed, $1/\cos\theta$ (\(\theta\) is a satellite zenith angle) and constant parameter.
It was found that cloudy radiances still remained and biases were not sufficiently removed at 37 GHz channel even after these QC and BC procedures were applied. Figure 6 (a) shows that O-B in TB after the cloud screening over the ocean has larger populations in a positive tail, indicating observed TB is higher than background calculated in clear conditions due to the additive radiation from clouds. The figure also shows that bias corrected O-B is not centered around zero. With a view of making the cloud screening stricter, a cloud test was added which identifies cloudy radiances when total column cloud liquid water (TCCLW) retrieved from Takeuchi (2002) was beyond 0.18 kg/m$^2$. To improve the bias correction, furthermore, TCCLW retrieved was included in VarBC predictors instead of $1/cos\theta$. These revisions made O-B distribution more symmetric and the bias correction better (Fig. 6 (b)).

With two month assimilation experiments in summer and winter times, they slightly but consistently improved the forecast of the lower tropospheric temperature (not shown). Because the criteria of 0.18 kg/m$^2$ might allow cloud contaminated data in the 85 GHz bands to survive, we are testing frequency dependent criteria (Okamoto and Derber 2006). They are planned to be introduced in the operational global analysis in 2008 or early 2009.

SSMIS window channels (19V, 22V, 37V and 92V) on DMSP-16 were experimentally assimilated together with the new cloud screening and VarBC predictors above. Quality controlled O-B mean and standard deviation (STD) from SSMIS were nearly equal to those from other MWIs already assimilated. Impact of the addition of SSMIS window channel radiances on the analysis and forecast were small and neutral. Assimilating radiances from sounding channels of SSMIS in the global analysis system and TCWV and rain rate retrievals in the meso analysis system are under development.

**Clear sky radiances of water vapor channels of geostationary satellite imagers**

Clear sky radiances of the water vapor channel (WV-CSRs) of MTSAT-1R imager has been
operationally assimilated since June 2007. They are thinned to one in 200 km box and every other time slot so that horizontal and temporal error correlation could be neglected in 4D-Var. The QC procedure removes WV-CSRs data with clear portion less than 35 % or TB STD over 1K, which are generated from 16x16 original pixels by MSC of JMA. The data with O-B in excess of 3K are screened out. Biases are removed with VarBC with predictors of background TB, jet level wind speed, 1/cosθ and constant parameter.

To evaluate impact of WV-CSR assimilation, three cycle experiments were carried out with the low resolution (TL319L60) global analysis system over 50 days in summer and winter seasons: 1) “EXP-NOCSR” run using no WV-CSRs, 2) “EXP-MTSAT” run using MTSAT-1R WV-CSRs in addition to EXP-NOCSR and 3) “EXP-5GEO” run using WV-CSRs of five geostationary satellites of MTSAT-1R, GOES-11, -12 and METEOSAT-7, -9 in addition to EXP-NOCSR. EXP-MTSAT showed small but positive impact on analysis (e.g. smaller O-B STD of NOAA18/MHS channel 3) and neutral to small positive impact on forecast (Fig. 7 (a)). EXP-5GEO yielded more positive impact: TCWV was increased in the mid- to upper-troposphere in wet areas and even in the lower-tropospheric in dry areas such as Sahara. This was likely caused by frequent measurements even over the land, which compensated microwave imagers. The humidity increase reduced the dry biases of the model: Analysis/guess humidity was closer to RAOB at 500 to 250 hPa and O-B STD of MHS and AMSU-B channel 3 was down. Improvement was obvious for T850, Z500 and wind speed at 850 and 250 especially at day 1 to 3 forecast (Fig. 7 (b)).

However, the use of WV-CSRs from MTSAT-1R has been suspended due to technical reasons since November 2007 when GSM was upgraded. It is planned that WV-CSRs from five geostationary satellites are introduced in the operational global analysis in mid 2008.

![Fig. 7: Improvement rate in (a) EXP-MTSAT run and (b) EXP-5GEO.](image-url)
Summary and Plan
JMA introduced in the global analysis AMSU-A and MHS radiances on NOAA18 and Metop, AMSU-A and MHS radiances from AP-RARS and EARS, refractivity from CHAMP and WV-CSR from MTSAT-1R since the last TOVS conference in October 2006. AMSU-A and MHS radiances from Metop yielded the greatest positive impact of these data probably due to the complementary orbital coverage to fill the gaps of NOAA and Aqua satellites, good stability and timeliness as well as the accuracy.

Ongoing developments with radiance assimilation in the global analysis are assimilating cloudy/rainy radiances, utilizing more data over land by introducing more accurate estimate of the land emissivity, optimizing observation errors in the variational scheme, reevaluating a thinning distance and improving a vertical interpolation method. In the meso analysis, radiance assimilation is planned to be implemented together with VarBC instead of the retrieval assimilation.

References
Stephens, G. L., D. G. Vane, J. B. Ronald, Gerald G. Mace, Kenneth Sassen, Zhien Wang, Anthony J.

Direct Radiance Assimilation for WRF: Implementation and Initial Results

Zhiquan Liu, Hui-Chuan Lin, Dale Barker, Thomas Auligne, Xiaoyan Zhang

Weather and Research Forecast (WRF) model as well as it variational assimilation system (WRF-Var) is widely used by both research community and the operational NWP centers in US (Air Force Weather Agency) as well as a number of international WRF partners in Asia, the Middle East, and Europe. A general satellite radiance assimilation framework has been developed in the WRF-Var system in the past two years. The WRF-Var radiance assimilation capability was designed for meeting requirements of both basic research and operational applications, which will be available to research community with the next WRF release. This presentation will begin with an overview of radiance assimilation capabilities in WRF-Var, including the core component -- Fast Radiative Transfer Model (RTM), air-mass dependent bias correction algorithm, quality control and observation error tuning and so on. In particular, two widely used RTMs, RTTOV developed by EUMETSAT in Europe and CRTM developed by JCSDA in USA, are incorporated into WRF-Var system. A preliminary comparison between RTTOV and CRTM will be present. Recent results on assimilating microwave radiance data to improve Hurricanes track and intensity forecast will be also presented. Results for the Katrina case show that assimilating AMSU-A radiance improves both track and intensity forecast, even most data are discarded over Hurricane votex area. One will also present a cloud/rain affected radiance assimilation scheme, which uses total cloud water as the control variable and a warm- rain physics process to partition total water to moisture and hydrometeor increments.
The Assimilation of Clear-Sky Infrared Radiances in the HIRLAM Model

Martin Stengel, Per Dahlgren, Magnus Lindskog, Per Unden, and Nils Gustafsson

The limited-area numerical weather prediction model HIRLAM has been adjusted to make use of the infrared (IR) radiances measured by SEVIRI on-board the MSG satellites. Therefore, the HIRLAM variational data assimilation system has been modified to take advantage of this additional observation type. Especially 4D-Var frameworks, which is one option in HIRLAM’s assimilation system, are assumed to be capable of utilizing the information content provided by SEVIRI with its high temporal resolution. For the time being, only the two water vapour channels are considered. Observation impact studies have been carried out for different time periods using 3D-Var and 4D-Var. For 3D-Var the nearest SEVIRI timeslot is chosen, whereas for 4D-Var SEVIRI data from six slots are used, which are equally distributed over the 6 hour assimilation window. For these experiments, all cloud contaminated pixels had been rejected. Generally, the impact studies show a neutral to slightly positive impact of SEVIRI’s clear sky infrared data on analysis and forecast fields. In all studies, the system seems to be able to use SEVIRI observations to decrease an upper-tropospheric humidity bias in the NWP model, which is found when comparing model fields and colocated radiosondes. This impact is visible up to 48 hours integration time with a decreasing magnitude. In addition, we find a slight positive impact on geopotential height and mean sea level pressure forecasts. This impact is a bit more distinct for 4D-Var and during summer. These results, as well as examples of preceding data preparation steps such as spatial thinning and quality checks, will be presented.
Recent developments in the use of
ATOVS data at ECMWF

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Introduction

Data from the ATOVS series of instruments continue to play a major role in the ECMWF assimilation system. Level 1c radiances are assimilated in clear-sky conditions, subject to a number of quality control checks. The data contribute significantly to the current forecast skill.

In the following, we will briefly summarise the status of the assimilation of ATOVS data at ECMWF, before highlighting some recent and upcoming changes in the use of ATOVS data. The latter includes the correction of an incorrect use of a parameterisation of the Zeeman effect for AMSU-A, a change in the bias correction for AMSU-A channel 14, and a planned change in the bias correction for HIRS (and AIRS) short wave channels.

Status of ATOVS data at ECMWF

Currently, ATOVS data from six satellites are assimilated (Table 1), subject to data availability and quality. Where available, data from the EARS system are also used, improving greatly the data coverage for our early-delivery analyses that are used to produce the operational forecasts. Data from the Asia-Pacific RARS system (e.g., Griersmith 2008) are monitored operationally since 3 June 2008, with a view to later operational use.

For NOAA-16 and AQUA, the lower tropospheric channels are not used, as the cloud/rain quality control for these currently relies on channel 4, which is very noisy for these satellites. Alternative ways of quality control are being investigated, so that these channels can be used again in the future.

Table 1: Current use of ATOVS data at ECMWF.

<table>
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<th>AMSU-A</th>
<th>AMSU-B/MHS</th>
<th>EARS</th>
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<td>Yes (not ch 6, 11, 14)</td>
<td>No: quality</td>
<td>Yes</td>
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<tr>
<td>NOAA-16</td>
<td>No: unstable</td>
<td>Yes (not ch 5-7/8)</td>
<td>No: quality</td>
<td>Yes</td>
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<td>NOAA-17</td>
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<td>Instrument failed</td>
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<td>Yes</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>AQUA</td>
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<tr>
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The latest additions to the ATOVS data use have been the AMSU-A, MHS, and HIRS instruments from METOP-A which was launched 19 October 2006. The first AMSU-A and MHS data were received and monitored operationally within two weeks after launch, and the AMSU-A and MHS radiances were assimilated operationally from 11 January 2007 onwards, thus becoming the first METOP-A data to be used operationally by an NWP centre. This was after the monitoring confirmed that the data characteristics were within expectations, and after a short assimilation trial demonstrated a small positive impact from using the extra data in the operational system (e.g., Fig. 1).

Figure 1: Colours indicate the normalised difference in the root mean square error of the 3-day 500 hPa geopotential forecast between the experiment with METOP-A AMSU-A and MHS and the control, averaged over 17 cases between 12 and 28 December 2006. Yellow/red colours indicate an improvement from the assimilation of METOP-A data. Contours show the mean geopotential [gpdm].

**Update of RTTOV coefficients for AMSU-A**

During the production of the ERA-40 reanalysis (e.g., Uppala et al. 2005), it was found that significant discrepancy existed between the treatment of the top stratospheric channels of SSU and AMSU-A, in particular between channel 3 of SSU and channel 14 of AMSU-A during the polar winters. The weighting functions for these two channels peak at similar altitudes. However, while the analysis followed one instrument, significant residual analysis departures remained in the other (e.g., Fig. 2), and these differences could not be resolved through retuning of the bias correction. As a result, channel 3 of SSU was excluded from the reanalysis after 3 July 1999.

Detailed investigations revealed that the origin of the discrepancy was an incorrect parameterisation of the Zeeman effect used in the line-by-line (LBL) model that was used to train RTTOV, the radiative transfer model employed in the ECMWF assimilation system (e.g., Saunders et al. 1999). The stratospheric channels of AMSU-A are located in the \( \text{O}_2 \) absorption band between 50 and 60 GHz. The \( \text{O}_2 \) molecule has a permanent magnetic dipole moment in the ground electronic state. In the presence of a geomagnetic field, isolated \( \text{O}_2 \) lines are split into a number of sub-lines because of the Zeeman effect. The Zeeman splitting of the \( \text{O}_2 \) lines becomes important for radiation originating from those regions of the atmosphere where the line-width becomes comparable to the effect from Zeeman splitting (e.g., pressures lower than 10 hPa) and for frequencies close to resonance. In the case of AMSU-A, Zeeman splitting has a measurable impact on the uppermost channel 14. While RTTOV itself does not include a parameterisation for the Zeeman effect, the LBL model used to train RTTOV...
included a scalar approximation of the Zeeman effect, as defined by Liebe et al. (1993). In this approximation, the Zeeman effect is modelled through a simple broadening of the O2 absorption line.

Figure 2: Mean uncorrected observation minus analysis departures for SSU channel 3 on NOAA-14 (black) and AMSU-A channel 14 on NOAA-15 (red) over the Arctic (left) and Antarctic (right) in ERA-40.

Figure 3: Attenuation rates near the pass-bands of AMSU-A channel 14 for pressures from 0.001 to 1.420 hPa for the US Standard Atmosphere. The pass-bands are indicated by the dashed vertical lines. The inset panels provide a more detailed view of these regions. Results for the scalar approximation are shown in blue, from the polarised radiative transfer model in red, and for a radiative transfer model without the Zeeman effect in black. The assumed magnetic field strength is 60 μT.

The scalar approximation to the Zeeman effect works well in the line-centre, but performs rather more poorly in the wings of the line and therefore in the pass-bands of AMSU-A channel 14. This can be best seen in attenuation rates calculated with a full polarized radiative transfer model and those
calculated with the scalar approximation (e.g., Fig. 3). In the pass-bands of AMSU-A channel 14, the scalar approximation significantly overestimates the attenuation, resulting in anomalously low transmittances for AMSU-A channel 14. Weighting functions obtained from the polarised RT model are in fact much closer to those calculated without taking the Zeeman effect into account (Fig. 4).

Figure 4: Weighting functions for the US Standard Atmosphere for AMSU-A channel 14, computed with a radiative transfer model with the scalar approximation of the Zeeman effect (blue), the polarised radiative transfer model (red), and a radiative transfer model that does not include the Zeeman effect (black). The assumed magnetic field strength is 60 μT.

Consequently, neglecting the Zeeman effect in the radiative transfer calculations for AMSU-A leads to a better consistency between the radiative transfer calculations for SSU and AMSU-A. This is highlighted in Fig. 5 which shows differences (in brightness temperature) between SSU channel 3 and AMSU-A channel 14 for a sample of observations collocated using the Simultaneous Nadir Overpass method, together with differences obtained from radiative transfer calculations. With the scalar approximation used, the differences from the radiative transfer simulations disagree significantly with the observed differences over the polar winters, whereas much better agreement is obtained when the Zeeman effect is neglected.

Figure 5: Differences (in brightness temperatures) between NOAA-11 SSU channel 3 and NOAA-15 AMSU-A channel 14 for a sample of data collocated using the Simultaneous Nadir Overpass method over the Antarctic region. Differences obtained from observations are shown in blue, whereas differences obtained from radiative transfer calculations are shown in red. Left: Radiative transfer computations are taken from RTTOV with the original coefficients. Right: Radiative transfer computations are taken from RTTOV for SSU, but a LBL model that excludes the Zeeman effect for AMSU-A. Note that due to different channel characteristics (not least infrared vs microwave) the differences between SSU channel 3 and AMSU-A channel 14 are expected to be non-zero.
New RTTOV coefficients have been generated for AMSU-A that neglect the Zeeman effect, and these coefficients have been used successfully in the ERA-Interim reanalysis (Uppala et al. 2008). The use of these new coefficients led to a reduction of spurious oscillations in the stratosphere over the winter poles (Fig. 6), and allowed a simultaneous use of SSU channel 3 and AMSU-A channel 14. The new coefficients were also introduced in the operational assimilation at ECMWF on 6 November 2007.

Figure 6: Timeseries of profiles of the mean temperature analysis over the South Polar region for a reanalysis experiment with the old RTTOV coefficients (top) and the new RTTOV coefficients without an implicit Zeeman parameterisation (bottom). The vertical axis in model levels, with level 25 at around 100 hPa, 14 at 10 hPa, and 5 at 1 hPa.

Assimilation of AMSU-A channel 14 without bias correction

Since 12 September 2006 ECMWF has been using a variational bias correction (VarBC) as described in Dee (2004) and Auligné et al. (2007). While this approach has been very successful in achieving a good consistency between the radiance bias corrections for different channels, instruments, and satellites, in agreement with other observations, problems were soon noted for stratospheric temperature channels. The bias corrections for these channels exhibited drifts, resulting in rather large bias corrections being applied to the data (exceeding 3 K for the highest AMSU-A channels after about a year of operational use of VarBC, e.g., Fig 7). The main reasons for this are the lack of other “anchoring” temperature observations in the upper stratosphere, and the fact that the current implementation of VarBC does not include a penalty for large bias corrections. As a result, the bias correction can drift to a state consistent with the climate of the forecast model.
To avoid this problem, it was decided to “anchor” the upper stratospheric temperature analysis by assimilating channel 14 of AMSU-A without bias correction. This is a somewhat pragmatic approach, based on the experience that model biases in the upper stratosphere tend to be much larger than estimates of biases in AMSU-A channels, especially over the polar regions. Residual scan biases and inter-satellite biases for AMSU-A channel 14 are neglected in the new approach for similar reasons.

![Figure 7: Departure statistics [K] for used NOAA-18 AMSU-A radiances over the Northern Hemisphere extra-tropics in June 2007. Solid lines indicate observation minus First Guess departures, whereas dotted lines show observation minus analysis departures, with statistics from an experiment with setting the bias correction of AMSU-A channel 14 to zero in black, and statistics from an experiment in which VarBC was allowed to evolve freely for over a year in red. Also shown are statistics for the bias correction for the experiment with no bias correction in AMSU-A channel 14 in pink and for the other experiment in green. Standard deviations are shown on the left, and biases on the right. The numbers between the two panels indicate the number of observations used (right) and the difference relative to the control experiment (left).]

Other stratospheric channels (of AMSU-A, AIRS, and IASI) also show reduced bias corrections when AMSU-A channel 14 is assimilated without bias correction (e.g., Fig. 7). The bias correction for these channels is allowed to evolve freely through VarBC, and the finding that the bias corrections for stratospheric channels settle at values close to zero indicates a good consistency within the radiance observations. As a result, stratospheric temperature analyses are colder by a few degrees Kelvin, leading to better agreement with the independent SPARC climatology (not shown). The change to assimilate channel 14 of AMSU-A without a bias correction was implemented in operations on 6 November 2007, together with the updated RTTOV coefficients without an inappropriate Zeeman parameterisation.

**Revised bias correction for HIRS and AIRS short wave channels**

Infrared short-wave channels are affected by solar radiation, for instance, through effects arising from the absence of local thermal equilibrium (LTE). LTE is usually assumed in today’s fast radiative transfer models, and as a result, ECMWF’s use of IR short-wave channels is restricted to channels for which this effect is relatively small. The only short-wave channels used are currently channels 14 (4.525 μm) and 15 (4.474 μm) of HIRS, and channels up to channel number 1928 (4.464 μm) for AIRS. Nevertheless, recent monitoring results showed that even these channels exhibit non-negligible day/night biases, especially HIRS channel 15 and AIRS channel 1928 (Fig. 8). The day/night differences are more notable in METOP-A than in NOAA-17 HIRS data, and some of the differences reach 0.4 K.
To address the day/night bias we examine here a modification to the bias correction model used for the short-wave channels, following work by McMillin and Crosby (2000). They showed that the solar effects for HIRS channel 15 can be modelled through a linear regression against the cosine of the solar zenith angle (for day-time data). In agreement with their findings, histograms of First Guess departures against the cosine of the solar zenith angle suggest that the residual biases may be adequately modelled using a predictor that is zero during nighttime and the cosine of the solar zenith angle during daytime (Fig. 9).

The modification of the bias correction was tested within a 2-month assimilation experiment over the period 1 June - 31 July 2007, using ECMWF’s 12-hour 4DVAR system, with a T511 (~40 km) model resolution, T159 (~125 km) incremental analysis resolution, and 91 levels in the vertical. The control
The experiment employed the standard bias correction model for all HIRS and AIRS channels (i.e., linear in four layer thicknesses and a 3rd order polynomial in the scan angle), used within VarBC. In the experiment with the modified bias corrections, a (linear) predictor, zero during nighttime and the cosine of the solar zenith angle during daytime, was added to the bias model for HIRS channels 14 and 15, and AIRS channels 1921-1928. We discard the first 14 days of the experiment, to allow VarBC to spin up the bias model for the additional predictor.

Figure 10: As Fig. 8, but with adding the extra day/night predictor to the bias correction model as described in the main text.

The additional bias predictor successfully reduces the day/night biases otherwise observed in mean FG departures (e.g., Fig. 10). While some day/night biases are still present, these are confined to the Southern Hemisphere mid-latitudes (associated here with higher solar zenith angles) for this experiment. The modification has a notable effect on the analyses of the mid-tropospheric geopotential (up to 3 gpm at 500 hPa), but a neutral effect on forecast scores (not shown). This is a positive finding, as additional experimentation showed that removing the affected channels altogether has a negative forecast impact, demonstrating that these channels are beneficial even despite the day/night biases.

Summary and conclusions

In this paper, we summarised some recent and upcoming developments in the use of ATOVS data at ECMWF. The main points are:

- ATOVS data from METOP-A has been assimilated operationally at ECMWF for well over a year now, with AMSU-A and MHS data being assimilated since 11 January 2007, and HIRS data since 19 March 2007. A small positive forecast impact was noted over the Southern Hemisphere from the additional data.
- Revised RTTOV coefficients for AMSU-A have been generated that exclude a scalar parameterisation of the Zeeman effect in the line-by-line model. This parameterisation was found to be inadequate for the pass-bands of AMSU-A channel 14, and the revised
coefficients allow better consistency with SSU data when both instruments are assimilated at the same time in the reanalysis. The same coefficients are used in operations since 6 November 2007. RTTOV coefficients without the inappropriate Zeeman parameterisation are also available via the RTTOV website. Future work will investigate the use of a fast parameterisation of the Zeeman effect, following work of Han et al. (2008).

- AMSU-A channel 14 is now assimilated without a bias correction since 6 November 2007 to anchor the upper stratospheric temperature analysis within VarBC.
- A revised bias correction that reduces day/night biases in the HIRS and AIRS short-wave channels used operationally will be implemented later in 2008.

Further work on an enhanced usage of ATOVS data includes the improved treatment of surface-sensitive microwave radiances over land (e.g., Krzeminski et al. 2008), a revision of quality control decisions, and the use of data in cloudy regions.

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A Comparison of IASI and SSMIS Impacts on NWP Analyses and Forecasts

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Abstract

Moisture increments produced by SSMIS and IASI in the Met Office 4D-Var assimilation system are compared in a study using co-locations from MetOp-A and F-16. Statistically the 4D-Var increments show similar structure in the vertical, however a direct comparison shows surprisingly weak correlation between the two sensors. The impact of SSMIS window channels (12-16) and IASI water vapour channels shows disappointingly small impacts on forecast accuracy with impacts around 1-2% or less on PMSL, geopotential height and wind scores. Impacts on forecast humidity fields are weaker still at 0.5% or less for forecast ranges 1-3 days.

Introduction

SSMI radiances, which contain information on atmospheric water vapour, are assimilated at many NWP Centres. Andersson et al [1] note that SSMI has the largest influence on lower tropospheric humidity analyses over oceans of all satellite data types currently used in the ECMWF model. Assimilation tests using the Met Office 3D-Var, and more recently 4D-Var, assimilation and forecasting system have never produced consistent positive impacts in both the tropics and extratropics. Occasional benefits in the tropics are offset by degradations in the southern hemisphere, or vice-versa. The aim of this study is to gain a better understanding of the impact of SSMI / SSMIS window channel radiances on moisture fields through comparisons with the impacts from IASI radiances on analyses and forecasts.

The existing SSMI series of sensors will be replaced by the SSMIS series of instruments, the first of which (F-16) was launched in 2003. The SSMIS series (F-16 - F-20) will provide operational continuity for this type of observation until 2020, at least, and therefore the continued investigation and optimisation of the impact of SSMI / SSMIS radiances on NWP moisture fields is worthwhile.

The launch of the IASI instrument on the MetOp-A platform, in a similar orbit plane to F-16 SSMIS offers the possibility of simultaneously comparing the analysis influence of moisture sensitive radiances from a high spectral resolution advanced IR sounder (associated with high vertical resolution) and a microwave imager (low resolution in the vertical). Figure 1 shows the averaging kernels derived from the 31 moisture sensitive channels of IASI used at the Met Office [see Hilton et al, these proceedings] and Figure 2 shows the averaging kernels corresponding to SSMIS channels 12-16 at 19 GHz (H&V polarisation), 22 GHz (V polarisation) and 37 GHz (V&H polarisation).
F-16 SSMIS / MetOp-A IASI Co-locations

The similar orbital planes of F-16 SSMIS (LTAN 20:03) and MetOp-A (LTAN 09:30) make it possible to generate a co-location data set. During the period 24\textsuperscript{th} - 27\textsuperscript{th} October 2007, 9,718 co-locations were generated, with a spatial co-location criteria of 20 km. The difference in orbit planes makes the temporal displacement nearly constant at 95 minutes. The co-locations are shown in Figure 3 below. Although not global in coverage, the dataset represents a wide range of tropical and extra-tropical meteorological situations.

The form of the increments in specific humidity from IASI and SSMIS at the co-location positions for both 1D-Var and 4D-Var analyses are shown in Figure 4 below. The largest increments appear in the tropics, as expected. For the 1D-Var increments, IASI and SSMIS appear to complement each other in that SSMIS increments peak close to the surface, whereas
Fig. 4: Moisture increments for SSMIS and IASI for both 1D-Var and 4D-Var. Solid lines represent the mean analysis increments, dotted lines show the standard deviation of the increments, and the shaded areas represent the envelope for all increments.

IASI increments span the troposphere, with slightly decreased sensitivity close to the surface. The 4D-Var increments show a much more similar form between sensors with a peak around 850 hPa for both SSMIS and IASI. For each pressure level, a direct comparison can be made of SSMIS and IASI driven moisture increments. This is shown for a subset of pressure levels in Figure 5 below. There is generally positive correlation for IASI and SSMIS driven increments.

Fig. 5: The correlation of IASI and SSMIS driven moisture increments at 367, 578, 835 and 1006 hPa for SH mid-latitudes, NH mid-latitudes and tropics. The gradients and correlation coefficients are also shown.

This is shown in a more compact form in Figure 6 below. Correlations are positive at all levels, but surprisingly weak, usually around 0.2-0.5. There are several possible causes of this weak correlation. Firstly, it can be hypothesised that both instruments are observing the same moisture
errors, but the different information content of the IR vs MW measurements (expressed via the averaging kernels presented earlier) results in a weak correlation. i.e. IASI and SSMIS smear the moisture errors in very different ways, and this weakens the correlation. Secondly, it may be a consequence of the temporal displacement of the observation. 95 minutes may be too long an interval over which it can be assumed the moisture structures remain constant.

Fig. 6: The correlation coefficient of IASI vs SSMIS driven moisture increments in the pressure range 300 - 1000 hPa. The shaded area represents 95% confidence limits.

Assimilation experiments

The impact of SSMIS window channels and IASI water vapour channels was compared thorough two assimilation experiments. The experiments covered the period 24th May - 24th June 2007. The impact on a range of verification measures is shown in Figure 7 below.

Fig. 7: Verification for assimilation experiments in which SSMIS window channels 12-16 (top plot) and 31 IASI water vapour channels (bottom plot) were added to a full operational system.

For SSMIS positive impacts in the southern hemisphere are offset by degradations in tropical winds. For IASI, neglecting verification statistics at long range (T+120 hours) impacts are fairly neutral in the extra-tropics and positive for tropical winds at 250 hPa. The contrasting performance
of IASI and SSMIS in the tropics could be the result of biases in both sets of observations. As can be seen in Figure 4, IASI observations appear dry in the tropical lower troposphere (mean moisture increments negative) whereas SSMIS exhibits a smaller, moist bias. Previous OSEs have shown that drying the tropics reduces convective activity and tends to improve wind scores.

Figure 8 shows the impacts on relative humidity forecasts for both IASI and SSMIS. Impacts are generally weak, with forecast humidity errors changed by less than 1% for both observation types.

Fig. 8: Verification for relative humidity for assimilation experiments in which SSMIS window channels 12-16 (left plot) and 31 IASI water vapour channels (right plot) were added to a full operational system.
The impact of the addition of the SSMIS observations on the global analysed humidity field, averaged over the 30 days of the trial period, is indicated in Figure 9, for the 850 hPa pressure level. The largest differences, of around 5%, are seen in the sub-tropical subsidence regions, although smaller impacts are seen in the northern and southern Pacific.

Precipitation estimates from the TRMM satellite were used to verify precipitation fields from both trial and control. The measured 24-hour forecast fields averaged over the trial period are shown in Figure 10.

**Fig. 10:** Averaged precipitation fields for trial (top) in which SSMIS window channel radiances are added to a full observing system, TRMM observations (middle) and control experiment (bottom)

Differences between observations and the forecast model (both trial and control experiment) are large in relation to differences between trial and control. One significant difference here is in the placement of the precipitation field associated with the Asian Monsoon, for which TRMM observations places the maximum close to the SW coast of India, whereas forecast fields place the maximum much further south, in the equatorial Indian Ocean. As shown in Figure 11, the trial experiment appears to be shifting this maximum in the correct direction.
Fig. 11: Differences between trial and control precipitation fields.

equatorial Indian Ocean. As shown in Figure 11, the trial experiment appears to be shifting this maximum in the correct direction.

Summary and conclusions

Co-locations between MetOp-A IASI and F-16 SSMIS have been used to study the consistency of analysed moisture profiles. At all levels, there is positive correlation between IASI and SSMIS driven moisture increments, but the correlation is surprisingly weak (-0.2 - 0.5). The reasons for this are not clear, but may be due to the differing information content of the IR and microwave data.

In assimilation experiments the impact of SSMIS is small but positive in the SH, but negative in the tropics. For IASI water vapour channels, impacts are generally neutral in the extra-tropics and positive in the tropics. This may be due to a bias between forecast model and IASI observations which results in IASI drying the tropics. Impacts of both observation types on forecast humidity fields are surprisingly weak, with forecast accuracy changing by less than 1% across all forecast ranges, and in all regions, upon the introduction of both data types. TRMM data has been used to assess the precipitation fields and there is some evidence that the inclusion of SSMIS data improves the positioning of the Asian monsoon.

References

Impact of combined AIRS and GPS-RO data in the new version of the Canadian global forecast model

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Introduction

Environment Canada is currently planning to raise the lid of its operational global forecast model GEM (Global Environmental Multiscale) from 10 hPa (~30 km) to 0.1 hPa (~60 km) in the first quarter of 2009. The new version is called GEM-Strato. This project has several major components: changes to the model physics, new vertical coordinate, new background error statistics, and additional data types for the assimilation system. These include AMSU-A stratospheric channels 11-14 in addition to data types recently implemented operationally: AIRS and SSM/I radiances and Quickscat oceanic winds. This paper presents results on the impact of the new model configuration, followed by that of adding the new data types mentioned above, and that from GPS-RO refractivity profiles in the variational assimilation system.

Model configuration

The essential new elements of the GEM-Strato configuration are the following:

- Model top raised from 10 hPa to 0.1 hPa
- Number of levels raised from 58 to 80
- Vertical coordinate changed from eta to hybrid
- Li and Barker (2005) radiation code implemented
- Non-orographic gravity wave drag implemented (Hines, 1997)
- New climatological ozone from Fortuin and Kelder (1998)

This model configuration, labeled baseline GEM-Strato, was tested in assimilation cycles with the data types used operationally, with the addition AMSU-A channels 11-14.

Background error covariances

With a new model configuration, an important task is the derivation of background error statistics. As for the current operational system, the background error covariances are based on the difference between 24-h and 48-h forecasts valid at the same time. With the current approach for modeling the geostrophic balance, it is not possible to filter noisy correlations of “balanced temperature” ($T_{bal}$) between troposphere and stratosphere. A new approach allows to explicitly compute the vertical correlations for $T_{bal}$ so that they can be localized. This eliminated a problem of spurious stratospheric increments. The ratio of unbalanced temperature ($T_{unbal}$) to total temperature standard deviation from forecast differences was maintained. Variances were adjusted using radiosonde temperature and wind observations as well as MLS (microwave limb sounder) temperature retrievals. Fig. 1 shows the total standard deviation stddev $T$ and ratios stddev $T_{unbal}$/stddev $T$ for January and July. Maximum temperature errors of ~3.5 K at 1 hPa are related to the winter polar vortex. For assimilation cycles to remain stable, it was found necessary to reduce the temperature errors near the model top.

First results

First results with the Gem-Strato configuration against the current model with model top at 10 hPa (but without the new data types listed in the introduction) showed a remarkable improvement. Fig. 2 presents time series of Northern Hemisphere (NH) geopotential 120-h forecasts verified against
radiosondes and Fig. 3 presents the corresponding validation statistics for the mass, and wind profiles. Fig. 2 indicates (100 hPa panel) that the gain is dominated by two major stratospheric busts which were eliminated. These baseline GEM-Strato results correspond to a predictability gain of about 6 hours at day 5 based on 500 hPa anomaly correlation (not shown). Results for the Southern Hemisphere (SH) and Tropics as well as for the summer verification period were also clearly positive, although not as spectacular as those presented in Figs 2-3.

Adding AIRS, SSM/I and Quickscat

On 28th May 2008, Aqua AIRS (87 channels) and SSM/I (7 channels, F13 and F14 satellites) radiances as well as Quickscat ocean surface winds started to be assimilated operationally. In addition, edges of scans from AMSU-A and AMSU-B are now assimilated, increasing by 25% the volume of these data. An offline dynamical radiance bias correction system was implemented, updated at every analysis using a 15-day window. Bias predictors for microwave radiances are classical background geopotential thicknesses, with scan bias removed as a first step. AIRS uses only one predictor, the observed radiance itself. These new data were again tested in GEM-Strato and lead to a clear positive impact, similar to that noticed before their original implementation (Wagneur et al., 2007, Garand et al. 2007). AIRS is the data type providing the largest impact. An example of impact from 3D-var FGAT cycles is provided in Fig. 4 for SH 120-h forecasts.

Adding GPS-RO and more AIRS channels

The impact of GPS-RO assimilation of refractivity profiles was evaluated separately. The main characteristics are the following:

- Assimilation from 4 to 40 km
- Data from CHAMP, GRACE and COSMIC, about 500 profiles per analysis (6-h period)
- About 1 km vertical thinning (data are available at 200 m resolution)
- Background check corresponds to about 12 K limit between observed and calculated temperature. Data are assumed unbiased.
- Observation error is in the range 0.5 to 1.5%, assigned dynamically

Results in terms of 300 hPa GZ anomaly correlation are shown in Fig 5, indicating a positive impact in both hemispheres in a 70-day winter assimilation cycle. Future tests will consider using data up to 60 km near the model top. Eventually, bending angles could be assimilated instead of refractivity profiles.

The higher model top allows in principle to assimilate higher-peaking AIRS channels. Currently, the highest peaking channel is # 156 at about 150 hPa. A group of 30 additional AIRS channels is being tested on top of the current 87, the highest one being # 72 peaking at ~30 hPa. Preliminary results indicate a modest positive impact on top of all other data types. One issue is that relatively large temperature analysis increments (> 5 K) can result from weak Jacobian values near 1 hPa where the temperature background errors are largest (Fig. 1). This issue requires further study from longer cycles.

Bias correction issue

It is worth mentioning that it was judged preferable to keep the bias correction parameters fixed for AMSU-A 11-14 (after a 2-week spin-up) because the global bias for these radiances, defined as the mean value of observed radiance (O) minus the 6-h GEM forecast radiance (P), was not stable. Fig. 6 illustrates this. Over a 3-month period, the global bias increases steadily. Assimilation of GPS-RO data did not change significantly that situation. However, keeping the bias parameters fixed solves the potential problem: the global bias remains constant. Additional independent data would help to anchor the analysis within realistic climatological bounds in the stratosphere.
Conclusion

GEM-Strato is planned to become operational in early 2009. The methodology to derive background error statistics for data assimilation was substantially revised, resulting in smoother and more localized analysis increments. Northern Hemisphere winter cycles showed a major improvement against the operational model. The higher model lid allows extending the assimilation of radiances and GPS-RO in the stratosphere. The impact of GPS-RO is clearly positive despite the limited number of assimilated profiles per analysis. Based on pre-operational results presented here, a significant improvement in forecast performance scores is expected with the implementation of GEM-Strato.

References


Fig.1 Background standard deviation of total temperature errors stddev T (top, K) and ratio stddev Tunbal (stddev T)^{-1} (bottom) for January (left) and July (right).
Fig. 2. Time series of stddev of radiosonde minus predicted geopotential height (dm) from NH 120-h forecasts at three pressure levels based on 4D-var cycles covering indicated period. Control (blue) is operational model with top at 10 hPa. Experiment (red) is baseline GEM-Strato.

Fig. 3. Validation statistics based on 101 NH 120-h forecasts against radiosondes for the same cycles as Fig. 2. Bias (dashed) and stddev (full) for wind components UU and UV, geopotential GZ and temperature TT. Statistical significance (over 95%) of the differences between control and experiment is indicated (pink for experiment better, cyan for control better).
Fig. 4 Validation statistics as in Fig. 3 from 3D-var cycles for 144 SH 120-h forecasts between 20 Dec 2006 and March 1 2007. Control (blue) is baseline GEM-Strato. Experiment (red) is control + new data types (AIRS, SSM/I, Quickscat).

Fig. 5 300 hPa geopotential anomaly correlation for in NH (left) and SH (right) for period 20 Dec 2006 to March 1 2007. Control (blue) is baseline GEM-Strato + new obs. Experiment (red) is control + GPS-RO.
Fig. 6 Monitoring for Aqua AMSU-A channel 13; bias (top) and stddev (bottom). Statistics for (O-A) in blue and (O-P) in red, where O is the radiance observation, P is the GEM 6-h forecast radiance, and A is the analysis value. Dotted red in top panels is raw mean (O-P) (bias before correction) and green line shows the correction. Left panels show results using dynamical bias correction. Right panels show results with bias correction parameters fixed.
The Assimilation of Cloudy Infrared Radiances in the HIRLAM Model: Initial Experiences

Martin Stengel, Per Dahlgren, Magnus Lindskog, Per Unden, and Nils Gustafsson

Efforts have been made at SMHI to examine the utilisation of measured infrared radiances in the presence of clouds in the limited-area numerical weather prediction model HIRLAM. Since a certain portion of observations are located in cloudy areas, many observations are rejected in the first place. We have started to investigate under which circumstances observations in cloudy conditions could be used. A first strategy focuses on low level clouds. Here, the assimilation of infrared sounding channels seems to be less problematic, as far as their sensitivity to the cloud layers is negligible. Nevertheless, the filtering of those cases relies on the information about the vertical location of the clouds. This can possible be optimized when providing more accurate information to keep as many useful observations as possible. Next to a fixed cloud top pressure (CTP) limit, the comparison of the derived CTP and the local Jacobians at observation point could be more effective as criteria in this context to identify such not-radiance-affecting clouds. Additionally, we consider clouds, whose effect on the radiance is small, which can possibly be parameterized properly in the observation operator by a simple cloud assumption. First assimilation experiments, using SEVIRI’s water vapour channels, have been carried out and initial results will be shown. Furthermore, we investigate the feasibility to extend the observation operator to include a simplified moist physics scheme. This framework can also be used to determine the sensitivity of modelled clouds (and subsequent simulated cloudy radiances) to the model variables. Under certain conditions, this could then be used to assimilate cloud-affected infrared radiances. Statistics of these modelled clouds in NWP model space and in observation space, as well as the sensitivity of simulated cloudy radiances will be discussed. Preliminary 1D-Var studies are currently being conducted and will be presented.
Impact of VASS radiance of FY3 assimilation on numerical typhoon prediction

Gang Ma, Zhang Fengying Li Xiaoqing etc.

A set of transmittance coefficients of IRAS (InfRared Atmospheric Sounder), MWTS (MicroWave Temperature Sounder) and MWHS (MicroWave Humidity Sounder) used in RTTOV7 has been build by multivariate linear regression analysis in line-by-line radiative transfer models. Comparison of 43 profiles of the channel radiance from these line-by-line models and those from RTTOV7 shows that bias are less than 0.7K for all the 20 infrared channels of IRAS and are less than 0.3K for all the 9 channels of MWTS and MWHS. With RTTOV7 and the new transmittance coefficients, a new satellite data assimilation module has been set up to directly assimilate VASS (Atmospheric Vertical Sounding System) radiance of FY3 into GRAPES 3DVar system. Because the radiance bias of infrared channels are less than 3K while those for microwave channels are less than 0.03K between ATOVS and VASS, quality control of the radiance and bias correction to simulated VASS radiance have been introduced in terms of ATOVS radiance assimilation. Radiance of ATOVS have been use to generate VASS radiance based on the spectral characteristics of the VASS instruments in a typhoon case. Then, new initial temperature, water vapor and wind fields for GRAPES model can be produced by directly assimilating these VASS radiance. Numerical tests show positive effect on typhoon track prediction by using those satellite data in GRAPES.
An Information Based Radiance Data Selection Scheme for Efficient Use of a Multi-Satellite Constellation

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Introduction

In this study we show that using a data selection method, up to six platforms delivering level-1D ATOVS radiances derived using the European ATOVS and AVHRR Processing Package (AAPP) in the BMRC Global Assimilation and Prediction (GASP) system can significantly improve prediction performance in both the mid-latitudes in the Southern Hemisphere and the Tropics. For this project we have implemented the GASP assimilation and prediction systems at a resolution of T239/L60, with the uppermost level at 0.1 hPa. This method of data selection uses only the forward model (RTTOV-7), reducing the need for expensive 1DVAR quality control, which allows a 30% increase in processing time. Moreover, out of the six platforms, NOAA-16, 17, 18, AQUA/AMSU-A, and MetOp, the only satellite fully functional with all the ATOVS instruments is MetOp. All the other platforms have either whole instruments malfunctioning, or a varying degree of usable channels.

1DVAR System

The one-dimensional variational retrieval system (1DVAR) used in both the local and global assimilation systems at the Bureau of Meteorology is based on the ECMWF formulation (Eyre et al. 1993). It performs an iterative retrieval of temperature and moisture at the sounding location using a background first guess, interpolated to the 43 level RTTOV-7 forward model. The temperatures and moistures are converted to thickness and precipitable water layers and the corresponding background and analysis errors are calculated for the same quantities. Following Purser (1990), the analysed increments and analysis errors are scaled dynamically for each sounding, thus allowing the information content to be reflected in the Optimal Interpolation (OI) analysis (Harris et al. 1999). The radiance bias correction (Harris and Kelly 2001) uses background derived bias predictors and a latitudinally varying scan correction.
The 60 Level GASP Model

In order to use AAPP derived radiances without the need for extra information or extrapolation, the operational GASP system with a top at 10hPa had to be extended to 0.1hpa. It currently assimilates NOAA-16, 17, 18, AQUA/AMSU-A and MetOp. The Bureau of Meteorology has been receiving global AAPP processed level-1d radiances from the Met Office for some time and it produced 1DVAR retrievals up to 0.4hPa, and thinned to 250km prior to 1DVAR via the information based selection method.

The Information Based Thinning System

All thinning is done prior to 1DVAR using only one call to RTTOV-7, which allows an extensive testing and classification scheme based on the atmospheric state, the surface type, and the particular peculiarities of the individual satellite. Table 1 shows the status of ATOVS instruments used in GASP, each with their particular variety of malfunction.

Table 1: Status of Sensors by Satellite

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<td>MetOp</td>
<td>Ok</td>
<td>Ok</td>
<td>Ok</td>
</tr>
</tbody>
</table>

To categorise the state of the atmosphere and the surface, there are many checks that are possible. Note to avoid any sort of feedback, none of the \((o-b)\) have been bias corrected.

To determine the surface characteristics, (with the exception of NOAA-17), a Grody type AMSU-A Ch 1, 2, 3 and 15 algorithm detects Sea (S), Sea-Ice (I) and Land (L). For NOAA-17, the background model is used, and any discrepancies will probably fail the cloud check.

To determine the atmospheric state, for NOAA-17 and MetOp there is a -2K window check for cloud contamination. If no HIRS, then the Grody algorithm also retrieves a liquid water path, and if it is less than 0.3 and \(|o-b| < 5K\) for AMSU-B2, then the state is denoted for historical reasons ‘Partly Cloudy’. This means that the IR is contaminated, but the combination of AMSU-A and AMSU-B may be used to produce a water-vapour as well as temperature retrieval. If the above checks fail, then AMSU-B and AMSU-A Ch 4 and 5 are not used. These are the ‘Cloudy’ soundings.

Table 2: Ranking by Satellite, Surface and Atmospheric State

<table>
<thead>
<tr>
<th></th>
<th>CS</th>
<th>PS</th>
<th>CIS</th>
<th>CI</th>
<th>PI</th>
<th>CH</th>
<th>CL</th>
<th>PL</th>
<th>CIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-16</td>
<td>X</td>
<td>5</td>
<td>9</td>
<td>X</td>
<td>14</td>
<td>18</td>
<td>X</td>
<td>22</td>
<td>26</td>
</tr>
<tr>
<td>N-17</td>
<td>2</td>
<td>X</td>
<td>X</td>
<td>11</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>N-18</td>
<td>X</td>
<td>4</td>
<td>8</td>
<td>X</td>
<td>13</td>
<td>17</td>
<td>X</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>Aq/A</td>
<td>X</td>
<td>X</td>
<td>6</td>
<td>X</td>
<td>15</td>
<td>X</td>
<td>X</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>MetOp</td>
<td>1</td>
<td>3</td>
<td>7</td>
<td>10</td>
<td>12</td>
<td>16</td>
<td>19</td>
<td>20</td>
<td>24</td>
</tr>
</tbody>
</table>
Once the surface and atmospheric type has been determined, this allows the obvious
unusable combinations such as NOAA-17 partly cloudy etc to be easily discarded. For the
usable combinations, a determination is made as to which platform can extract the most
information for a given combination of (Satellite X Surface X Atmosphere) and a ranking
number is given.

**Effect of Inclusion of MetOp in GASP**

A global analysis was done on 00Z on 13 January 2008, one using the (then)
operational system which did not use MetOp, against an experimental run using MetOp in
addition to the other four satellites.

![Fig. 1: Australian Region Data Selection Without Metop. (NOAA-17 = RED, NOAA-18 = GREEN)](image)

Note at the time there were some type-4 (NOAA-18, PS) east of New Zealand, but the
only other platform in the general Australian region was type-2 (NOAA-17, CS), only able to
retrieve clear spots over the sea.
Notice here that almost all of the type-2 NOAA-17’s have been replaced by MetOp, with many different sounding types \{1, 3, 7\} for sea and \{19, 20, 24\} for land. Anomalous sounding types such as type-19/20 over the sea indicate that the quality control has flagged a problem and fewer channels (“land”) have been used. Notice the variety of MetOp sounding types \{1,3,7,20\} north and west of New Zealand. This indicates that the different sounding channels are being appropriately chosen in a region with an unstable tropical air-mass. This is likely to be related to the increase in forecast skill.
Fig. 3: 120 hour forecast with Operational GASP (no MetOp).

Fig. 4: 120 hour forecast from analysis trial using MetOp.
This has been a demonstration of the utility of a fast satellite thinning technique based on choosing the platform which can extract the most information from a given situation. We have shown that by simply adding the satellite with the most information content (MetOp) to the analysis, has given rise to a forecast of a tropical storm near New Caledonia at 120h, whereas the analysis without MetOp produced only a weak trough. As a result of this case, and general improvement in forecast skill over a period of over a month, MetOp ATOVS radiances were included in the operational GASP system.

References


Use of Hyperspectral IR Data in 4D Assimilation at NRL

Benjamin Ruston, Nancy Baker, William Campbell, Tim Hogan, Xu Liu

A newly developed weak-constraint 4D-Var system is in parallel pre-operational testing at the Naval Research Laboratory. The NRL Atmospheric Variational Data Assimilation System – Accelerated Representer (NAVDAS-AR) is targeted to be the next generation assimilation system for the US Navy replacing the 3D-Var NAVDAS system within the next year. In particular, NAVDAS-AR scales much better to the high data volumes encountered working with hyperspectral instruments such as AIRS and IASI. The NAVDAS-AR system has been configured to use both the JCSDA Community Radiative Transfer Model (CRTM) and RTTOV-8.7 and a brief comparison of the two will be presented. The adjoints of NAVDAS-AR and the Navy Operational Global Atmospheric Prediction System (NOGAPS) are used to produce observation sensitivities for all simulated channels allowing for additional guidance in channel selection for assimilation. Primary channel selection begins by identifying the spectral region of interest for assimilation. The assimilation has focused initially on the longwave CO2 channels in the 13-15 micron range. Further channel selection is done by leveraging advice from other modeling centers (UK-Met Office and ECMWF), examining Jacobians for sensitivity above the model top, and the use of the NAVDAS-AR and NOGAPS adjoint sensitivities. Quality control is being done primarily by the NWP-SAF released cloud detection package for high resolution infrared sounders. Results of the assimilation runs will present standard diagnostics including the 500hPa anomaly correlations from the Northern and Southern hemispheres, vector wind RMS from 850 hPa, and tropical cyclone tracks from the 2007 season for AIRS assimilation only. Lastly, Xu Liu, a visitor from NASA Langley has incorporated the principle component version of the CRTM (pCRTM) to be used with NAVDAS-AR and IASI data. This allows direct assimilation of principle components rather than individual channels. These results are contrasted with the results from the conventional channel style assimilation runs in both computational efficiency and most importantly in NWP performance.
**Intercomparison of the Cross-Track and Conical Scanning**

**Banghua Yan, Fuzhong Weng, and John Derber**

The NOAA Advanced Microwave Sounding Unit (AMSU) and DMPS Special Sensor Microwave Imager/Sounder (SSMIS) instruments have similar temperature and water vapor sounding channels but different cross-track and conical scan geometries. For cross-track scanning, the angle of earth incidence varies, resulting in angle-dependent weighting function and satellite measurements for a given frequency. For conical scanning, a fixed angle of incidence and a vertical axis of rotation are used, in which the viewing area and slant path remains nearly constant. The differences in this scan geometry can result in differences in impacts on model forecasts. Distinct bias correction and quality control schemes also must be utilized for AMSU and SSMIS data due to differences in error characteristics of the satellite data. These error characteristics and different bias correction and quality control schemes associated with AMSU and SSMIS data can further result in different impacts on Numerical Weather Prediction (NWP). To quantify characteristics of cross-track and conical scanning satellite microwave sounding impacts, AMSU and F16 SSMIS measurements are assimilated separately into National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) associated with Gridpoint Statistical Interpolation (GSI) subsystem. In this process, the current bias correction and quality control schemes for AMSU and SSMIS data in GSI are assessed, and the data usage in GSI and impacts of each instrument of measurements on various analysis variables and forecast score in GFS are estimated by carrying out a set of assimilation experiments for both winter and summer seasons. Since the original F16 SSMIS atmospheric sounding channels display persistent radiance anomalies, the F16 SSMIS data used in this study is corrected using both the Calibrated Temperature Data Record (CTDR) by applying the Naval Research Laboratory (NRL) and United Kingdom Met Office (UKMO) unified SSMIS preprocessor and the National Environmental Satellite, Data, and Information Service (NESDIS) SSMIS preprocessor.
Impact of AIRS and AMSU-A data in regional data assimilation over the Antarctic

Thomas Auligne, Hui Shao, Dale Barker, Zhiquan Liu and Hui-Chuan Lin

The Antarctic Mesoscale Prediction System (AMPS) is an experimental, real-time numerical weather prediction capability that provides a twice-daily forecast covering Antarctica. The current version uses the regional mesoscale model Weather Research and Forecasting (WRF). The model can be initialized through a variational assimilation system (WRF-Var), which involves specific background error statistics. The impact of observations from the Atmospheric Infrared Sounder (AIRS) and the Advanced Microwave Sounding Unit (AMSU) is studied for the Antarctic region. Temperature and water vapor information are retrieved through the latest version of AIRS Standard Retrieval Products from NASA. The quality of the data is assessed for high latitudes and errors associated with these quantities are estimated. The performance of retrievals is then compared to the direct assimilation of radiances. Objective methods are used to estimate the radiance error statistics and to perform quality control. A cloud detection scheme is developed for AIRS and adapted to the polar regions where clouds are often more difficult to identify. The relevance of cloud-cleared radiances is also studied. Finally, a significant effort is focused on systematic errors in the innovations, which are a major problem for data assimilation in the polar regions. In particular, we will show results from the combination of a variational bias correction of observations with estimations of model bias.
Neural Network Estimation of Atmospheric Profiles Using AIRS/IASI/AMSU Data in the Presence of Clouds

William J. Blackwell, Frederick W. Chen, and Michael Pieper

A novel statistical method for the retrieval of atmospheric temperature and moisture (relative humidity) profiles has been developed and evaluated with sounding data from the Atmospheric InfraRed Sounder (AIRS) and the Advanced Microwave Sounding Unit (AMSU) on the NASA Aqua satellite and the Infrared Atmospheric Sounding Interferometer (IASI) and AMSU on the EUMETAT MetOp-A satellite. The present work focuses on the cloud impact on the AIRS and IASI radiances and explores the use of stochastic cloud clearing mechanisms together with neural network estimation. A stand-alone statistical algorithm will be presented that operates directly on cloud-impacted AIRS/AMSU and IASI/AMSU data, with no need for a physical cloud clearing process. The algorithm is implemented in three stages. First, the infrared radiance perturbations due to clouds are estimated and corrected by combined processing of the infrared and microwave data using a Stochastic Cloud Clearing (SCC) approach. The cloud clearing of the infrared radiances was performed using principal components analysis of infrared brightness temperature contrasts in adjacent fields of view and microwave-derived estimates of the infrared clear-column radiances to estimate and correct the radiance contamination introduced by clouds. Second, a Projected Principal Components (PPC) transform is used to reduce the dimensionality of and optimally extract geophysical profile information from the cloud-cleared infrared radiance data. Third, an artificial feedforward neural network (NN) is used to estimate the desired geophysical parameters from the projected principal components. The performance of the method was evaluated using global (ascending and descending) EOS-Aqua orbits co-located with ECMWF forecasts (generated every three hours on a 0.5-degree lat/lon grid) and radiosonde observations (RAOBs) for a variety of days throughout 2003, 2004, and 2005. Over 1,000,000 fields of regard (3x3 arrays of footprints) over ocean and land were used in the study. The performance of the SCC/NN algorithm exceeded that of the AIRS Level 2 (Version~4) algorithm throughout most of the troposphere while achieving approximately four times the yield. Furthermore, the SCC/NN performance in the lowest 1 km of the atmosphere greatly exceeds that of the AIRS Level 2 algorithm as the level of cloudiness increases. The SCC/NN algorithm requires significantly less computation than traditional variational retrieval methods while achieving comparable performance, thus the algorithm is particularly suitable for quick-look retrieval generation for post-launch CrIMSS performance validation. Recent work has focused on retrieval performance in “problem areas” over land, near the poles, elevated terrain, etc. Retrieval performance has been improved by stratifying...
the neural network training data into distinct groups based on geographical (latitude, for example), geophysical (atmospheric pressure, for example), and sensor geometrical considerations (scan angle, for example.) Performance using IASI/AMSU has also been evaluated, with emphasis on the impact of vibration-induced noise on the cloud-clearing accuracy. In this talk, the algorithm methodology will be briefly reviewed, including a discussion of implementation differences for AIRS and IASI. Algorithm performance will then be discussed and compared with other methods. This work was sponsored by the National Oceanic and Atmospheric Administration under Air Force contract FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and not necessarily endorsed by the United States Government.
Using AVHRR radiances analysis for retrieving atmospheric profiles with IASI in cloudy conditions

L. Lavanant

Developments are on-going at Météo-France/CMS for the processing of the IASI/AMSU/MHS sounders over Europe for helping French forecasters. A preliminary atmospheric retrieval scheme in clear and cloudy conditions is defined and its implementation in progress. This paper focuses on the processing of the IASI IR spectra in cloudy conditions. The processing of the AVHRR imager mapped inside the IASI fov allows to detect small amount of clouds and to determine the number of cloud layers and their cloud top temperature if they are black-body. Also possible is the hyper-fast treatment of the AVHRR clusters performed within the OPS IASI pre-processor and available at a global scale on the GTS and EUMETCast in the BUFR format. The CO2-slicing method based on a selection of IASI sounding channels is applied to homogeneous and semi-transparent cloudy situations to access cloud parameters when AVHRR methods fails. Systematic comparisons of observations to synthetic IASI spectra using retrieved cloud parameters allow to estimate the cloud information accuracy. The previous cloud information is used for the retrieval of the atmospheric profile in cloudy conditions from a selection of IASI channels. Two methods are compared. First, only the non-contaminated channels are selected above the cloud using the ECMWF method and the 1DVar retrieval process is done in clear conditions. Second, the cloud top pressure and effective cloud amount from the AVHRR/CO2-slicing method are used in the cost function of the 1DVar method. In that case more informative channels above/in the cloud are used. Status on these developments and preliminary accuracy assessment on meteorological situations of NWC interest will be presented.
CO2 Slicing Method for IASI

Arlindo Arriaga, Peter Schlüssel, Xavier Calbet, Thomas August, Olusoji Oduluye, Tim Hultberg

Slicing Method for IASI Arlindo Arriaga, Peter Schlüssel, Xavier Calbet, Thomas August, Olusoji Oduleye, Tim Hultberg EUMETSAT, Am Kavalleriesand 31, 64297 Darmstadt, Germany ABSTRACT The retrieval of the cloud top pressure and effective cloud amount within the fields of view of IASI is supported with the CO2 slicing method, based upon its classical version with a fixed number of pre-selected sampling frequencies. A few tests are implemented in the respective algorithm to characterize the feasibility of its application to a particular situation, as well as to refine further the selection of sampling frequencies, to account for temperature inversions in the lower troposphere, and for quality control purposes. The thermodynamic structure of the atmosphere and the surface skin temperature are available as forecasts from ECMWF, and the model outgoing cloud free radiance is computed with the RTIASI-4. The surface emissivity is modelled either for a rough sea surface or for a land surface with different fractional land type coverage corresponding to the scene within the IASI IFOV. The pre-selection of a set of fixed sampling frequencies is performed with a simple methodology, whose application has been supported by two large data sets with a large variety of surface-atmosphere-clouds scenarios, covering the whole globe and all seasons of the year. The criterion to select such a set of frequencies for retrievals is based on a trade off between the accepted lowest significance of a pre-defined critical retrieval error and the accepted percentage of scenarios left as non-retrievable. The results achieved with the present algorithm are based upon a pre-selected set of 41 CO2 sampling frequencies between 707.5 and 756.0 cm⁻¹. The distribution of the retrieval error computed for realistic scenarios with multilevel ice or water clouds shows low bias (below 15 hPa) for cloud tops between 200 and 700 hPa, and respective cloud amounts not lower than 40%. The results achieved with a much larger data set of sampling frequencies have shown only marginal improvements. Broad results over different cloud fields have shown good spatial consistency with respect to co-located AVHRR images within the channels in the visible (0.6 μm) and infrared (10.8 μm) windows. The retrieval error is evaluated with cloud-radar measurements during an atmospheric sounding campaign at Lindenberg, Germany, from June to September 2007, in support of the validation of Metop products.
Impact of rain-affected microwave data assimilation on the analyses and forecasts of tropical cyclones

R. Montrotty, F. Rabier, S. Westrelin, and G. Faure

Tropical cyclones are tremendous natural hazards that threaten coastal populations worldwide. The purpose of this study is to perform data impact studies with the Aladin Reunion Limited Area Model, with a focus on the Indian Ocean area and a 3DVar data assimilation. Studies are performed for several storms of the 2006/2007 cyclonic season of the South West Indian Ocean basin. This last season proved to be very active with 10 named storms, 4 of which attained the major hurricane wind threshold of 50m/s. Satellite data has proven most invaluable when trying to initialize Numerical Weather Prediction (NWP) models since the oceanic zones over which the cyclones develop are, by nature, data sparse. Yet, the occurrence of clouds or rain proves to be a challenge when trying to assimilate satellite data: non linear processes dominate and the use of refined, costly numerical methods might be required. These computational costs are usually found to be prohibitive and cloudy/rainy data assimilation usually is a missing component in most operational centres. This proves to be of critical importance when dealing with tropical cyclones because their dynamics take place in the core, consistently missed by observations. Of the few centres that do not suffer from this crucial observational lack, the European Centre for Medium Range Weather Forecasting (ECMWF) has implemented a 1DVar inversion for cloudy/rainy areas which uses complex moist physical schemes to retrieve a Total Column Water Vapour (TCWV) equivalent from the rainy radiances, which is then used as pseudo-observation in the 4DVar assimilation. In order to alleviate the constraints posed by such a costly 1DVar inversion, we investigated an alternative to this approach. A statistical multi-linear regression that fits TCWV with the brightness temperatures of the SSM/I instrument in cloudy/rainy conditions is used, relying on the ECMWF analyses during a learning period. The convergence of the regression is investigated, and the tuning of the TCWV assimilation is performed. The resulting data are shown to be of good quality and to alter the hydrological cycle of the resulting analyses. The algorithm is then applied to combine clear-sky radiances with cloudy/rainy TCWV in the 3DVar data assimilation scheme. Impacts of further observations and pseudo-observations such as a 3D wind bogus and microwave SST are also conducted, both in terms of forecast impacts and of measures of data impact. High resolution forecasting nested from the 10km runs is also investigated in the AROME model.
Experiment of the Use of Satellite Microwave Data Affected by Cloud in Numerical Prediction

Peiming Dong, Qiang Ren and Jishan Xue

Chinese Academy of Meteorological Sciences
Chinese Meteorological Administration
Beijing, China

Abstract

Currently, only cloud-free satellite data are used in most data assimilation systems. The observations in cloudy area contain useful information for the numerical weather forecast. The use of satellite data affected by cloud may improve the accuracy of numerical weather forecasts.

The Community Radiative Transfer Model (CRTM), being developed currently in the Joint Center for Satellite Data Assimilation (JCSDA) USA, is implemented in our Grapes-3dvar, a three dimensional variational data assimilation system developed by Chinese Academy of Meteorological Sciences, to conduct research associated with the use of satellite data, especially the data affected by cloud and rain.

Taking the typhoon 0604 “Bilis” as research case, a set of experiments is designed to use the satellite data affected by cloud in numerical forecast firstly based on the cloud examination scheme. The simulation of satellite observation in cloudy area is verified by using CRTM with input of cloud and rain information. The cloud examination methods include Scattering Index, precipitation probability, precipitation examination and the bias between simulated bright temperature and observation. The screen of satellite data affected by cloud, together with their influences on the numerical forecast of Bilis’s three periods, corresponding to formation, maturation and landing, respectively are examined. The characteristics of simulated bright temperature in cloudy and rainy area is investigated to show how the satellite observation affected by cloud and rain be improved under the consideration of the radiant effect of cloud and precipitation particle.

Introduction

Satellite data are used in numerical weather prediction and already are the main data source among the observations used because of the good data coverage, thus providing high spatial resolution atmospheric information, especially for the wide zones of ocean, plateau and desert with few conventional observations, it improves greatly the quality of initial condition and the accuracy of numerical weather forecast.

However, more than 97% satellite data passes the pre-process are discarded before they enter into the data assimilation system. Among them, it is shown that the satellite data affected by cloud held more than 75% in the ECMWF statistical report. For the complexity to cope with the radiant effect of cloud and rain particles in radiative transfer model, only cloud-cleared satellite data are used in most current data assimilation systems. But, the observations in cloudy and rainy area imply much information to weather system and numerical forecast. The use of satellite data affected by cloud and precipitation will be one of the effective technological methods to improve the accuracy of numerical weather forecast continuously.

At present, the satellite data affected by cloud is examined through the cloud examination method.
Different cloud examination schemes are taken in different numerical forecast centers. For example, the bias between the simulated bright temperature and observation of AMSU-A channel 4 is used in Météo-France. The AMSU-A data is contaminated by cloud when the bias is beyond 1.5 K. In MetOffice UK, the observation of AMSU-A channel 4, 5 and AMSU-B channel 5 is thought to be affected by cloud when the total perceptible water is greater than 100 gm$^{-2}$. The AMSU-A channel 4-8 and AMSU-B all channel data are discarded by precipitation examination. In addition, Cirrus examination is performed for three AMSU-B high frequency channels. The Bennartz Scattering Index is used for AMSU-B in Canadian Meteorological Centre. The thresholds are 0, 15 and 40 for land, sea and sea ice, respectively. The cloud examination schemes in AAPP include Scattering Index, precipitation probability, precipitation examination and so on.

At the same time, the code for simulation of cloud-affected radiance is being developed in the fast radiative transfer model. In the RTTOV latest version 9.1 developed within the context of the EUMETSAT Satellite Application Facility on Numerical Weather Prediction (NWP SAF), the cloud radiant effects for the infrared are parameterized rather than treated explicitly, while a slower, explicit approach is applied to the microwave in an individual module RTTOV-SCATT. The Community Radiative Transfer Model (CRTM), being developed currently in the Joint Center for Satellite Data Assimilation (JCSDA) USA, is designed to make use of satellite data under all weather conditions by including scattering and emission from the earth’s atmosphere. The CRTM is already implemented in our Grapes-3dvar, a three dimensional variational data assimilation system developed by Chinese Academy of Meteorological Sciences.

A set of experiments to use the satellite data in cloudy and rainy area through the cloud examination scheme, together with the verification of simulation of satellite observation with input of cloud and rain information by CRTM are presented in our talk. The details are described in the following two sections, respectively. The final section is a brief conclusion and discussion.

The experiment of cloud examination

1) Cloud examination method

Table 1: The cloud examination method for AMSU data

<table>
<thead>
<tr>
<th>Data</th>
<th>Examination method</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMSU-A</td>
<td>Scattering Index</td>
<td>SI=ETB15-TB15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ETB15=a+b×TB1+c×TB2+d×TB3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where, $a$, $b$, $c$ and $d$ are tri-polynomial for tangent of scanning angle.</td>
</tr>
<tr>
<td></td>
<td>Precipitation probability</td>
<td>$P=1/(1+c^d \times 100)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where, $c=10.5+0.184 \times TB1-0.221 \times TB15$</td>
</tr>
<tr>
<td></td>
<td>Precipitation examination</td>
<td>$R=ETB1-TB1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where, $ETB1=38+0.88 \times TB2$</td>
</tr>
<tr>
<td>AMSU-B</td>
<td>Bias between simulated bright temperature and observation for Channel 2</td>
<td>$\Delta=</td>
</tr>
<tr>
<td></td>
<td>Bennartz Scattering Index</td>
<td>$SI=TB1-TB2-(-39.2010+0.1104 \Theta)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Where, $\Theta$ is the local zenith angle of scanning field.</td>
</tr>
</tbody>
</table>

Different screen of the satellite data in cloudy and rainy area will be brought about by different cloud examination method. In our experiment, Scattering Index, precipitation probability and precipitation...
examination are taken for AMSU-A. The bias between simulated bright temperature and observation of AMSU-B channel 2 and Bennartz Scattering Index are utilized in the cloud examination for AMSU-B. The cloud examination method and their formula for AMSU satellite data are given in Table 1.

![Figure 1](image1.png)

Fig. 1: The value of cloud examination methods for AMSU-A. (a) Scattering Index; (b) precipitation probability; (c) precipitation examination

![Figure 2](image2.png)

Fig. 2: The value of cloud examination methods for AMSU-B. (a) Bias between simulated bright temperature and observation for Channel 2; (b) Bennartz Scattering Index

Taking the typhoon 0604 “Bilis” as research case, the values of cloud examination at 1800 UTC 10 July, 2006 are shown in Fig. 1 and Fig. 2 for AMSU-A and AMSU-B, respectively. It could be found that the Scattering Index is a nice match for the corresponding cloud map (not presented) for AMSU-A. While only a rainy core is mainly figured out by both precipitation probability and precipitation
examination. For AMSU-B, the bias between simulated bright temperature and observation for Channel 2 matches the cloud distribution much better than the Bennartz Scattering Index. Even the clearance between cloud and clear sky is distinguished.

2) Experiment design

The list of experiments is presented in Table 2. The discussion is mainly applied for AMSU-A channel 5-7 and AMSU-B channel 3-5, respectively. Several experiments are designed for the different threshold of Scattering Index and channel selection including AMSU-A channel 8-10.

Table 2: List of numerical experiment design

<table>
<thead>
<tr>
<th>Experiment design</th>
<th>Data</th>
<th>Criterion</th>
<th>Channel selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control experiment</td>
<td></td>
<td></td>
<td>The initial background without data assimilation is used for numerical simulation</td>
</tr>
<tr>
<td>Assimilation experiment</td>
<td></td>
<td></td>
<td>The initial condition with the correction by satellite data is used</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>AMSU-A</td>
<td>SI&gt;10</td>
<td>5 7</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>AMSU-A</td>
<td>SI&gt;10</td>
<td>5 10</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>AMSU-A</td>
<td>SI&gt;15</td>
<td>5 7</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>AMSU-A</td>
<td>SI&gt;20</td>
<td>5 7</td>
</tr>
<tr>
<td>Experiment 5</td>
<td>AMSU-A</td>
<td>P&gt;5</td>
<td>5 7</td>
</tr>
<tr>
<td>Experiment 6</td>
<td>AMSU-B</td>
<td>R&gt;0</td>
<td>5 7</td>
</tr>
<tr>
<td>Experiment 7</td>
<td>AMSU-B</td>
<td>Δ≥5K</td>
<td>3 5</td>
</tr>
<tr>
<td>Experiment 8</td>
<td>AMSU-B</td>
<td>Bennartz SI&gt;15</td>
<td>3 5</td>
</tr>
</tbody>
</table>

3) Screen of data affected by cloud

For AMSU-A Scattering Index, the number of satellite data affected by cloud decreases with the increase of the value of threshold. Only a few satellite observations are distinguished by the precipitation probability and precipitation examination. Even the number of satellite data affected by cloud decided by Scattering Index with threshold 20 is greater than that of precipitation probability and precipitation examination. The number of satellite observation decided by precipitation examination is the least.

Table 3: The number of cloudy satellite and the root mean square error of the bias between background simulated bright temperature and observation for AMSU-A channel 5-10

<table>
<thead>
<tr>
<th>Cloud examination and threshold</th>
<th>The number of cloudy satellite observation</th>
<th>Channel RMSE</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI&gt;10</td>
<td>1827</td>
<td>0.89</td>
<td>0.34</td>
<td>0.43</td>
<td>0.53</td>
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The screen of satellite data used in the assimilation system is done by both cloud examination and the extreme check of the bias between background simulated bright temperature and observation. Table 3 is a statistic of the number of cloudy satellite observation and the root mean square error of the bias.
between background simulated bright temperature and observation for AMSU-A channel 5-10. It can be found that most of the satellite data affected by cloud distinguished by Scattering Index with threshold 20, precipitation probability and precipitation examination could also be discarded by the extreme check. Most satellite data could be used for these three cloud examination methods. While most satellite data are discarded for the Scattering Index with threshold 10.

For AMSU-B, the number of satellite data affected by cloud distinguished by the bias between simulated bright temperature and observation of AMSU-B channel 2 is less than that of Bennartz Scattering Index. That is, more satellite data could be used in the assimilation system (Table 4).

Table 4: The number of cloudy satellite and the root mean square error of the bias between background simulated bright temperature and observation for AMSU-B channel 3-5

<table>
<thead>
<tr>
<th>Cloud examination and threshold</th>
<th>The number of cloudy satellite observation</th>
<th>Channel RMSE</th>
</tr>
</thead>
</table>
| \(|ob-fg|\geq 5K\) Bennartz SI 
\(>20\) | 1160 9.17 16.54 28.44 | 3 4 5 |
| Threshold of the bias between simulated bright temperature and observation | 2843 6.73 10.99 18.33 | 7.98 7.14 7.38 |

4) **Effect on the numerical forecast**

The numerical integral is performed for typhoon Bilis’s three periods, corresponding to formation, maturation and landing, respectively. The error between simulated and observation trace is presented in Table 5.

Comparing with Exp1, it is shown that the numerical forecast is degraded in Exp2. It is confirmed that there is no need of cloud examination for the use of AMSU-A channel 8-10 satellite data. The forecast of Exp3, in which more satellite data are used than Exp1, is much better than that of Exp1. It means that the introduction of more AMSU-A data in cloudy area by Scattering Index with threshold 15 have positive effect on the forecast. While with the number of satellite data increasing by using Scattering Index with threshold 20, precipitation probability and precipitation examination (Exp4-Exp6), the forecast becomes worse. It is indicated that the negative effect is brought by the use of more satellite data in cloudy area. It seems that the Scattering Index with threshold 15 is a suitable cloud examination scheme for the use of AMSU-A data. It is pointed out that the result is not supported by the forecast of first period, which suggests that the assimilation of satellite data is a complex issue. There is a need to verify it by doing a long period run.

For AMSU-B, the forecast of Exp7 is the same as that of Exp1. It is attributed to the cloud examination for AMSU-A in Exp1 is used, while the cloud examination for AMSU-B in Exp7 is utilized in Exp1. It is found that the forecast of Exp7 is better than that of Exp8.

**Verification of simulation of satellite microwave data in cloudy and rainy area**

1) **Input of cloud and rain information**

With the cloud and rain information as input to CRTM, the satellite observation could be simulated including the radiant effect of cloud and precipitation particle. The cloud and rain information is provided by the forecast of WRF model. The total cloud water, rain water and ice water contents are presented in Fig. 3. The distributions match well with the weather system. Together with the analysis of vertical profile (not presented), it is shown that the cloud and rain water concentrate near the lower level and the ice water is on the upper.
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</table>
2) Characteristics of the simulated satellite observation

The investigation is performed on the simulated bright temperature with no water contents, with cloud water, rain water, ice water and all water contents against the observation. Only the patterns for AMSU-A channel 1 and AMSU-B channel 5 are presented in Fig. 4 and Fig. 5, respectively. Generally speaking, the inclusion of radiant effect of water contents in radiative transfer model makes the simulation match the observation closely. For AMSU-A window channel 1-3, the cloud and rain water contribute to the high bright temperature core associated with the typhoon system. Rain water has greater effect on channel 1-2 than cloud water. While the latter takes the leading role in channel 3. The inclusion of water contents contribute to the low bright temperature core from channel 4 to the channels after. The contribution is going less with the increase of channel number. It is noted that the effect of water contents is not obviously shown in channel 5-7. These channels are thought to be affected by cloud and rain. Cloud examination is taken when they are used in the assimilation system. For AMSU-A channel 15, the radiant effect of water contents contribute to the low bright temperature core in the high bright temperature area associated with the typhoon. Rain water plays a much important role. Ice water performs as a minor part in all AMSU-A channels.

For AMSU-B channel 1-2, the water contents perform almost the same as that of AMSU-A channel 15. The effect is most obvious in channel 2. What is more, the effect of ice water is presented in channel 2. The scattering of ice particle dominates the radiant effect in AMSU-B channel 3-5. It implies that the cloud examination should pay special attention to the effect of ice water.

The bias between observation and simulation for all AMSU is also presented in Fig. 6. It is shown that the simulation of satellite observation in cloudy and rainy area could really be improved by the
inclusion of the radiant effect of cloud and rain particle in the fast radiative transfer model.

Fig. 4: The observation and simulation of bright temperature with no water contents, with cloud water, rain water, ice water and all water contents for AMSU-A channel 1.

Fig. 5: The same as Fig. 4, but for AMSU-B channel 5.
Conclusion and discussion

A set of experiments has been described to use the satellite microwave data in cloudy area based on the cloud examination scheme. Scattering Index, precipitation probability and precipitation examination are taken for AMSU-A. For AMSU-B, the bias between simulated bright temperature and observation of AMSU-B channel 2 and Bennartz Scattering Index are utilized. The result shows that more AMSU-A satellite data could be screened by Scattering Index than precipitation probability and precipitation examination. The Scattering Index with threshold 15 is suitable for the use of AMSU-A data in regional model. For AMSU-B, the bias between simulated bright temperature and observation of AMSU-B channel 2 performs well than Bennartz Scattering Index.

With the cloud and rain information as input to CRTM, the simulation of satellite data in cloudy and rainy area is verified. It is found that the inclusion of radiant effect of water contents in radiative transfer model makes the simulation match the observation closely. The effect of water contents corresponding well with the observation characteristic of each channel. It will definitely push the use of cloudy radiances directly in NWP model and enhance the impacts of satellite data that have been demonstrated through clear radiance assimilation.

It should be pointed out that there is still a little large bias between simulated and observation though the effect of water contents is introduced in the radiative transfer model. More issues, including how the cloud and rain output from numerical model is competent for the background information and the sensitivity of simulation bias to the water contents error and so on, will be discussed further.

Acknowledgment. This work is supported by the National Natural Science Foundation of China under Grant No. 40775027 and the State Key Laboratory of Severe Weather under Grant No. 2007LASW03.

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The inclusion of cloudy radiances in the NCEP GSI analysis system

Min-Jeong Kim, Fuzhong Weng, and John Derber

The impact of AMSU-A, AMSU-B and MHS radiance on numerical weather predictions has been found to be significant. The major limitation on the use of these data has been the presence of clouds. In the Joint Center for Satellite Data Assimilation (JCSDA) we have begun to develop the capability to use the information from cloudy microwave radiance in the NCEP Gridpoint Statistical Interpolation (GSI) analysis system. Radiance data assimilation in cloudy regions requires rapid and accurate radiative transfer and radiance gradient models. The Community Radiative Transfer Model (CRTM) was developed at the JCSDA for use in the radiance assimilation problem and has incorporated appropriate physics for a vertically stratified scattering and emitting atmosphere. This CRTM is employed in this study to calculate radiances and Jacobians at various microwave wavelengths for radiance assimilation under all weather conditions. In the first part of this study, the sensitivity of CRTM calculated radiances to the cloud variables are presented and the accuracy of CRTM calculated Jacobians for cloud profiles are evaluated. In the second part, methodologies for the cloudy radiance related bias corrections in the GSI are addressed. Preliminary results showing the impacts of cloudy radiance assimilation on analysis fields and forecast results will be presented.
Using Clear and Cloudy AIRS Data in Numerical Weather Prediction

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Abstract

Expanded use of the information content of infrared hyperspectral radiance data has resulted in an improvement in the beneficial impact of these data on numerical weather prediction. Experiments which have shown the benefit of improved spatial coverage, spectral coverage and the use of moisture channel data, have been briefly summarised in this paper. In addition, an experiment which has recorded the benefit of using hyperspectral radiance data from fields of view containing clouds is also described. Again it is demonstrated that a more complete use of the information content in the observations available from hyperspectral sounders has resulted in improved benefits to numerical weather prediction. This conclusion is also supported by early experiments reported using IASI data.

Introduction

The Atmospheric Infrared Sounder (AIRS) (Aumann et al. 2003, Chahine et al., 2006) was launched in 2002 on AQUA, the second of the EOS polar-orbiting satellites. The AIRS was the first of a new generation of meteorological advanced sounders able to provide hyperspectral data for operational and research use. After the launch of the AIRS and the subsequent six-month calibration period, the AIRS was able to provide operational data. The improved spectral resolution it provided compared to earlier passive infrared (IR) sounders, led to a significant increase in vertical resolution and accuracy in determining thermal and moisture fields, increased accuracy in the determination of the concentrations of absorbers such as ozone and improved numerical weather prediction (NWP), (Chahine et al. 2006, Le Marshall et al. 2006). Here, the use and beneficial impact of radiances free from cloud effects, on global NWP is reviewed. The use and subsequent beneficial impact of radiances derived from cloudy AIRS fields of view (fovs) on global NWP is also described.

The first radiance assimilation trial to use full spatial resolution and higher spectral resolution hyperspectral data, available in real time from the AIRS instrument is briefly reviewed here. The
result from this assimilation trial was significant improvement in forecast skill in the National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS), compared to the global system without AIRS data over both the northern and southern hemispheres. A second trial, which was an experiment which showed the advantage of using all AIRS fields of view (fovs) in analysis as opposed to the use of sampled fields of view (typically one-in-eighteen) commonly used at the time of the experiment, by NWP Centers, is also reviewed. Another trial which showed the benefit of using hyperspectral data with expanded spectral coverage is also described.

To gain more information from the majority of the AIRS fields of view, which are covered to some extent by cloud, radiance data from AIRS fields of view, which generally contain cloud with a single cloud top height have been used. The differences in cloud cover in these fields of view have enabled the estimation of radiance emanating from the cloud-free portions of these fields. Recent experiments are then described, where radiances, derived from cloudy AIRS fovs and which represent the radiance emanating from the clear part of the cloudy fov, have been assimilated for global NWP. The beneficial impact of these data in both the Northern and Southern Hemispheres on the GDAS is recorded. This may be the first example of the beneficial impact of using cloudy hyperspectral radiances in global NWP. A final experiment is also described which shows the beneficial impact of using Infrared Atmospheric Sounding Interferometer (IASI) hyperspectral data in global NWP.

Recent AIRS data assimilation studies

In mid-2004 the Joint Center for Satellite Data Assimilation (JCSDA) demonstrated significant impact from AIRS data in both the northern and southern hemispheres (Le Marshall 2005a, b). This was achieved through use of an enhanced spatial and spectral AIRS observational dataset in conjunction with an analysis methodology that paid additional attention to the possible presence of clouds. Experiments demonstrating the benefits of AIRS data assimilation and the contribution of enhanced spatial and spectral resolution data (Le Marshall et al., 2006b) are summarised below.

Assimilation of full spatial and enhanced spectral resolution AIRS data

To examine the impact of adding full spatial and spectral resolution AIRS radiances to the operational database (without AIRS), the NCEP operational T254 64-level version of the Global Forecast System (GFS), (November 2004 version) was employed. All channels for all fields of view from the AIRS instrument on the AQUA satellite were processed into the current BUFR format. This provided 281 channels of AIRS data at each footprint, or field of view, of which 251 were found suitable for assimilation. (Note: Current operational systems usually assimilate 152 channels or less). These particular channels described most of the variance of the 2,378 AIRS channels (Susskind et al. 2003). The NCEP operational global analysis and prognosis system (Derber and Wu 1998; Derber et al. 2003) using the full operational database, without AIRS data, was employed as the control (‘Ops’). The database included all available conventional data and the satellite data listed in Tables 1 and 2. The radiances from the AQUA Advanced Microwave Sounding Unit-A (AMSU-A) instrument were not included in the control or experimental database. The experimental system also employed the GFS with the full operational database (i.e. the control database) plus full spatial resolution AIRS radiance data (‘Ops +AIRS’), available within operational time constraints.
Table 1: The satellite data used by the control forecasts

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<tr>
<td>SSM/I precipitation rates</td>
<td>SBUV/2 ozone profile and total ozone</td>
</tr>
</tbody>
</table>

Table 2. Conventional data used by the control forecasts

<table>
<thead>
<tr>
<th>Rawinsonde temperature and humidity</th>
<th>Rawinsonde u and v</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIREP and PIREP aircraft temperatures</td>
<td>AIREP and PIREP aircraft u and v</td>
</tr>
<tr>
<td>ASDAR aircraft temperatures</td>
<td>ASDAR aircraft u and v</td>
</tr>
<tr>
<td>Flight-level reconnaissance and dropsonde temperature, humidity and station pressure</td>
<td>Flight-level reconnaissance and dropsonde u and v</td>
</tr>
<tr>
<td>MDCARS aircraft temperatures</td>
<td>MDCARS aircraft u and v</td>
</tr>
<tr>
<td>Surface marine ship, buoy and c-man temperature, humidity and station pressure</td>
<td>Surface marine ship, buoy and c-man u &amp; v</td>
</tr>
<tr>
<td>Surface land synoptic and Metar temperature, humidity and station pressure</td>
<td>Surface land synoptic and metar u and v</td>
</tr>
<tr>
<td>Ship temperature, humidity and station pressure</td>
<td>Wind Profiler u and v</td>
</tr>
<tr>
<td></td>
<td>NEXRAD Vertical Azimuth Display u and v</td>
</tr>
<tr>
<td></td>
<td>Pibal u and v</td>
</tr>
</tbody>
</table>

The analysis methodology is described in Le Marshall et al. (2005a, b). The experiment was performed for January 2004. In a typical six-hour global assimilation cycle approximately 200 million AIRS radiances (i.e. 200x106 / 281 fields of view), were input to the analysis system. From these data, about 2,100,000 radiances (281 radiances (channels) in approximately 7450 analysis boxes) were selected for possible use, and resulted in about 850,000 radiances free of cloud effects being...
used in the analysis process. That is effective use was made of approximately 41 per cent of the data selected for possible utilization.

A summary of the results is seen in Figures 1 and 2. Figure 1 shows the geopotential height anomaly correlations (AC) for the GFS at 500 hPa over the southern hemisphere for January 2004 at one to seven days, with and without AIRS data. It is clear the AIRS data have had a beneficial effect on forecast skill over the southern hemisphere during this period. Figure 2 shows the 500 hPa AC over the northern hemisphere for January 2004. The results again show improved forecast skill. This improvement is quite significant when compared to the rate of general forecast improvement over the last decade. A several hour increase in forecast range at 5 or 6 days normally takes several years to achieve at operational weather centres.

Assimilation of full and reduced spatial resolution AIRS data

To examine the importance of using the full spatial resolution AIRS data as opposed to the one in eighteen fields of view used, earlier, for NWP, further assimilation experiments were run. In these cases, the operational control (CNTL) database was as before with the addition of AQUA AMSU-A and one in eighteen AIRS fovs. The experimental runs (SpEn AIRS) used full spatial resolution AIRS data. The trial again used the NCEP operational T254, 64 level GFS (November 2004 version). The experiments were performed during August – September 2004. Identical versions of the GFS were used in both cases. Results may be seen in Figure 3. It is clear, that the increased information related to atmospheric temperature and moisture contained in the (spatially enhanced - SpEn) full spatial density dataset and the thinning of the data set paying attention to cloud distribution, has resulted in improved analyses and forecasts. The improvement in forecast skill at 6 days is equivalent to gaining an extension of forecast capability of several hours.
Assimilation of full and reduced spectral coverage AIRS data

The Control experiment used the full NCEP operational database including AQUA AMSU-A for the period 2 January to 15 February 2004 to provide a series of control analyses and forecasts from the NCEP operational T254 64 level GFS (June 2005 version). The forecasts were then repeated using AIRS data with different channel sets.

The analyses and forecasts were undertaken for the full operational database plus full spatial resolution AIRS observations from the 115 AIRS channels whose central wavelength is between 3.7 and 9.3 μm (‘short AIRS’). In a third series of analyses and forecasts, the full operational database has been used with 152 channels of AIRS data i.e. full spatial resolution, including 152 of the 281 channels currently available for real-time NWP covering the full spectral range 3.7 - 15.4 μm (‘airs – 152ch’). In a fourth series of analyses and forecasts, the full operational database has been used with all (251 channels) of AIRS data (‘airs – 251ch’) i.e. full spatial resolution, including 251 of the current 281 channels available for real-time NWP covering the full spectral range 3.7 - 15.4 μm. The results from these experiments are seen in Figure 4. This figure shows the 1000 hPa and 500 hPa geopotential height (Z) five-day forecast anomaly correlations for the northern and southern hemispheres. It was apparent in this trial that addition of the short wave channels (‘short AIRS’) to the operational observation database generally provided a positive forecast skill increment at five days with a larger improvement being seen in the southern hemisphere 1000 hPa fields. It was also clear for this period that addition of long wave channels (whose central wavelength is greater than 9.3μm, ‘airs-152ch’, ‘airs-251ch’) generally provided improved forecasts in each of the categories. The clear advantage from using the full spectral range with 251 channels of AIRS data was also apparent in the experiments for this period.

During a similar series of impact studies from January 15 to February 15, 2004, using 251 AIRS channels and full spatial resolution AIRS data, an examination was undertaken of the forecast moisture field in the lower troposphere. An example of the Forecast Impact is seen in Figure 5 where Forecast Impact evaluates which forecast (with or without AIRS) is closer to the analysis valid at the same time.

\[
\text{Forecast Impact} = 100 \left( \frac{\text{Err}_{\text{AIRS DENIAL}} - \text{Err}_{\text{Ctrl}}}{\text{Err}_{\text{Ctrl}}} \right)
\]

where Err_{Ctrl} is the error in the Control forecast. Err_{AIRS DENIAL} is the error in the AIRS denial forecast. Dividing by the error in the control forecast and multiplying by 100 normalizes the results and provides a percent improvement or degradation. A positive Forecast Impact means the forecast is
better with AIRS data included. Figure 5 shows a degree of improvement over a significant area in the 925 hPa relative humidity in the 24 hour forecast with AIRS. Significant areas of improvement were also seen in the 850 hPa relative humidity and the Total Precipitable Water at 12 and 24 hours. This result is not unexpected, given the large number of channels sensing water vapour in the 281 channel set.

**Assimilating data from cloudy fields of view**

Recently, attention has turned to extending the use and coverage of AIRS observations by use of cloud effected fields of view. As an initial step towards a fuller use of cloud effected radiances in NWP, fields of view with preferably single level cloud were included in variational analyses and forecasts (Le Marshall et al. 2007). Initially, the radiances used were those where the distribution of the cloud coverage has allowed accurate estimation of radiances from the clear parts of the fields of view. In these initial experiments, between 1 January 2007 and 24 February 2007, the observed channel radiances in each fov, $R_j$, is given by

$$R_j = (1 - \alpha_j)R_{\text{clr}} + \alpha_j R_{\text{cld}}$$

where $R_{\text{clr}}$ is the radiance from a clear field of view, $R_{\text{cld}}$ is the radiance if the fov was totally covered with single level cloud and $\alpha_j$ is effective cloud cover. The nine fovs on each AQUA AMSU-A footprint were used to estimate $R_{\text{clr}}$ with the assumption that the only variability in the AIRS fovs was the cloud amount.

A fuller description of the process is found in Susskind et al., 2003. The initial experiments used the current NCEP operational configuration of 152 AIRS channels from all AIRS footprints with

**Figure 6 (a):** The impact of AIRS data on GFS forecasts at 500hPa (20°N - 80°N), 1 Jan. – 24 Feb. 2007; The pink curve denotes use of clear radiances from clear and cloudy AIRS fovs (see text) and the blue curve denotes use of non cloud effected radiances (Control).

**Figure 6 (b):** The impact of AIRS data on GFS forecasts at 500hPa (20°S - 80°S), 1 Jan. – 24 Feb. 2007; The pink curve denotes use of clear radiances from clear and cloudy AIRS fovs (see text) and the blue curve denotes use of non cloud effected radiances (Control).
operational thinning. The experimental runs used the operational configuration minus the operational AIRS data, and added AIRS cloud free radiances and radiances from the clear air part of selected cloudy fovs (with operational thinning).

The radiances were processed as potentially cloud-affected. Use of the data representing radiances from the clear parts of cloudy fields of view resulted in a 10% increase in this experiment in the number of channels used in the analysis from each radiance profile. Forecast verifications from northern and southern hemisphere forecasts are seen in Figure 6 (a) and (b) and Figure 7, where the latter shows the impact of the data on the 5-day 1000 hPa and 500 hPa forecasts. The 500hPa results were examined employing serial correlation considerations (Seaman, 1992) and the southern hemisphere results were found to be significant near the 95% level while those for the northern hemisphere were found to be significant at a much reduced level. These figures provide an indication of potential gains which may be had by the use of cloudy radiances, which provide far greater spatial and spectral coverage than cloud free radiances alone.

The future

Recently, NWP experiments have been undertaken to examine the impact of additional hyperspectral radiance observations on the current NCEP GDAS. The additional hyperspectral data was from the Infrared Atmospheric Sounding Interferometer (IASI) on METOP2. The control and experimental runs used the December 2007 operational configuration of the GDAS. The Control experiment used the full operational database including AQUA AIRS data for the period 1 December 2007 to 12

![Figure 7: The impact of AIRS data on the GFS forecast at 500 and 1000hPa at 5 days. The red columns denote use of clear radiances from clear and cloudy fields of view and the blue columns denote use of AIRS radiance observations not affected by clouds.](image)

![Figure 7: The impact of AIRS data on the GFS forecast at 500 and 1000hPa at 5 days. The red columns denote use of clear radiances from clear and cloudy fields of view and the blue columns denote use of AIRS radiance observations not affected by clouds.](image)

![Figure 8: The impact of IASI data on GFS forecasts at 500hPa (20°S - 80°S), 1 December 2007 – 12 January 2008; the pink (blue) curve shows the AC with (without) IASI data.](image)

![Figure 9: The impact of IASI data on GFS forecasts at 500hPa (20°N - 80°N), 1 December 2007 – 12 January 2008; the pink (blue) curve shows the AC with (without) IASI data.](image)
January 2008, to provide a series of control analyses and forecasts. The experimental analyses and forecasts were then produced for the same period using IASI data plus the full operational database. In these experiments 165 IASI longwave channels were employed to improve the accuracy of the analysis. The results of this experiment can be seen in Figures 8 and 9 where it is apparent the addition of the IASI hyperspectral observations has added to the accuracy of the ensuing forecasts both in the northern and southern hemispheres.

Conclusions

The introduction of AIRS hyperspectral data into environmental prognosis centres was anticipated to provide significant improvements in forecast skill. Here, results are noted where AIRS hyperspectral data at higher spectral and spatial resolution than usual have shown significant positive impact in forecast skill over both the northern and southern hemisphere for January 2004. The magnitude of the improvement was quite significant and would normally take several years to achieve at an operational weather centre. Also noted was the improvement gained from using AIRS at a spatial density greater than that initially used for operational NWP. In addition some studies have been completed to look at the impact of spectral coverage and they found for the period studied, use of a fuller AIRS spectral coverage and the full AIRS spectral range, namely 3.7 to 15.4 µm, provided superior forecasts. The efficacy of using higher spatial and spectral resolution data for depicting the moisture field was also recorded.

In a new experiment, to extend the use of AIRS radiances to cloudy fields of view, radiances, preferably from fields of view with single level cloud, were used. The potential for gaining improved coverage in channels sensing the lower part of the troposphere and also the potential gains in forecast skill that may be obtained by the use of radiances generated from the clear parts of cloudy fields of view were shown.

Finally, results have been reported for an experiment where data from the Infrared Atmospheric Sounding Interferometer, IASI on METOP2 have been assimilated into the current NCEP GDAS and have provided positive forecast impact. This again shows an improvement in forecast capacity, with use of increased information from hyperspectral instruments.

In conclusion, given the opportunities for future enhancement of assimilation systems and for improved use of the hyperspectral database, the results indicate a considerable opportunity to improve current operational analysis and forecast systems. It is anticipated that future gains will be made through use of higher spectral and spatial resolution data and from use of cloudy data. The gains may be further increased through use of complementary data such as Moderate Resolution Imaging Spectroradiometer (MODIS) radiances for determining cloud characteristics. Improvements are also expected from the effective exploitation of the new hyperspectral data from the Infrared Atmospheric Sounding Interferometer (IASI), and those which will become available from the Cross-track Infrared Sounder (CrIS) and geostationary instruments such as the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS).

Of note in this manuscript is a first report of the forecast improvements resulting from the use of radiances in the significantly cloudy regions of the globe. The results indicate that radiances from cloudy regions of the atmosphere have the potential to provide significant information on atmospheric state in a global forecast model and their use should be further developed.

In terms of the future it is also intended to use a new BUFR format which will contain more information on the quality of the clear radiances from cloudy fields of view and to begin to test the use of raw cloudy radiances in a simple single-level cloudy inversion within the analysis (see, for example, Le Marshall et al., 1994) as the next steps in using cloudy radiances.
References


A 1DVAR system was developed to process space-borne microwave measurements. The particularity of the system is its potential applicability in cloudy and precipitating conditions. The Microwave Integrated Retrieval System (MIRS) solves for the inversion of the radiative transfer equation by finding radiometrically appropriate profiles of temperature and moisture and cloud parameters as well as surface emissivity spectrum and skin temperature. The inclusion of the emissivity spectrum in the solved-for state vector makes the system applicable globally with the only differences between land, ocean, sea-ice and snow backgrounds residing in the covariance matrix chosen to constrain spectrally the emissivity spectrum. The forward operator used in the MIRS is the Community Radiative Transfer Model (CRTM) which provides both radiances and derivatives with respect to all geophysical parameters to be inverted, including hydrometeors. The computation of the derivatives (k-matrix) is performed using tangent linear and adjoint approaches. When used in absorption-only mode, it is found that convergence of the system is reached globally, even in coastal areas, with pockets of non-convergence being highly correlated to cases of precipitation, suspicious measurements and generally with any situation that the forward operator can not handle properly. The system convergence is modulated by computed instrument errors and by estimated modeling errors. The fitting of the measurements could be made stricter by reducing the assumed modeling errors, making the convergence stricter. The system is applied routinely to NOAA-18 and Metop-A AMSU and MHS sensors and the assumed modeling errors are around one Kelvin in all situations, except for the temperature-sounding channels, where they are estimated to be lower (between 0.17 and 0.45 Kelvin depending on the channel). It is suggested in this paper that the system could be an excellent tool to pre-process and filter microwave data for Numerical Weather Prediction (NWP) assimilation applications, based on the convergence metric. An additional benefit would be obviously to get an estimate of the geophysical state before starting the assimilation. This might be very useful especially if there is an interest in assimilating measurements taken in cloudy, rainy conditions and/or if there is interest in extending the assimilation over non-standard surface backgrounds.
**Effect and Improvement of Aerosol on Temperature Profile from MODIS**

Jie Zhang, Jun Li, Qiang Zhang

Based on statistical synthetic regression algorithm from America, temperature and moisture profile of atmosphere is retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) longwave infrared radiances, on the basis of profile result, spectrum transmittance is estimated by using Pressure-Layer Fast Algorithm for Atmospheric Transmittances (PFAAST), then, temperature profile is retrieved by using Nonlinear physical retrieval algorithm. The results show that atmosphere temperature above the top of boundary layer is well retrieved, the error is within 2K, in boundary layer, retrieval error is large, the error is positive correlated with aerosol optical depth and estimated error of skin temperature, but it is not correlated with atmosphere water vapor mixing ratio. According to theory of radiative transfer equation, the research analyze effect of aerosol optical depth on retrieval error, moreover, the sensitivity of which with weighting functions are analyzed. Finally, aerosol optical depth is used for improving on atmospheric transmittance and physical algorithm, the results show that temperature profile can reflect real value of atmospheric temperature within boundary layer after improving on aerosol effect.
Evaluation of Special Sensor Microwave Imager/Sounder (SSMIS) Environmental Data Records

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I. M. Systems Group, Inc., Kensington, Maryland, USA

Fuzhong Weng
NOAA/National Environmental Satellite, Data and Information Service/Center for Satellite Applications and Research, Camp Springs, Maryland, USA

Abstract

Compared to the Special Sensor Microwave Imager (SSM/I), the new Special Sensor Microwave Imager/Sounder (SSMIS) aboard the Defense Microwave Satellite Program (DMSP) F16 satellite has the similar seven imaging channels except for two at 85.5 GHz replaced by the 91.655 GHz frequency. After the NRL calibration of SSMIS imager channels, the temperature data record (TDR) can be utilized operationally to derive both atmospheric and surface parameters. In this study, several products are developed from the SSM/I heritage algorithms, including total precipitable water, cloud liquid water path, snow cover, sea ice cover, rain rate and land surface temperature. Some new products are also derived from SSMIS, such as land emissivity. The retrieved products from F15 SSM/I and F16 SSMIS are inter-compared to quantify the mean bias and standard deviation. It is found that because of both the relatively small mean bias and standard deviation the F16 SSMIS products, such as total precipitable water, cloud liquid water path, snow and sea ice, may replace the SSM/I products for operational use. However, discrepancies remain in the global rainfall estimates, land surface temperature and land emissivity produced by each sensor. This is likely due to the imperfect F16 SSM/I-like channels to F15 SSM/I channels linear mapping, especially for 91.655 GHz channels, whose frequency is shifted from 85.5 GHz in SSM/I.

INTRODUCTION

The Special Sensor Microwave/Imager (SSM/I) was developed as part of the Defense Meteorological Satellite Program (DMSP) and first launched in June 1987 aboard DMSP F-8 satellite. The SSM/I measures thermal radiation from the Earth’s surface and atmosphere at four frequencies from 19.35 GHz to 85.5 GHz with both vertical and horizontal polarizations, and has provided critical information on global hydrological parameters such as water vapor, cloud water and precipitation. SSM/I data and the retrieved products have been widely used in data assimilation systems with positive impacts (Tsuyuki 1997; Deblonde 1999; Hou et al. 2000; Okamoto and Derber 2006).

The DMSP F16 satellite was successfully launched on October 18, 2003, carrying the first Special Sensor Microwave Imager/Sounder (SSMIS) onboard. SSMIS marks the beginning of a new series of passive microwave conically scanning imagers and sounders to be launched over the next two decades. This instrument provides measurements at 24 channels. Seven include imaging channels, similar to SSM/I, of which two channels have been slightly shifted from the SSM/I 85.5 GHz vertical and horizontal polarizations (V and H will be used to represent vertical horizontal polarizations for simplicity hereafter) to the SSMIS 91.655 GHz V and H. SSMIS also has seven lower atmosphere temperature sounding (LAS) and six upper atmosphere temperature sounding (UAS) channels near the 50 to 60 GHz oxygen absorption...
bands. In addition, SSMIS contains one horizontally polarized 150 GHz and three horizontally polarized channels with double sidebands about 183.31 GHz for mid-to-upper troposphere water vapor sounding. With a larger scan angle, 144° versus 102° for SSM/I, SSMIS increases the imaging channel scene number to 90 compared with 64 in the SSM/I A-scan and to 180 from 128 in the SSM/I B-scan. This effectively reduces the scan gap area in mid-latitude regions. Based on its ability to measure microwave radiation from a broader spectrum, SSMIS can provide temperature profiles up to 80 km altitude as well as water vapor profiles and surface information under varying weather conditions.

This study will focus on the evaluation of the retrieval of a number of heritage environmental parameters from F16 SSM/I-like channels, which are 19.35 GHz V/H, 22.235 GHz V, 37.0 GHz V/H, and 91.655 GHz V/H, in the SSMIS. In section 2, the F16 SSMIS data and its calibration algorithm are briefly introduced. The description of retrieval algorithms and the inter-comparison results of these environmental parameters from F15 and F16 measurements will be given in section 3. The final section will summarize the results of this study and give a preliminary conclusion based on the discussions.

**DMSP Data and Evaluation Methodology**

National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite Data, Information Services (NESDIS) received SSM/I and SSMIS antenna brightness temperature data records (TDRs) through a data-sharing agreement with DMSP. The F16 SSMIS TDRs have been archived at NOAA/NESDIS since January, 2005. At present, DMSP F15 and F16 are used as primary sensors in NOAA operations with DMSP F-13 and F-14 SSM/I as backup sensors. In addition, the activation of radar calibration (RADCAL) beacons on DMSP F15 on August 14, 2006 seriously contaminates the 22.235 GHz channel. Without accurate measurements from this channel, water vapor related products cannot be correctly retrieved. Since it is desirable to take advantage of the closeness of scan times of F16 and F15 in order to compare SSMIS with SSM/I, data acquired from F15 before the activation of the RADCAL beacons will be used in our comparison study.

After preliminary analysis of the SSMIS TDRs distributed by Fleet Numerical Meteorology and Oceanography Center (FNMOC), it was found that the original TDRs display notable anomalies, compared to radiative transfer model outputs, and the scale of such anomalies also vary with frequency. For example, due to the solar heating of reflector when spacecraft emerging from earth or spacecraft shadow and warm load solar intrusions, the lower atmosphere sounding (LAS) temperature channels may have biases reaching a peak about 2 K (Kunkee et al. 2008; Wessel et al. 2008; Swadley et al. to be submitted). In fact, reflector emission occurs for all scenes where the reflector and scene temperature differ, but its impact is most notable when reflector emerges from shadow and solar elevation angles are impinging from below the canister top, resulting in a dramatic jump in the reflector face temperature of 70 K or more. In our study, Earth and spacecraft shadowing only occur on the ascending portion of the rev in the December 2005 to February 2006 time frame. Nevertheless, SSM/I-like channels, especially those below 40 GHz, which are primarily used to produce environmental parameters in our study, do not exhibit very significant anomalies as LAS, UAS and Moisture sensing channels do. However, due to the apparent frequency dependence in the main reflector emissivity, there are residual biases that affect the 91.655 GHz in a more significant manner. The biases could in turn cause residual error in the EDRs. Because of the poor surface emissivity information forward model cannot well simulate the radiance at 91.655 GHz. But,
with the data sets matched using Simultaneous Conical Overpassing (SCO) and comparisons between F16 and F15 over global areas, the difference of mean TDR bias of the imaging channels between F16 and F15 between high latitudes and cloud free areas is found to be 0.5 K or less except for 91.655 GHz channels (Yan and Weng 2008), in which the biases come from both frequency shifting from 85.5 GHz in F15 and the difference in emission and scattering from atmosphere. At the same time, the resulting ‘bias’ in F16 TDRs, SDRs and EDRs are also dependent on the temperature difference between the main reflector surface and the scene temperature, which complicates the assessment. The assessment is further complicated by the slight frequency difference between F15 (85.5 GHz) and F16 (91.655 GHz).

The TDR data actually contains earth-located sets of antenna temperature. In the retrieval of parameters, not only antenna temperature but also brightness temperature will be used. The brightness temperature (Sensor Data Record or SDR) is obtained after Doppler correction, cross polarization and spill-over correction (or antenna pattern correction) on TDR data. In our retrieval, a set of coefficients was provided by Navy Research Lab (NRL) and is applied to linearly map the SSMI/S imaging channels from TDR to SDR. The coefficients are based on collocated F16 SSMI/S and F15 SSM/I imaging channel data. Note that that this linear mapping also converts SSMI/S 91.655 GHz to 85.5 GHz.

At both NRL and NOAA/NESDIS, algorithms are proposed to effectively detect and correct TDR anomalies caused by different factors. In these recalibration algorithms (Kunkee et al. 2008; Wessel et al. 2008; Swadley et al. to be submitted), the effect of solar radiation contamination on warm loads which affects TDRs in LAS channels, is dynamically detected through a Fast Fourier Transform (FFT) analysis. The regular periodic bias components identified by FFT are then removed. Research (Yan and Weng 2008) showed that nonlinearity terms in calibration equation could contribute to imaging channels TDR bias, therefore a set of nonlinear calibration coefficients are also derived to reduce the bias.

The TDRs actually contain earth-located sets of brightness temperature directly converted from the original sensor counts. However, due to the sensor hardware limitation or deficiency, e.g. feedhorn spillover loss and unavoidable leak of vertical polarization signal into horizontal polarization receiver, the antenna pattern correction (APC) is needed to correct such errors in order to obtain usable sensor brightness temperature (a.k.a Sensor Data Records or SDRs). In our study, the APC algorithm consists of a linear correction for the feedhorn spillover loss and cross-polarization coupling as shown in Eq. (1).

\[
TB_{v(h)} = \frac{[TA_{v(h)} - a_{v(h)} TA_{h(v)}]}{\eta_{v(h)} (1 - a_{v(h)})}
\]

Where,

\[
TB_{v(h)} = \text{SDR at vertical (horizontal) polarization}
\]

\[
TA_{v(h)} = \text{TDR at vertical (horizontal) polarization}
\]

\[
\eta_{v(h)} = \text{Feedhorn spillover factor}
\]

\[
a_{v(h)} = \text{Cross-polarized coupling coefficient}
\]

Because the maximum cross-polarization occurs when the SSMIS views a cloudless dry atmosphere over calm ocean surface, \(a_{v(h)}\) approaches zero in LAS and UAS channels. Only the spillover correction term is kept in the APC linear equation for those channels. The DMSP
F16 SSMIS has a larger than expected correction for antenna cross polarization effects even though the APC for SSMIS was originally intended to correct primarily for antenna spillover. In our study, the DMSP F16 SSMIS SSM/I-like lower frequency channels’ linear mapping coefficients and APC are take from (Yan and Weng 2008) while linear mapping coefficients for 91.655 GHz channels were kindly provided by Mr. Steve Swadley of Naval Research Laboratory (NRL).

In this study, due to the different sampling resolution in SSM/I-like channels, we first produce global grid data at a resolution of 1/3 degree in latitude and longitude, and then separate them into two files corresponding to ascending and descending nodes. Next, a set of empirical linear remapping coefficients are applied to F16 SSM/I-like channels. Eq. (2) is used to make these channels signatures closer to corresponding heritage SSM/I channels.

\[ T_A'_{ichan} = \alpha_{ichan} + \beta_{ichan} T_A_{ichan} \]  

Where,

\[ T_A'_{ichan} \] = remapped antenna brightness temperature

\[ T_A_{ichan} \] = original antenna brightness temperature

\[ \alpha_{ichan}, \beta_{ichan} \] = remapping coefficients

Note that such remapping also includes the mapping of F16 SSMIS 91.655 GHz to SSM/I 85.5 GHz so as to minimize the effects of the channel frequency shift, thereby allowing existing F15 SSM/I retrieval algorithms to be used with F16 data. Finally, the TDR to SDR conversion will be implemented by applying the linear APC algorithm to the remapped TDRs, as shown in Eq. (1).

The retrieval algorithms used to generate environmental products were previously developed by the SSM/I Cal/Val science team and have been widely used at NOAA since 1990s, as described in (Ferraro et al. 1996). The products used in this evaluation include total precipitable water (TPW), cloud liquid water path (LWP), snow and sea ice coverage, land surface temperature (LST), rainfall rate, and land emissivity as shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Channels</th>
<th>Units</th>
<th>Area</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Precipitable Water</td>
<td>19.35V, 22.235V, 37.0V</td>
<td>mm</td>
<td>Ocean</td>
<td>(Alishouse et al. 1990)</td>
</tr>
<tr>
<td>Cloud Liquid Water</td>
<td>19.35V, 22.235V, 37.0V, 85.5H</td>
<td>mm</td>
<td>Land</td>
<td>(Weng and Grody 1994; Weng et al. 1997)</td>
</tr>
<tr>
<td>Snow Cover</td>
<td>19.35V/H, 22.235V, 37.0V, 85.5V</td>
<td>Land</td>
<td></td>
<td>(Grody 1991; Grody and Basist 1996)</td>
</tr>
<tr>
<td>Sea Ice Cover</td>
<td>19.35V/H, 22.235V, 37.0V/H, 85.5V</td>
<td>Ocean</td>
<td></td>
<td>unpublished</td>
</tr>
<tr>
<td>Land Surface Temperature</td>
<td>22.235V, 37.0V, 85.5V</td>
<td>K</td>
<td>Land</td>
<td>(Weng and Grody 1998)</td>
</tr>
<tr>
<td>Rain Rate</td>
<td>19.35V, 22.235V, 37.0V, 85.5V</td>
<td>mm/hr</td>
<td>All</td>
<td>(Grody 1991; Ferraro and Marks 1995)</td>
</tr>
</tbody>
</table>

In addition to comparing the global imaging of retrieval figures, we also plot them as scatter diagrams for TPW, LWP, land surface temperature, and land emissivity retrievals in order to give readers more straightforward sense of whether heritage retrieval algorithms are fit for the
application to F16 SSM/I-like channels, and whether the F16 SSMIS TDR recalibration algorithm performs well.

Results and Discussion

To demonstrate the product retrieval quality and stability, data between December 2005 and February 2006 (DJF) are processed. By evaluating these products from hydrometeor (TPW, LWP and RR) to land surface products (LST, emissivity) as well as snow and ice cover, we may not only better understand the quality of DMSP F16 SSMIS but also keep the continuity of heritage environmental product algorithms retrieved from preexisting sensors in DMSP. In this section, each product will be illustrated and statistical analyses on several products will also be given.

Total Precipitable Water

The water vapor path retrieval, also known as total precipitable water (TPW), has been made over ocean from passive microwave instruments since 1987 when the first SSM/I was launched on board DMSP F-8 satellite. The algorithm was updated from (Alishouse et al. 1990) by using brightness temperatures at 19.35V, 22.235V, 37.0V, and 85.5V. As one of the most accurate parameters retrieved by passive microwave sensors, the error is only around 10% on a globally averaged basis compared with radiosondes observations. In our study, a slight modification is applied to Alishouse et al.’s original algorithm in order to obtain more accurate results under extreme weather conditions.

\[
TPW = 232.89 - 0.1486(TB_{19.35}) - 0.3695(TB_{37.0}) - [1.8291 - 0.006193(TB_{22.235})]TB_{22.235}
\]

(3)

\[
TPW_{corrected} = -3.753 + 1.507(TPW) - 0.1933(TPW)^2 + 0.00219(TPW)^3
\]

(4)

In the retrieval process, TPW is firstly calculated using Eq. (3). At the same time, a scattering index is also computed (the detail of this index will be introduced in the discussion of rain rate retrieval). Whenever the scattering index is greater than 10K, the additional cubic correction is made to the original TPW as shown in Eq. (4).

Plotted in Fig. 1(a) and (b) are the TPW retrieved from F16 and F15, respectively. Please note that no TPW is retrieved over sea ice due to its high and variable emissivity. From both figures, we can observe many similar features and phenomena associated with the Inter-tropical Convergence Zone (ITCZ), South Pacific Convergence Zone (SPCZ) and South Atlantic Convergence Zone (SACZ). Fig. 5(a) is a statistical comparison between TPW retrievals from F16 and F15. The mean bias, standard deviation (STDEV) and root mean square (RMS) are given in Table 3. It seems that the preprocessing of F16 SSMIS data produces a good quality of the TPW from its imager channels at 19.35 GHz, 22.235 GHz and 37.0 GHz.

Cloud Liquid Water Path

The retrieval algorithm for cloud liquid water path (LWP), adopted in our study, was introduced in (Weng and Grody 1994; Weng et al. 1997). This algorithm makes use of brightness temperature measurements at both low and high frequencies to retrieve LWP in precipitating and non-precipitating clouds over ocean. Three LWPs are pre-calculated using three different channel combinations (19.35 V/22.235 V, 37.0V/22.235 V, and 85.5 H/22.235 V). The final LWP is determined by several criteria, as shown in Eq. (5). Fig. 3 and Fig. 4 give
the rain rate retrieval from F15 and F16. Again, we found quite similar distribution pattern of rainfall rate all over the world in both figures. Most global critical weather regions are emphasized, such as ITCZ. The rain rate distribution over ocean is also well corresponding to the cloud liquid water distribution in previous section.

Fig. 1. TPW, LWP, LST and RR retrieved from F16 SSMIS and F15 SSM/I

\[
LWP = \begin{cases} 
-3.2(\ln(290-TB_{\text{wv}})) - 2.8 - 0.42\ln(290-TB_{\text{zv}}), & LWP > 0.7 \\
-0.44(\ln(290-TB_{\text{wv}})) - 1.6 + 1.35\ln(290-TB_{\text{zv}}), & LWP > 0.28 \text{ and } TPW < 30 \\
-1.66(\ln(290-TB_{\text{wv}})) + 2.9 + 0.35\ln(290-TB_{\text{zv}}), & \text{else}
\end{cases}
\]
This algorithm improves the former LWP retrievals by detecting LWP both in optically thin stratus and low-level clouds as well as highly convective clouds. The global LWP retrievals in boreal winter using F15 and F16 data are given in Fig. 1(c) and (d).

Cloud liquid water path retrieved from the two sensors are similar in spatial distribution. Some expected features have been captured in the global figures, such as strong convection over western Pacific warm pool, SPCZ and SACZ. However, along continental coast and sea ice edges there are some anomalously large LWP points. This may be caused by a mismatch of TDRs or contamination of surface sea ice. Meanwhile, near the high LWP areas, some anomalously low points may be due to the saturation of SSMIS imaging channels from heavy precipitation. The correlation between F15 and F16 is presented in Fig. 5(b) and is nearly linear. The increased scatter at higher LWP is probably due to the mismatch of observations and spatial inhomogeneity of clouds and precipitation. However, the small mean bias and STDEV indicate that the LWP retrieval from SSMIS is reliable and can be used for operation.

**Land Surface Temperature**

The land surface temperature (LST) algorithm for SSM/I was originally presented in (Weng and Grody 1998). As a linear regression algorithm developed from ground truth data, LST can be easily obtained over crop/range, moist and dry soils and other surface types. SDR measurements at 22.235 GHz V, 37.0 GHz V and 85.5 GHz V are used in this algorithm as shown by Eq. (6).

\[
LST = 0.02509[1.7167 - 0.005514(TB_{22V})]TB_{22V} \\
- [0.1083 + 0.001976(TB_{37V})]TB_{37V} \\
+ [1.1763 - 0.000636(TB_{85V})]TB_{85V}
\] (6)

The global retrieval results can be found in Fig. 1(e) and (f). The LST patterns of F15 and F16 are highly consistent with each other. Compared to the summer season retrievals (not shown here) which shows the expected changes, most of Eurasia presents a lower LST due to the snow cover. However, it is shown (see Fig. 5(c)) that the mean LST of F15 is about 1.5 K higher than that of F16. The bias and standard deviation also increase with increasing LST. The outliers with large bias in Fig.5(c) are probably caused by measurement mismatch along coastal regions and the deficiency in the remapping algorithm which excludes scattering and emission adjustment. Overall, the SSM/I LST retrieval algorithm may be migrated to SSMIS for operational use but there is still a need to refine the remapping coefficients that convert SSMIS brightness temperatures at 91.655 GHz to SSM/I brightness temperature at 85.5 GHz, since Eq. (6) are used for both SSM/I and SSMIS.

**Rain Rate**

The rainfall rate (RR) algorithm developed at NESDIS (Ferraro and Marks 1995) makes use of the scattering of upwelling radiation by precipitation-size ice particles and large raindrops at 85 GHz to detect rainfall both over land and oceans. The difference between actual and an estimated (through 19.35 GHz V and 22.235 GHz V observation) brightness temperature at 85.5 GHz V, called ”scattering index” in (Grody 1991), is calculated by Eq.(7).

\[
SI = EST_{TB_{85V}} - TB_{85V}
\] (7)

Where,
A rain indicator is obtained if SI is greater than 10K. In addition, the LWP retrieval is also used over ocean to identify the rainfall area. As a result, the minimum detectable rain rate is about 0.5 mm/h over land and 0.2 mm/hr over ocean. Fig. 1(g) and (h) display the rain rate retrieval from F16 and F15. Over ocean, RR retrievals from each sensor correlate highly to their own high LWP retrieval regions and also between each other. One can also easily find heavy rainfall over critical areas, such as the western Pacific warm pool and SPCZ. The smooth continuous RR transition between land and ocean in both figures confirms that the RR retrieval algorithm can correctly catch rainfall signals both over land and over ocean. However, even though geophysical locations for RR are close to each other over land, the scales are not consistent between F15 and F16. As RR is a parameter highly dependent on the scan time, bias could be very large even when the scan time difference between F15 and F16 is around 30 minutes. Therefore, it is yet to be determined whether the source of bias is due to scan time difference or sensor differences. Furthermore, because the RR retrieval also uses 85.5 GHz channel measurements remapped from 91.655 GHz in F16 SSMIS by globally derived linear coefficients, the more localized RR retrieval will present a larger bias between F16 SSMIS and F15 SSM/I.

Sea Ice
Several sea ice concentration and ice age algorithms have been developed for passive microwave radiometers (Rubinstein et al. 1994; Markus and Cavalieri 2000). Comparison between these algorithms has also been performed (Markus and Dokken 2002; Shokr and Markus 2006). To keep the continuity of our heritage study of sea ice cover, a simple algorithm is used to identify the presence of sea ice. The retrieval function is given as,

\[ ICE = \begin{cases} 
91.9 - 2.99(TB_{19}) + 2.85(TB_{37}) - 0.39(TB_{15}) + 0.50(TB_{35}) + 1.01(TB_{37}) - 0.90(TB_{37}) & \text{land} \\
-182.7 - 0.75(TB_{19}) + 2.543(TB_{37}) - 0.00543(TB_{37})^2 & \text{ocean} 
\end{cases} \]

where ICE greater than 70% is defined as sea ice. In our sea ice averaging processing, the percentage of sea ice present during the three winter months (December, January, February) is calculated. Fig. 2(a), (b), (c), and (d) give the sea ice cover retrieved from F16 and F15, respectively. The sea ice
cover in the northern hemisphere extends south exceeding 50°N both along east coast of North America and the Eurasian continent. Due to the North-Atlantic current, there is a lack of sea ice in the Barents Sea. Overall, the sea ice cover of F15 SSM/I and F16 SSMIS are in good agreement.

**Snow Cover**
The snow coverage retrieval algorithm used in our study was published in (Grody 1991; Grody and Basist 1996). It includes measurements at 85.5 GHz to detect shallow snow cover and also screens for precipitation, cold desert, frozen ground, and other signatures which could potentially increase retrieval error. In this algorithm, brightness temperature measurements at 19.35 GHz V, 22.235 GHz V, 37.0 GHz V and 85.5 GHz V are used.

Fig 3. Snow Cover retrieved from F16 SSMIS and F15 SSM/I near North and South Pole

Snow cover retrieved from F15 and F16 in the northern hemisphere and the Antarctic are shown in Fig.3(a), (b), (c), and (d). Because the retrievals are from December 2005 to February
2006, most of areas north of 40°N are covered by snow. Overall, the snow cover retrievals from two sensors are highly consistent. However, because snow retrieval also uses 85.5 GHz measurements to derive the scattering parameter, the globally derived remapping coefficient may also affect snow cover retrieval. Therefore stratified remapping coefficients will be developed.

**Land Emissivity**

The land emissivity is an important parameter that can be used to infer some other geophysical parameters, such as soil moisture, vegetation water and soil wetness. The land emissivity algorithm was published in (Weng et al. 2001; Yan and Weng 2003). For low frequency channels at 19.35 GHz V/H and 37.0 GHz V/H, their emissivity is based on a linear regression relationship among all seven SSM/I-like channel SDR measurements, shown in Eq. (9).

\[
\varepsilon = a_0 + a_1(TB_{91v}) + a_2(TB_{91h}) + a_3(TB_{19v}) + a_4(TB_{19h}) + a_5(TB_{37v}) + a_6(TB_{37h}) + a_7(TB_{85v}) + a_8(TB_{85h})
\]  

(9)

For emissivity at 85v and 85h, a nonlinear relation is built from 37.0 GHz V and 85.5 GHz V/H by Eq. (10),

\[
\varepsilon = b_0 + (b_1 + b_2(TB_{37v}))(TB_{85v}) + (b_1 + b_2(TB_{85v}))(TB_{85h})
\]  

(10)

Table 2 presents the coefficients of in Eq. (9) and Eq. (10) for each channel. Here we choose

<table>
<thead>
<tr>
<th>TABLE 2: Coefficients Used in Land Emissivity Retrieval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>19.35 V</td>
</tr>
<tr>
<td>19.35 H</td>
</tr>
<tr>
<td>22.235 V</td>
</tr>
<tr>
<td>37.0 V</td>
</tr>
<tr>
<td>37.0 H</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>b0</th>
<th>b1</th>
<th>b2</th>
<th>b3</th>
<th>b4</th>
<th>b5</th>
<th>b6</th>
</tr>
</thead>
<tbody>
<tr>
<td>85.5 V</td>
<td>-0.9435</td>
<td>4.1137E-3</td>
<td>-7.0109E-6</td>
<td>1.5677E-2</td>
<td>-3.1055E-5</td>
<td>-6.5089E-3</td>
<td>1.4984E-5</td>
</tr>
<tr>
<td>85.5 H</td>
<td>-0.9788</td>
<td>3.0851E-3</td>
<td>-5.2696E-6</td>
<td>7.4612E-3</td>
<td>-2.2772E-5</td>
<td>2.9755E-3</td>
<td>4.5324E-6</td>
</tr>
</tbody>
</table>

retrievals at 19.35 GHz (H/V) and 37.0 GHz (H/V) for demonstration purpose. The results are shown in Fig. 4. Because the channel frequency shifts from 85.5 GHz in F15 SSM/I to 91.655 GHz in F16 SSM/I, we do not include these two channel emissivities in this comparison.
The retrievals from each sensor capture land surface signatures well. For example, vertical polarization over deserts shows a larger emissivity compared to horizontal polarization. In addition, emissivity retrieved from 37.0 GHz is more sensitive to snow surface condition than 19.35 GHz channels. Generally speaking, the retrievals are very well correlated. However, very similar to the land surface temperature retrieval, the difference between emissivities retrieved for F16 and F15 at 37.0 GHz horizontal polarization is observed over a large dynamic range as
the emissivity increases (Fig. 5(d)). Furthermore, the differences become larger in the desert and snow cover areas where surface scattering is present.

**Summary**

Retrievals of hydrological and surface parameters from F16 SSMIS are demonstrated using the SSM/I algorithms. The products are compared for three months of data from both sensors. All F16 TDRs have been reprocessed as the experimental TDR data. The procedure for TDR to SDR correction and the remapping of F16 SSMIS imaging channels to F15 SSM/I is based on
the algorithm from NRL. After the reprocessing on F16 SSMIS, contamination of measured antenna temperatures, direct solar radiation, cross polarization coupling, and antenna spillover are effectively reduced. The F16 SSMIS to SSM/I imaging channel remapping is a critical step in our study because it allows us to use the same algorithms for two instruments.

Both satellites’ orbit data have been processed to 1/3 degree grid data. Because the time difference between DMSP F15 and F16 is about 30 minutes, most retrieval products will not be affected much by such small time variation except for rain rate, which is temporally variable. The products, including TPW, LWP, LST, Snow Cover, Sea Ice Cover, and land emissivity, are presented. It is shown that the retrievals from both sensors demonstrate a high level of agreement with each other. The statistical results based on the seasonal averaged data for TPW, LWP, LST, RR and emissivity at five SSM/I channels are listed in Table 3. Both the relatively small mean bias and

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean Bias</th>
<th>STDEV</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPW</td>
<td>-0.753 mm</td>
<td>0.629 mm</td>
<td>0.981 mm</td>
</tr>
<tr>
<td>LWP</td>
<td>-0.007 mm</td>
<td>0.017 mm</td>
<td>0.018 mm</td>
</tr>
<tr>
<td>LST</td>
<td>1.531 K</td>
<td>1.373 K</td>
<td>2.056 K</td>
</tr>
<tr>
<td>RR</td>
<td>-0.013 mm/hr</td>
<td>0.110 mm/hr</td>
<td>0.111 mm/hr</td>
</tr>
<tr>
<td>$e_{10.35F}$</td>
<td>0.0017</td>
<td>0.0034</td>
<td>0.0038</td>
</tr>
<tr>
<td>$e_{19.35F}$</td>
<td>0.0019</td>
<td>0.0045</td>
<td>0.0049</td>
</tr>
<tr>
<td>$e_{22.215F}$</td>
<td>0.0017</td>
<td>0.0034</td>
<td>0.0038</td>
</tr>
<tr>
<td>$e_{37.0F}$</td>
<td>0.0007</td>
<td>0.0050</td>
<td>0.0051</td>
</tr>
<tr>
<td>$e_{37.0F}$</td>
<td>0.0017</td>
<td>0.0063</td>
<td>0.0065</td>
</tr>
</tbody>
</table>

standard deviation prove that F16 SSMIS data can be successfully using the retrievals previously developed for use with SSM/I channels. However, retrievals sensitive to 85.5 GHz measurements, such as the land surface temperature and the land emissivity, displays some biases. For example, over Sahara deserts LST retrieved from F16 is slightly lower than that from F15 while no significant biases over non-desert areas. Because LST retrieval algorithm uses the quadratic term of vertically polarized 85.5 GHz brightness temperature, the higher scattering feature of 91.655 GHz in F16, which even has been remapped to 85.5 GHz, might be the source of the biases. Therefore, the F16 SSMIS to SSM/I remapping algorithm requires further improvement over the simple linear remapping algorithm used to correct the change from 85.5 to 91.655 GHz which cannot account for scattering and emission effects under all weather and surface conditions.

Among these evaluated retrieval algorithms, other issues are also notable. For example, rain rate retrievals along coastal regions or sea ice boundaries always give some non-zero values. This may be due to the mixing of land and ocean or sea ice within a single footprint while using an emission-based algorithm. Fortunately, because DMSP F16 SSMIS contains not only imaging channels but environmental channels at 150 GHz and 183.31 GHz, new algorithms based on particle scattering are being developed for precipitation applications (Weng and Grody 2000; Zhao and Weng 2002). This will allow rain rate to be inferred by using the direct relation to cloud ice water path (IWP). Meanwhile, the IWP retrieval will directly use channel measurements at 91.655 GHz. Thus, there is no need for remapping F16 SSMIS and SSM/I for precipitation studies.
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Disclaimer

The contents of this study are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of NOAA or the U.S. Government.

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Potential of CO2 Retrieval from IASI

L. Chaumat, O. Lezeaux, P. Prunet, B. Tournier, F.-R. Cayla, C. Camy-Peyret and T. Phulpin

A specific processing of the high resolution infrared spectra, based on Discrete Fourier Transform (DFT) filtering to efficiently exploit the CO2 information of the IASI spectrum, is used to retrieve CO2 from IASI. Inversion experiments on a representative set of real data are performed to quantify the precision and quality of retrieved CO2 concentration. This analysis shows that one can retrieve the mean atmospheric CO2 concentration from a single IASI spectrum with a precision better than 2 ppmv, i.e., better than 1 %. These results are compared and consolidated with information content analysis and inversion based on simulations, in order to fully specify and characterize the IASI CO2 product, in terms of error figure, weighting function, profile information. In particular, the possibility to derive CO2 profile information from IASI (about 3 pieces of information) is demonstrated.
Analysis of Arctic clouds by means of hyper-spectral satellite

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Introduction

Polar satellite measurements provide frequent overpass on the Arctic area and high spatial resolution, but the cloud parameter retrieval and their detection is very difficult at high latitudes. In great part the Arctic surface is covered by snow and ice, reducing the visible contrast between clouds and the surface. Also, often there are strong surface temperature inversions and during the winter there is no solar contribution, then the techniques based on reflectance in the visible and near infrared (e.g. 1.6 μm channel) are not applicable. Moreover, Arctic clouds are often low and thin and composed of mixtures of ice and water (Curry et al., 1996).

The main objective of this study is to understand if the new generation of infrared high spectral resolution satellite instruments offer an opportunity to improve the detection of clouds in the Arctic. The paper shows the effect of sea/ice/snow emissivity spectra on simulated radiances in the IR wavenumber range often used for cloud detection (700-1000 cm⁻¹), and the impact of surface emissivity uncertainties on the performances of current polar night-time cloud detection techniques based on hyper-spectral observations. Finally, a possible improvement to the polar cloud detection is presented and validated on the basis of the Cloud Profiling Radar (CPR) data.

Simulates data sets

Arctic regions are characterized by different surface types, ice, snow, and sea-water. These surface types present significantly different infrared spectral emissivity (ελ). Infrared spectral emissivities for a large variety of natural materials were measured at the Institute for Computational Earth System Science (ICESS) of the University of California at Santa Barbara (UCSB) as described by Li et al. (1999), and are available through the UCSB Emissivity Library web site (http://www.icess.ucsb.edu/modis/EMIS/html/em.html). Note that the observing angle used to measure these ελ spectra is 10 deg off nadir. In this study, we considered the UCSB emissivity spectra for ice, snow, and sea-water, as illustrated in Figure 1. Large emissivity values differences are evident between 700-1000 cm⁻¹ range, as showed in Figure 1. In this range, ελ for ice, snow, and sea-water surfaces differ for as much as 5-6%. Therefore, due to the spectral features in the 700-1000 cm⁻¹ range, uncertainties in ελ may play an important role in cloud detection. In the following, we used these ελ emissivities to compute a set of high resolution upwelling IR radiances for studying the effect of ελ into cloud detection algorithms.

The high resolution Infrared Atmospheric Sounding Interferometer (IASI) radiance spectra are simulated in clear sky by processing 305 polar thermodynamic profiles using LBLRTM (Clough et. al, 1995). Figure 2 shows 5 of the profiles used and the simulation for ice and water emissivity corresponding to these 5 profiles.
Fig. 1: Spectral emissivity for cases of sea water, ice, and snow surfaces (data from the UCSB Emissivity Library)

Cloudy sky radiance spectra are simulated with RTX (Rizzi et al., 2001; Amorati and Rizzi, 2002, Maestri et al., 2005). RTX solves the radiative transfer equation with the adding and doubling method taking into account the multiple scattering by randomly-oriented particles with a plane of symmetry. Polarized radiation is considered in term of Stokes parameters under the hypothesis of a plane-parallel and vertically inhomogeneous atmosphere including both thermal and solar sources. Spectral properties of atmospheric gases are computed with the LBLRTM model while the extinction and scattering coefficients, the single scattering albedo and the Lagrange coefficients are computed for a gamma-modified size distribution of spherical cloud particles (water and ice) using a Mie code (Wiscombe 1979).

The observing angle is kept fixed at nadir, while other parameters are varied, as indicated in Table 1. In particular, we considered 3 different spectral surface emissivities ($\varepsilon_{\lambda}$), 3 thermodynamic cloud phases, 3 different profiles, 8 values for cloud particle effective radius ($r_{\text{eff}}$), 6 different cloud top heights (CT) and 6 different values for liquid or ice water content (cwc). Figure 3 shows the emissivities and the profile, measured by a radiosonde during the Arctic Water Vapor Intensive Operational Period 2004 (Westwater et al., 2006) used in the simulation showed in the figures 4 to 6.

Table 1: List of parameters varied for producing the data set of high resolution IR upwelling spectra.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\lambda}$</td>
<td>Ice, snow, sea-water and $\varepsilon_{\lambda}=1$</td>
</tr>
<tr>
<td>Cloud Phase</td>
<td>Clear-sky, liquid, ice, and mixed phase</td>
</tr>
<tr>
<td>$r_{\text{eff}}$</td>
<td>5, 10, 15, 20, 30, 50, 70, 100 $\mu$m</td>
</tr>
<tr>
<td>Ice or liquid water content (cwc)</td>
<td>0.001-0.005, 0.01, 0.03, 0.05, 0.07</td>
</tr>
<tr>
<td>Cloud top (CT)</td>
<td>2.2, 2.7, 3.2, 3.7, 5.1, 5.5 km</td>
</tr>
</tbody>
</table>
Fig. 2: Clear IASI BT simulation, a) temperature profiles, b) water vapour profile, c) Simulation with ice emissivity and d) with water emissivity.

Fig. 3: Left: Emissivities used for BT IASI simulations. Right: Radiosonde profile in the Arctic Winter.
**Fig. 4:** IASI BT spectra in clear and cloudy sky using ice emissivity. Left: water clouds with $r_{\text{eff}} = 5 \, \mu m$, cwc=0.01 and 0.05 g/Kg, CT=3.2 and 3.7 km. Right: ice clouds with $r_{\text{eff}} = 5 \, \mu m$, cwc=0.01 and 0.05 g/Kg, CT=2.2 and 2.7 km.

**Fig. 5:** IASI BT spectra in clear and cloudy sky using snow emissivity. Left: water clouds with $r_{\text{eff}} = 5 \, \mu m$, cwc=0.01 and 0.05 g/Kg, CT=3.2 and 3.7 km. Right: ice clouds with $r_{\text{eff}} = 5 \, \mu m$, cwc=0.01 and 0.05 g/Kg, CT=2.2 and 2.7 km.
Fig. 6: IASI BT spectra in clear and cloudy sky using water emissivity. Left: water clouds with $r_{\text{eff}} = 5$ μm, cwc=0.01 and 0.05 g/Kg, CT=3.2 and 3.7 km. Right: ice clouds with $r_{\text{eff}}=5$ μm, cwc=0.01 and 0.05 g/Kg, CT=2.2 and 2.7 km.

Figures 4-6 show selected spectra simulated with the different emissivity for clear and cloudy sky with different values of the parameters in Table 1. It is evident that spectral features caused by emissivity typical of polar surfaces are very similar to cloud spectral signatures. Therefore, it seems difficult for cloud detection techniques relying on thresholds to distinguish between clear-sky cases and cloudy cases.

It is evident on the previous figures that both the clouds and the emissivity cause the slope of the atmospheric window to change significantly, but it seems difficult to detect on the basis of the window spectral region clouds presence. Ice clouds for instance increase the slope for a constant emissivity, but decrease the slope for ice surface emissivity.

## Arctic Cloud Detection

Examining the slope in the 750-950 cm$^{-1}$ range for clear-sky spectra with different surface emissivity, it is evident that the slope values remain within a different range for each emissivity and the window shape is the same for the same emissivity, the same satellite zenith angle and the same solar illumination. We have developed an identification algorithm that exploits the expected spectral signal in the window region for the polar region.

The first test (the slope window test) is restricted to a suitable set of micro window differences that give a fine representation of the atmospheric window shape. The central wave numbers of micro windows used are: 790.0, 803.5, 885.7, 953.0 cm$^{-1}$.

The thresholds have been derived using a measured and a simulated clear dataset. Simulated data also provide a useful estimate of variability around the mean value which should be exploited.

In this approach, the difference between predicted and measured channels must be within a range, whose medium value is calculated from measured data, while the boundaries (minimum and maximum) are estimated from simulated data.

The algorithm scheme selects the thresholds according to satellite zenith angle, land cover (3km resolution), solar illumination and the brightness temperature ranges of the image. When the probability to be clear or cloudy is low, we apply a second test, the correlation test. We have built a database based on clear spectra on arctic region for different satellite zenith angles, solar illumination and land cover, identified using Cloud Profiling Radar (CPR) data and ground measurements. The fit is restricted to a suitable set of 20 wavenumbers that give a fine representation of the atmospheric window shape.
The correlation index is computed on a restricted set of spectra according to surface, solar zenith angle and solar illumination of the examined IASI spectrum:

\[
 r = \frac{\text{cov}(BT, BT0)}{\sqrt{\text{var}(BT) \text{var}(BT0)}}
\]

**Validation of cloud detection**

The validation has been carried out on the basis of spatial-temporal collocated Cloud profiling radar (CPR) data. The CPR is a 94 GHz nadir looking radar that measures the power backscattered by clouds as a function of distance from radar. It sends a series of short pulses of microwave energy down through the atmosphere and a fraction of these return to the satellite. The strength of the returned signal reveals the characteristic of the cloud layers that lie below. The CPR Cloud Mask is one of the GeoProf products. It assigns a set of 125 bit mask values to each CPR resolution volume (2.5kmx1.2km). The CPR 2B-GeoProf product is distributed by the CLOUDSAT data processing centre. Figure 7 shows IASI spectra and CPR cloud profiling collocated on different IASI footprint.

![Fig. 7: Left: IASI BT spectra in cloudy sky. Right: CPR cloud profiling on IASI footprint.](image)

The validation is split into two disjoint parts, the first takes into consideration the IASI FOVs overcast, the second the inhomogeneous IASI FOVs. The IASI FOV homogeneity has been investigated on the basis on collocated AVHRR pixels within IASI footprint, because the Cloud Profiling does not cover all IASI FOVs.

Table 2 and 3 show the percentage of FOVs detected exactly, the percentage of clear detected cloud and vice versa.

**Tab. 2:** Percentage of IASI FOVs exactly detected, the percentage of clear detected cloudy and vice versa by means of the cloud detection algorithm for overcast FOVs.
### Tab. 3: Percentage of IASI FOVs exactly detected, the percentage of clear detected cloud and vice versa by means of the cloud detection algorithm for partially cloudy FOVs.

<table>
<thead>
<tr>
<th>Percentage of “clear–detected-clear”</th>
<th>96.9 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of “cloud–detected-cloud”</td>
<td>98.7 %</td>
</tr>
<tr>
<td>Percentage of “clear–detected-cloud”</td>
<td>3.03 %</td>
</tr>
<tr>
<td>Percentage of “cloud–detected-clear”</td>
<td>3.70 %</td>
</tr>
</tbody>
</table>

For overcast IASI FOVs the scheme classifies as cloudy 98.7% of the pixels classified by CPR as cloudy and as clear 96.9% of the pixels classified by CPR as clear. For partially cloudy IASI pixels the scheme detects 80.14% pixels correctly, very low broken clouds sometimes are not identified correctly from the scheme.

## CONCLUSION

The cloud detection scheme developed is able to detect cloudy IASI FOVs in the arctic region, for different and complex surface types. Moreover the IASI instrument is a powerful tool to detect ice and thin clouds. For overcast IASI FOVs the scheme classifies as cloudy 98.7% of the pixels classified by CPR as cloudy and as clear 96.9% of the pixels classified by CPR as clear. No homogeneous IASI FOVs are more difficult to classify specially FOVs cover partially with very low clouds.

## REFERENCES


**NOAA Products Integrated Validation Dataset / Database**

**Tony Reale, Bomin Sun, Frank Tilley and Michael Pettey**

Strategies to process, screen, collocate and analyze multiple data platforms of ground truth (radiosondes, GPS and NWP) and weather satellite (ATOVS, MetOp, GOES, Aqua-AIRS and COSMIC) observations and preliminary results are presented. Plans to migrate from the existing sounding profile oriented dataset (Phase-1) to more generalized sensor oriented radiometric database (Phase-2) are outlined. The status of historical collocation database generation at NOAA-STAR (beginning with TOVS in 1979) is also presented in context of the longer term goal of producing consistent historical observations for tracking the performance of past, present and next generation sensor and product capabilities consistent with GEOSS (and climate).
Combined use of infrared measurements, sensitive to both temperature and carbon dioxide (CO2) variations, and of microwave measurements, only sensitive to temperature, allows deriving information on CO2 concentration in the mid-to-upper troposphere. Using a non-linear inference scheme based on neural networks, four years (1987-1991) of TOVS observations, as well as five years (2003-2007) from the AIRS/AMSU instruments have been interpreted in terms of midtropospheric CO2 integrated content. Following the launch of the hyper-spectral infrared sounder IASI, together with AMSU, on board ESA/MetOp on October 2006, a set of IASI channels presenting optimum characteristics for CO2 estimation has been selected, based on a systematic sensitivity study of the observations to CO2, temperature, and other absorbers. Due to a better spectral coverage and a lower instrumental noise, the CO2 fields retrieved from IASI show a lower variability than those from AIRS. The first ten months of CO2 retrieved from IASI will be presented and compared with corresponding retrievals from AIRS, as well as with simulations from atmospheric transport and in situ data.
The Neural Network Ozone Retrieval System (NNORSY) developed by ZSW was successfully applied to long term TOVS data for total ozone column retrieval and to GOME Level 1 spectra for total column and ozone profile retrieval. This presentation will focus on NNORSY-GOME ozone profiles retrieval and resulting products of the latest reprocessing of global GOME data in the time range 1995 to 2003. Beside ozone profile retrieval itself in a second step an new approach based on neural network technique for a dynamic ozone profile climatology was undertaken yielding to an easy to use software package for the dynamic NNORSY ozone profile climatology. NNORSY for GOME is a very fast ozone profile retrieval scheme based on neural networks. For training, ozone measurement data from ground based (e.g. ozone sondes and lidar) and satellite (e.g. SAGE, HALOE, POAM) based ozone profile measurements are used. In the first step we developed a special training procedure based on RPROP which is able to deal with incomplete target data without loss of generalization ability during application and in the second we established a two stage quality control (QC) procedure for ozone profile measurement data where the second stage is based on partial neural network training to find outlier and additional measurement errors that passed the first QC stage. After training application to GOME data is very fast. A whole GOME orbit with full spatial resolution can be processed in less than 1 minute and therefore NNORSY-GOME ozone profile retrieval can easily be applied in real-time with minimal costs on a simple workstation computer. NNORSY-GOME was already implemented in near-real-time at DLR-DFD but the service was stopped in June 2003 when the data recorder on ERS2 failed. Within the ESA project CHEOPS-GOME ZSW reprocessed of all available GOME Level 1 data at full spatial and temporal resolution up to June 2003 yielding to NNORSY-GOME Version 3 global 8 year ozone profile data. Beside the ozone profile information from ground up to 61 km height with a sampling rate of 1 km the data comprises for each profile level an ozone profile error estimation and contains temperature profile data derived from GEOS 4 model data. This data set was used to training different neural works without satellite instrument data yielding to the new dynamic NNORSY ozone profile climatology. Depending on which user input information is available, the NNORSY-CLIMATOLOGY does not only consider standard input information such as date, time and geographical position but also optional dynamic input parameters like total ozone column and/or temperature profile into account which represents the current state of the atmosphere. Due to this option of respecting dynamic parameters this new approach exploits the supplied
dynamic information leading to a significant gain of accuracy in climatological ozone profile retrieval. Each climatology product is delivered with ozone profile information as well as according standard deviations. If no input temperature profile is provided the NNORSY-CLIMATOLOGY delivers a climatological temperature profile as well. The presentation will show comparison of derived ozone profile data with independent data sources for single measurements as well as for long term time series of different regions and ozone profile regimes. It can be shown that the neural networks are able to compensate for GOME instrument degradation and calibration uncertainties if parameters about the GOME instrument (e.g. time in orbit) are supplied as input to the neural network trained with real ozone profile measurement data. The climatology ozone profile data are compared with measured time series as well as with classical lookup-up-table climatology products. Current developments for NNORSY are underway for ozone profile retrieval and near-real-time application from SCIAMACHY data and we are looking forward to implement NNORSY for the new atmospheric sounding instruments IASI and GOME-2 MetOp satellite in an new synergistic approach using UV and IR sounding data.
Pronounced Changes in Water Vapor, Ozone and Metrological Parameters Associated with Dust Storms Using MULTI SENSOR Data

Ramesh P. Singh, Anup K. Prasad, Ritesh Gautam and Menas Kafatos

During the pre-monsoon season, the Indo-Gangetic plains is affected by the dust storms that affect the daily life of million people living in the Indo-Gangetic plains. These dust storms significantly affect the air quality, hydrological cycle and climatic conditions. The dust storms are originated from the Arabia peninsula and neighboring countries in the western parts of India. The multi sensor (MODIS, AIRS, MISR, AMSR, SSM/I, CALIPSO, TOMOS, OMI AURA) data for the period 2000 – 2006 show pronounced changes in the surface, aerosol, ozone, cloud, snow cover and meteorological parameters. The detailed analysis of these parameters have revealed that soon after the dust storm water vapor and ozone column enhanced and meteorological parameters (air temperature, relative humidity) change significantly at the pressure level 500 – 700 HPa. The changes in the surface, atmosphere and meteorological parameters will be discussed in the melting of snow cover and its consequence in hydrological cycle and climatic conditions. The radiative forcing calculations have shown changes in the surface and top of atmosphere forcing associated with the dust storms.
Advanced Infrared Sounding System for Future Geostationary Satellites

Timothy J. Schmit, Jun Li, James J. Gurka, Jaime Daniels, Mitch Goldberg

The United States Geostationary Operational Environmental Satellite (GOES) Sounders (GOES-8/9/10/11/12) have provided hourly infrared (IR) radiances and derived products over the continental U.S. (CONUS) and adjacent oceans for over 14 years. The GOES-10 sounder now also provides hourly coverage over South America. The products derived include: clear-sky radiances; temperature and moisture profiles; Total Precipitable Water vapor (TPW) and layer PW; atmospheric stability indices such as Convective Available Potential Energy (CAPE), Lifted Index (LI) and K-Index; cloud-top properties; water vapor motion winds through radiance tracking; and total column ozone. These products are used in numerical weather prediction (NWP), short range forecasts and nowcasts, including severe weather forecasts. While broadband geo-sounding has proven useful, hyperspectral IR sounding will provide measurements that serve user requirements much better. Developing a GOES IR sounding capability with high temporal, spatial, and spectral resolutions is very important for supporting regional and convective-scale NWP over CONUS, as it will provide unprecedented detail on 3D fields of wind, temperature, and humidity. Nowcasting and very-short range forecasting (VSRF) will also benefit from these 3D fields from the monitoring of moisture convergence and convective instability and improving warnings of location and intensity of convective storms. The combination of high spectral and temporal resolution will allow resolving the critical low-level moisture. Studies with available aircraft and satellite data have demonstrated the importance of geostationary hyperspectral IR radiances and products on severe storm forecasts. The benefits of a spaceflight demonstration in parallel with any operational program would be enormous.
Dust aerosol layer altitude from AIRS (01/2003 to 11/2007) and from Calipso (06/2006 to 11/2007): a comparison

S. Peyridieu, A. Chédin, C. Pierangelo, R. Armante and N. Lamquin

Mean infrared (10 µm) dust aerosol layer optical depth and altitude are retrieved over the tropics (30°S–30°N) for five years of Atmospheric Infrared Sounder (AIRS) observations covering the period January 2003 to December 2007. Retrieved optical depths show a very good correlation with the Moderate resolution Imaging Spectroradiometer (MODIS-Aqua) retrieved visible optical depths during the dust season. AIRS simultaneously retrieved mean dust layer altitude are then compared to Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP/CALIPSO) aerosol layer retrieved altitude for the period June 2006 to November 2007. Results for a region of the north tropical Atlantic downwind of the Sahara show a remarkably good agreement between the two products and demonstrate the capability of passive infrared sounders to accurately retrieve the mean dust layer altitude. An interesting conclusion is the fact that if the AOD clearly decreases from Africa to Caribbean as a result of transport and dilution, altitude does not exhibit a significant regular decrease. This is in agreement with in situ measurements made during the Puerto Rico Dust Experiment (PRIDE) campaign.
Evolution of the Global Observing System

John Eyre and Jerome Lafeuille

In 2002, the Commission for Basic Systems (CBS) of WMO adopted a “Vision for the Global Observing System (GOS) to 2015”. This vision covers both space-based and ground-based observing systems. Since 2002, there has been considerable development in thinking about the future of the GOS: the potential of several new observing systems to make substantial contributions to the GOS has emerged, and the GOS has been asked to respond to user requirements for an increased range of applications, in particular those of climate monitoring. These developments have prompted an activity within WMO to refresh the Vision for the GOS. By the end of 2008, CBS is expected to endorse a new “Vision for the GOS in 2025”, following discussion with a wide range of stakeholders. A draft of the new Vision for the GOS will be presented, with particular emphasis on the space-based component and on those systems in which ITWG members have considerable expertise. ITWG will be invited to comment on this draft, as part of the current discussion process.
Status report on the Global RARS initiative

David Griersmith

Regional ATOVS Retransmission Services (RARS) are operational arrangements for rapid delivery of satellite data to the global community (especially NWP Centres). In particular the services involve acquisition of polar-orbiting satellite data over a wide region containing a network of NOAA/METOP ground reception stations with subsequent fast delivery to users. The Global RARS system comprises several regional RARS (e.g., Europe including North America, Asia-Pacific, and South America) each of which involves acquisition of satellite data from HRPT stations in that Region. The data are then locally processed and passed to a regional Processing Centre that is responsible for overall coordination, for near-real time concentration of local data from the direct readout stations and for rapid delivery of consistent sets of data covering the region, for use throughout the region and worldwide. The impact of the global RARS system has been significant through improvements in NWP modelling since much larger quantities of sounder data have become available for assimilation. This paper will present a status report on the global RARS including recent developments in the Asia-Pacific Region and RARS planned evolution.
Abstract
In this paper EUMETSAT programmes, both mandatory and optional, are summarised. EUMETSAT is currently operating the Meteosat-6/7 and two satellites of the Second Generation of Meteosat (Meteosat Second Generation (MSG-1 and MSG-2)), now named Meteosat-8 and Meteosat-9. The MSG-3/4 satellites are under storage or production respectively (Tentative launch dates are January 2011 and January 2013 respectively.). The MSG Programme has been developed in co-operation between EUMETSAT and ESA. In parallel, EUMETSAT has developed jointly with ESA, NOAA and CNES EUMETSAT Polar System (EPS). After the successful launch of Metop-A, the first of a series of three satellites, on 19th October 2006, Metop-A provides operational services from the mid-morning polar orbit in the frame of the Initial Joint Polar System (IJPS) with the US. Tentative launch dates for Metop-B is April 2011. The EUMETSAT Advanced Retransmission Service (EARS) continued its operational services and provides observations from partner HRPT (High Resolution Picture Transmission) stations. Jason-2 is EUMETSAT’s first optional programme, which will provide operational Ocean Surface Topography information services. It is a joint programme with CNES, NOAA and NASA. The launch of Jason-2 is planned on 19th June 2008. Preparations for Meteosat Third Generation (MTG) and Post EPS are under way. A MTG preparatory programme was approved by the EUMETSAT Council in 2007.

Introduction
EUMETSAT, the European Organisation for the Exploitation of Meteorological Satellites contributes to the WMO Space Programme with a number of operational meteorological satellites. The related satellite programmes include the European geostationary meteorological satellite system (Meteosat first generation under the Meteosat Transition Programme (MTP), and the Meteosat Second Generation (MSG)). The EUMETSAT Polar System (EPS) is EUMETSAT’s contribution to the low
Earth orbiting, sun synchronous weather satellites system (Initial Joint Polar System (IJPS) with the United States). Together with these systems User and Data Services are provided.

**Programmatic Aspects**

**EUMETSAT Polar System (EPS)**

The EUMETSAT Polar System (Klaes et al., 2008) complements the US provided system and provides services in the mid-morning orbit. Together with the US it continues the NOAA polar orbiting satellite system in the frame of the Initial Joint Polar System (IJPS). The EUMETSAT satellites of EPS are the Metop (METeorological OPerational) satellites, jointly developed with ESA (Edwards et al., 2006). They provide hyperspectral sounding and high-resolution imagery in global coverage. The EPS programme activities have started in September 1998, while full approval to the programme was given in June 1999. The Metop satellites are flown in a Sun synchronous orbit with 9:30 a.m. equator crossing (descending node). After the successful launch of Metop-A on 19th October 2006 EPS provides data and products. Metop-B and Metop-C respectively, will follow Metop-A. They are recurrent copies. Metop satellites have a nominal lifetime of 5 years.

![EPS Space Segment](image)

Figure 1: EPS Space Segment (Metop launch 19 October 2006 from Baikonur).

No HIRS/4 will be flown on Metop-C, as IASI will have proven its value. The EPS programme will cover at least 14 years of operation. For mission objectives and expected capabilities see Klaes et al. (2007).
Geostationary Systems

Meteosat-7 provided since 1997 the European meteorological geostationary satellite data coverage under the Meteosat Transition Programme (MTP). Meteosat-7 has the same capabilities as its predecessors. Together with the first MSG satellite Meteosat-8, Meteosat-7 was operated as part of a redundant two-satellite system until June 2006. The first spacecraft of the MSG Programme was successfully launched in August 2002 and started its operational service in January 2004. It has significant improvements in the observation capability and a nominal lifetime of seven years. In addition to the main observation mission it embarks a climatology experimental mission (the Geostationary Earth Radiation Budget (GERB) Instrument), a Search and Rescue mission and a mission communication payload. The second satellite of this series, MSG-2, was launched on 21st December 2005. It is currently providing the the operational satellite service at 0° W as Meteosat-9. Meteosat-8 was relocated to 9.5 ° E in March 2008 and is currently providing rapid scan services over Europe. MSG-3 and MSG-4 are foreseen to be launched in 2011 and 2013.

The Meteosat-8, and -9 satellites represent the current operational geostationary satellites. The Indian Ocean Coverage with Meteosat-5 ended and Meteosat-7 (after successful commissioning of MSG-2/Meteosat-9) took over this service at 57.5° E. The direct dissemination service of Meteosat-7 ended 14/06/2006. Meteosat-6 provides coverage for the Data Collection Platform and back up to imagery mission over the Indian Ocean at 67.5 °E.

Optional Programmes: Jason-2

The Jason-2 programme EUMETSAT’s first optional programme. EUMETSAT will contribute to the operations of the overall system and to the generation of the data stream, using a European Earth Terminal and a real time processing chain.

Within this programme EUMETSAT contributes to a joint undertaking with four agencies: EUMETSAT, the French Centre National d’Etudes Spatiales (CNES), the US National Oceanic and Atmospheric Administration (NOAA) and the US National Aeronautics and Space Administration (NASA). This forms the Ocean Surface Topography Mission (OSTM). OSTM is an important element in the overall altimetry data system and will bring high precision altimetry to a full operational status. The launch of Jason-2 is planned for the 15 June 2008 from Vandenberg AFB, Ca., U.S.A.
EUMETSAT and NOAA will process and disseminate the Near Real Time products, whereas CNES will process and deliver off-line high precision products.

**SPACECRAFT AND INSTRUMENTS**

**EUMETSAT Polar System (EPS/Metop)**

The Metop satellites of EPS are launched into a Sun synchronous, near polar orbit with an equator crossing time of 09:30 AM (descending node), i.e. the so called (mid-)morning orbit. To achieve the mission objectives in operational meteorology and climate monitoring an appropriate payload is embarked on Metop, with a number of sounding instruments. Novel technology and hyperspectral infrared sounding capability is provided by the IASI (Infrared Atmospheric Sounding Interferometer) instrument, improving soundings both in unprecedented accuracy and also vertical and horizontal resolution. The HIRS/4 (High Resolution Infrared Radiation Sounder) instrument, the AMSU-A (Advanced Microwave Sounding Unit - A) and the MHS (Microwave Humidity Sounder) instrument as successor of AMSU-B (MHS was developed by EUMETSAT), provide the continuity to the current polar sounding capabilities onboard the NOAA-15, NOAA-16 and NOAA-17 spacecraft and complement the payload of the first IJPS spacecraft, NOAA-18, in orbit since May 2005. The sounding payload is complemented by the proven AVHRR/3 (Advanced Very High-Resolution Radiometer) multi-spectral imager, which will provide visible and infrared imagery at high horizontal resolution. EPS products are be processed centrally, level 1

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Figure 2. EPS services.
products from all instruments and level 2 sounding products from ATOVS and IASI (from the EPS Core Ground Segment (CGS)) and in the distributed Satellite Application Facilities, which provide a large number of level 2 and higher level products (see Figure 2 for EPS services.). All products are operational.

Instruments, successfully flown as research missions, are now flown in longer term operational service. The Global Ozone Monitoring Experiment (GOME-2) for ozone profiling and trace gas retrieval continues the services of the GOME-1 instrument on ESA’s ERS-2 and will provide product to support global change monitoring, climate monitoring and atmospheric chemistry. An Advanced Scatterometer (ASCAT) will provide improved retrieval capabilities to derive wind vectors at the ocean surface, continuing the successful SCAT instrument on ESA’s ERS-1 and ERS-2 satellites.

GRAS (GNSS Radio-Occultation Atmospheric Sounder) will provide further sounding capabilities, which will make use of the information on the atmosphere and ionosphere contained in the GPS navigation satellite signals through the radio-occultation technique. It will be the first operational radio-occultation mission for meteorology and climate monitoring. A full system including a GRAS Ground Support Network (GSN) to support the clock error corrections required for the GPS and Metop clocks as well as a precise orbit determination service will be installed.

Figure 3: Hurricane “Dean”, seen with MHS from Metop-A, RGB MHS Ch5Ch4CH3 (left), RGB MHS Ch1Ch2Ch3 (right), 20 August 20071457 UTC.

Metop-A was successfully launched in October 2006 and declared operational in March 2007. Data and products were made available for users the earliest as possible during the commissioning phase (Spoto et al., 2006) already. All products are now operational (see Figure 3 for an example) and have
already in 2007 demonstrated their positive impact on applications, namely Numerical Weather Prediction. Preparation for Metop-B has started.

After successful investigation of the root cause of an anomaly with the HRPT service, which caused its switch off in July 2007, a re-switch on with periodical operations over areas, where the risk of heavy ion impact has low probability, is being planned.

Improvements of the product timeliness is planned through an Antarctic Data Acquisition (ADA) service being investigated in co-operation with NOAA.

**Geostationary Satellites**

**Meteosat Transition Programme**

The first generation Meteosat and the equivalent Meteosat Transition Programme Satellites (Meteosat-7) have as payload a three-channel imager with broad-band channels in the visible, infrared, and water-vapour regions of the spectrum. The spacecraft is spin stabilised with 100 rotations per minute. The imager yields a full disk image every 30 minutes. The sampling distance at the sub satellite point is 2.5 km for the visible, 5 km for the infrared and water vapour channels. There are 5000 x 5000 pixels of visible and 2500 x 2500 pixels of infrared and water vapour channel data per full disk image. The products include satellite-tracked winds, cloud products, upper level tropospheric humidity, and others. Meteosat-7 has was transferred towards a position at 57.5 ° over the Indian Ocean to provide the IODC, after Meteosat-9 became operational. The decision that Meteosat-9 is the primary operational spacecraft was taken after the Steering Committee of the Image Product Validation Review of MSG-2 on 05 March 2007.
Meteosat Second Generation

The Meteosat Second Generation spacecraft is also a spin-stabilised satellite. Its payload comprises

![Image of Earth with different wavelengths](image)

**Figure 5: MSG capabilities: Example images from 12 SEVIRI Channels.**

The Spinning Enhanced Visible and Infrared Imager (SEVIRI) with 12 different spectral channels
(see Figure 5) in the visible and infrared region of the spectrum (see example image in Figure 6) and the GERB (Geostationary Earth Radiation Budget) instrument intended to provide measurements of the Earth Radiation Budget from geostationary orbit. As new products stability parameters will be derived from pseudo-sounding (e.g. lifted index). Humidity fields are derived in the upper and mid-troposphere and total ozone fields are estimated. The sampling of the image data at the sub-satellite point are 3 km with exception of the High Resolution Visible channel (HRV), where the resolution is planned to be 1 km. The full disk image is composed of 3750 x 3750 pixels (except for HRV). One full disk image is provided every 15 minutes, but alternative repeat cycles up to 3 minutes are also possible. In HRV mode the scan area can be selected among predetermined rectangular blocks. Products are generated in the ground segment facilities at EUMETSAT’s HQ and in the distributed part of the EUMETSAT application ground segment, the Satellite Application Facilities (SAF’s). Meteosat-9 is providing the operational service over 0° W, whereas Meteosat-8 provides rapid scan service for Europe over 9.5 °E.

**EUMETSAT ADVANCED RETRANSMISSION SERVICE**

EUMETSAT provides a fast delivery service of Advanced TOVS data, based on HRPT stations for the North Atlantic and European Area. The service was installed based on an initiative of the members of the HIRLAM Group (Denmark, Finland, Ireland, The Netherlands, Norway, Spain, Sweden and Iceland) in November 2000. The service provides ATOVS level 1a and level 1c data with a timeliness of 30 minutes to cover the needs of EUMETSAT Member States regional and local numerical weather prediction requirements for sounder data. Today the data of ten HRPT stations are distributed...
Outlook

EUMETSAT and ESA have in 2001 jointly started the process to define the follow on service for the geostationary satellite service, the Meteosat Third Generation (MTG), aimed at having the first satellite in orbit around 2015. Several user and expert workshops have been conducted, and baseline concepts are being explored. Missions investigated are a) Multispectral imaging (SEVIRI continuity, but enhanced capability), b) Infrared high spectral resolution sounding, c) Lightning imager, d) UV sounding. A preparatory programme has been approved at EUMETSAT level to cover the close out of phase A activities and the Phase B. ESA is in parallel running Phase A studies, entering phase B after their Council at ministerial level in November 2008. The final payload will be decided in autumn 2008. The detailed design and production of the Satellites and of the Ground Segment is planned to start after the approval by EUMETSAT Council of the programme proposal for the Development and Operations Phase in 2010.

The requirements analyses for the post-EPS era have also been started and a mission team has been formed. They aim for a need date in 2018 (core-mission) / 2020 (full mission) for an EPS follow-on service.

EUMETSAT is working with ESA to implement the operations of the Sentinel-3 satellite of the Global Monitoring for Environment and Security (GMES) initiative of the EU and ESA.

Conclusions

EUMETSAT’s contribution to the global system of satellite observation within the WMO Space Programme comprise considerably improved sounding capabilities which provide a major contribution towards the improvement of operational meteorological services, in particular numerical weather prediction. Impact studies for various instruments on Metop have shown that the forecast skill does improve. The MSG satellites are currently the most advanced geostationary meteorological satellites. An important contribution to climate monitoring arises from EPS and the coming programmes and satellites. Further contributions from EUMETSAT include optional programmes like the Jason-2 data processing and distribution.
References


Agency status reports: JMA and JAXA

Kozo Okamoto

Current status of the Multi-functional Transport Satellite–1R (MTSAT-1R) and MTSAT-2 and future plans of MTSAT follow-on satellite of Japan Meteorological Agency (JMA) are presented. Plans of earth observing satellites of the Japan Aerospace Exploration Agency (JAXA) are also presented. They include the Greenhouse gas Observing Satellite (GOSAT) launched in Japanese fiscal year (JFY) 2008, the Global Change Observation Mission–Water (GCOM-W) carrying the Advanced Microwave Scanning Radiometer-2 (AMSR-2) in JFY2011 and a Japanese and European joint satellite of the Earth Clouds, Aerosol and Radiation Explorer (EarthCARE) carrying the Cloud Profiling Radar (CPR) in JFY2013, and the Global Precipitation Measurement (GPM) proposed jointly with the U.S. They are all going to be substantially beneficial to assimilation, climate monitoring and model validation.
The National Polar-orbiting Operational Environmental Satellite System (NPOESS) and the NPOESS Preparatory Project (NPP) – Program Status and International Initiatives

Status

Peter A. Wilczynski

A Presidential Decision Directive (PDD), signed in May of 1994, directed the convergence of the polar orbiting weather satellites systems into a single national system. The Integrated Program Office (IPO) within NOAA was established in October 1994 as a result of the signing of a tri-agency Memorandum of Agreement (MOA) in May 1994. The new converged system was identified as the National Polar-orbiting Operational Environmental Satellite System (NPOESS). The IPO is staffed with representatives of NOAA, Department of Defense and NASA. This unique tri-agency office has the mission to provide a converged polar-orbiting operational, environmental satellite system that meets user community requirements.

The NPP is a joint-agency mission intending to serve the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO) and the National Aeronautics and Space Administration (NASA) and their user communities. The NPP provides the Earth science community with data continuity and also provides the IPO and its users a risk reduction demonstration of capabilities for critical NPOESS instruments.

NPOESS was formally restructured in 2007. This restructure has changed the NPOESS and NPP payload compliments and has changed the anticipated launch dates. All these changes impact NPOESS-NPP data users as they prepare to receive data from this next generation polar-orbiting system. As a result of the restructure, the NPOESS Program Executive Office (PEO) initiated installing additional ground resources in Antarctica to capture Europe’s current MetOp satellites, thus potentially reducing data latency by almost half of the current timeliness. This capability could be operational by 2012. Additionally, the PEO office is actively engaged internationally to seek other sources of satellite data to compliment NPOESS. For example, the PEO office and NOAA are actively discussing how to have JAXA’s GCOM series of satellites compliment the NPOESS constellation. This paper shall briefly discuss NPOESS-NPP program status as well as a comprehensive update on international activities that will positively affect our world-wide data users.
The Joint Capabilities and Opportunities of Advanced Sounders on MetOp and NPOESS for NWP and Climate Monitoring In a GEOSS Era

Stephen A. Mango

NPOESS, the National Polar-orbiting Operational Environmental Satellite System, managed by the Integrated Program Office [IPO], is structured as an operational, long-term, environmental, satellite monitoring system for weather, climate, and several other application/discipline areas for the ”Next Generation” (~2009-2029). The IPO is developing for a 1st generation NPOESS a suite of advanced, atmospheric sounding/probing instruments as a major part of the next generation meteorological, environmental and climate operational satellite system in polar, low earth orbit [LEO]. The CrIS, Cross-track Infrared Sounder, an Advanced Technology Microwave Sounder [ATMS], an Ozone Mapping & Profiler Suite [OMPS], a MIS [Microwave Imager and Sounder] and a VIIRS – Visible and Infrared Imager and Radiometer. In addition, the 2nd generation NPOESS – post 2025, is already in its very early conceptual phase.

The European community, EUMETSAT, European Organization for the Exploitation of Meteorological Satellite Systems, has already launched (October 2006) the first of three next generation, operational polar-orbiting LEO system, MetOp, as part of its European Polar System [EPS]. MetOp has a highly capable FTS sounder, IASI [Infrared Atmospheric Sounder Interferometer], an Advanced Microwave Sounding Unit [AMSU], a Global Ozone Monitoring Experiment [GOME], a GNSS Receiver for Atmospheric Sounding [GRAS] and an Advanced Very High Resolution Radiometer [AVHRR]. EUTMETSAT is already in the Mission Formulation stage for their 2nd generation EPS – post 2020.

The combined MetOp and NPOESS sounders, which will be in complementary polar orbits, will represent a very significant combined capability and set of opportunities to establish a formative GEOSS grand sounding “system”.

This paper will focus on the projected joint capabilities, synergies and opportunities of advanced sounders on MetOp and NPOESS during the emerging GEOSS era for primarily NWP and climate monitoring, namely – the IASI, AMSU, GOME and GRAS on MetOp and the CrIS, ATMS, OMPS and MIS on NPOESS, the different requirements for the MetOP and NPOESS sounding sensors which will actually facilitate the the cross-calibration of the sounders of a formative GEOSS system, and the different requirements for the MetOp and NPOESS sounding products which will actually facilitate an initial formulation of common
requirements for the sounding products for GEOSS sounders and provide an opportunity for the mutual validation of the sounding products.
PAPERS FROM POSTER PRESENTATIONS
Radiative Transfer in Vertically Layered Soil

Fuzhong Weng

At thermal wavelengths, the upwelling radiation at surface is often expressed as a product of emissivity and surface temperature. For a vertical stratified medium (e.g. permittivity varies with soil depth), the emissivity at the surface is normally calculated from Fresnell formula. For an electromagnetic (EM) wave that does not penetrate through soil (e.g. zero transmissivity), the emissivity and reflectivity equals unit. However, when the EM wave penetrates through the medium, the emitted radiation must be considered from the energy contributed from the deeper layers and can be calculated from variable radiative transfer schemes. This study will investigate on uses of auxiliary soil information to quantify the optical parameters used in surface radiative transfer schemes. The impacts of this newly developed approach on simulations of the radiances at the top of the atmosphere will be also discussed.
A clear sky radiative transfer model for MTG-IRS

Stephen Tjemkes, Jochen Grandell and Rolf Stuhlmann

In support of the development of an end-to-end processing chain for METEOSAT Third Generation Infrared Sounder (MTG-IRS) candidate mission EUMETSAT has procured the radiative transfer model based on the Optimal Spectral Sampling (OSS) method from Atmospheric and Environmental Research, Inc. To build confidence in this radiative transfer code, a comparison has been performed involving results generated by OSS and results generated by LBLRTM for real IASI observations, and for MTG-IRS simulations for a number of atmospheric clear sky conditions. In addition to results for the upwelling radiance at top of the atmosphere, also jacobians for a number of state variables are included in the comparison.
Scenes Analysis for the Meteosat Third Generation Infrared Sounder Observations

Stephen Tjemkes, Jochen Grandell, Phil Watts and Rolf Stuhlmann

EUMETSAT prepares for the next generation of geostationary satellites. Among the three candidate missions is an infrared sounder. The preparatory activities for especially this candidate mission will greatly benefit from exploring the hyperspectral IASI observations. The MTG-IRS candidate mission observations would be used to monitor vertical distributions of temperature and moisture. Although there are a number of promising activities, regarding the retrieval of thermodynamical properties from all sky observations, initially these temperature and moisture profiles will be derived from cloud free spatial samples. Thus an accurate scenes analysis is required to classify each observation according to its cloud amount. McNally and Watts (2003) described a cloud detection algorithm for high spectral resolution infrared sounders. To understand the performance of this algorithm in relation to a possible application to MTG-IRS observations, a number of tasks have been performed. First, in order to increase the confidence in the performance of this cloud detection algorithm, it was applied to IASI observations and compared to results of other scenes analysis methods like the CO2 slicing method and the operational cloud mask derived from collocated AVHRR observations. Results of this comparison will be presented during the presentation, as well as results of the method when applied to IASI as a proxy for MTG-IRS. This means that the spectral coverage of the original IASI data is reduced to match the MTG-IRS coverage, and also the spectral sampling is modified according to the MTG-IRS specifications. The effect of these modifications on the performance of the cloud detection is presented.
Comparison of IASI radiances with models from seven operational centres

Fiona Hilton, Andrew Collard, Lars Fiedler, Vincent Guidard, Sylvain Heilliette, Lydie Lavanant, and Benjamin Ruston

Bias and noise in IASI spectra may be identified by comparing the data with radiances calculated from forecasts and analyses from Numerical Weather Prediction (NWP) models. The bias and standard deviation of fit against model fields are compared for seven operational centres: the Met Office, ECMWF, EUMETSAT, Meteo-France/GMAP, Meteo-France/CMS. Good agreement is found between IASI and NWP fields, showing that IASI is performing within its specification. Areas of the spectrum where the comparisons differ or agree can be used to investigate whether errors arise from the NWP model, the spectroscopy or the instrument.
IASI Validation Studies using Airborne Field Campaign Data


Measurement system validation is critical for advanced satellite sensors to improve observations of the Earth’s atmosphere, clouds, and surface for enabling enhancements in weather prediction, climate monitoring capability, and environmental change detection. Field campaigns including satellite under-flights with well-calibrated FTS sensors aboard high-altitude aircraft are an essential part of the validation task. This presentation focuses on IASI validation studies performed using data from the recently-completed Joint Airborne IASI Validation Experiment (JAIVEx) field campaign. Methodology developed and employed herein for IASI radiance validation will be discussed along with recent results.
Identification of biases in the modelling of high peaking water vapour channels from IASI

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International research aircraft campaigns have been used to validate radiances from the Infrared Atmospheric Sounding Interferometer (IASI) and identify sources of error in the radiative transfer modelling. This paper investigates the modelling of strong water vapour emission lines for three such case studies.

IASI observations are compared with coincident data from the aircraft campaigns combined with upper atmosphere forecasts from the Met Office and ECMWF global models, forward-modelled using a line-by-line radiative transfer model. The resulting biases identified in the research aircraft case studies for high-peaking water vapour lines are found to be consistent with operational biases from the Met Office and ECMWF assimilation schemes.

It is shown that in the models’ current configuration ECMWF humidity fields are more successful in reproducing observed IASI radiances. Differences in the observed biases for the two centres are explored in relation to differing schemes for the treatment of upper atmospheric humidity in the 4D-Var assimilation scheme.

1. Airborne campaigns

This study uses data gathered by aircraft campaigns conducted during 2007 and 2008 dedicated to IASI calibration and validation. The underpinning strategy in airborne research studies for satellite cal/val is to characterise rigorously both the absolute upwelling atmospheric radiance and the state of the atmosphere (in particular temperature and humidity). Temporal and spatial collocation of these measurements is important, to minimise representivity errors. The UK Facility for Airborne Atmospheric Measurements (FAAM) BAe 146 aircraft is a well instrumented airborne research laboratory, suited to satellite cal/val exercises of this kind. The FAAM aircraft instruments used in this study include:

- Airborne Research Interferometer Evaluation System (ARIES) measuring upwelling and downwelling infrared radiances at 1 cm\(^{-1}\) spectral resolution;
- Heimann broadband infrared radiometer for mapping surface temperatures;
- AVAPS dropsonde system, allowing profiles of temperature and humidity below the aircraft to be sampled at high spatial resolution;
Onboard temperature and humidity probes for measuring in situ atmospheric conditions, and aerosol and cloud probes for measuring particulates;

Onboard chemistry probes for measuring in situ atmospheric concentrations of trace gases such as ozone and carbon monoxide.

Description of the case studies

For the three case studies described here, flights of the FAAM aircraft were coordinated with overpasses of IASI on the MetOp-A satellite. Only measurements within the same geographic area and small time window have been considered, to give maximum confidence that all measurements relate to the same atmospheric airmass. Exclusively clear sky fields of view for radiometric measurements have been analysed, as determined from onboard observations and MetOp AVHRR imagery.

The first campaign, the Joint Airborne IASI Validation Experiment (JAIVEx) was based in Houston, Texas during April and May 2007. The FAAM 146 was joined by the NASA WB-57 high altitude aircraft, carrying two additional airborne interferometers. This enabled collocated measurements of infrared nadir radiances from space, the stratosphere and the upper troposphere. Sorties were conducted over ocean (Gulf of Mexico) and over land (ARM Southern Great Plains facility, Oklahoma). This dataset is intended to be representative of warm, moist atmospheric conditions.

In order to sample contrasting climatic conditions, the FAAM 146 undertook a flight in December 2007 off the northwest coast of Scotland, timed to coincide with a MetOp overpass in predominantly clear sky conditions.

A further series of flights occurred during the Cold Land Processes Experiment (CLPX-II) based in Alaska in February 2008. Flights over sea ice and over the snow pack enabled measurements in cold, dry conditions.

Line-by-line simulations

The IASI observations are compared with brightness temperatures simulated by a line-by-line radiative transfer model. The atmospheric profiles for input into the radiative transfer code, representative of the observed radiances, were constructed in the following way:

1. The nearest collocated dropsonde profile was used for temperature and humidity below the FAAM 146 altitude (typically around 10 km);

2. Trace gas profiles for ozone and carbon monoxide were derived for this lower atmosphere range from in situ aircraft probes;

3. In the absence of closely coincident radiosonde observations, temperature and humidity for the upper atmosphere (above around 10 km) were derived from operational NWP model fields. Fields were available from both the Met Office and ECMWF global model forecast (run from the closest previous analysis with on
average three hours lead-time to the time of the overpass). Ozone was available as a variable parameter from the ECMWF model.

4. The surface skin temperature was derived from Heimann radiometer measurements, coupled with spot retrievals of temperature and emissivity using ARIES hyperspectral radiances.

GENLN2 (Edwards, 1992) was used as the line-by-line code. Recent updates to spectroscopic parameters (HITRAN 2004) and the water vapour continuum (MT_CKD_1.0) were implemented in the simulations. Comparisons with another line-by-line code (LBLRTM) show no significant differences in the strong water vapour band of interest in this paper.

This paper investigates differences in bias between the IASI measurement and the simulated observation when using Met Office and ECMWF forecasts. These can be attributed to differences in the upper atmospheric forecasts themselves since all other parts of the simulation are identical.

2. Operational biases

In order to verify whether the biases between the IASI observations and the simulated brightness temperatures identified in the case study are representative of the forecast model in general, they are compared with operational biases from the Met Office model for the same day over a wider region. Observations are taken from a latitude band spanning the area of the case study over a six hour assimilation cycle.

In addition, a comparison is made for a full day of operational bias statistics from the Met Office and ECMWF for 30 April 2007. The statistics are split into three latitude bands and represent all valid night time observations over the sea surface determined to be unaffected by cloud. This global comparison serves to reinforce the results of the case studies.

The operational processing of IASI data is described for the Met Office and ECMWF respectively in Hilton et al. (2008) and Collard et al (2008). Biases between IASI and the model forecast are calculated using the RTTOV radiative transfer model – RTTOV-7 at the Met Office (Saunders et al., 2002) and RTTOV-8 at ECMWF (Saunders et al., 2005). Both versions of RTTOV use coefficients derived from kCARTA (Strow et al., 1998) and there is not expected to be a difference in bias between the models.
### 3. Case study results

FAAM flight B290 on 30 April 2007 was conducted over the Gulf of Mexico, with a coincident MetOp overpass at 1529 UTC. Figure 1 below shows results from the strong water vapour band 1400-1800 cm\(^{-1}\), where IASI observations are compared with line-by-line simulations.

**Figure 1:** (Upper panel) IASI clear-sky brightness temperature spectrum recorded during JAIVEx flight B290, overlaid with simulation using ECMWF upper atmosphere fields. (Lower panel) residual differences (IASI observed – calculated GENLN2 spectrum) for both Met Office and ECMWF upper atmosphere fields, see legend. Overlaid as connected data points are Met Office operational observed – background biases for IASI data selected as clear over ocean between latitudes 10-40° N.

Comparisons for the averages of two sets of simulations are shown, where the upper atmosphere model field data comes respectively from the Met Office and ECMWF global NWP models. It is apparent that with ECMWF fields the residuals are limited to ±1 K over much of the water vapour band. However, when Met Office fields are included in the simulation there are significant negative residuals, reaching −4 K at some frequencies. The latter is well matched by the observed-background (O-B) residual, generated from Met Office assimilated IASI fields of view over a much larger area (10-40° N clear sky over sea for 30 April 2007). The assimilated channels are limited to the channel selection for NWP described in Collard (2007).

Figure 2 below compares the average of the Met Office and ECMWF temperature and water vapour profiles, matched to the case study observations’ location and time. The temperatures do not differ greatly, but the Met Office water vapour field exhibits a distinct dry bias relative to ECMWF, leading to the observed negative brightness temperature bias for IASI. Simulations combining ECMWF water vapour with Met Office temperature fields, and vice-
versa, (not shown) confirm that the water vapour profile differences are dominant in producing the differing radiance biases in the 1400-1800 cm$^{-1}$ band.

![Gulf of Mexico case study](image)

**Figure 2:** Comparison of temperature and water fields from JAIVEx on 30 April 2007. The left-hand panels compare the fields above 400 hPa, with the differences shown on the right.

Results for the mid-latitude UK flight on 12 December 2007 are shown in Figure 3. Here a slight positive bias for ECMWF fields is accompanied by a negative bias for Met Office fields. Once again the agreement between the latter and operational O-B biases for selected channels (and over a much wider geographic area) is striking.

Results for the Alaska case on 26 February 2008 are less clear-cut (Figure 4). The residuals for the Met Office and ECMWF fields do not differ greatly, with slightly negative residuals in both cases. However, the Met Office operational O-B bias remains consistent with that found for the case study.
Figure 3: (Upper panel) IASI clear-sky brightness temperature spectrum recorded during flight B332, overlaid with simulation using ECMWF upper atmosphere fields. (Lower panel) residual differences (IASI observed – calculated GENLN2 spectrum) for both Met Office and ECMWF upper atmosphere fields, see legend. Overlaid as connected data points are Met Office operational observed – background biases for IASI data selected as clear over ocean between latitudes 40-70° N.

Figure 4: (Upper panel) IASI clear-sky brightness temperature spectrum recorded during flight B332, overlaid with simulation using ECMWF upper atmosphere fields. (Lower panel) residual differences for both Met Office and ECMWF upper atmosphere fields, see legend. Overlaid as connected data points are Met Office operational observed – background biases for IASI data selected as clear between latitudes 70-90° N.
A comparison of profiles from model fields for the mid-latitude and Alaska cases is shown in Figure 5. Although some details differ, there is broad agreement in all cases of a Met Office dry bias relative to ECMWF at the tropopause level (c.f. Figure 2).

Figure 5: Comparison of temperature and water fields from cases on 12 December 2007 (UK winter) and 26 February 2008 (Alaska).
4. Assessment of whether case studies are representative

The case study results are remarkably consistent, given the wide variety of locations and different seasons covered by the three campaigns. The agreement of the bias found when using the Met Office fields for the upper atmosphere in the case studies, with the Met Office operational O-B statistics gives confidence that the results are representative over a wider area.

To confirm this, Figure 6 shows Met Office operational biases for a single channel sensitive to water vapour (channel 3168 at 1436.75 cm\(^{-1}\)) for 18 hours of data, and indicates that the JAIVEx case study area on 30 April 2007 is not atypical. The majority of global data points show a negative bias for the channel shown.

**Figure 6:** Global bias for IASI channel at 1436.75 cm\(^{-1}\) for the Met Office model (obs – calc) for 18 hours of data on 30 April 2007 (sea clear observations). The JAIVEx case study area is shown with a red box in the inset plot.
The difference between the operational bias statistics from the Met Office and ECMWF are also globally consistent. Figure 7 shows a comparison of Mean O-B values in the water vapour band between the Met Office and ECMWF for all valid clear, sea night-time observations on 30 April 2007. It is clear that the Met Office model has a large negative bias for high-peaking channels, and that this behaviour is seen for all latitude bands. The ECMWF bias is consistently slightly positive. Figures 6 and 7 therefore indicate that the negative radiance biases seen in the strong water vapour band are not restricted to the case study location.

Figure 7: Observed – calculated biases for ECMWF and the Met Office for all clear, night-time, sea observations on 30 April 2007, showing strong water vapour band channels. The biases are discriminated by latitude (see legend).
5. Characteristics of channels showing largest biases

Typically the channels exhibiting the worst O-B biases are those closest to the centres of strong lines. The sensitivity of the strong water vapour lines to atmospheric water vapour can be seen by plotting Jacobians for selected channels, see Figure 9. These strongest lines are sensitive to water vapour throughout the stratosphere. Although assimilation of IASI data could help to correct the model bias, these channels cause problems for operational assimilation because a large model bias in the stratosphere leading to an observation-background difference can result in an erroneous humidity increment in the mid-troposphere.

![Figure 9:](image)

**Figure 9:** (Left panel) expanded section of water vapour band showing simulated brightness temperature at full resolution and at IASI resolution for JAIVEx case study. The coloured symbols refer to the Jacobian plot. (Right panel) RTTOV-7 Jacobians for six selected IASI channels, colour-coded as shown in the legend by sensitivity to water vapour above 100 hPa.
6. Assessment of model water vapour biases

The discrepancies between observed and calculated radiances in the strong water vapour band, when using Met Office model fields in the simulation, are indicative of a model bias in the treatment of water vapour. Comparing the model fields for April 2007 (Figure 8) it is clear that the Met Office Unified Model is extremely dry near the tropopause relative to ECMWF. Other monthly periods show similar behaviour.

Figure 8: Zonal mean relative humidity field for April 2007. The left hand panel shows the Met Office field as a function of pressure, while the right hand panel show the difference (Met Office – ECMWF). The black contours at the tropopause level indicate a relative humidity difference more negative than −8%.

The reasons for the dry bias in the Met Office upper atmosphere are still under investigation. Climate runs of the Met Office unified model with no data assimilation which are allowed to relax towards climatology exhibit a smaller dry bias than the short-range forecasts and analyses (Sean Milton, 2008, pers. comm.) which is suggestive of the introduction of a bias at analysis time.

One possible contributory factor is that the data assimilation scheme constrains the stratospheric water vapour to be between 1 and 3 mg/kg. The stratosphere has a simple definition in the scheme, identified by a globally constant value of potential vorticity. This definition can lead to increments in the upper troposphere which tend to dry the model, particularly in the extra-tropics (David Jackson, 2008, pers. comm.).

Work is underway to investigate the impact of this constraint term on the analysis. In the longer term, a new project aims to address the upper-tropospheric/lower-stratospheric humidity increments by introducing a new moist control variable in 4D-Var which is normalised by the variance of the relative humidity at each model level.
7. Summary

Comparisons between IASI data and Met Office and ECMWF model profiles have helped to identify a large and as yet unresolved dry bias in the Met Office global model near the tropopause. This bias is present all year round and across all latitude ranges. In contrast, the ECMWF model tends to show a small moist bias. It is likely that this bias is introduced by the assimilation scheme. Work is now underway to understand the source of the bias and to correct for it. Verification of the model against observations such as IASI will play an important role in determining whether changes to the assimilation code have helped to improve the model forecast.

Acknowledgements

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References


The water vapor continuum effect on the surface transmitted irradiance at 8 – 12 μm atmospheric window

Simone M.S. Costa, Keith P. Shine, Juan C. Ceballos and Rodrigo A. F Souza

The continuum of the atmospheric water vapor plays an important role in the 8-12 μm infrared window by absorbing the warmer radiation from the surface and re-emitting it at cooler temperature. This study aims to present an estimate of the continuum effect on the surface transmitted irradiance (STI, in Wm-2). Irradiances were calculated based on the state-of-the-art line-by-line radiation model; 12-year climatological dataset from ECMWF reanalyzes and clouds from the International Satellite Cloud Climatology Project (ISCCP). Results show that the global annual mean surface transmitted irradiance at the top of the atmosphere is around 65 Wm-2 for clear sky, and decreases to 22 Wm-2 due to clouds. The water vapor continuum absorbs more than 60% of the clear sky surface transmitted irradiance at the tropics, around 20% at mid-latitudes and around 7% at the poles. The stronger effect on the lower latitudes is because self-broadened continuum absorption is proportional to the square of the partial pressure of the water vapor. Future work will extend the analyses of the effect of water vapor continuum absorption on the satellite signal (i.e. brightness temperature/radiance).
The Effect of Earth-rotation Doppler Shift on SSMIS UAS Channel Measurements

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Abstract

The atmospheric radiation near 60 GHz received by the Special Sensor Microwave Imager/Sounder (SSMIS) on board the US Defense Meteorology Satellite Program (DMSP) F-16 satellite exhibits a Doppler shift of up to 75 KHz, due to the Earth’s rotation. The magnitude of the Doppler shift varies with the latitude of the observations. Effect of the Doppler shift on the measurements is a function of the Earth magnetic field strength and the angle between the Earth’s magnetic field and propagation direction of the electromagnetic wave, which is related to the so called Zeeman-splitting effect. As a result of the frequency shift, the brightness temperatures can differ by 2 K at SSMIS channels 19 – 21. Our analyses also confirm that the SSMIS upper atmosphere sounding channels measure the right-circularly polarized radiation.

Introduction

Special Sensor Microwave Imager/Sounder (SSMIS) on board the US Defense Meteorology Satellite Program (DMSP) F-16 satellite includes six upper atmosphere sounding (UAS) channels, channels 19 – 24. These channels have narrow spectral passbands near the line centers of the O2 magnetic dipole transitions. Their sensitivities peak in the upper stratosphere and mesosphere. Because of Zeeman-splitting, the energy received in some of the UAS channels is partially polarized and depends strongly on the geomagnetic field and its orientation with respect to the propagation direction of the electromagnetic wave. To assimilate measurements from the UAS channels, a radiative transfer (RT) model has been developed for rapid radiance simulations and radiance derivative (Jacobian) calculations, in which the Zeeman-splitting effect has been taken into account [Han et al., 2007]. However, the frequency shift of the radiation spectrum due to the Earth’s rotation [Kerola, 2007; Swadley et al., 2008] is ignored in the model.

SSMIS is a conical scanner viewing the Earth at a constant 45° angle from nadir on a polar orbit with an inclination of 98.8° and an average orbital altitude of approximately 850 km. Thus, both the satellite orbital motion and the Earth’s rotation can result in Doppler shift in the received radiation spectrum. The Doppler component due to the satellite orbital motion has been compensated instrumentally by tuning the frequency of the receiver phase-locked local oscillator as a function of scan angle. This onboard “hardware Doppler” compensation removes the requirement for the RT model to deal the Doppler shift effect when brightness temperatures are calculated and compared to satellite measurements. However, the same measure has not been implemented for the Doppler component due to the Earth’s rotation. Kerola [2007] gives an example of the simulated brightness temperature (BT) measurements near the Equator, where the Doppler shift is the largest at certain scan positions, showing the affect of the Earth-rotation Doppler shift is up to a couple of tenths of a degree in Kelvin (K). In our work reported here, an analysis of the Doppler shift effect on a global scale was carried out. The results show that the effect can be as large as 2 K in certain regions and therefore can not be ignored in radiance simulations in these regions.

There has been confusion about whether the measured radiation is left-circularly polarized (LCP) or right-circularly polarized (RCP). The source of the confusion may come from distributed documents which use different conventions to describe the LCP or RCP radiation. For instance, [Kerola, 2007] adopts the physics convention and assumes LCP measurement when modeling the deviation of measurements from the desired values due to antenna system axial ratios departure from unity. However, the report [Poe et al., 2001] describes the measured radiation is RCP. Another possible source of the confusion is that the polarization specification can be made for a radiometer system which may or may not include the reflector that directs
the incoming radiation to the receivers. The reflector reverses the polarization. As a result, the RCP radiation is actually measured with an LCP radiometer and vice versa. It will be explained later that the polarization issue is not important if there is no frequency shift in the radiation spectrum, because an LCP system will receive approximately the same amount of energy as an RCP system. But it becomes important if the frequency shift has a measurable effect. In this paper, the Institute of Electrical Engineers convention is used, which is the opposite of the physics convention, and the reflector is assumed to be included in the radiometer system.

### The impact of the Doppler-shift predicted from theory

It is not straightforward to observe the Doppler-shift effect in the measurements, because the variations from other factors such as the Earth’s magnetic field $Be$ and the angle $\theta_B$ and the wave propagation direction $k$ may dominate the features in the received signals. To isolate the Doppler-shift effect, we first conducted a theoretical analysis by simulating radiance measurements.

#### Radiance simulation

In the upper stratosphere and mesosphere, the $O_2$ transition lines are narrow, and the Zeeman splitting may become an important factor in the RT modeling [Lenoir, 1968]. Each line splits into three groups of sublines, usually referred as the $\pi$, $\sigma^+$ or $\sigma^-$ components. The spread width of the sublines is on the order of 0.05$Be$ MHz, where $Be$ is the magnitude of $Be$, which may take a value in the range of $23 – 65 \mu T$ near the Earth surface. Thus, the Zeeman splitting effect may be observed by a space-based sensor only with narrow passbands near the centers of the unsplit transition lines. As listed in Table 1, SSMIS channels 19 and 20 have passbands centered on the transition lines, designated as $7^+$, $9^+$, $15^+$ and $17^+$ [Rosenkranz, 1993], with passband widths about 1 MHz, and therefore are strongly influenced by the Zeeman effect. The other four channels each have four passbands, paired and situated symmetrically on opposite sides of the transition lines $7^+$ or $9^+$ with increased bandwidths and band frequency-offsets from the line centers as the channel number increases. Thus their sensitivity to the Zeeman effect decreases with the channel number. For channels 23 and 24, the Zeeman effect is negligible.

In a circular polarization basis, the spectral intensity of thermal microwave radiation may be expressed by the BT coherent matrix, as

$$T_{b,v} = \begin{bmatrix} T_{b,r,v} & T_{b,l,v} \\ T^{*\ d}_{b,l,v} & T^{*\ d}_{b,r,v} \end{bmatrix}$$

where $T_{b,r,v}$ and $T_{b,l,v}$ are respectively the RCP and LCP components, $T_{b,l,v}$ is the coherency (the symbol $*$ represents complex conjugate) and $v$ is the frequency. The solution solving the radiative transfer equation for $T_{b,v}$ at the top of atmosphere (TOA) is given in [Rosenkranz and Staelin, 1988]. The simulation of the radiance measurement or channel BT, labeled here as $T_{b,ch}$, is performed by convolving $T_{b,v}$ with the channel’s spectral response function (SRF). Both $T_{b,v}$ and $T_{b,ch}$ are a function of air temperature $T_{air}$, $Be$ and $\cos(\theta_B)$.

When there is a Doppler-shift $\Delta v$ in the incoming radiation spectrum, $T_{b,ch}$ also depends on $\Delta v$. Moreover, the characteristics of the dependence are different between RCP and LCP systems. Figure 1 shows an example of $T_{b,r,v}$ and $T_{b,l,v}$ spectra near the $9^+$ line, computed for the US 76 standard atmosphere at $Be = 50 \mu T$ and three values of $\theta_B$ (0, 90° and 180°). It can be seen that the spectra of $T_{b,r,v}$ and $T_{b,l,v}$ are in mirror symmetry, that is, $T_{b,r,v}$ at $v_{\theta}$ is the same as $T_{b,l,v}$ at $v_{\theta} - v_{\theta}$, where $v_{\theta}$ is the center of the unsplit line. This property may be proved by applying Theorem 3 and equation 45 in [Stogryn, 1989] and holds in general at other values of $Be$ and $\theta_B$ near the line center $v_{\theta}$ where the contributions from other lines may be ignored.

The property implies that the LCP and RCP systems with symmetrical passbands would receive the same amount of energy if there is no frequency shift in the radiation spectrum. However, if the spectrum is shifted, the two systems would in general receive a different amount of energy if $\theta_B \neq 90°$. For example, the passbands of channels 19 and 20 are centered on the transition lines, and it can be seen from Figure 1 that a small positive frequency shift of the spectrum (add a constant to the spectral frequency) would increase...
(decrease) $T_{b,r,ch}$ but decrease (increase) $T_{b,l,ch}$ at $\theta_B > 90^\circ$ ($\theta_B < 90^\circ$). The situation is reversed for a small negative frequency shift. At $\theta_B = 90^\circ$, the three Zeeman components are all linear polarized and the LCP and RCP systems would observe the same radiance. Notice also that the curves for $\theta_B = 90^\circ$ in Figure 1 are quite flat near the center of the line, implying that the variation due to the Doppler-shift would be small under this condition.

![Figure 1. A brightness temperature spectrum near the 9+ transition line centered at $\nu_0 = 61.150560$ GHz, for the US 76 standard atmosphere and $Be = 50$ µT. Note that the curve for the right-circularly polarization (RCP) at $\theta_B$ is identical with that for the left-circularly polarization (LCP) at $180^\circ - \theta_B$.](image)

**Table 1. SSMIS UAS channel parameters.** Offset – passband central frequency offset from the unsplit O$_2$ transition line center; BW – bandwidth. The line centers of the transitions, represented with 7+, 9+, 15+ and 17+, are 60.434776, 61.150560, 62.997977 and 63.568518 GHz, respectively.

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<tr>
<td>19</td>
<td>0 (15+)</td>
<td>1.34</td>
<td>0 (17+)</td>
<td>1.36</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0 (7+)</td>
<td>1.34</td>
<td>0 (9+)</td>
<td>1.37</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>-2 (7+)</td>
<td>1.26</td>
<td>2 (7+)</td>
<td>1.23</td>
<td>-2 (9+)</td>
</tr>
<tr>
<td>22</td>
<td>-5.5 (7+)</td>
<td>2.62</td>
<td>5.5 (7+)</td>
<td>2.61</td>
<td>-5.5 (9+)</td>
</tr>
<tr>
<td>23</td>
<td>-16 (7+)</td>
<td>7.01</td>
<td>16 (7+)</td>
<td>7.17</td>
<td>-16 (9+)</td>
</tr>
<tr>
<td>24</td>
<td>-50 (7+)</td>
<td>26.83</td>
<td>50 (7+)</td>
<td>26.33</td>
<td>-50 (9+)</td>
</tr>
</tbody>
</table>

**Doppler shift due to Earth’s rotation**

The radial velocity of the radiation emitters due to the Earth’s rotation at a given direction $k$ is independent of the distance between the emitters and satellite, and the Doppler frequency shift $\Delta \nu$ is given by [Swadley et al., 2008] and is written here in a slightly different form, as

$$\Delta \nu = -\frac{\nabla \cdot \Omega R_e \cos(\psi)[\cos(i) \cos(\phi) \pm \sin(\phi) \sqrt{\sin(i - \lambda) \sin(i + \lambda)}][2)] \tag{2}$$

where $\nabla$ is the mean frequency of the channel passbands, $c$ is the speed of light, $\Omega$ is the angular velocity of the Earth’s rotation, $R_e$ is the distance of the satellite from the center of the Earth, $\psi$ is the viewing angle from nadir, $i$ is the inclination of the orbit, $\lambda$ is the latitude (positive in Northern Hemisphere, negative in Southern Hemisphere and zero at Equator) of the satellite nadir point, and $\phi$ is the scan angle from the satellite orbital motion direction. The scan angle $\phi$ is related to the scan position $j$, as
\[ \varphi = \frac{1 - j - 1}{2N - 1} \Gamma, \quad j = 1, N \] (3)

where \( N = 30 \) is the number of scan positions and \( \Gamma \) is the total scan angle between scan positions 1 and \( N \). Scan position 1 corresponds to the east-most pixel in each scan data set for the ascending observations and west-most for the descending observations. The plus and minus signs before the second term in (2) correspond to the ascending and descending orbits, respectively. The first term in (2) is due to the departure of \( i \) from 90° and is a positive contribution at \( \varphi = 0^\circ \), since \( k \) has a component to the East at this angle. The second term is due to an angle from the North and is zero at \( \varphi = 0^\circ \). The shift may reach 75 KHz in the tropical region at the edges of the scans.

The dependence of the Doppler-shift effect on \( Be \) and \( \theta_B \)

The effect of the Doppler-shift in the range computed with (2) is first evaluated by comparing simulated brightness temperatures with and without the inclusion of a frequency shift. The simulations use temperature profiles from the empirical model, COSPAR International Reference Atmosphere [Fleming et al. 1988] (CIRA-88). The lower part (0 – 120 km) of the model profile includes monthly values of the temperature field on the latitude grid points with a 5-degree interval from 80°N to 80°S, generated from data including ground-based and satellite measurements. Figure 2 shows the BT differences, BT(\( \Delta \nu \))-BT(\( \Delta \nu = 0 \)), for channels 19-22 as a function of the frequency shift, calculated at three values of \( \cos(\theta_B) \) (-1, 0, 1). Figure 2a and 2b are for RCP and LCP radiometer systems, respectively, with the calculations conditioned at \( Be = 30 \mu T \). Figure 2c is for an RCP system with \( Be = 60 \mu T \) (The figure for an LCP system is not shown since the pattern is similar to Figure 2b). It can be seen that for channels 19 and 20, the BT differences can reach a value of about 2 K when \( \cos(\theta_B) \) is near 1 or -1, and become small when \( \cos(\theta_B) \) is near zero. The BT differences for an RCP system are almost the same as those for an LCP system, which is consistent with the mirror symmetric property of the spectrum discussed in the previous section. The dependence of the BT differences on \( Be \) is larger for smaller \( Be \), since the width of the Zeeman-splitting (see Figure 1) becomes narrower for smaller \( Be \), resulting in a larger sensitivity to the Doppler-shift. Small \( Be \) occurs near Equator (see Figure 5), which may coincide with large Doppler-shifts. The temperature profile used in the calculations for Figure 2 is an annual mean at 17°N. Hence we emphasize that the magnitude of the BT difference also depends on the temperature lapse rate of the portion of the atmosphere which the channels are sensitive to. As the frequency of the radiation spectrum is shifted, the peak height of the channel’s weighting function (WF) may shift up or down accordingly, resulting in a decrease or increase of the amount of BT depending on the temperature lapse rate. For channel 21, the BT differences are relatively small, and the sign of the differences are opposite to those in channels 19 and 20, mainly due to the differences in their passbands’ spectral locations. For channel 22, as well as channels 23 and 24, the effect of the frequency shift is negligible.

To evaluate the Doppler-shift effect on a global scale, we simulated the measurements of channel 20 for the full day of January 1, 2006. The result is shown in Figure 3a for ascending orbit and Figure 3b for descending orbit, plotted as BT differences between the simulations with and without the inclusion of the effect of the Earth’s rotation. The corresponding data for the simulations, including \( Be \) and \( |\cos(\theta_B)| \) (the absolute value of \( \cos(\theta_B) \)), are taken from the SSMIS Sensor Data Records (SDRs). The signs of the \( \cos(\theta_B) \) data, not included in SDRs, were derived with the help of the 10th International Goemagnetic Reference Field (IGRF) model [Mandea et al., 2000]. It can be seen from the figures that the BT differences can be as large as 2K, but not necessarily occur in the tropical region, where the tangent velocity of the Earth’s rotation is the largest, because of the dependence of the effect on the angle \( \theta_B \) discussed earlier. To discuss it further, the corresponding \( \cos(\theta_B) \) and \( Be \) data are plotted and shown in Figure 4 and 5, respectively. It can be seen that the BT differences are large at the pixel positions where the Doppler-shifts are large and the values of \( |\cos(\theta_B)| \) are close to 1. They become small in high latitudes, where Doppler shifts are small, and in regions where the values of \( \cos(\theta_B) \) are near zero \( (\theta_B \approx 90^\circ) \). Note also the difference of the patterns of the BT differences between the ascending and descending orbits, which is in large degree due to the differences of the angle \( \theta_B \) between the two sets of data. Finally we observe from the \( \cos(\theta_B) \) images that between 10°N and 40°N from the ascending observations and -40°S and 0° from the descending observations, there are
pixels in the same scan on which the values of \( \cos(\theta_B) \) on the east and west sides with respect to the ground track are approximately the same and close to -1 or 1, and the signs of \( \Delta v \) are opposite between the two sides. This feature provides a way to evaluate the Doppler-shift effect in the measurements.

Figure 2. Simulated brightness temperature (BT) differences using the RT models with and without the inclusion of the Doppler-shift effect, with the solid, long-dashed and short-dashed curves corresponding to \( \cos(\theta_B) = -1, 0, 1 \), respectively. (a) \( B_e = 30 \mu T \) and an RCP radiometer system, (b) \( B_e = 30 \mu T \) and LCP, and (c) \( B_e = 60 \mu T \) and RCP.

Figure 3. Simulated brightness temperature (BT) differences for channel 20 using the RT models with and without the inclusion of the Doppler shift effect, for ascending (a) and descending (b) observations on January 1, 2006. For the simulations, the pixel’s geometric parameters, \( B_e \) and \( |\cos(\theta_B)| \), are taken from the SDRs and the temperature profiles are from the CIRA-88 model. The signs of the \( \cos(\theta_B) \) data are recovered with the assistance of the IGRF model.
Figure 4. The cosine of the angle between the magnetic field and wave propagation direction for the ascending (a) and descending (b) observations on January 1, 2006.

Figure 5. The Earth’s magnetic field strength in $\mu$T at 00:00 Greenwich Mean Time on January 1, 2006 at the height of 60 km, computed using the IGRF model

Observations of the Doppler-shift effect

As discussed earlier, the BTs in channels $19 - 21$ vary with $B_e$, $\cos(\theta_B)$, $T_{air}$ and $\Delta\nu$. Thus, efforts were made to minimize the variations due to the first three factors. The variation due to $T_{air}$ was minimized by averaging data over different locations and a long period of time. To minimize the variations due to $B_e$ and $\cos(\theta_B)$ and at the same time maximize the Doppler-shift effect, data were selected from the pixels at the edges of the scans with $|\cos(\theta_B)|$ close to 1 and minimal differences in both $B_e$ and $\cos(\theta_B)$ between the data points on the east and west sides of the scans. Specifically, the data selection criteria are the following. The latitudes of the data are confined between $10^\circ N$ and $40^\circ N$ for the ascending orbits and between $-40^\circ S$ and $0^\circ$ for the descending orbits. The reason for such a selection has been discussed in the previous sections. These data were further filtered by selecting data with the absolute values of $\Delta\nu$ to be greater than 55 KHz and the variations in $B_e$ and $\cos(\theta_B)$ are less than 1 $\mu$T and 0.01, respectively. Finally, the data points on the east and west sides of the same scan were paired according to the smallest difference in $\cos(\theta_B)$. The BT differences, $BT(\text{west point}) - BT(\text{east point})$, were then computed for each pair of the data points. Note that the Doppler shift is positive on the west data points and negative on the east data points.

The set of data meeting the above criteria were collected from the SDRs in the period of the entire year of 2006, which include 41772 pairs of data samples from ascending orbits and 65476 pairs from descending orbits. The Root-Mean-Square (RMS) differences in $B_e$ and $\cos(\theta_B)$ between the paired data points are 0.6 $\mu$T and 0.006, respectively, for both the ascending and descending data. The mean values and standard deviations of $B_e$, $\cos(\theta_B)$, $\Delta\nu$ and scan positions of the data set are summarized in Table 2. As listed in the table, the values of $|\cos(\theta_B)|$ in the data set are about 0.7, which are the highest value we can obtain for such paired data in order to maximize the Doppler-shift effect and in the meantime minimize the influence from
other factors. The BT differences between the paired data points are plotted as histograms shown in Figure 6, with the solid curves for ascending observations and dashed curves for descending observations. The corresponding mean values and standard deviations of the BT differences are listed in Table 3 in the rows labeled “Measured”. The results show that for channels 19 and 20, there is a positive mean BT difference of about 2 K for the ascending set of data whose cos(θ_B) values are negative, and a negative difference of approximately the same magnitude from the descending data whose cos(θ_B) values are positive. For channel 21, the BT differences are relatively small but the signs are opposite to those for channels 19 and 20. Since, as mentioned earlier, Δν is negative on the east edge and positive on the west edge, of the scans, this pattern of the BT differences in channels 19 – 21 is consistent with the analysis given in Section 2 and is matched to that of an RCP system. The BT differences for channels 22-24 are small, as expected since the Doppler-shift effect is negligible in these channels.

More insights about the above results may be gained by simulating the BT differences for the same data set. The CIRA-88 model was used to provide the temperature profiles for the simulations. Three sets of simulations were performed. The first two are for RCP and LCP systems, respectively, and the third for an RCP system but without the inclusion of the Doppler-shift. The statistics of the simulations are listed also in Table 3. It can be seen that within the uncertainties in the measurements and model temperature profiles, the effect of the Doppler-shift seen in the measurements agree with that predicted from the theory. Moreover, the measured radiation is clearly not LCP because the signs of the simulated BT differences in channels 19 – 21 under the LCP assumption are opposite to those observed in the measurements. Finally, it is noted that the widths (standard deviations) of the measured BT differences are larger than the simulations, but they decrease with the channel number. One cause for the large widths is likely related to the instrument noise as suggested by the instrument noise levels listed in Table 1. Another possible cause is the variations of the temperature profiles, which are not possible to be taken into account fully in the simulations with the CIRA-88 profile model.

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![Figure 6](image)

Figure 6. The histograms of the differences of the measured brightness temperature (BT) between the paired data points on the east and west edges of the scans, BT(west) – BT(east), with the solid curves from the ascending observations (sample size = 41772) and the dashed curves from the descending observations (sample size = 65476).

Table 2. Means (the first numbers) and standard deviations (the second numbers) of the Earth’s magnetic field strength $B_e$, cosine of the angle between the magnetic field and the wave propagation direction cos(θ_B), Doppler frequency shift Δν and pixel position, over the data set of n samples corresponding to the results in Table 3 and Figure 6. The words “East” and “West” refer to the data pixel positions on the east and west edges of the scans, which containing 30 pixel positions (1 – 30), numbered sequentially from east to west for ascending orbits and west to east for descending orbits.

<table>
<thead>
<tr>
<th></th>
<th>$B_e$ (μT)</th>
<th>cos(θ_B)</th>
<th>East Δν (KHz)</th>
<th>West Δν (KHz)</th>
<th>East position</th>
<th>West position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascending (n=41772)</td>
<td>41.3, 4</td>
<td>-0.66, 0.05</td>
<td>-62.2, 3.2</td>
<td>65.3, 4.5</td>
<td>2, 1</td>
<td>26, 2</td>
</tr>
<tr>
<td>Descending (n=65476)</td>
<td>45.3, 7</td>
<td>0.68, 0.06</td>
<td>-63.0, 3.8</td>
<td>67.4, 4.7</td>
<td>29, 1</td>
<td>4, 2</td>
</tr>
</tbody>
</table>
Table 3. Means (the first numbers) and standard deviations (the second numbers) of the brightness temperature (BT) differences between the paired data points on the east and west edges of the scans, BT(West) – BT(East). The words “Measured” and “simulated” refer to the measured and simulated data, respectively, and “RCP” and “LCP” refer to the radiometer systems with right-circularly and left-circularly polarizations, respectively. The issue of polarization is not important in the simulations with no Doppler shift (∆ν=0).

<table>
<thead>
<tr>
<th></th>
<th>Chan 19</th>
<th>Chan 20</th>
<th>Chan 21</th>
<th>Chan 22</th>
<th>Chan 23</th>
<th>Chan 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascending orbit (n=41772)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>2.54, 2.14</td>
<td>2.03, 2.40</td>
<td>-0.72, 1.38</td>
<td>-0.14, 1.49</td>
<td>-0.05, 1.01</td>
<td>-0.07, 0.68</td>
</tr>
<tr>
<td>Simulated RCP</td>
<td>1.76, 0.38</td>
<td>1.65, 0.37</td>
<td>-0.61, 0.28</td>
<td>0.02, 0.22</td>
<td>0.04, 0.23</td>
<td>0.02, 0.14</td>
</tr>
<tr>
<td>Simulated LCP</td>
<td>-1.71, 0.32</td>
<td>-1.67, 0.31</td>
<td>0.65, 0.21</td>
<td>0.06, 0.22</td>
<td>0.03, 0.23</td>
<td>0.02, 0.14</td>
</tr>
<tr>
<td>Simulated ∆ν=0</td>
<td>0.02, 0.24</td>
<td>-0.01, 0.23</td>
<td>0.04, 0.20</td>
<td>0.02, 0.22</td>
<td>0.04, 0.23</td>
<td>0.02, 0.14</td>
</tr>
<tr>
<td>Descending orbit (n=65476)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>-1.84, 2.08</td>
<td>-2.02, 2.32</td>
<td>0.01, 1.80</td>
<td>-0.26, 1.45</td>
<td>-0.14, 0.97</td>
<td>-0.05, 0.65</td>
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<tr>
<td>Simulated RCP</td>
<td>-1.62, 0.41</td>
<td>-1.66, 0.43</td>
<td>0.95, 0.35</td>
<td>0.15, 0.35</td>
<td>0.14, 0.40</td>
<td>0.03, 0.25</td>
</tr>
<tr>
<td>Simulated LCP</td>
<td>1.94, 0.46</td>
<td>1.72, 0.54</td>
<td>-1.01, 0.41</td>
<td>0.10, 0.35</td>
<td>0.14, 0.40</td>
<td>0.03, 0.25</td>
</tr>
<tr>
<td>Simulated ∆ν=0</td>
<td>0.16, 0.26</td>
<td>0.03, 0.34</td>
<td>0.01, 0.18</td>
<td>0.15, 0.35</td>
<td>0.14, 0.40</td>
<td>0.03, 0.25</td>
</tr>
</tbody>
</table>

Conclusions and remarks

The Doppler-shift in the radiation spectrum due to the Earths’ rotation can have an effect of up to 2 K on the BT simulations for SSMIS channels 19 – 21. The degree of the effect depends on not only the amount of shift ∆ν, but also cos(θB) and Be as well as Tair. The value of ∆ν may be calculated with (2). The magnitude of ∆ν is about 75 KHz near Equator at the pixels on the edges of the scans and decreases with latitude. However, the largest impact of the Doppler-shift does not necessary occur near Equator because of the dependence on cos(θB). The effect can be large if |∆ν| and |cos(θB)| are large and Be is small, and become small if cos(θB) is near zero. Be is usually small in low latitudes, but cos(θB) can vary significantly in these regions. The effect of the Doppler-shift may be neglected at high latitudes in the radiance simulation. For channels 22 – 24, the effect of the Doppler-shift is insignificant. Our analyses also confirm the measured radiation in the UAS channels is RCP.

Recently, the fast RT model [Han et al., 2007] has been improved to take the Doppler shift effect into account. However, operational applications of the model require two additional parameters to be included in the SDRs. One is the Doppler-shift ∆ν and the other is the sign of cos(θB). The SDR data used in this study include only the absolute value of cos(θB). As shown in this paper, the sign becomes important if there is a significant Doppler-shift in the radiation spectrum.

References


Lenoir, W. B. (1968), Microwave spectrum of molecular oxygen in the mesosphere, J. Geophys. Res. 73, 361-376.


A Fast Radiative Transfer Model for AMSU-A Channel-14 with the Inclusion of Zeeman-splitting Effect

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Abstract

AMSU-A channel 14 has four narrow passbands, centered on the sides of the 11- (57.6125 GHz) and 13- (56.9682 GHz) O2 magnetic dipole transition lines, and the sensitivity of the channel peaks around 40 km. Because of the Zeeman-splitting, the radiances are partially polarized and dependent on the Earth’s magnetic field and its orientation with respect to the observation direction. So far, the Zeeman-splitting effect has either not been taken into account or incorrectly modelled in the radiative transfer scheme applied for radiance assimilations. The work reported here is an attempt to model the Zeeman-splitting effect as part of the development of the Community Radiative Transfer Model (CRTM).

Introduction

Zeeman splitting has a small, but non-negligible effect on AMSU-A channel 14. This paper describes a fast radiative transfer model that takes the Zeeman effect into account for this channel and introduces a way to derive from the AMSU-A 1B data stream the parameters which are required as the model inputs. The first section provides a description about the Zeeman effect on the channel, followed by a section describing the model algorithm. The next section presents procedures for obtaining the model inputs from the 1B data stream. The last section summarizes the results.

Effect of Zeeman-splitting on AMSU-A channel 14

In the 60 GHz frequency region, there is a cluster of O2 magnetic dipole transition lines. These lines are usually designated as the N+ and N- lines, representing respectively the transitions between the J = N and J=N+1 and between J=N and J=N-1 energy levels, where J is the quantum number of the total angular momentum and N (an odd number) is the quantum number of the rotational angular momentum. In the upper stratosphere and mesosphere, the lines become sharp and a phenomenon called the Zeeman effect appears, induced by the interaction of the O2 molecule’s magnetic dipole moment with the earth’s magnetic field. The energy level J splits into 2J+1 new levels, associated with the azimuth quantum number M, which may take any integer number from –J to J. The selection rules permit the N+ and N- transitions for which the M number can either remain fixed or change by one. Thus, each of the N+ and N- lines splits into three groups of sublines. The line components obtained when M is unchanged are called the π components. When M increases or decreases by one, the components are called the σ+ or σ- components.

The three groups of components show different behaviours in polarization. The π components are linearly polarized in the direction perpendicular to the plane containing the magnetic field vector Be and the wave propagation direction k. Their magnitudes reach a maximum when the angle θ_{Be} between Be and k is 90° and become zero when the angle is zero. The σ+ and σ- components are respectively right and left circularly polarized when Be and k point in the same direction (θ_{Be} = 0°) and exchange the polarizations when Be and k point in the opposite direction (θ_{Be} = 180°). They become linearly polarized at θ_{Be}=90° in the plane containing Be and k. When the angle θ_{Be} takes other values, the polarization of the σ+ and σ- components are elliptical. The total splitting width (the spread range of the sublines) is about 0.5Be MHz, where Be is the strength of the earth’s magnetic field, which may take a value in the range of 0.23 – 0.65 in Gauss unit near the earth surface. Thus,
the Zeeman effect can only be observed by sensors with very narrow passbands on or near the centers of the unsplit \(N^+\) and \(N^-\) lines and their sensitivity peak in the upper stratosphere and mesosphere.

AMSU-A channel 14 has four passbands, 4.5 MHz away from the centers of the transition lines 11- and 13- with bandwidths of 2.9 MHz. Its sensitivity peaks around 40 km as shown in Figure 1. The impact of the Zeeman effect on this channel is revealed by a slight shift of the weighting function upward when the magnetic field strength \(B_e\) increases. The impact is also illustrated in Figure 2, which shows its dependence on \(B_e\), \(\theta_{Be}\), and the orientation of the receiver’s polarization. As the figure shows, in theory it can have an impact up to 1K. However, in reality, the combination of the AMSU-A observation geometry and the orientation of \(B_e\), shown in Figure 3A and 3B, does not provide the conditions for the maximum impact to happen, as shown in Figure 3C. In these figures, the global distributions of the \(B_e\) and \(\cos(\theta_{Be})\) parameters on the AMSU-A pixels are computed from the data in the 1B data stream. Figure 3C shows the difference between simulated brightness temperatures with and without the inclusion of Zeeman effect. The variations of the receiver’s polarization due to scanning have been taken into account. It can be seen that in the low latitude regions, although \(\theta_{Be}\) can reach a value of 90°, a condition for the maximum impact, the \(B_e\) value is generally low, resulting in a relatively small impact. On the other hand, in the regions in which \(B_e\) has large values (around 0.65 Gauss), the \(B_e\) vector is near parallel with the \(k\) vector (\(\theta_{Be} \approx 0^\circ\)), resulting in a moderate impact compared with the maximum impact level which requires \(\theta_{Be} = 90^\circ\).

![Figure 1. Weighting function of AMSU-A channel 14, calculated using the US76 standard atmospheric temperature profile at \(B_e=0.23\) and 0.65 in Gauss with \(\cos(\theta_{Be})=0\) for the \(V^\prime\) polarization component.](image1)

![Figure 2. Differences of simulated brightness temperatures (BT) between the models with and without the Zeeman effect.](image2)
Figure 3A, Earth magnetic field strength $B_e$ at the pixels of AMSU-A ascending orbits, calculated using the 10th International Geomagnetic Reference Field (IGRF) model and the parameters in the 1B data stream.

Figure 3B, The $\cos(\theta_{Be})$ field, i.e. the cosine of the angle between the Earth magnetic field and the wave propagation direction $k$ at the pixels of AMSU-A ascending orbits, calculated using the 10th International Geomagnetic Reference Field (IGRF) model and the parameters in the 1B data stream.

Figure 3C. Differences of the simulated brightness temperatures between the models with and without the inclusion of the Zeeman effect using the data shown in Figure 3A and 3B and the US76 temperature profile, which is applied globally.
Fast radiative transfer models with the inclusion of Zeeman effect

Line-by-line base model

The fast RT model is based on the line-by-line (LBL) model Rosenkranz88 (Rosenkranz and Staelin, 1988), which uses a circular polarization basis. The LBL model solves the radiative transfer problem for the brightness temperature coherency matrix,

\[
T_b = \begin{bmatrix}
T_{b11} & T_{b12} \\
T_{b21} & T_{b22}
\end{bmatrix},
\]

(1)

where \(T_{b11}\) is the component of the right circular polarization, \(T_{b22}\) is the left circular polarization and \(T_{b12}\) is the coherency (the symbol * represents complex conjugate). The solution of the radiative transfer is given in a numerical form as

\[
T_b = \sum_{k=1}^{N} (P_{k-1}P^*_{k-1} - P_kP^*_{k})T_{a,k},
\]

(2)

where

\[
P_0 = I, \quad P_k = P_{k-1}\exp(-G_k\Delta z_k),
\]

(3)

\(G_k\) is the complex propagation matrix, \(T_{a,k}\) is the temperature of the \(k\)th layer, \(I\) is a unit matrix and \(\Delta z_k\) is the thickness of the \(k\)th layer.

On a linear polarization basis, such as the one used for AMSU-A, the element \(T_{b11}\) in (1) is the brightness temperature with polarization along the \(v'\) axis in the coordinates system shown in Figure 4, in which the three vectors \(v', h',\) and \(k\) form a right-handed orthogonal triad, with \(k\) points to the propagation direction and the \((v', k)\) plane contains the earth’s magnetic field vector \(Be\). It follows that the element \(T_{b22}\) is the component with polarization along the \(h'\) axis and the off-diagonal elements are the corresponding coherency. The RT solution of brightness temperature matrix with a linear polarization basis can be obtained from the solution on the circular polarization basis through a component transformation and is given by

\[
T_{b \text{ linear}} = CT_{b \text{ circular}} C^{-1},
\]

(4)

where

\[
C = \frac{1}{\sqrt{2}} \begin{bmatrix}
1 & 1 \\
-i & i
\end{bmatrix}.
\]

(5)

AMSU-A channel 14 receives linearly polarized radiation whose polarization varies with scan angle \(\theta_s\) from nadir. It is therefore necessary to transform the brightness temperature components defined in the coordinates shown in Figure 4 into a new coordinates system with the vertical and horizontal polarization defined in a usual way as shown in Figure 5. The result is (Stogryn, 1989),

\[
T_{b,v'v'} = \cos^2 \phi_{be} T_{b,v'v'} + \sin^2 \phi_{be} T_{b,h'h'} - 2\sin \phi_{be} \cos \phi_{be} \Re T_{b,v'v'}
\]

\[
T_{b,h'h'} = \sin^2 \phi_{be} T_{b,v'v'} + \cos^2 \phi_{be} T_{b,h'h'} + 2\sin \phi_{be} \cos \phi_{be} \Re T_{b,v'v'}
\]

\[
T_{b,v'h'} = \sin \phi_{be} \cos \phi_{be} (T_{b,v'v'} - T_{b,h'h'}) + \cos^2 \phi_{be} T_{b,v'v'} - \sin^2 \phi_{be} T_{b,v'v'}^* - \sin \phi_{be} \cos \phi_{be} \Re T_{h'h'v'}
\]

(6)

where \(\Re()\) is a function for taking the real part of the input variable and the other symbols are defined in Figure 5.

For AMSU-A channel 14, the third terms in the first two equations are not important (well below the 0.1 K level) and thus can be neglected. The brightness temperature that is measured by this channel is thus given by

\[
T_b = \sin^2 (\theta_s)T_{b,v'v'} + \cos^2 (\theta_s)T_{b,h'h'}.
\]

(7)
Figure 4. Coordinates with the three vectors $v'$, $h'$, and $k$ forming a right-handed orthogonal triad.

Figure 5. The AMSU-A oriented coordinate system.

**Fast RT model**

For an atmosphere vertically divided into $n+1$ levels from the top of the atmosphere (TOA) to the Earth’s surface, the solution for a brightness temperature component with a polarization $p$ at frequency $\nu$ may be expressed as

$$ T_{b,v,p} = \sum_{k=1}^{N} (\tau_{v,k-1,p} - \tau_{v,k,p}) T_{a,k}, \quad (8) $$

where $\tau_{v,k,p}$ is an apparent transmittance from level $k$ to TOA, which was computed using Rosenkranz88, and $T_{a,k}$ is the mean temperature of the layer between levels $k-1$ and $k$. By averaging both sides of (8) over the channel’s passbands we obtain the equation for the passband-averaged brightness temperature,

$$ T_{b,ch,p} = \sum_{k=1}^{N} (\tau_{ch,k-1,p} - \tau_{ch,k,p}) T_{a,k}, \quad (9) $$

where $\tau_{ch,k,p}$ is the passband-averaged (channel) transmittance. On a linear polarization basis, the transmittance in general depends on geomagnetic field strength $Be$, the angle $\theta_{Be}$ between the magnetic field and wave propagation direction, the azimuth angle $\phi_{Be}$ (see Figure 5) and air
temperature. However, the $\varphi_{Be}$ dependence can be first ignored in the transmittance calculation by computing the transmittance in the special coordinates shown in Figure 4 ($\varphi_{Be}=0$). Then, the radiance at an arbitrary $\varphi_{Be}$ value can be obtained by applying Equation 6.

A linear equation is developed to predict the $k^{th}$ layer optical depth $\sigma_k$ (for the convenience the symbol $p$ for polarization is dropped),

$$\tilde{\sigma}_k = c_{k,0} + \sum_{j=1}^{m} c_{k,j} x_{k,j}, \quad (10)$$

where $c_{k,j}$ are coefficients and $x_{k,j}$ are predictors. With the optical depth profile, the channel transmittances at a zenith angle $\theta_z$ are then calculated as

$$\tilde{\tau}_{ch,k} = \exp\left(-\sum_{i=1}^{k} \tilde{\sigma}_i / \cos(\theta_z)\right), \quad (11)$$

The coefficients $c_{k,j}$ are obtained through regression. In the regression (training) process, the channel transmittances $\tau_{ch,k}$ are calculated from a set of diversified atmospheric profiles. The transmittances are then converted to the optical depth $\sigma_k$ as

$$\sigma_k = \ln(\tau_{ch,k-1} / \tau_{ch,k}) \cos(\theta_z) \quad , (12)$$

which is the predictand in the training (dependent) data set. The UMBC 48 profile set (Strow et al., 2003) was adopted and interpolated on the specified levels. The training data set was prepared at the zenith angles corresponding to air masses 1, 1.25, 1.5, 1.75, 2 and 2.5 with eleven points on $Be$ ($20 \leq B \leq 70 \mu T$) and 11 points on $\cos(\theta_{Be})$. The predictors were configured based on the radiance characteristics and in part on trial and error. Table 1 lists the predictors used for the fast RT models.

The fitting error for AMSU-A channel 14 is shown in Figure 6, plotted as a function of the top level set in the fast model (the top level for LBL model is fixed). The fitting error is about 0.035 K for the model with the top level set above 0.02 hPa level.

Table 1. Predictors. $\psi = 300./T_a$, $T_a$ - air temperature; $Be$ – geomagnetic field strength; $\theta_{Be}$ – angle between the geomagnetic field and wave propagation direction; $\theta_z$ - sensor’s zenith angle.

<table>
<thead>
<tr>
<th>AMSU-A channel 14 Predictors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi$, $\psi\sec(\theta_z)\cos(\theta_{Be})$, $Be\sec(\theta_z)\secant(\theta_z)$, $\cos(\theta_{Be})Be^2\secant(\theta_z)$</td>
</tr>
</tbody>
</table>

Figure 6. Fitting errors as a function of top pressure level set in the fast model for AMSU-A channel 14.
Implementation issues

Handling polarization

As described in the previous section, the AMSU-A Zeeman model requires computations of transmittances for two orthogonal polarizations. This requirement may not be consistent with the model into which the fast Zeeman model is to be implemented, such as the CRTM model (Han et al., 2006), which computes only one transmittance component. To simplify the implementation, polarization may be ignored in the sense that only the following averaged transmittance is predicted,

\[ \tau = 0.5(\tau_v + \tau_h), \]  

(13)

where \( \tau_v \) and \( \tau_h \) are transmittances of the two orthogonal polarizations. This is equivalent to setting the weights of the two brightness temperature components in Eq. (7) to a value of 0.5. With this approach the transmittance calculation and RT integration for this channel can be treated in the same way as the other AMSU channels. It appears that the approach of using the averaged transmittance profile does not significantly degrade the model accuracy (errors in brightness temperature are about 0.1 K or less, depending on the geophysical location and sensor scan angle).

Obtaining the required input parameters from 1B data set

The AMSU-A 1B data stream does not include the parameters \( Be \), \( \cos(\phi_{Be}) \) and \( \cos(\theta_{Be}) \), but they can be derived from the data provided. The following is the steps to compute the parameters.

(a) Compute the magnetic field vector \( Be \) using a lookup table (LUT), which contains pre-computed \( Be \) vectors (a snapshot of the field at a certain date and time) on the grid points of the latitude and longitude with a 2x2 degree grid size. The variation of the vector field with time is less than 2 % and is not important for this channel.

(b) Compute the sensor azimuth angle \( \phi_{sat} \), defined here is the angle on the local horizontal plane from the East to the projected line of the \( k \) vector, positive towards North. The 1B data stream provides a relative sensor azimuth angle \( \phi_{r} \), relative to the azimuth angle \( \phi_{sun} \) of the Sun (see Figure 7), which is not included in the data stream. It is therefore necessary to compute \( \phi_{sun} \) using the date and time information in the data stream. The sensor’s absolute azimuth angle is then computed as

\[ \phi_{sat} = 90 - (\phi_{r} + \phi_{sun}). \]  

(14)

(c) Compute \( k \) from \( \theta_z \) (sensor’s zenith angle) and \( \phi_{sat} \).

(d) Compute \( \cos(\theta_{Be}) \) and \( \cos(\phi_{Be}) \), as

\[ \cos(\theta_{Be}) = Be \cdot k / |Be| \]

and

\[ \cos(\phi_{Be}) = Be_V / Be_P \]

where, \( Be_V \) is the component of \( Be \) on the axis of the vertical polarization V (see Figure 5) and \( Be_P \) is the component of \( Be \) projected on the plane containing the V and H vectors.
Summary

The Zeeman-splitting can have an effect up to 0.5 K in brightness temperature on AMSU-A channel 14, depending on the pixel locations and the observation direction relative to the Earth magnetic field vector. To take the effect into account, a fast radiative transfer model has been developed for applications requiring rapid radiance calculations. The fast model is trained with the LBL mode Rosenkranz88 and has a RMS difference of less than 0.1 K compared with the LBL base model. To simplify the implementation, polarization may be ignored with a small reduction of the model accuracy (up to 0.1 K).

References


A graphical user interface for RTTOV

Philippe Marguinaud, Pascal Brunel

RTTOV is the radiative transfer model developed by the NWP SAF. The project has decided to create a graphical user interface to run the RTTOV model. We have chosen to develop an interface based on the Linux Desktop (Gnome/KDE). This interface will allow users to edit RTTOV initial conditions (atmospheric profiles, ground parameters, etc...) run the RTTOV model efficiently (keeping coefficients in memory, possibly using multithreading) and view the results (radiances, transmittances). Our poster will present the principles of this interface, and we intend to have a laptop running a demo as well.
4A/OP: An operational fast and accurate radiative transfer model for the infrared

L. Chaumat, C. Standfuss, B. Tournier, R. Armante and N.A. Scott

4A/OP is a user-friendly software for various scientific applications, co-developed by LMD (Laboratoire de Meteorologie Dynamique) and NOVELTIS with the support of CNES (the French Space Agency). NOVELTIS is in charge of the industrialization and the distribution of the LMD 4A radiative transfer model. 4A (4A stands for Automatized Atmospheric Absorption Atlas) is a fast and accurate line-by-line radiative transfer model particularly efficient in the thermal infrared region of the spectrum. NOVELTIS has created an "operational" version of this code called 4A/OP. The 4A/OP software is a version of the 4A code for distribution to registered users. This version is regularly updated and improved and contains a graphical user interface and a reference documentation. The associated Website http://www.noveltis.fr/4AOP/ includes an on-line registration form. 4A/OP has the official support of CNES for radiative transfer applications in the infrared. This software is used by several research groups and can be integrated in operational processing chains. In particular, 4A/OP is the reference radiative transfer model for IASI level 1 Cal/Val and level 1 operational processing. Thanks to the computation of Jacobians, the model can also be coupled with an inversion algorithm for the atmospheric constituent retrieval from infrared radiance measurements.
**Forward Simulation for FY-3 MWHS using RTTOV-7**

Xiaqing Li, Gang Ma, Fengying Zhang, Xuebao Wu

MWHS (MicroWave Humidity Sounder), together with MWTS (MicroWave Temperature Sounder) and IRAS (Infrared Atmospheric Sounder), constitutes vertical atmospheric sounding system (VASS) in FY3, the next generation polar orbit meteorological satellite of China. MWHS can provide three-dimensional distribution of global atmospheric humidity for all weather. Before research has been performed on forward simulation for MWHS by using RTTOV-7, Liebe-MPM89 and Liebe-MPM92 are used to compute line-by-line transmittances. Based on these transmittances, spectral parameters for MWHS and predictors defined in RTTOV-7, coefficients are calculated by a multiple linear regression model. In order to compare with AMSU-B, standard atmospheric profile of the United States is used to generate the weighting function of MWHS. After profiles in TIGR43 dataset are selected to yield the fast transmittances coefficients for MWHS, validation is performed by comparing the brightness temperature and the transmittances calculated by RTTOV7 and generated by the Line-by-line model.
Convective-scale data assimilation of satellite infrared radiances over the Mediterranean: adaptation of the observation operator to the high-resolution.

Fanny Duffourg, Véronique Ducrocq, Geneviève Jaubert, Nadia Fourrière and Vincent Guidard

National Centre for Meteorological Research CNRM/GAME
(Météo-France/CNRS - National Centre for Scientific Research)
Mesoscale Meteorology Department (GMME)

Abstract

Fine scale phenomena are still badly grasped whereas they are an important challenge to take up. For that reason, some meteorological centres have recently developed numerical weather prediction models with a kilometric mesh that explicitly resolve moist convective processes. With this higher resolution, new problems, particularly in assimilation, have appeared. For example, the model mesh is now smaller than any satellite observation spot. As a consequence, we need to gather model information from different grid points to simulate correctly the brightness temperature measured. This issue is examined more specifically for the newly developed convective scale 3D-Var data assimilation system of Météo-France: AROME. In AROME, satellite observations are simulated thanks to the RTTOV radiative transfer model. The brightness temperature is estimated at the centre of the satellite observation spot using the four closest model columns surrounding this point. This interpolation procedure comes from previous assimilation systems for which the model mesh was larger than the observation spot. But with fine scale data assimilation systems such as AROME (2.5 km), such a procedure is no longer valid as a single AIRS or IASI observation spot covers more than 12 model grid points at nadir. That is why, in this study, we explore different ways of aggregating the model information within a satellite spot in order to better represent the whole atmosphere sounded at once by these instruments. We then compare the different brightness temperatures obtained by using RTTOV with these different aggregating methods. The first results show almost no differences for temperature channels (the differences in brightness temperature are smaller than 0.1 K) but bigger ones (from 0.5 K to 1 K) for water vapour channels in some places where important gradients in the humidity field are present.

Introduction

A number of meteorological centres have recently developed convective-scale numerical weather prediction systems with the specific aim of improving forecasts of high impact weather events. Their kilometric grid-mesh, nonhydrostatic equations and improved microphysics enable the explicit treatment of atmospheric deep convection. The representation of the precipitating systems is thus significantly improved. But this ability to simulate the dynamical and physical processes at a fine scale is not always sufficient to prevent bad forecasts: if some mesoscale key ingredients are missing in the initial conditions, the model cannot then reproduce the precipitating systems. In agreement with these two remarks,
case studies focusing on Mediterranean heavy rainfall events have already shown significant improvements using nonhydrostatic convective-scale research models. But these studies have also pointed out the necessity to improve the initial mesoscale conditions (Ducrocq et al. 2002, Guidard et al. 2006 with a 10 km mesh model). This is particularly true for the initial moisture field: Mediterranean heavy rainfall events are very sensitive to the fine scale structure of this highly variable field which presents strong gradients.

Convective-scale assimilation of observations over sea is a way to improve the initial conditions of kilometric scale models. Such improvement is of particular importance in case of Mediterranean heavy rainfall events as they originate from the Mediterranean Sea (Nuissier et al. 2007, Ricard et al. 2007). Over sea, satellite data are nearly the only routinely available observations with a sufficient coverage. With the new infrared sounders IASI (Cayla 2001, Chalon et al. 2001) and AIRS (Pagano et al. 2002, Aumann et al. 2003), we now have high-resolution and very accurate information on temperature and humidity over sea. IASI sounds indeed the atmosphere with an horizontal resolution of 12 km at nadir and a vertical resolution finer than 1 km. The accuracy of its measurements is better than 1 K for temperature retrievals and 10 % below 500 hPa for relative humidity retrievals. The initial analysis may therefore gain a lot from the fine-scale assimilation of such precise information over sea.

However the assimilation of satellite data in a convective-scale data assimilation system is not straightforward as new problems arise with the increase of resolution. In particular, the simulation of brightness temperatures from a high-resolution model for its comparison with observations raises new questions. Indeed, the model grid is now smaller than any satellite observation spot. As a consequence, we need to aggregate model information from different grid points to simulate correctly the brightness temperature measured, whereas with previous larger-scale assimilation systems we could use a single model column. This is what this work is about, focusing on IASI and AIRS because of their particularly interesting characteristics.

The main purpose here is to evaluate the impact on infrared radiances simulation of using all atmospheric model information contained in the observation spot instead of only the single vertical column situated at the centre of the observation spot. This issue is examined more specifically for the newly developed convective scale 3D-Var data assimilation system of Météo-France: AROME. For that, we develop different ways of aggregating the model information within a IASI or AIRS spot so as to better represent the whole atmosphere sounded at once by these instruments. These new methods as well as the current one will be presented in the first section along with the IASI, AIRS and AROME system main characteristics. Then, the various methods are evaluated statistically and finally the most important differences are characterised thanks to a case study.

**IASI and AIRS radiances simulation**

**IASI and AIRS radiances**

IASI (Cayla 2001, Chalon et al. 2001) and AIRS (Pagano et al. 2002, Aumann et al. 2003) are hyperspectral infrared passive sounders, respectively on board the European and the American polar orbiting satellites MetOp and Aqua. They measure the radiation coming out of the atmosphere in thousands of channels in the infrared spectrum. This outgoing radiation is strongly linked with the concentrations of various atmospheric gases, with humidity and temperature. Thus, thanks to their numerous channels (8461 for IASI and
2378 for AIRS) with high spectral resolution (0.29 cm\(^{-1}\) for IASI and from 2.2 cm\(^{-1}\) at 3.7 \(\mu\)m to 0.5 cm\(^{-1}\) at 15.4 \(\mu\)m for AIRS), IASI and AIRS measurements provide very accurate information on temperature and humidity (1 K for temperature retrievals and 10 % below 500 hPa for relative humidity retrievals with 1 km vertical resolution).

IASI and AIRS are nadir-viewing sounders: they scan the atmosphere below the satellite for different look positions along a plane which is perpendicular to the satellite orbit track. When looking at an off-nadir position, the atmosphere is scanned along a slanted line-of-sight. Table 1 gives the maximum angle formed between the line-of-sight and the nadir direction. As IASI and AIRS fields-of-view are respectively 0.825° and 1.1°, the horizontal resolution of their measurements varies with the scan angle. The minimum (at nadir) and maximum (at swath edge) values are given in table 1.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Horizontal resolution at nadir (diameter of the circular spot)</th>
<th>Maximum scan angle</th>
<th>Horizontal resolution at swath edge (major and minor axes of the ellipsoidal spot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IASI</td>
<td>12 km</td>
<td>48.3°</td>
<td>38 km (\times) 20 km</td>
</tr>
<tr>
<td>AIRS</td>
<td>13.5 km</td>
<td>49.5°</td>
<td>40 km (\times) 22 km</td>
</tr>
</tbody>
</table>

Table 1: IASI and AIRS geometrical characteristics

The AROME 3D-Var

Such high-resolution and very accurate information on temperature and humidity is very interesting to assimilate in a convective-scale model such as AROME, the newly developed numerical weather prediction system of Météo-France. AROME is to become operational by the end of the year 2008.

This model has a grid mesh of 2.5 km and 41 unequally spaced vertical levels up to 1.36 hPa. Its dynamics is based on non-hydrostatic equations. Many physical processes such as cloud microphysics, deep convection or turbulence are explicitly resolved while shallow convection, radiation, etc. remain parametrized. Cloud processes are particularly well described because of the explicit treatment of cloud microphysics but also thanks to the detailed description of hydrometeors through five different species: liquid water, rain water, cloud ice, snow and graupels.

AROME has its own 3D-Var data assimilation process, cycled every 3 h: each cycle produces 3 h forecasts which are used as background fields for the next analysis in the next cycle. In the AROME 3D-Var, inherited from the ALADIN one (Fischer et al. 2005), satellite radiances (previously converted into brightness temperatures thanks to the Planck function) are directly assimilated, without any previous retrieval. For that, the background and the satellite observations have to be compared directly in terms of brightness temperatures. This is performed by calculating simulated brightness temperatures from the background and by comparing them with the observed brightness temperatures.

Simulation of satellite radiances with the current observation operator

The simulation of satellite brightness temperatures from the background is performed in two main steps, grouped together in the observation operator. The first step aims at
forming a model column that represents the atmosphere sounded and the second step is the effective brightness temperature calculation, using the model column formed in the first step.

In the AROME data assimilation process, the brightness temperature calculation is performed with the RTTOV radiative transfer model (Saunders and Brunel 2005).

Currently, the model column representing the sounded atmosphere is estimated at the centre of the satellite observation spot by interpolating the four closest model columns surrounding this point. This procedure, hereafter referred to as \textbf{Tb1column}, comes from previous assimilation systems for which the model mesh is larger than the observation spot.

It is however very rough for a 2.5 km resolution model: a single IASI or AIRS observation spot covers more than 12 AROME grid points at nadir, about a hundred at swath edge, and all these points contribute similarly to the measure (the instrument point spread function is quasi-uniform over the spot).

\textbf{Adaptations of the observation operator to the convective-scale}

We have modified the observation operator to aggregate the model information within the satellite spots.

A first modification affects the representation of the sounded atmosphere. We now compute the mean of all the model columns located in the observation spot and use this mean model column as representative of the sounded atmosphere to estimate the brightness temperature with RTTOV. This new operator is called hereafter \textbf{Tbspot1}.

In order to be further close to the way of how the instrument measurement is achieved, we also average the brightness temperatures estimated for each model column in the spot rather than estimate the brightness temperature from an averaged model information. This third version of the observation operator, called \textbf{Tbspot2}, is however much more computing time consuming which is an important drawback for an operational use.

\textbf{Statistical evaluation of the new observation operators}

\textbf{Evaluation method}

We will now evaluate the impact of these modifications of the observation operator. For that, IASI and AIRS brightness temperatures are simulated using the three observation operators at each clear AROME grid point situated over the Mediterranean Sea. We consider that a grid point is clear if the model contains less than $10^{-6}$ kg of hydrometeors per kg of air in the whole sounded atmosphere. These simulations are performed for all AROME analyses (every 3 hours) of September 2007. The brightness temperatures are calculated only for tropospheric channels because there are not enough AROME levels in the stratosphere to ensure a good representation of the radiative transfer in this part of the atmosphere. For AIRS, the calculations are performed for all the tropospheric channels that are not blacklisted in the data assimilation process of the ECMWF’s Integrated Forecasting System. For IASI, we also compute only the tropospheric channels that are not blacklisted in the ECMWF’s IFS for the temperature band. For IASI water vapour band, we compute all the tropospheric channels. With all these data, we compute statistics of the brightness temperature differences between calculations using the three observation operators presented above.
For reference, the instrument noise is also evaluated in terms of Noise Equivalent Differential Temperature (NEDT). For IASI we took the NEDT values at 280 K given in Blumstein (2007), for AIRS the values at 250 K given in Pagano et al. (2002 and 2003) and, for each channel, we computed the NEDT values at the mean brightness temperature over the month and at the mean brightness temperature plus or minus the brightness temperature standard-deviation over the month (to get an idea of the variation of the instrument noise).

To maximize the potential differences between the calculations using the various operators, the brightness temperatures are simulated for the maximum scan angle and therefore the maximum size of observation spot.

### Differences between the various observation operators

#### Differences between Tbspot1 and Tbl1column

Figures 1 and 2 show the standard-deviations of the brightness temperature differences between calculations using simply averaged (Tbspot1) and punctual (Tbl1column) model information, together with the instruments Noise Equivalent Differential Temperature (NEDT).

![Figure 1: Standard-deviation of the brightness temperature differences between calculations using Tbspot1 and Tbl1column and instrument Noise Equivalent Differential Temperature (NEDT) for IASI and AIRS water vapour channels.](image)

We can see on figure 1 that the standard-deviations of the brightness temperature (Tb) differences between calculations using Tbspot1 and Tbl1column are larger than the instrument noise for all AIRS water vapour channels and for IASI water vapour channels peaking under 350 hPa (wavelengths between 7 µm and 7.6 µm). Therefore, for all these channels, there are significant differences between the simple new observation operator Tbspot1 and the current one Tbl1column.

However, the differences between Tbspot1 and Tbl1column are negligible for temperature channels (cf. fig. 2 for IASI).

For each temperature and water vapour channel, the average of the brightness temperature differences is very close to 0 K: no new biases have been introduced.
Differences between $T_{bspot1}$ and $T_{bspot2}$

Figure 3 is similar to figure 1 but for the differences between the two new observation operators ($T_{bspot2}$, where the brightness temperatures are estimated for each model column in the observation spot before being averaged, and $T_{bspot1}$, where the model information within the observation spot is averaged before applying the radiative transfer). Figure 4 shows scattering plots comparing the brightness temperature differences between calculations using $T_{bspot2}$ and $T_{b1column}$ and the brightness temperature differences between calculations using $T_{bspot1}$ and $T_{b1column}$.

The differences between the two new observation operators are globally negligible (cf. fig. 3) even if $T_{bspot1}$ sometimes gives slightly larger - and probably overestimated - differences with $T_{b1column}$ than $T_{bspot2}$, in particular when we have large differences with $T_{b1column}$ (cf. fig. 4). As a consequence, the more realistic observation operator $T_{bspot2}$ being too much computing time consuming for an operational and real time use, from now on, we choose to work only with the simpler one, $T_{bspot1}$.
Figure 4: Scattering plots comparing the brightness temperature differences between calculations using Tbspot2 and Tb1column (ordinate) and the brightness temperature differences between calculations using Tbspot1 and Tb1column (abscissa) for all IASI (on the left) and AIRS (on the right) water vapour channels studied. The regression line is in red and the line y=x is in black.

**Characterization of the most important differences**

We have seen previously that using the simple new observation operator Tbspot1 instead of the current observation operator Tb1column may modify significantly the simulated brightness temperatures. Figure 5 shows that the importance of these modifications varies a lot with time and that their variations are consistent for the different channels. Thus, some specific situations with specific meteorological structures aggregate the most important differences between calculations using the various operators while in other situations, the differences are much smaller.
Figure 5: Time series over September 2007 of the standard-deviation of the brightness temperature (Tb) differences between calculations using Tbspot1 and Tbspot2 for the 4 IASI 2019 (8.7 μm), 2889 (7.32 μm), 2919 (7.28 μm) and 5381 (5.03 μm) (a) and the 4 AIRS 1455 (7.49 μm), 1520 (7.31 μm), 1627 (7.01 μm) and 1794 (6.4 μm) (c) water vapour channels, whose weight functions are shown on the right (b for IASI and d for AIRS).

Conclusions and outlooks

Aggregating the model information within the satellite spot, as it is done in the new observation operators Tbspot1 and Tbspot2, instead of using a single central model column (Tb1column) leads to significant differences in the simulated brightness temperatures for water vapour channels only (peaking under 350 hPa for IASI). These differences are particularly important in some specific meteorological situations. The study of these situations (not displayed here) shows that the most important differences appear in the places where fine-scale humidity gradients occur: with the new observation operators, the fine-scale
model humidity variations are filtered which is not the case with the current observation
operator Tb1column.

Averaging before applying the radiative transfer (Tbspot1) or after (Tbspot2) leads
in most cases in no significant differences. The new observation operators both simulate
brightness temperature fields at a scale which is more comparable with IASI and AIRS
measurements than the current observation operator. This may avoid the rejection of
some observations or too large analysis increments. This will be verified in a future work
by estimating if the brightness temperatures simulated with the new observation operators
are really closer to the real IASI and AIRS measurements. This will help in deciding the
possible implementation of Tbspot1 in the 3D-Var AROME assimilation scheme.

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The SSMIS Upper Atmosphere Sounding (UAS) channel set provides the first operational measurements of microwave radiation emitted by the earth’s atmosphere at mesospheric altitudes. The SSMIS receives polarized radiation in the 60 GHz oxygen complex, specifically the 7+, 9+, 15+ and 17+ O2 lines. Significant hardware and scientific technical challenges arise from microwave temperature sounding of the mesosphere. These include 1) addressing the impact of large Noise Equivalent Temperature Difference (NEDT) associated with narrow channel bandwidths; 2) achieving high channel center frequency stability; 3) compensation of large spacecraft-induced Doppler shift; 4) better characterization the Zeeman splitting of the oxygen absorption lines; 5) development of a fast polarimetric radiative transfer model (RTM). Preliminary global simulation results comparing the fully polarized NRL Line-by-Line (LBL) RTM with the fast RTM including Zeeman effects (CRTM-Z) showed the two models agreed to under a 1.0 K RMS, but the bias patterns indicated both residual geomagnetic and earth rotation Doppler signatures. Earth rotation Doppler signatures were shown to be significant when circular polarized radiation is being measured. The preliminary global simulations were performed using ECMWF analyses merged with COSPAR climatology above ~80 km level, and showed OB-BK biases in the 10-15 K for the highest peaking UAS channels. Results using the fast RTM with Zeeman effects to map the model backgrounds into SSMIS brightness temperatures for both NRL’s high-altitude global NWP model (NOGAPS-ALPHA) and the new L70 Met Office global forecast model (model lid at ~80km) will be presented. Details of the SSMIS UAS preprocessing steps required prior to assimilation will also be presented.
Due to improve the weather forecast through the geopotential height profiles data assimilation, this paper aims to present a case study occurred in the south of Brazil considering a period of the winter season (in the Southern Hemisphere), when strong raining events were occurred. This season were characterized by the incursion of several frontal systems which caused low temperatures, several strong raining and storms. The assimilation system used to data assimilation were the CPTEC's Data Assimilation System, the RPSAS – Regional Physical-Statistical Assimilation System, based on the DAO’s Assimilation System (PSAS). In this process, the geopotencial height profile were assimilated during the period and some of the results show that the 1-3 days forecast are improved for some variables like temperature and precipitable water for the analysis.
Impact of ATOVS geopotential heights retrievals on analyses generated by RPSAS

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Abstract: South America and the adjoining oceans are known for having a very irregular and sparse meteorological data acquiring net. The sparcity of data causes the Numerical Weather Prediction models operated by most weather predictions centers to perform worse than they should on computational capability. However, this lack of in situ observations has been addressed by the usage of satellite-processed radiances. In this work, conventional data (e.g. from surface and oceanic stations, airplane and radiosondes) and ATOVS retrievals, in the form of geopotential heights, were assimilated by RPSAS (Regional Physical-Space Statistical Analyses System) at CPTEC (Center of Weather Prediction and Climate Studies – Centro de Previsão de Tempo e Estudos Climáticos) and verifications were done with RPSAS outputs to quantify the impact of the assimilated data on its analyses. Also a case study was carried out about a frontal system that appeared in Brazil in 09 of July of 2007. Comparisons to a control experiment without ATOVS profiles, as Mean Absolute Error, were made to observe the impact of these retrievals on the analysis generated by RPSAS. Furthermore, an Analysis Impact Index (AI) was calculated by taking the NCEP analyses as a “perfect” representation of the atmosphere state at some synoptic times during the period of 01st to 31 of July of 2007. The results show that the profiles assimilation of the profiles provided improvements in analysis quality, although these improvements were not observed over the entire RPSAS domain.

Introduction:

In a data assimilation system, satellite data are combined with conventional data (e.g. surface data, TEMP) and short range forecasts (first guess) to yield a best estimate of the atmospheric state. This representation is the “analysis” and will be used as an initial condition to a new run of the atmospheric model. The satellite data can be used in one of two ways: the most traditional, using geophysical variables derived from vertical profiles, or by direct assimilation of the radiance (Joiner and Da Silva, 1998).
The main purpose of this study is to evaluate the impact of the assimilation of geopotential ATOVS (Advanced TIROS N Operational Vertical Sounder) retrievals on the analyses generated by RPSAS, and on the precipitation forecast generated by a frontal system that took place in the South region of Brazil in July of 2007.

The chosen frontal system started on the 9th of July and originated from a low pressure system in the state of Rio Grande do Sul. It then intensified due to a low level jet and a trough in medium and high levels, which gave support to the system at surface. By the coastline, this system went fast since Florianópolis-SC till Campos-RJ, where arrived on 12th of July. Due to its strength, anomalous precipitation totals were observed in its convective area and intense cold was also observed in the South of Brazil.

**Data and Methodology:**

Two experiments were conducted with RPSAS, coupled with Eta model, using a horizontal resolution of 20km. In the first, hereafter called ATOVS, conventional and geopotential ATOVS profiles were assimilated, from the 01st through the 31st of July of 2007. In the second experiment, hereafter called CONTROL, only conventional data were assimilated over the same period. The ATOVS profiles used in both experiments were obtained from the GTS (Global Telecommunication System) after using the Hydrostatic relationship.

NCEP analyses were interpolated for the Eta grid, after being processed by the global model CPTEC/COLA T213L42 to trigger its Physical packages.

With the RPSAS outputs some verification was performed:

A) The Mean Absolute Error (MAE) between the ATOVS and CONTROL analyses was calculated for the synoptic times of 00, 06, 12 and 18Z on the pressure surface layers of 850, 500 and 300hPa. In addition, the MAE was calculated for the mean of 00 and 12Z between NCEP’s analysis over the same period, for the temperature, specific humidity, geopotential height and zonal wind fields. In the first case, the spatial distribution of MAE indicates the regions where the profiles’ inclusion had the larger impact, although it does not indicate if there is improvement in the analysis quality.

B) The Analysis Impact Index (IP) was calculated for the ATOVS and CONTROL experiment analyses, taking NCEP analysis as the standard. IP was calculated using the formulation proposed by Zapotocny et al (2005) for forecasts and by Andreoli et al (2007) for analysis. The period used in the integrations was the 01st through the 31st of July, 2007, and the synoptic times were 00 and 12Z.
\[ IP = 100 \times \left[ \frac{\sqrt{\sum_{i=1}^{N} (\text{CONTROL}_i - \text{NCEP}_i)^2}}{N} - \frac{\sqrt{\sum_{i=1}^{N} (\text{ATOVS}_i - \text{NCEP}_i)^2}}{N} \right] \frac{\sqrt{\sum_{i=1}^{N} (\text{ATOVS}_i - \text{NCEP}_i)^2}}{N} \] (1.1)

This index indicates, as a normalized percentage, the positive/negative impact produced by the inclusion of ATOVS data on the same fields and levels of the latter analysis. Positive values show a closer relationship between the analysis generated by RPSAS (ATOVS experiment) and that of NCEP, while negative values indicate the contrary.

C) Analyses of precipitation forecast for 1 to 3 days, and subjective compares between ATOVS and CONTROL experiments data with observed data obtained from the INMET (National Meteorological Institute - Instituto Nacional de Meteorologia) observation net, for the period of 09 to 11 of July.

Results and discussions:

The verification based on MAE proves that the impact of assimilation of geopotential ATOVS heights is greatest at 06 and 18Z, except in the specific humidity fields (figures not shown). This fact is due to the larger number of profiles assimilated at those times (see Figure 1), which is a function of the satellite orbit (figure not shown). Thus, only the field states for 06 and 18Z will be presented for MAE.

Figure 2 shows the MAE values for temperature, zonal wind, geopotential height and specific humidity for the pressure levels of 850, 500 and 300hPa. It is possible to observe the regions where the assimilation of ATOVS profiles generates stronger impacts, in a monthly mean approach, in comparison with the CONTROL. Also it is observed that, except for the specific humidity, the impact was greater in high and medium levels.

Figure 3 presents the absolute difference between analyses from ATOVS and analyses from NCEP. This indicates the “mean accuracy” of the RPSAS, when it is assumed that the NCEP analyses represent the real, or perfect, state of atmosphere. The fields of geopotential and specific humidity are not shown.

When looking at the results for Analysis Impact Index (IP), it must be considered that they provide relative information. Figure 4 shows that, for the temperature field, there are negative impacts on North and South regions of Brazil, and on the adjoining Atlantic at 500hPa, and positive impacts in western Colombia and Peru. At 300hPa, positive impacts are seen over Northeast and North of Brazil, southeast of Argentina, and negative impacts over Southeast and South of Brazil, and on the adjoining ocean. For the zonal wind field, it is observed a negative impact over South and Southeast regions of Brazil and on the adjoining Atlantic, at 500 and 300hPa. Positive impact is observed northward of North...
region of Brazil, also at 500 and 300hPa. In the geopotential height field, negative impacts are observed over Atlantic Ocean close to South and Southeast regions of Brazil, at 500 and 300hPa, and positive on Northeast region of Brazil and adjoining ocean, at 500hPa. For the specific humidity field, it is observed at 850hPa, negative impacts over Center-West of Brazil, Southeast of Brazil and adjoining Atlantic. Positive impacts are seen, at that pressure level, on the Northeast of Brazil.

Figure 1: Typical distribution of ATOVS profiles along synoptic times for experiment ATOVS. (a) 09\textsuperscript{th}, at 00Z. (b) 09\textsuperscript{th}, at 06Z. (c) 09\textsuperscript{th}, at 12Z. (d) 09\textsuperscript{th}, at 18Z.

Figure 2: Mean Absolute Error for temperature, zonal wind, geopotential height and specific humidity fields for the synoptic time of 06Z (monthly mean for RPSAS analyses for the period of the 01\textsuperscript{st} through 31\textsuperscript{st} of July of 2007).
Figure 3: Mean Absolute Error for temperature and zonal wind fields. Mean for 00 and 12Z synoptic times averaged monthly for the period of the 01st through 31st of July of 2007.

Figure 4: Analyses Impact Index for Temperature, Zonal wind, Geopotential and Specific Humidity fields. Improvements to analysis are showed in yellow, orange and red. Aqua and dark blue shows the opposite.

Figure 5 shows the precipitation forecasts for 24, 48 and 72h for the ATOVS and CONTROL experiments and the observed precipitation data for 10th of July for the South region of Brazil. Like the comparisons conducted for the 09th and the 11th (figures not
shown), the precipitation fields from ATOVS and CONTROL with observed precipitation (derived from SYNOP net) indicate that the inclusion of ATOVS geopotential profiles does not yield better precipitation forecasts. This can be attributed to the Eta model deficiencies in forecasting precipitation. For the period studied, 48h and 72h forecasts produced better results than 24h forecasts, which is an already operationally known response of the Eta model (Espinoza et al, 2002, 2004).

Figure 5: Precipitation Forecasts for 1-3 days generated by CONTROL and ATOVS experiments, and the observed precipitation field for the 10th of July of 2007 (data from INMET).

**Final Comments and grateful:**

This preliminary study suggests that, for the period of July 1st to 31st, 2007, the ATOVS data assimilation yields a significant improvement in a quality of analysis fields over much, but not all, of the domain of RPSAS. More diagnostic studies are needed to determine, with more confidence and accuracy, the impacts of ATOVS geopotential height data assimilated by RPSAS over South America. Further studies will also evaluate whether there exists a temporal dependence (monthly or seasonal) in the experiment’s performance.
Further studies made by the Data Assimilation Group of CPTEC, in a form of Operational Research, suggested that the newer parameterizations of surface changes implemented to RPSAS implied a “spin-up” (time demanded for the system to be stabilized) of about two and a half months, because the boundaries conditions have been taken from Eta model instead of from global model CPTEC/COLA T213L42. This work was carried out using data processed within this spin-up period, and some care must be taken with analyses considered specially with humidity near the surface and other surface chances.

The first writer would like to thanks DSc Rita Valeria Andreoli and DSc Henrique de Melo Jorge Barbosa for their support and appreciated scientific comments and DSc Matthew Hoffman (University of Maryland) for the text revision.

References:


Investigating the assimilation of IASI data in a limited area model

Roger Randriamampianina

The assimilation of IASI data in the ALADIN/Norway data assimilation system at the Norwegian Meteorological Institute is being carried out in the frame of the THORPEX-IPY Norway project. This project aims to improve the accuracy of high-impact weather forecasts in the Arctic region. The use of limited number of channels is being tested at the first stage using all the available IASI field of view. The next step concerns evaluation of the use of IASI data applying different bias correction techniques.
Does the ATOVS RARS Network Matter for Global NWP?

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1. Introduction

Along with other global numerical weather prediction centres, the Met Office routinely assimilates data from Regional ATOVS Retransmission (RARS) networks, such as the EARS service provided by EUMETSAT. Recently additional data has been made available for the Asia-Pacific and South American regions. In this study we investigate the forecast impact of using this data in addition to the standard global ATOVS datasets. We also examine the forecast benefit if all ATOVS data arrived in time to make the main forecast runs. This latter study gives insight into geographical areas in which extensions to the RARS network would be useful.

2. Sources of ATOVS data

The main ATOVS data used at the Met Office are the global dumps arriving at the 1b level (antenna temperatures) from NOAA/NESDIS for NOAA's 15 to 18. Global MetOp data at the 1c level (brightness temperatures) arrives via EUMETCast. NOAA-18 1c data also is disseminated via this route and provides a level of robustness. In addition to these global streams, data from RARS stations arrives via ftp and EUMETCast at the 1c level.

Data from each RARS station is routinely checked for the following:

- Consistency of brightness temperatures against global equivalent
- Consistency of navigation against global equivalent
- Data delay (time between the observation and its arrival in the Met Office database)
- Robustness – how often does each station miss all available passes in 24 hours

Monitoring of the above is available on an external website (see Section 6). Figure 1 shows an example of the brightness temperature consistency check.

3. Use of RARS data in Operations

During a six hour assimilation window the volume of RARS data (from 17 stations) is typically in excess of 200000 observations. This is a large amount of data and so a duplicate check is applied prior to quality control and 1D-Var retrievals. Within this check observations from the same satellite that are within 20 km apart are considered duplicates, from which the global data is given preference. Consequently the RARS data is used to fill in regions where the global data did not arrive in time. At each analysis time (0, 6, 12, 18 UTC) two assimilation/forecast runs are performed, a main run and an update. The main run is the most time critical as the forecasts go out to two days, and at 0 and 12 UTC, to five days. Currently the main run starts 2 hours 45 minutes after the nominal analysis time, i.e. the 12 UTC run starts at 14:45 UTC. At six hours after the nominal analysis time an update run is performed, whose purpose is to provide a six hour forecast for the next cycle. Because of the time constraint it is in the main run analyses that we expect RARS data to be of most use, although it will also be of benefit in the update analyses should the global stream suffer an outage.
Figure 2 shows the RARS data that has passed the duplicate check for a series of main run. Note the large amount of NOAA-16 data which is being supplied by RARS. This is because over 24 hours several orbits from this platform suffer appreciable delays via the global stream. Once the duplicate check has been performed the global and RARS data streams are treated in an identical way through the pre-processing and assimilation, with the exception of channels from the HIRS instrument. These are rejected from RARS stations and not used in the assimilation step, due to the likelihood of missing calibration scans at the beginning and end.

![Figure 1](hirs_20080703_1656_noaa18_16080_cptl1c.l1de)

Figure 1: The brightness temperature difference between RARS and the corresponding global data for AMSUA channel 15 mapped to the HIRS grid. The RARS ground station is Cachoeira Paulista in Brazil.
of the overpass, which can lead to significant differences in the brightness temperatures between the global and local streams for this instrument. Figure 3 shows that typically around 25% of the satellite observations made during each assimilation window do not arrive in time via the global stream to make the main forecast runs, though on several occasions the loss can be in excess of 40%. The current network of RARS stations helps to fill in and typically recovers around 30% of the missing data.

4. The Impact of RARS in NWP

4.1 Robustness

Whilst the dissemination from NESDIS of the global stream is very reliable, there are occasional outages. In these cases RARS provides a useful backup as demonstrated by Figure
4 which shows the last occasion during which the global stream from NOAA platforms was unavailable.

**Figure 4:** An example of the amount of ATOVS data assimilated if the global stream from NESDIS was unavailable.

### 4.2 RARS Forecast Impact Experiments

In section 3 it was shown that a significant amount of ATOVS data is missing from the main forecast runs and so in the following section the impact of using this late data is investigated, along with an assessment of whether the RARS network can recover some of this impact.

This work follows on from an earlier study by Candy et al. (2004) which demonstrated that the late ATOVS data does have a useful forecast impact of between 1 and 4% in the 500 hPa height in the extra-tropics. The study also showed evidence that some of this impact was recovered by using data from the EARS network.

The investigation has been repeated as we now have a better distribution of RARS stations (Figure 5). However there are several factors which may result in a reduced impact from the late ATOVS data:

- 2004 study used AMSU data from three satellites (NOAAs-15, 16 & 17), in 2008 four satellites are assimilated (NOAA-16, 17 (HIRS only), 18 & MetOp-A).
- Svalbard downlink is now used for MetOp-A and certain orbits of NOAA-18 so timeliness of global stream improved for these platforms.
- In 2004 the sole satellite sounding information was provided by ATOVS, in 2008 AIRS, IASI & SSMIS are also operationally assimilated.
- In 2004 main run was started 2 hrs after analysis time, in 2008 this has been relaxed to 2 hrs 45 mins, so the amount of late data is reduced.
A control run of the global assimilation and forecast system was performed during mid-December 2007 to mid-January 2008 in which observations were assimilated as in operations, apart from ATOVS, which only used data from the global stream. All data arriving beyond a certain time limit was not used in the assimilation. This was set to 2 hrs 45 mins after the analysis time of each main run and mimics the operational schedule. Hereafter this run is referred to as *ATOVSG*. Two experiment runs were then performed:

- **RARS.** As *ATOVSG* and also RARS data from 17 stations for NOAAs 16 & 18.
- **ALL ATOVS.** As *ATOVSG* but the time limit is ignored for ATOVS observations only, i.e. all observations in the global stream are used regardless of their arrival time.

The forecast impact of the RARS and All ATOVS experiments against the control is summarised in Figure 6. This shows the impact on pressure at mean sea level (PMSL) forecasts for both northern and southern extra-tropical regions. The impact of the late global stream data that does not make the main run forecasts is significant, particularly in the Southern Hemisphere. The impact from the current RARS network is smaller, although provides a useful impact at long range (beyond 72 hours) in the Southern Hemisphere. This impact is perhaps smaller than might be expected, however it should be noted that for the principle ATOVS satellites used at the Met Office the RARS service only supports NOAA16 & 18, as currently the MetOp satellite does not broadcast the HRPT stream.
Figure 6: The forecast impact in the All ATOVS and RARS experiments.

Given the increasing number of RARS stations providing data it is instructive to examine the regions that are most sensitive to the late ATOVS data. In Figure 7 the RMS difference between the All ATOVS and ATOVSG main run analyses is shown. The largest differences are in the Southern Ocean and in the North Pacific regions and so it is potentially in these regions where further RARS stations would be of most benefit.

Figure 7: The RMS difference between the main run analyses at 12 UTC from the All ATOVS experiment and the ATOVSG control.
5. Conclusions

The RARS network has grown considerably over the last four years and now contains stations in both hemispheres. Global coverage has grown from ~25% to ~60%. This increased coverage makes it a useful auxiliary source of data in global models, both for robustness should the global stream be interrupted, and to provide more observations in the time-critical main forecast runs.

Experiments carried out during winter 2007/08 demonstrated that the late ATOVS data which does not make the main forecast runs has a significant forecast impact, even in an assimilation system that uses sounding data from several diverse systems such as AIRS and SSMIS. This shows that timeliness of the sounding data is still an important issue and use of the RARS network helps to recover some of the lost impact, particularly in the Southern Hemisphere.

Analyses appear to be most sensitive to the late ATOVS data in the Southern Ocean and North Pacific regions. Data from Argentina and the Antarctic Peninsula are also now available, while further expansion is expected during 2008 and 2009 – e.g. Hawaii, Fiji and La Réunion. These will be added at the earliest opportunity to the 17 RARS stations already used in Met Office operations.

6. References and Websites


NWP SAF Regional and Global ATOVS intercomparison Website:  
http://www.metoffice.gov.uk/research/interproj/nwpsaf/index.html
Satellite Data Assimilation over Antarctica: The Concordiasi Field Experiment

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1 Introduction

In the framework of the International Polar year, a field experiment will take place in Antarctica during the Austral Spring 2008 and 2009: Concordiasi.

(http://www.cnrm.meteo.fr/concordiasi, Rabier et al., 2007)

This project is supported by the following agencies: Météo-France, CNES, IPEV, PNRA, CNRS/INSU, NSF, NCAR, Concordia consortium, University of Wyoming and Purdue University. ECMWF also contributes to the project through computer resources and support, and scientific expertise. From September 2008, additional conventional observations will be operated over Antarctica such as radiosoundings at the Concordia (DomeC: 75°12′S, 123°37′E) and Dumont d’Urville stations (66°40′S, 140°E). Moreover, 600 dropsoundings will be dropped by twelve stratospheric pressurised balloons (SPB) in 2009. Thanks to these additional in-situ observations, studies will be performed in order to improve the assimilation of infrared and microwave observations over high latitudes.

The model chosen for these studies is the meteorological model of Météo-France, ARPEGE (Courtier et al., 1994), developed in collaboration with ECMWF. It uses an advanced data assimilation system (Rabier et al., 2000) and the Variational Bias Correction method (Auligne et al., 2007) for the treatment of the radiance biases.

The first main modification in order to study polar assimilation was to change the geometry of ARPEGE. The centre of the model has been moved southward from France to DomeC. With this stretched model, the horizontal scale is less than 30km over Antarctica (see the horizontal resolution in Fig. 1).

Based on a better resolution model over Antarctica, different problems associated to the high latitudes have been studied. The problem recalled in many papers (Barker, 2005, Nordeng (WMO bulletin, 2007), McNally, 2007, Powers, 2007) is the spatial and temporal density of observations for these latitudes. Over Antarctica, there are few conventional data and mainly on the coast (see Fig. 2).

Studies have already shown the positive impact of an increase of the number of data assimilated, such as GPS radio-occultation (Wee and Kuo, 2004, à verifier). The orbitography of polar satellites allows to enhance the time sampling of observations. The use of these data is restricted due to two main problems: the estimation of the surface emissivity and the cloud detection (McNally, 2007). These two points will be seen in the following section.
Fig. 1 – Horizontal resolution of the ARPEGE model, stretched on DomeC

2 Microwave sensors

Radiance assimilation depends on the difference in brightness temperature between the model and the observations. In order to improve the brightness temperature calculated by the model, a good estimation of the surface emissivity is needed. Usually, only the observations over open sea are assimilated thanks to a better estimation of emissivity over sea. Over land and mainly cold surfaces, the variability of the surface emissivity is much more complicated (Weng, 2003). For cold surfaces, the emissivity will depend on the vertical structure of the surface (presence of snow, first-year ice, multiyear ice) and of course of the physical properties of the different layers. The interaction between microwave radiation and the cold surface will vary in function of the frequency (variation of the depth penetration) (Mathew, 2007; Picard, 2007).

Karbou has developed a method, within the constraints of 4D-Var, to help the assimilation of the microwave observations over land (Karbou et al. 2006). These methods have been successfully tested at a global scale and have shown to be beneficial to our 4D-Var system. This approach is called a "dynamical approach". The emissivity derived from AMSU-A, channel 3 (50.3Ghz) and AMSU-B, channel 1 (89Ghz) are assigned to the temperature and humidity sounding channels respectively. We have compared this approach to the operational emissivity scheme (Grody, 1988 or Weng, 2001, depending on the frequency). The two approach for emissivity calculation use observations, but Karbou use also the measurement physics and the observations for each pixel in the assimilation system rather than a linear regression approach. The impact of these approximations at high latitudes is presented in Fig. 3 to 6 through the difference between the observations and the model (called "fg-departure"). Note that no bias correction has been applied to this difference.

Figures 3 and 4 show the fg-departure with the two approaches, for channel 5 (53Ghz) of AMSUA. The main difference between these figures is the decrease of the fg-departure.
Fig. 2 – Radiosounding assimilated over Antarctica in ARPEGE
So, the model with the dynamical approach has a better fit to the observations. As a consequence, more observations will be assimilated, in this case up to 41%. The impact can also be seen through the comparison of the histogram of the "fg-departure" (Fig. 5 and 6). The histograms have been calculated for a two-week period, over Antarctica.

In Fig. 5 and 6, the plots for the operational emissivity scheme is in light blue and the dynamical approach in dark blue. With the new approach, one can see, for all channels...
for each sensor, a histogram thinner and closest to the zero line. So, the model is closer to the observations for the dynamical approach. For example, the histogram with the operational emissivity show two peaks near -40K and 0K for the channel 2 of AMSUB (fig. 6). For the same case, with the new approach, the histogram have only one peak centred near OK, which reached more 10000 pixels. So, with this approach, most of the points are close to the observations.

Studies have also been performed over sea ice. Fig. 7 and 8 show the comparison between the operational and dynamical models for which the calculation of emissivity is based on satellite data, over sea ice. As for land studies, the difference between observations and the model is smaller in the case of the dynamical approach.

3 Infrared sensor

One aim of the campaign is the validation of IASI (Infrared Atmospheric Sounding Interferometer) sensor. As recalled before, the main problem with the estimation of the infrared emissivity over land is the cloud detection. Nowadays, in NWP, only clear radiances
are assimilated. In the cold regions, the radiative impact of a cloud is different. A cloud can be seen warmer than the surface and so more difficult to detect. The method used is called "cloud detect", developed by McNally and Watts (2003). A pixel can be classified as "cloudy", based on a cloud test. For one pixel, all channels will be examined and classified. Clear channels above the detected cloud will be kept and assimilated. A previous study by Dahoui, 2006, has shown that the cloud detection algorithm is not so accurate for low clouds at these latitudes. Specific problems to high latitudes is the detection of the Polar Stratospheric Cloud (PSC) (McCormick, 1982). Two infrared sensors have been studied: AIRS (Atmospheric Infrared Sounder) and IASI. In order to compare the cloud detection by the model for these sensors, satellite data not assimilated in operational, have been chosen as references. In the case of the AIRS sensor, profiles along the track of this sensor have been compared to CloudSat product (Fig. 9a and b). The CloudSat (Nasa-Colorado State University - Department of Energy) mission, part of the A-Train constellation, has an on-board millimeter wavelength radar (Stephens et al., 2002). The product shown here on Fig. 9a is the radar reflectivity (2B-GEOPROF data product), the 9th January 2008 over Antarctica. Fig. 9b show the Cloud Fraction defined by the Cloud Detect method in ARPEGE, for AIRS track, the same day. 0 means clear pixel and 1 for cloudy. For one pixel, each channel is plotted. On the both figures, the abscissa axis give an information on the time along the track of the satellite. The ordinate axis indicates
the range (km) for the reflectivity radar and the maximum of the weight function (hPa) for AIRS. Orography is also represented by the black curves on plots.

![Graph](image)

Fig. 9 – Reflectivity Radar (Z) (dBZ) from CloudSat, on the left side (9a). Cloud Fraction for AIRS/ARPEGE, on the right side (9b). The dark line on 9b indicates the orography.

The comparison of Fig. 9a and b, shows quite a good agreement between CloudSat and AIRS/ARPEGE. For example, the good detection of the presence of the cloud near the time 17.16s for CloudSat and 17.08s, for AIRS.

For the IASI sensor, the cloud fraction (0: clear; 1: cloud) is compared to the MODIS cloud product (Fig 10a and b). MODIS (MOderate Resolution imaging Spectroradiometer), on Aqua, supplies informations about cloud properties (such as cloud particle phase or cloud top temperature ... ) (Platnick, 2003). Cloud Top Pressure product of MODIS has been compared to cloud fraction of IASI/ARPEGE for the Channel 242. Channel 242 has a maximum of weighting function at 286 hPa. This channel brings an information on the localisation of the high cloud.

Around the Antarctica Peninsula, the comparison of the two figures shows a good agreement in the position of the cloud for high clouds. For example, the pixels, located on the Antarctica Peninsula, between 60°S and 65°S, where the cloud top pressure reaches 300hPa (in blue on Fig. 10a) are also seen cloudy (red pixel on Fig. 10b) by IASI/ARPEGE. Of course, this channel will be classified as clear for all clouds in the lower layer of the troposphere.
Fig. 10 – Cloud Top Pressure (hPa) for MODIS, on the left side (10a). Cloud Fraction for IASI/ARPEGE (10b), on the right side, for the channel 242. For Cloud Fraction, 0: clear, 1: cloudy.

4 Conclusion

These preliminary tests have shown a positive impact, at high latitudes (over sea ice and land), of the assimilation of the microwave sensors (AMSU-A/B), using the emissivity dynamical approach, developed by Karbou. In a future work, the assimilation of microwave data will be performed adjusting thresholds for these areas. Moreover, recent studies on the emissivity computation, show that using a lambertian or semi-lambertian surface rather than a specular surface could be interesting.
For infrared sensors, the "cloud detect" method seems to bring quite good results over cold areas. This last point indicates that the assimilation of IASI and AIRS, in the troposphere, over cold land could be possible. Of course, more tests must be done, to continue the validation of "cloud detect" over cold surfaces. Other methods such as MMR (Methode Multi-variee du Residu Minimum) (Auligne, 2007) could also be tested.

5 Reference


Mathew N., 2007 : Retrieval of Surface Emissivity of Sea Ice and Temperature Profiles over Sea Ice from Passive Microwave Radiometers, Berichte aus dem Institut für Umwelphysik.


Case studies of 4D-Var assimilation of potential vorticity observations derived from image processing

Y. Michel and F. Bouttier

Short-range forecasts errors occurring in numerical weather prediction are often diagnosed by forecasters as being displacement errors: forecast locations of meteorological structures are displaced from their observations, and this displacement can be evaluated through inspection of satellite images. However, current representations of background error are based on Gaussian assumptions, and linear or weakly non-linear data assimilation schemes are used to correct errors. This hypothesis is more and more critical as resolution increases and as the meteorological situation evolves more and more non-linearly. Therefore, high resolution forecasts models of strongly non-linear processes, such as thunderstorms or tropical cyclones, need a different, more realistic initialization. Some methods have been developed to identify and correct the position and amplitude of storm-scale thunderstorms and of tropical cyclones, including bogussing practices and variational assimilation of simulated observations. Despite the growing number of radiance data being assimilated, global models sometimes fail to predict mid-latitude cyclogenesis, even if the upper or lower level precursors are visible in the images from advanced sounders or geostationary satellites. Different operational procedures, often based on potential vorticity inversion, have been developed to exploit the link between water vapour images and the initial state of the upper level of the troposphere. Our goal is to build observations of potential vorticity that correct the displacement and amplitude error of the dry intrusions using a image satellite processing technique. An algorithm developed for the identification and tracking of dry intrusions in water vapour imageries is used to define potential vorticity pseudo-observations in the upper troposphere. A simple object-based methodology produces observations that are built to locally correct the amplitude and displacement errors as diagnosed from the comparison of the trajectories in the image processing tool. An approximate form of Ertel potential vorticity operator is used to incorporate the pseudo-observations inside a 4D-var assimilation scheme. It is applied to real cases of cyclogenesis forecasts and within an operational data assimilation scheme, the high resolution (20 km over Europe) global model ARPEGE. Experiments on several cases studies highlight the ability of the algorithm to correct locally the tropopause and to partially improve the forecasts of the cyclogenesis. Advantages and drawbacks of this procedure are finally discussed.
Impact of variable O3 and CO2 on assimilation of high spectral resolution sounder data

J. Cameron, S. English, F. Hilton, E. Pavelin

The bias of AIRS observations relative to observations simulated from the Met Office global model show both seasonal variations and an on-going trend. Some of these changes are clearly caused by upgrades to the model but others are due to variable gases and in particular O3 and CO2. The variations that have been observed are displayed and possible approaches to reduce the effect of variable O3 and CO2 are presented.
Impact Analysis of Assimilation of Integrated Water Vapor Estimates from AIRS/AMSU over Amazonian Region

Luiz Fernando Sapucci, Dirceu Luis Herdies, Rita Valéria Andreoli, Renata Weissmann, B. Mendonça, Rodrigo Augusto F. de Souza, Sérgio Henrique S. Ferreira, José Antônio Aravéquia

The Amazonian region is one of the most humid of the planet [Integrated Water Vapor (IWV) median values are in the order of 50 kg m\(^{-2}\)] and it is also characterized by large space-time variability in the humidity fields. The cause of this large variability is the intense convective activity associated with the great humidity potential generated by high temperatures. Consequently, in the Numerical Weather Prediction the usage of initial conditions with errors in characterizing humidity over Amazonian region can generate erroneous precipitation forecast in the some areas over South American continent. In this aspect, there are two important points. The first point is the most realistic atmospheric state depends significantly on available data, and the second one is the low density of conventional information in the Amazonian region. Data from Atmospheric InfraRed Sounder/Advanced Microwave Sounding Unit (AIRS/AMSU) incorporate the most recent inversion procedure, which are able to produce IWV values of good quality over continental areas. Nowadays, this sensor is one of the most important sources of humidity over Amazonian region. Within this context, the present study investigates the impact on humidity forecast over Amazonian region with the inclusion of IWV estimate from AIRS/AMSU in the CPTEC data assimilation system: Physical-space Statistical Analysis System (PSAS). Two different cyclic processes using Atmospheric Global Circulation Model CPTEC/COLA were carried. In the first cyclic process all available data were assimilated, such as geopotential height from temperature profiles measured by NOAA/ATOVS [Advanced TIROS Vertical Operational Sounder]; derived surface winds from Quik Scatterometer; Cloud Track Wind from geostationary satellites; conventional data (SYNOP, BUOY SHIP, radiosonde, aircraft, pilot balloons); and IWV values over ocean region from the SSMI/DMSP (Defense Meteorological Satellite Program). In the other cyclic process the same data set was assimilated with the IWV values from AIRS/AMSU. The results obtained applying factor separation show that the inclusion of IWV-AIRS values present a significant impact in the IWV values from initial conditions over Amazonian region, the which is also observed in the short-range predictions of humidity. Some studies are being carried out using rainfall data from TRMM Passive Microwave Sensor to evaluate this impact on precipitation forecast.
Towards better usage of AMSU observations over land at ECMWF

Blazej Krzeminski, Niels Bormann, Fatima Karbou, Jean-Noel Thepaut, Anthony McNally and Peter Bauer

Assimilation of AMSU observations over land at the ECMWF has been limited in case of channels receiving strong contribution from the surface. This is due to the difficulties in accurately estimating surface emissivity in the microwave frequencies. Currently used ECMWF land surface emissivity models and their limitations will be discussed. There is an ongoing effort to improve the emissivity estimations. Retrieving emissivities from the observations in the microwave window region showed to be a promising approach. Issues covered in the presentation also include correction of biases and the quality control of the observations over land in the context of Numerical Weather Prediction.
A series of data withholding experiments was conducted with the Global Physical-space Statistical Analysis System (GPSAS) - a combination of the Spectral Atmospheric Global Circulation Model (CPTEC/COLA) with the Physical-space Statistical Analysis System (PSAS) -, with the purpose of assessing the relative contributions of the several types of observation within the context of the CPTEC data assimilation system. In these experiments one or more type of observation is removed from the assimilation cycle and the impact on the forecast skill indicates the effectiveness of that source of observation in the system. The major observing system included the conventional data (SYNOP, BUOY, SHIP, radiosonde, aircraft, pilot balloons), and satellite data (ATOVS and AIRS/AMSU retrievals, QuikScat wind, Cloud Track Wind and Total Precipitation Water from SSM-I sensor). The experiment including all these data is called control experiment and it is used as reference. The experiments involving “data denied” indicated that conventional data including all surface observations (SYNOP, SHIP, BUOY), rawinsonde and aircraft data, are the primary source of information utilized by GPSAS in the Northern Hemisphere. The largest impact in the Southern Hemisphere (SH) was obtained when all satellite-derived retrieval data were removed. Additional experiments were performed to assess the impact of removing ATOVS and AIRS/AMSU retrievals data individually. The results showed that withholding the AIRS/AMSU retrievals has a greater impact than withholding the ATOVS retrievals data. This disparity may be associated to fact that the AIRS/AMSU retrievals are reported in assimilation cycle as it independent observation of the model, while ATOVS retrievals were anchored in the first guess field generated by model. Over the South America, AIRS/AMSU retrievals and conventional data present similar contribution and have a positive impact on all range forecast (1-5 days). Besides it is found that all the types of observations generally contribute in a positive way to the overall improvement of the CPTEC forecast system. However, is important to note that the impact of several observations varies depending on the chosen verifying variable, vertical level or forecast period.
Assimilation of cloudy AIRS observation in the French global atmospheric model: ARPEGE

T. Panguaud, V. Guidard, N. Fourrié, F. Rabier, P. Poli
Météo-France/CNRM-CNRS/GAME

July 9, 2008

Abstract

Infrared and microwave clear-sky observations from polar orbiting satellites are assimilated in the French numerical weather prediction (NWP) model ARPEGE through a 4 dimensional variational (4D-Var) assimilation scheme and represent an important source of information. Since the end of 2006, a few stratospheric channels of the Atmospheric InfraRed Sounder (AIRS) are assimilated in ARPEGE. On the other hand, a large majority of measurements from such advanced infrared sounders are affected by clouds, and cloud contaminated observations are currently rejected by the data assimilation system. The observation operator which simulates the radiances from model fields include a radiative transfer model, RTTOV in the case of ARPEGE. Since clouds can affect the infrared observations, a cloud detection is necessary before data are assimilated. Several cloud detection schemes have been used: a cloud detection scheme based on channel ranking, called Cloud-Detect, from the ECMWF; a CO2-slicing method and a cloud detection based on the simulation of the sea surface temperature. Previous studies have shown that the two first cloud detection schemes are the most accurate ones. This paper focuses on the validation of both schemes applied to AIRS, by using independent data coming from the MODIS imager and from the POLDER radiometer. The validation of the cloud top pressure will also be discussed. It is now well known that the sensitive regions, where cyclones occur, are often cloudy. This motivates our research efforts to assimilate AIRS cloudy radiances inside the 4D-Var assimilation scheme. Two approaches may be tested: the first one uses the cloud top pressure and the cloud cover derived from the CO2-slicing technique (CO2-slicing outputs are directly used by RTTOV to simulate the cloud-affected spectrum). In the second one, CO2-slicing outputs are adjusted by a prior 1D-Var before being used by RTTOV. Preliminary experiments have been done which consisted in assimilating AIRS radiances, including those contaminated by clouds between 600 and 950 hPa, only over sea for 54 stratospheric and tropospheric peaking channels. A slightly positive impact is found for the first method. The impact of the cloudy assimilation on cloud fields in ARPEGE will be studied in this paper.

1 Introduction

Infrared and microwave clear-sky observations from polar orbiting satellites are assimilated in the French Numerical Weather Prediction (NWP) global model ARPEGE through a 4 dimensional variational (4D-Var) assimilation scheme and represent an important source of information. The Atmospheric Infrared Sounder (AIRS) onboard Aqua satellite makes part of a new generation of advanced satellite sounding instruments (with IASI) which allows to provide information about atmospheric temperature and humidity profiles with spectral resolution far exceeding that of previous sounders (HIRS). These highly informative observations are to be used to improve NWP analysis and forecast accuracy. On the other hand, a large majority of measurements from such advanced infrared sounders are affected by clouds (90%), and cloud-contaminated observations are currently rejected by the data assimilation system because of the deficiencies in the representation of cloud processes within the atmospheric models. Furthermore, it is now well known that the sensitive regions, where cyclones occur, are often cloudy (McNally, 2002; Fourrié and Rabier, 2004). This motivates our research efforts to assimilate AIRS cloudy radiances inside the 4D-Var assimilation scheme.
Since clouds can affect the infrared observations, clouds have to be detected before data are assimilated. Indeed, unfiltered cloud observations can have a negative impact on the quality of NWP analysis. Several cloud detection schemes have been used: a cloud detection scheme based on channel ranking, called Cloud-Detect, from the ECMWF (European Centre for Medium-range Weather Forecast); a CO2-slicing method and a cloud detection based on the simulation of the sea surface temperature. Previous studies have shown that the two first cloud detection schemes are the most accurate ones (Dahoui M., 2005).

This paper first focuses on the validation of both schemes applied to AIRS, by using independent data coming from the MODIS (Moderate Resolution Imaging Spectroradiometer) imager. The validation of the cloud top pressure will also be discussed for the CO2-Slicing scheme. After the validation of both cloud schemes, the method used to directly assimilate cloudy radiances in the 4D-VAR assimilation scheme of ARPEGE will be presented in a third part. The results in term of impact on the quality of the analysis product and on the accuracy of the forecast of this first step of assimilation of cloudy radiances will then be discussed.

2 Validation of AIRS clouds detection schemes

2.1 AIRS clouds detection scheme

2.1.1 ECMWF scheme

The ECMWF scheme ( McNally and Watts, 2003 ) aims at detecting clear channels within a measured spectrum rather than the location of totally clear pixels. If the background spectrum is close enough from the true state of atmosphere, the cloud signature is identified by the first-guess departure of the observed spectrum from clear-sky background values. Channels are first re-ordered into a vertically ranked space that reflects their relative sensitivity to the presence of cloud. The ranking consists in assigning for each channel, a pressure level \( p \) (in RTTOV coordinates) at which the radiation effect of a one-layer black cloud defined as \( \frac{R_{\text{clear}} - R_{\text{cl,clear}}}{R_{\text{clear}}} \) at \( p \) is less than 1%. \( R_{\text{clear}} \) denotes the simulated clear radiance and \( R_{\text{cl,clear}} \) denotes the simulated black-body radiance at the cloud level \( p \).

A low-pass filter is then applied to the ranked departures to reduce the instrument noise and the cloud emissivity effect.

Finally a search for the channel at which a monotonically growing departure can first be detected permits to determine the first significant cloud contamination. Having found this channel, all channels ranked less sensitive are flagged free and all channels ranked more sensitive are flagged cloudy.

2.1.2 CO2-Slicing scheme

The CO2-Slicing method ( Chahine, 1974; Menzel, 1983 ), based on radiative transfer principles, is currently used to retrieve cloud-top pressure (CTP) and effective cloud emissivity or effective cloud amount (ECA). This method uses a simplistic cloud model: cloud is considered as a single layer of opaque or semi-transparent thin cloud with an homogeneous emissivity. The algorithm uses observed radiances of a set of AIRS channels selected in the CO2 absorption band: 124 channels situated in the spectral band between 649 cm\(^{-1}\) and 843 cm\(^{-1}\) ( which is very sensitive to the presence of clouds ) are used for this study. For each AIRS pixel, and for each channel of the set, the following function is calculated:

\[
F_{k,p} = \frac{(R_{\text{clear}}^k - R_{\text{cl,clear}}^k)}{(R_{\text{clear}}^k - R_{\text{meas}}^k)} - \frac{(R_{\text{clear},p}^k - R_{\text{ref},p}^k)}{(R_{\text{clear}}^k - R_{\text{cl,clear},p}^k)},
\]

where:

- \( p \): pressure level number,
- \( k \): channel in the CO2 band,
- \( k_{\text{ref}} \): reference window channel ( 979, 1279 cm\(^{-1}\) ),
- \( R_{\text{meas}}^k \): measured radiance in channel \( k \),
• $p_{clea}^k$: simulated clear radiances in channel $k$.
• $R_{clid}^k,p$: simulated black-body radiances for channel $k$ at the cloud level $p$.

The cloud-top pressure level $p_{c,k}$ assigned to each channel $k$ is the pressure level which minimizes the function $F_{k,p}$. Before the determination of the CTP of an hypothetic cloud, a filter which distinguish channels with $\Delta T Bs$ ($\Delta T Bs$ represents the difference between observed brightness temperature and simulated brightness temperature) lower than the radiometric noise is applied to the algorithm. If all channels are filtered, the pixel is flagged clear.

If the pixel is cloudy, the cloud-top pressure $p_c$ is then calculated by the following expression:

$$p_c = \frac{\sum p_{c,k} w_k^2}{\sum w_k^2}$$

where $w_k = \delta F_{k,p}/\delta \ln p$ is the derivative of the cloud pressure function.

The effective emissivity is obtained for each AIRS pixel by the following expression:

$$N_e = \frac{(R_{clid}^{k,ref} - R_{clea}^{k,ref})}{(R_{clid}^{k,ref} - R_{clea}^{k,ref})}$$

If the algorithm produces a retrieved $N_e$ smaller than 0.1, the pixel is flagged clear. The pixel is rejected if the algorithm generates a retrieved $N_e$ lower than 0 or larger than 1.2 (non physical emissivity).

2.2 A validation based on independant data: the imager MODIS

2.2.1 MODIS cloud description

The first part of this study aims at statistically comparing both above-described cloud-detection schemes applied to AIRS data onboard Aqua satellite. Independent data are thus required to get an accurate reference. For this study, we have used a cloud-detection scheme product based on MODIS data. The MODIS imager is a key instrument onboard the EOS Terra and Aqua satellites which provides global observations of Earth’s land, sea and atmosphere in 36 spectral bands ranging from 0.41 $\mu$m to 14.385 $\mu$m (visible, near infrared and infrared regions). In this study we have used the MODIS Cloud data product file MYD06-L2, containing level 2 data collected from the Aqua platform. The determination of cloud-top properties will require the use of MODIS bands 29 and 31 to 36, along with the cloud-mask product to screen for clouds. Two output parameters were retrieved to validate our cloud-detection schemes: the Cloud-Fraction (Day and Night) and the Cloud-Top-Pressure (Day and Night). These level-2 Cloud Product parameters are produced at an horizontal resolution of 5 km at nadir and cover a five-minute time interval. We have used in this study, Cloud data products from the ICARE centre (http ://www-icare.univ-lille1.fr/archive/index.php?dir = MODIS/MYD06L2/) which produces and distributes remote sensing data derived from Earth observation missions from CNES, NASA and EUMETSAT.

2.2.2 Spatial collocation of MODIS and AIRS

As noted above, MODIS cloud product will be used to evaluate the accuracy of AIRS cloud detection scheme. This requires a MODIS cloud description for each AIRS pixels. Because MODIS and AIRS are two independent instruments with different scanning geometry and resolution, the merge of MODIS into AIRS geometry is necessary. The first step is to represent each AIRS pixels as an oversized circle according to Tobin method (Tobin et al., 2006): each diameter of AIRS pixel is 10% oversized; the nadir footprint is then considered as a circle with a diameter of 14.85 km (instead of 13.5 km) and at the maximum scan angle of 49.5°, the footprint is considered as a circle 36.3 km (instead of an ellipse which a 33 km-long major axe). The representation of AIRS footprints as circle leads to a better computational efficiency in case of large scale collocation with as good results as without this approximation. The second step is to determine MODIS pixels that are geolocated within the AIRS footprint determined above by a mapping algorithm. Finally, the third step is to compute the weighted average of each MODIS pixels values (in function of the relative distance between the geolocated MODIS pixel and the center of the AIRS circle) geolocated within a AIRS footprint.
2.3 Comparison of the BOMIP scheme and the CO2 Slicing scheme with MODIS imager

2.3.1 Data sets

Due to downloading resource limitations, the comparison is limited to the Atlantic region from 60° South to 60° North; only situations over sea have thus been processed. The validation is performed within a ten day and ten night period: from 01 to 10 September 2006. The validation was performed from 13h00 to 15h30 UTC during daytime and from 02h00 to 04h30 UTC during night-time (when AQUA is above Atlantic ocean). A total of 6538 AIRS pixels during daytime and 9168 AIRS pixels during night-time have been processed. For both cloud-detection algorithms, the same subset of 124 channels is used (those situated in the CO2 band).

2.3.2 Results and discussion

Once AIRS and MODIS data are collocated, categorical contingency tables will split data into 4 different categories (see following table) which will then be used to compute some verification scores to evaluate the accuracy in term of detection of both cloud-detection scheme.

<table>
<thead>
<tr>
<th></th>
<th>HITS</th>
<th>FALSE ALARMS</th>
<th>forecasted cloud</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MISSES</td>
<td>CORRECT REJECTIONS</td>
<td>non forecasted cloud</td>
</tr>
<tr>
<td>observed cloud</td>
<td></td>
<td></td>
<td>N=total</td>
</tr>
</tbody>
</table>

The verification scores are:

- the frequency bias (BIAS) which gives the ratio of the forecast cloud frequency to the observed cloud frequency:

  \[ BIAS = \frac{HITS + FALSEALARMS}{HITS + MISSES} \]

- the proportion of correct (PC) which gives the fraction of all forecasts (by MODIS) that were correct:

  \[ PC = \frac{HITS + CORRECTREJECTIONS}{N} \]

- the probability of detection (POD and POD') which measures the fraction of observed events that were correctly forecast by MODIS (POD is a cloudy pixel event and POD' is a clear pixel event):

  \[ POD = \frac{HITS}{HITS + MISSES} \]
  \[ POD' = \frac{CORRECTREJECTIONS}{CORRECTREJECTIONS + FALSEALARMS} \]

- the false alarm ratio (FAR) which gives the fraction of forecast event that were observed to be non-events:

  \[ FAR = \frac{FALSEALARMS}{HITS + FALSEALARMS} \]

- the non detection rate (NDR) which measures the fraction of observed events that were badly forecast:

  \[ NDR = 1 - POD \]
In this study, clear/cloudy thresholds have been chosen according to Lavanant (Lavanant et al., 2004): a pixel is flagged cloudy by MODIS if the retrieved cloud fraction is more than 5% and a pixel is flagged cloudy by CO2-Slicing if the retrieved cloud fraction is more than 10%. With the Cloud-Detect scheme, a pixel is flagged cloudy if all channels used in this algorithm are cloud-free. As mentioned in part 2.1.2, the CO2-Slicing scheme can produce a non-physical retrieved Ne. According to Dahoui (Dahoui, M., 2005), these pixels with non-physical Ne are clear in most of cases but we have noticed that some of these pixels are flagged cloudy by MODIS (about 30%) and we thus made the choice not to evaluate these pixels.

The following table gives the main results in term of accuracy of detection for both cloud-detection scheme during day and night:

<table>
<thead>
<tr>
<th></th>
<th>Cloud-Detect</th>
<th>CO2-Slicing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day</td>
<td>Night</td>
</tr>
<tr>
<td>BIAS</td>
<td>80%</td>
<td>83%</td>
</tr>
<tr>
<td>PC</td>
<td>80%</td>
<td>76%</td>
</tr>
<tr>
<td>POD</td>
<td>82%</td>
<td>78%</td>
</tr>
<tr>
<td>POD*</td>
<td>65%</td>
<td>63%</td>
</tr>
<tr>
<td>FAR</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>NDR</td>
<td>18%</td>
<td>22%</td>
</tr>
</tbody>
</table>

Results show that a small percentage of "FALSE ALARMS" is found for both schemes: between 6 and 8% and between 3.5 and 4.5% respectively for the Cloud-Detect scheme and the CO2-Slicing scheme (not shown). These percentages can mainly be explained by two reasons: (i) the bias correction could be not stringent enough and systematic biases remain and (ii) schemes are tuned to reject some doubtful clear pixels instead of assimilate a cloudy pixel as a clear one (Dahoui, M., 2005). A small percentage of "MISSSES" is also found for both schemes (about 20% for the Cloud-Detect scheme and 18% for the CO2-Slicing scheme): it can be explained by (i) the lower spatial resolution of AIRS according to MODIS (13.5 km against 5 km) which prevent the detection of fractional clouds (sub-pixel clouds) by AIRS; (ii) the weakness of both cloud detection schemes to detect low clouds (as we will see below). However, this percentage is not due to a bad choice of clear/cloudy threshold for MODIS (5%) as results are worst with a 10% threshold (not shown).

As we can see in the above-written table, the Cloud-Detect scheme seems to produce better results during daytime: 89% (BIAS) of forecast clouds are actually observed (83% during night-time), 82% (POD) of the observed clouds are actually forecast (78% during night-time), the detection of clear pixels (POD*) and the proportions of correct (PC) are also better during daytime. An opposite diagnostic can be made for the CO2-Slicing scheme: both BIAS, PC and POD are better from 2 to 4% during night-time. POD*, much better during daytime, is the only remaining exception for the CO2-Slicing. These day/night statistics are made under the hypothesis of same performances of MODIS during the day and during the night. Although a sea surface temperature (SST) test has been implemented to improve the MODIS cloud mask during the night (Baum, 2006), we did not find any study which compare the day/night performances of the MODIS cloud mask.

Furthermore, performances of both schemes are comparable in BIAS, PC, POD, FAR and NDR (the CO2-Slicing is more accurate than Cloud-Detect during night-time but the latter is more accurate during daytime). However, the detection of clear sky pixel which is comparable for both schemes during night-time is much more performant for CO2-Slicing during daytime.

Figure 1 highlights the accuracy of cloud detection (POD) according to cloud-top pressure for both schemes in a diurnal cycle. As we can see, the detection of high clouds (cloud-top pressure <400 hPa) is better during night-time (except between 300 and 400 hPa for the Cloud-Detect scheme). This could be explained to a better accuracy of the SST used in both scheme during night-time. Performances of both schemes are comparable during night-time but the Cloud-Detect is more performant to detect this kind of cloud during daytime. The detection of medium clouds (between 400 and 800 hPa) delivers the best results. This detection is better for CO2-Slicing during night-time than for the Cloud-Detect but the latter is better during day-time. Finally the detection of low clouds (cloud-top pressure >800 hPa) delivers the worst results. This detection is better during night-time for both schemes.
Figure 1: Efficiency of the cloud detection according to the retrieved PTOP from MODIS. Validation from 09/01/06 to 09/10/06. The thick solid line represents the potential of detection of clouds of the CO2-Slicing during the day, the thick dashed line represents the potential of detection of clouds of the Cloud-Detect during the day, the thin solid line represents the potential of detection of clouds of the CO2-Slicing during the night and the thin dashed line represents the potential of detection of clouds of the Cloud-Detect during the night.

Figure 2: Cloud Top Pressure accuracy for CO2-Slicing for Day (left) and Night (right) according to MODIS Cloud Top Pressure. Validation from 01/09/06 to 10/09/06.

The retrieved PTOP from CO2-Slicing exhibits a quite good correlation with the PTOP inferred with MODIS for both day (figure 2(a)) and night (figure 2(b)). This result seems normal because the MODIS cloud height is based on a CO2-Slicing method. The difference observed in figure 2 (specially for low
3 Assimilation of cloud-affected Infra-red satellite radiances

In the previous chapter, the cloud detection scheme validation permitted first to consolidate our skill in term of assimilation of clear radiances, namely a good detection and rejection of pixels contaminated by clouds. With the CO2-Slicing method, tools are also made available to classify an AIRS pixels in function of the nature of a potential cloud. In the following chapter we will use these characterization tools to assimilate cloudy radiances.

3.1 Methodology : direct use of the CO2-Slicing cloud parameters

The observation operator for the assimilation of cloudy radiances consists in this work of a cloud scheme (CO2-Slicing) and a radiative transfer model (RTM), RTTOV : in this approach, cloud parameters (CTP and ECA) are retrieved from infrared radiance measurements using the CO2-Slicing algorithm and are then directly used as inputs of RTTOV which will then simulate the cloud-affected spectrum. In this method, ECA and CTP are thus determined in the beginning of the assimilation cycle with no adjustments during the minimisation.

3.2 Simulation study framework

3.2.1 Satellite data

This study uses data from AIRS. We have used in this study a subset of 54 channels located in the temperature long-wave window chosen among the 2378 channels available on AIRS instrument: 20 stratospheric channels with weighting-functions peaking from 69 to 102 hPa and 34 upper-tropospheric channels with weighting-functions peaking from 122 to 478 hPa. This channel subset is the operational one in Météo-France since July 2008. The assimilation period of this study is 5 week long, from the 01/09/06 to the 05/10/06. First experiments have been run in a simplified framework: AIRS radiances have been assimilated, included those contaminated by clouds between 600 and 950 hPa, only over sea.

3.2.2 Model data

The NWP model used in this work is ARPEGE (Courtier et al., 1991) which is Météo-France operational global model. The code version used here is the CY32r0 with a 4 dimensional variational (4D-VAR) assimilation. Satellite radiance data are bias corrected using the variational bias correction VarBC (Dee, 2004; Auxilné et al., 2007). As we have seen in the part 3.1, the model needs a RTM to simulate radiances from atmospheric, geophysical and spectroscopical variables. In this work, we use a fast RTM, the 8.5 version of RTTOV which is the operational version of RTTOV in Météo-France.

Two different types of experiments have been run to test the impact of the direct assimilation of cloudy radiances: the first one (B0A8) assimilates cloudy radiances in the configuration presented in part 3.1; the second one (B0A9) is a reference experiment which only assimilates clear radiances, similarly to an operational configuration.

3.3 Results

3.3.1 Impact on analyses

The impact of the assimilation of cloudy radiances on the analysis will be evaluated by comparing biases and root mean square (RMS) errors of both analyses and background with respect to various observations, for the experiment and the reference. This impact will be evaluated over 18 days, from the 12/09/06 to the 30/06/09.
We first can remark that model errors are almost not impacted by the assimilation of cloudy radiances (not shown). On the other hand, both background and analysis biases are improved at many geographic locations and for many parameters. We have only shown in this paper the most significant improvements:

- improvements of background and analysis biases to conventional data in Northern Hemisphere: temperature (figure 3(b)) and zonal winds (figure 3(a)) from radiosoundings and zonal and meridional winds from winds profilers (figure 3(c)). All these improvements are better for background biases then for analysis biases.

- improvements of background and analysis biases for satellites data: especially for SSMI in the Tropics (figure 3(d)) and AMSU-A in northern hemisphere (not shown).

Figure 3: Biases from BOA8 and BOA9 (ref) from 12 to 30/09/06. The solid-black line represents the background departure of BOA8, the dot-black line represents the analysis departure of BOA8, the dot-dashed red line represents the analysis departure of BOA9 (ref) and the dashed-red line represents the background departure of BOA9 (ref)

### 3.3.2 Impact on forecasts

The impact of the assimilation of cloudy radiances on the forecasts will be determined by comparing the forecast objective score with respect to radiosoundings data from both experiment and reference. This impact is globally neutral for wind and humidity.
For the geopotential (figure 4(a) and figure 4(b)), we can notice a significant improvement of the forecast in the stratosphere for all domains and for all ranges of forecast.

For the temperature (figure 5(a) and figure 5(b)), the impact is less significant but still positive, especially over Europe and in Tropics. This impact is mainly situated in the troposphere.

Figure 4: Forecasts objective scores for the geopotential with respect to radiosounds data from the 01/09/06 to the 04/10/06. The left column represents the root mean square error, the middle column represents the standard deviation, the right column represents the bias.
Figure 5: Forecasts objective scores for the temperature with respect to radiosounds data from the 01/09/06 to the 04/10/06. The left column represents the root mean square error, the middle column represents the standard deviation, and the right column represents the bias.
4 Conclusion and future developments

The goal of this paper was first to validate two cloud-detection schemes: The Co2-Slicing and the Cloud-Detect scheme. We have seen that both schemes exhibit quite good results and comparable performances, with best performances during day for the Cloud-Detect scheme and best performances during night for the CO2-Slicing. The cloud detection performances fluctuates with respect to the elevation of the cloud considered: the detection is better for medium clouds (400-800 hPa) and worse for low clouds (800-1000 hPa) for both schemes. We have also seen that the retrieved PTOP from CO2-Slicing exhibits a quite good correlation with the PTOP inferred from MODIS for both day and night. We also have noticed a better correlation for high and medium clouds (from 100 to 500 hPa) than for low clouds (from 600 to 1000 hPa).

Once the validation of both cloud-detection schemes made, we have used the CO2-Slicing cloud-characterization tools to directly assimilate cloudy radiances in ARPEGE, in a simplified framework. First results are promising in term of improvement on analyses and forecasts: analyses and background biases are reduced for most of conventional data and for some of satellites data. Forecasts are also improved especially for geopotential and temperature.

The next step will consists in assimilating cloudy radiances in a more realistic framework: assimilation of cloudy radiances between 400 and 950 hPa over sea and over land. Others assimilation techniques will also be conducted: in a first time, a prior adjusment of cloud parameters by a 1D-VAR scheme before being used by RTTOV could help to reduce characterizations errors (detection of low clouds and some caracterisation errors in term of cloud-cover or CTP). In a second time, the adjustment of cloud parameters could be made into the 4D-Var minimization process so as to obtain cloud parameters more consistent with others control variable. The assimilation of cloud-affected radiances will then be extended to IASI data.

References


Data assimilation and use of EOS data in land surface model

Qifeng Lu, Zhongdong Yang, Shihao Tang, Peng Zhang, Naimeng Lu

For the land products retrieved from the remotely sensed datasets better using in the land surface model and weather/climate model, Land Data Assimilation Systems (LDAS) based on EnKF Technology and Community Land Model, has been developed at NSMC/CMA. In the context of numerical weather prediction applications, LDAS can provide optimal estimates of land surface state initial conditions by integrating with an ensemble of land surface models, the available atmospheric forcing data, remotely sensed observations of precipitation, radiation and some land surface parameters such as land cover and leaf area index. The validation from Yucheng comprehensive experiment site indicates that the preliminary results obtained are still inspiring. There are still many detailed work to do for the routine operation of LDAS, such as how to get dynamic P in 3dvar, how to select the spacing interpolation algorithm, etc.
The GMAO 4d-Var System

Ricardo Todling and Yannick Tremolet

The fifth generation of the Goddard Earth Observing System (GEOS-5) Data Assimilation System (DAS) is a 3d-var system that uses the Grid-point Statistical Interpolation (GSI) system developed in collaboration with NCEP, and a general circulation model developed at Goddard, that includes the finite-volume hydrodynamics of GEOS-4 wrapped in the Earth System Modeling Framework and physical packages tuned to provide a reliable hydrological cycle for the integration of the Modern Era Retrospective-analysis for Research and Applications (MERRA). This MERRA system is essentially complete and the next generation GEOS is under intense development. A prototype next generation system is now complete and has been producing preliminary results. This prototype system replaces the GSI-based Incremental Analysis Update procedure with a GSI-based 4d-var which uses the adjoint of the finite-volume hydrodynamics of GEOS-4 together with a vertical diffusing scheme for simplified physics. As part of this development we have kept the GEOS-5 IAU procedure as an option and have added the capability to experiment with a First Guess at the Appropriate Time (FGAT) procedure, thus allowing for at least three modes of running the data assimilation experiments. The prototype system is a large extension of GEOS-5 as it also includes various adjoint-based tools, namely, a forecast sensitivity tool, a singular vector tool, and an observation impact tool, that combines the model sensitivity tool with a GSI-based adjoint tool. These features bring the global data assimilation effort at Goddard up to date with technologies used in data assimilation systems at major meteorological centers elsewhere. Various aspects of the next generation GEOS will be discussed during the presentation at the Workshop, and preliminary results will illustrate the discussion.
Implementing Radiance Assimilation in NAVDAS-AR: Lessons Learned

Nancy Baker, Ben Ruston and Tim Hogan and Tom Rosmond

NAVDAS – the NRL Atmospheric Variational Data Assimilation System – is an observation space 3dvar system and provides the initial conditions for the U.S. Navy’s global NWP model (NOGAPS) and mesoscale model (COAMPS®). NAVDAS was designed to be the precursor for the 4dvar assimilation system NAVDAS-AR (Accelerated Representer). Because NAVDAS was designed to accommodate variable grid dimensions and map projections, the observation pre-processing is separate from the 3D-Var solution, which in turn is separate from the final mapping of correction vector into model space. The observations types are pre-processed independently, then combined into single file containing the observation and ancillary information needed for the 3D-Var solution. For satellite radiances, the pre-processor routine includes the quality control, observation selection and thinning, bias correction, radiance monitoring and Jacobian calculation using a fast radiative transfer model. One advantage to this approach is that it easily allows radiance observations to be passively monitored, rather than assimilated, by the operational assimilation/forecast model without appreciably affecting the total run time of the system. For example, with NOAA-18 AMSU-A, we were able to move from passive monitoring to active assimilation within three weeks of the data becoming operationally available (and without operational code changes). While this approach provides flexibility for the development of new observation pre-processors, it has contributed to unexpected difficulties during the implementation of radiance assimilation with NAVDAS-AR. The initial NAVDAS-AR implementation followed the operational NAVDAS configuration. The NOGAPS fields are output on 30 fixed pressure levels at 0.5° resolution, and the 3-, 6-, 9-hour forecast fields from the previous update cycle are interpolated in space and time to the observation location. Within NAVDAS-AR, the observations are binned within 30 minute windows, and the background values are interpolated from the model Gaussian grid/sigma level fields. Differences between background fields used in the observation pre-processors and the NOGAPS trajectory lead to systematic differences in the computed brightness temperatures, inconsistencies with bias corrections and degraded forecast skill. We will present our diagnostic results and solutions, which have involved a re-examination of the role of observation pre-processors for data monitoring and selection, quality control, and bias correction. We have also encountered various difficulties upgrading our radiative transfer model from RTTOV-6, and results from assimilation tests using the JCSDA Community Radiative Transfer Model and RTTOV-8.7 will be presented. Finally, the
differences in observation impact (computed using adjoint methods) between NAVDAS and NAVDAS-AR will be presented and discussed.
Environmental Forecasting at NIWA: A Progress Report

Michael Uddstrom, Hilary Oliver, Stuart Moore, Stuart Webster, Phil Andrews, Vanessa Sherlock, Trevor Carey Smith, Richard Turner, Mike Revell, Ed Yang and Martyn Clark

The New Zealand Limited Area Model (NZLAM) is an operational implementation of the Met Office Unified ModelTM (i.e. OPS, VAR (FGAT7), UM, SCS) on a 12 km resolution domain using a 6 hour assimilation cycle. NZLAM predictions are also being used to forecast weather impacts, including river flood. In the context of New Zealand’s complex and steep topography and short rise time catchments, flood forecast accuracy is very sensitive to timing and magnitude errors in quantitative precipitation forecasts (QPF), which in turn are sensitive to the accuracy of the analysis and (NWP) model resolution. The poster outlines the operational NWP system, information delivery system and indicative verification statistics, and reports on data assimilation and model resolution experiments carried out to better understand forecast accuracy constraints.
Fostering a new generation of Remote Sensing Scientists

Paolo Antonelli, Steve Ackerman, Leanne Avila, Steve Dutcher, Liam Gumley, Allen Huang, Jean Phillips, Hank Revercomb, Tom Rink, Kathy Strabala, Bill Smith, and Paul Menzel

At the ITSC-XV we indicated that in addition to focusing on the design and development of future instruments and the associated data processing algorithms, SSEC also pursues educational goals by spreading environmental awareness and emphasizing the relevance of satellite remote sensing of the Earth in a wide variety of activities. Following the example of the distribution of the TOVS processing package and the personal efforts of SSEC and CIMSS leading scientists in the eighties, some of SSEC’s recent training efforts have reached out to an international audience interested in theoretical and operational aspects of remote sensing. In the last two years SSEC and CIMSS have continued teaching weeklong remote sensing seminars that provide a broad fundamental perspective to young researchers as well as to graduate students around the World. Lectures are supplemented with laboratory exercises that emphasize investigation of high spatial resolution (MODIS) and high spectral resolution (AIRS, IASI) data; more recently high temporal resolution data (SEVIRI, GOES) have also been added. During 2006 and 2007, SSEC and CIMSS scientists, in collaboration with EUMETSAT and NOAA, have attempted to bring greater understanding of remote sensing technology to the international community, and to African and South American scientists in particular with the unchanged goal of helping in fostering a new generation of environmental scientists.
Since 2004 SSEC/CIMSS has conducted international direct broadcast (DB) training workshops centered around the DB receiving countries/sites. So far six (6) DB workshops have been conducted at Perth/Australia, Nanjing/China, Beijing/China, Chung-Li/Taiwan, Andoya/Norway and Pretoria/South Africa. One additional workshop under the GEOSS initiative was conducted at Cachoeira Paulista/Brazil. These workshops focus on the complete end-to-end processing of the data into geophysical products. Basic remote sensing principals, algorithm theory, and limitations and applications of the products are taught in lectures followed by hands-on computer laboratory exercises. The user friendly visualization software tool HYDRA is freely distributed for students in the classroom and allows examination of data and products at the pixel level for the purpose of manipulating and interrogating DB measurements, imagery, and products. SSEC/CIMSS is devoted to continue this kind of training workshop tailored for the international DB community as part of an ongoing effort to maintain and expand the use of the International MODIS/AIRS Processing Package (IMAPP), and in preparation for the development of the future International Polar Orbit Processing Package (IPOPP) for the National Polar-orbiting Operational Environmental Satellite System (NPOESS).
The First international IASI conference, organized by CNES and Eumetsat, took place in Anglet (France) from 13 to 16 November 2007, only one year after the successful launch of the IASI instrument on the MetOp-A platform. It is a credit to CNES and Eumetsat and to the manufacturers of IASI that so soon after launch users are already making significant use of IASI data and were able to present exciting first results. The main topics of the conference were: the performance of IASI, the impact of IASI on NWP, the clouds and surface parameters, climate and atmospheric chemistry. The performance of IASI was assessed by the IASI Technical Center in CNES and validated against NWP model output and airborne and balloon coincidence flights. The results showed that the radiometric performance of IASI is better than 0.5K, likely between (0 and 0.2 K). ECMWF was the first to assimilate IASI data and showed already a significant impact of IASI on NWP – the largest single impact of any instrument despite coming on top of existing systems. The high spectral resolution of IASI is already showing benefits with several users describing techniques to use this information to retrieve surface and cloud properties – paving the way for even greater use of IASI data in NWP. Other sessions during the conference concentrated on retrieval of cloud and aerosol properties and on the growing number of trace gases that can be detected in IASI data. This highlights another critical role of IASI in the monitoring of the Earth’s climate over a long time period. The IASI Sounding Science Working Group is called to maintain a coordination on the development of IASI products and will assist CNES and Eumetsat to organize the 2nd conference in 2009.
Synergy between IASI sounding and AVHRR imagery for the processing of IASI data in non-uniform scenes

P. Prunet, S. Bijac, J. Donnadille, D. Coppens, B. Tournier, O. Lezeaux

A processing chain for the infrared sounding measurements above heterogeneous scenes was developed for IASI. It makes use of the information provided by a co-registered imager for characterizing the sounder sub-pixel information in terms of homogeneous radiative surfaces, and for extracting the sounder spectrum component associated with each homogeneous surface. Such a processing is required for any exploitation of non-homogeneous pixel measurements. This processing is applied for validation on a representative set of measured IASI spectra. The first results on partially cloudy scenes indicate that the global percentage of IASI measurements exploitable for atmospheric parameter retrieval and NWP assimilation should be increased by a factor of 3. This preliminary validation also suggests that improved geophysical products (e.g., low troposphere constituent concentration, surface properties classification) could be derived from this processing.
Validation of IASI spectral radiances using aircraft underflight data collected during JAIVEx

David Tobin, Hank Revercomb, Fred Best, Joe Taylor, Steve Dutcher, Bob Knuteson, William Smith

Direct airborne validation of radiances from the new IASI interferometer sounder on Metop was successfully performed during the Joint Airborne IASI Validation Experiment (JAIVEx) conducted 14 April - 4 May 2007. The experiment included the NASA WB57 aircraft carrying the UW Scanning HIS, the LaRC NAST-I, and the MIT/LL NAST-Microwave, flown in coordination with the Facility for Airborne Atmospheric Measurements BAe146-301 carrying the ARIES interferometer plus a wide range of in situ instrumentation and dropsondes. This presentation focuses on validation of IASI spectral radiances using the high altitude aircraft observations and a double observed minus calculated analysis technique. Results for various JAIVEx flights will be presented.
Principle component analysis of IASI spectra with a focus on non-uniform scene effects on the ILS

David Tobin, Hank Revercomb, Paolo Antonelli

Exploiting the inherent redundancy in hyperspectral observations, Principle Component Analysis (PCA) is a simple yet very powerful tool not only for noise filtering and lossy compression, but also for the characterization of sensor noise and other variable artifacts using Earth scene data. This presentation will include a description of our approach for dependent set PCA of IASI radiance spectra, characterization of the IASI sensor noise using PCA, and the characterization and removal of spectral artifacts due to scene inhomogeneity.
Evaluation of IASI and AIRS spectral radiances using Simultaneous Nadir Overpasses

David Tobin, Hank Revercomb, Fred Nagle, Robert Holz

We present direct comparisons of high spectral resolution radiance observations from today’s two advanced infrared sounders. Observations collected by the Atmospheric Infrared Sounder on the NASA Aqua platform and by the Infrared Atmospheric Sounding Interferometer on the METOP-A platform for Simultaneous Nadir Overpasses (SNOs) are intercompared and, with knowledge of the different characteristics of each sensor, are evaluated to assess the spectral and radiometric accuracy of each set of observations. Preliminary results show no significant trend in the results versus time and mean channel by channel differences typically less than 0.2K.
The use of principal component analysis in monitoring IASI radiances and diagnosing climate anomaly

Zhaohui Cheng, Lihang Zhou, Thomas King, Walter Wolf, Mitch Goldberg, Chris Barnet and Haibing Sun

Principal component analysis (PCA) is a useful technique in analyzing high spectral infrared radiance data (such as AIRS, IASI) due to the high correlation among the different spectral channels. IASI 8461 channels can be well represented by relatively few empirical orthogonal functions (EOFs), also called principle components. Each IASI spectrum can be expressed as a linear function of these EOFs by a unique set of coefficients. These coefficients are also called principal component scores (PCS). Reconstructed radiances and PCS can be used to estimate instrument noise and detect anomalies by comparing reconstructed with the original spectra. NOAA/NESDIS has made the IASI level 1C data products operationally available since October, 2007. NOAA/NESDIS/STAR has used PCA to process the real IASI data for the data monitoring and quality control for a couple of months. PCS and the corresponding reconstruction scores are computed in near real time. A web site was built to monitor the global IASI observations, IASI reconstructed radiances and reconstruction score on daily basis. Large reconstruction bias can be used to identify the suspicious channels/bands and climate anomalies. Monthly monitoring of statistics of IASI radiances had also been implemented in this visualization system. Static PCS are very stable over time. However, when some special event occurs, the anomaly signature of PCS will appear in the reconstruction scores. The STAR IASI monitoring system indicated that there was a big bias of reconstruction scores over the Ionian Sea between south Italy and Greece (around 19E, 39N) on Nov. 24th, 2007. More investigations showed that there was a high SO2 area due to the eruption of a volcano. The PCS level 1C product is a critical factor in regression retrieval. The accuracy of PCS will affect the quality of the level 2 products. The case study to be presented will show the effect of a climate anomaly event like above mentioned volcano case on the reconstruction scores. We will also show that by added this event to the training dataset, that we can dramatically decrease the reconstruction errors.
Operational Processing of ATOVS data at the Satellite Application Facility on Climate monitoring

Nathalie Selbach and Petra Fuchs

The Satellite Application Facility on Climate Monitoring (CM-SAF) generates, archives and distributes widely recognized high-quality satellite-derived products and services relevant for climate monitoring in an operational mode. Products covering cloud, radiation and humidity parameters are derived from different operational satellite and sensor types. The International ATOVS Processing package (IAPP) is applied for the retrieval of humidity and temperature parameters. Currently, data from ATOVS onboard NOAA 15, 16 and 18 are used for the generation of global environmental data records in near real time at the CM-SAF. It is intended to include data from ATOVS onboard the Metop in the operational processing. Daily and monthly products including mean value and error information are provided to the user in a 90 km x 90 km sinusoidal projection. The current status and future plans concerning the ATOVS processing routines at CM-SAF will be presented from the operational point of view.
Validation of level1b/1c LEO instruments in synergy with LEO/GEO companion instruments or in stand alone mode: Application to AIRS/Aqua, IIR/Calipso, IASI/Metop

R. Armante, N.A. Scott, V. Capelle, L. Crépeau, N. Jacquinet, A. Chédin

High spectral resolution instruments as AIRS/Aqua or IASI and companion instruments on board Metop or other instruments of the A-Train (IIR/Calipso) etc. support the scientific community data requirements for weather forecasting and climate research. Such researches require quality data, well controlled (identification of systematic biases or spurious trends or variability). As an heritage of similar process for long term satellite data analysis (TOVS data of the NOAA/NASA Pathfinder programme, a five year-period of AIRS/Aqua data or, more recently IIR/Calipso) LMD is developing control of IASI channels primarily relevant to its own retrievals of level2 products: GHG (CO2, CO, CH4, ...), clouds, aerosols and surface characteristics. This is obtained through the coupling of a validated and stable forward model (the LMD 4A model) with collocated ancillary or auxiliary data or instruments (LEO or GEO, radiosondes, analyses). The detection of bias, trends etc. from cloud free day/night land/sea spectra is performed globally or over selected areas. Validation approach – including the validation of the forward model itself - and results will be discussed. Relevance of such an approach to the GSICS (Global Space-Based Inter-Calibration System) mission and goals will also be discussed.
Cloud properties from AIRS and evaluation with Calipso

C. J. Stubenrauch, S. Cros, N. Lamquin, R. Armante, A. Chédin, C. Crevoisier, and N. A. Scott

Since May 2002 the Atmospheric Infrared Sounder (AIRS), in combination with the Advanced Microwave Sounder Unit (AMSU), onboard the NASA Aqua satellite provides measurements at very high spectral resolution of radiation emitted and scattered from the atmosphere and surface. The instrument was developed to provide atmospheric temperature and water vapour profiles at a vertical resolution of about 1 km and 2 km, respectively, but the high spectral resolution of this instrument also allows the retrieval of cloud properties (especially cirrus), aerosol and surface properties as well as the quantity of trace gases. We present a cloud property retrieval scheme, which is based on a weighted $\chi^2$ method using channels around the 15 micron CO2 absorption band, to determine effective cloud emissivity and cloud pressure. The influence of channel choice, cloud detection, spatial resolution and of assumed atmospheric profiles on the retrieval are discussed. The retrieval scheme is applied to all spots, without distinction between cloudy or clear sky spots. Cloud detection plays an important role in the cloud property retrieval: the tighter the cloud detection the larger the average cloud pressure and low cloud amount, because partly cloudy spots are identified as low clouds. To be independent on cloud detection thresholds which vary regionally and seasonally, a posteriori cloud detection is developed by comparing cloud pressure differences between AIRS and collocated L2 data from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard CALIPSO, both instruments part of the A-Train, for January and July 2007. This cloud detection is based on the coherence of cloud emissivity at different wavelengths and on brightness temperature heterogeneity. At the same time, CALIOP is used to evaluate the AIRS cloud altitude. Results are also compared to cloud properties from AIRS L2 products (version 5) and from the Moderate Resolution Imaging Spectroradiometer (MODIS) of the same time period, as well as to the cloud climatologies of the International Satellite Cloud Climatology Project (ISCCP) and TOVS (TIROS-N Operational Vertical Sounder) Path-B. The seasonal cycles of high, midlevel and low cloud amount in the tropical and subtropical regions are compared to the one of CALIPSO, using one year of data (August 2006 to July 2007) to results of cloud climatologies.
A quantitative link between CO2 emissions from tropical vegetation fires and the daily tropospheric excess (DTE) of CO2 seen by NOAA-10 (1987-1991)

A. Chédin, N. A. Scott, R. Armante, C. Pierangelo, C. Crevoisier and P. Ciais

Four years of monthly mean mid-tropospheric CO2 columns over the tropics have been retrieved from evening and morning observations of NOAA-10 (1987-1991). The difference between these two columns shows a “Daily Tropospheric Excess” (DTE) up to 3 ppm over regions affected by fires. At regional scale over Africa, America, and Australia, the variations of the DTE are in good agreement with those of independently derived biomass burning CO2 emissions. In particular, a strong correlation (R2~ 0.8) is found between regional mean DTE and fire CO2 emissions values from the Global Fire Emissions Data base (GFEDv2) even though the two products span over periods ten years apart from each other. The DTE distribution over Africa is in good agreement with interannual variation of climate as indicated by temperature, precipitation and ENSO index. For instance, the southern hemisphere experiences 20% more fire activity during El Niño conditions than during La Niña conditions and the reverse for the northern hemisphere, even if the estimated one sigma uncertainty on the DTE remains close to the DTE ENSO variability. The physical mechanism linking DTE with emissions is not fully elucidated. Hot convective fire plumes injecting CO2 into the troposphere during the afternoon peak of fire activity, seen by the satellite at 1930 LT, and then being diluted by large scale atmospheric transport, before the next satellite pass at 0730 LT, could explain the tight observed relationship between DTE and fire CO2 emissions. Through the reprocessing of the 25-year archive of TOVS observations, the DTE data may prove very useful to quantitatively reconstruct fire emission patterns before the ATSR and MODIS era when better quality fire count and burned area data became available.
SIFTI : a Static Infrared Fourier Transform Interferometer dedicated to ozone and CO pollution monitoring

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Abstract

Measuring pollutant concentrations in the boundary layer of the atmosphere is a major challenge for air quality. Infrared sounding, providing vertically resolved profiles for several trace gases in the troposphere, is a must for pollution observation. In this framework, CNES is currently leading a phase-A study for SIFTI, a Static Infrared Fourier Transform Interferometer devoted principally to ozone and CO measurements in the thermal (TIR) and short-wave infrared (SWIR).

We will first describe the high-level mission requirements, including orbital considerations like the revisit frequency or the need for cloud-free observations. Instrument specifications, like spectral band position, spectral resolution, radiometric noise, are then derived from the precision needed in CO and ozone profile retrievals. The sensitivity of the profile retrievals, given in terms of vertical sensitivity and errors, to instrument performances are studied using the optimal estimation theory.

The instrument concept proposed by CNES (Centre National d’Etudes Spatiales, the French space agency), an interferometer with no moving part, based on scaled mirrors, is a simple and efficient solution to meet these requirements and obtain very high resolution spectra (better than 0.1 cm⁻¹) with a high signal-to-noise ratio. Spectra are measured within two thermal infrared bands (for CO and O₃) and one optional shortwave infrared band (for CO and CH₄) for synergetic more accurate SWIR/TIR inversion of CO profile. Thanks to an intelligent pointing mechanism based on real-time analysis of observations from an imbedded infrared imager, the probability of clear sky is dramatically increased. An optimization of the instrument, based on an irregular but well-chosen sampling of the interferogram, opens the way to still higher quality profiles.

Introduction

Measuring pollutant concentrations in the boundary layer of the atmosphere is a major challenge for air quality. Infrared sounding, providing vertically resolved profiles for several trace gases in the troposphere, is a must for pollution observation. In particular, current infrared sounders like
IASI (Infrared Atmospheric Sounding Interferometer) provide operational quantitative products for CO, ozone, and CH$_4$ (Turquety et al. 2004). More elaborated research products from advanced infrared sounders include molecules like SO$_2$, C$_2$H$_6$, CH$_3$O$_2$H (Clerbaux et al. 2008) or dust aerosols (Peyridieu et al. 2008). However, current sounders are primarily designed for meteorological and climate applications. In order to improve their ability to provide relevant data for pollution survey, CNES is currently leading a phase-A study for SIFTI, a Static Infrared Fourier Transform Interferometer especially devoted to ozone and carbon monoxide (CO) measurements in the thermal (TIR) and short-wave infrared (SWIR).

In this paper, we will first give the science objectives of a typical satellite air quality remote sensing mission. From this high-level needs, we will derive both the geometric requirements (when and where to observe the atmosphere) and the instrument requirements applying to SIFTI. The expected product performances are then shown for both the ozone and CO vertical profiles. In the last part, the static interferometric concept, the retained solution to reach the instrument requirements, is detailed.

**Science objectives**

The first science objective of the SIFTI mission covers the air quality and tropospheric composition on a global and regional scale. As air quality relates to human health, it focuses on mega-cities. This implies also to observe the atmosphere as close as possible to the surface. Diurnal cycle of atmospheric pollution shows very sharp variations of pollutant concentrations (e.g. for ozone). So, frequent observations (roughly every one hour) are of great interest to improve air quality forecast. The long range transport of pollutants is another key parameter for tropospheric composition.

Another major objective of the mission concerns the localization and quantification of sources and sinks of trace gases. These are determined from atmospheric models based on emissions that actually rely on still poor inventories. Satellite-based remote sensing observations of gas concentrations must distinguish between the boundary layer (from the surface to a few hundreds of meters or kilometres) and be accurate enough to bring benefit to chemistry and transport models through assimilation. Note that CO is a tracer for combustion processes and biomass burning and proves very useful for improving the estimated biomass emissions. Sinks for pollutants are mainly depending on the oxidising capacity of the atmosphere, which is controlled by ozone. CO and NO$_x$ also play a role as ozone precursors.

The last challenge of the mission is to contribute to study the link between the tropospheric composition and global change, through the measurement of tropospheric ozone and optionally methane (30% of greenhouse effect together). Stratospheric ozone is a first importance climate variable, while CO and CH$_4$ oxidation is an important source of CO$_2$.

**Geometric requirements : when, where?**

The geometric requirements are driven by the high revisit frequency need. A time period of the order of one hour is necessary to monitor the rapidly evolving pollution peaks. A classical sun-synchronous orbit provides one observation every 12 hours and thus does not satisfy this need. A geostationary orbit provides this requirement for part of the globe. However, the very high
altitude of the geostationary orbit (36,000 km) reduces the radiation flux entering the instrument and significantly reduces the signal-to-noise compared with a low Earth orbit, considering a given pupilla diameter. Therefore, an original drifting orbit has been proposed by CNES. Its altitude is 720 km, and its angle with respect to the equator is 55°. Combined with a field of view spanning from -50° to +50° with respect to nadir, such an orbit ensures in the mid-latitudes up to 5 revisit per day (see Fig. 1). The time period between two visibility passes over the same point is 90 minutes, and the hours of passes drift by a few minutes every day, as represented in Fig. 2. Consequently, the 5 revisits span over 6 hours possibly during day-time only, possibly during both day-time and night-time, and possibly during night-time only. Together with a sampling point every 50 km at nadir, the orbit also ensures a good regional covering, adapted to the spatial variability of the pollution.

Fig. 1: number of passes per 24 h for the drifted orbit of the mission.

Fig. 2: local time of the 5 satellite passes over Paris for day 1 (from 8.30 a.m. to 3.30 p.m.) and day 2.

The geolocalisation need is 1 km. It comes from the potential use of SIFTI in synergy with other instruments on the same platform, for example a UV-VIS spectrometer for NO₂ and O₃ measurement and/or a directional polarised spectrometer for aerosols. The SIFTI geophysical products must be well localised also for their use in atmospheric models.

For a given orbit, the number of useful observations is maximised through spatial sampling, a wide swath, a small pixel size (between 10 and 12 km) to reduce the risk of cloud contamination, possibly cloud-clearing algorithm (research in progress) and “intelligent
pointing”. This later strategy relies on a mechanism allowing a slight modification of the pointing direction to avoid clouds in the field of view (Fig. 3).

Fig. 3 : spatial distribution of SIFTI pixels using the intelligent pointing option.

An optional cloud imager, CLIM, with 2 bands in the thermal infrared domain, will provide cloud cover information within the SIFTI instantaneous field of view. Real time cloud analysis, based on these CLIM measurements, will be used to anticipate the optimal viewing direction for SIFTI with respect to this cloud cover. The potential gain in cloud-free footprints using this intelligent pointing strategy (with respect to a regular scanning pattern) depends strongly on the observed scene. For a typical orbit over Europe, the gain of intelligent pointing, evaluated thanks to a 2-bands version of the MAIA algorithm (Lavanant et al. 2007) is roughly 1.5 (see Fig. 4).

Fig. 4 : simulation of the gain of the intelligent pointing for one orbit : CLIM imager pixel classification (on the left), SIFTI pixels classification using regular pointing mode (in the middle), SIFTI pixels classification using intelligent pointing mode (on the right). Red=cloudy, blue=clear.

**Instrument requirements**

The spectral band position is determined by the target molecules: O$_3$ and CO (see Fig. 5), with some care to reduce the water vapour contamination. The SIFTI spectral band “B1” is dedicated to ozone measurement and covers 25 to 30 cm$^{-1}$ in the 1030-1070 cm$^{-1}$ range (about 9.5 µm). The SIFTI spectral band “B2” is dedicated to carbon monoxide measurement and covers 25 to 30 cm$^{-1}$ in 2140-2180 cm$^{-1}$ (about 4.6 µm). Finally, a third band, located in the short-wave
infrared domain, is studied as a possible option: band “B3” dedicated to CO and CH₄, from 4270 to 4300 cm⁻¹ (about 2.3 µm).

Fig. 5: main absorbing molecules in the thermal infrared and position of SIFTI spectral bands.

The apodised spectral resolution is 0.125 cm⁻¹, the spectral sampling being 0.0625 cm⁻¹. The purpose of such a high spectral resolution is to be compatible with CO narrow lines, in order to observe the line wings and probe the lower troposphere.

Next, the instrument noise requirements are very high too: the Noise equivalent difference Temperature (NedT) at 280 K should be between 0.08 K and 0.1 K for B1, and between 0.12 and 0.2 K for B2.

**Expected product performances**

SIFTI is expected to produce high quality concentration profiles. The vertical resolution is such that it provides 5 to 7 independent pieces of information (DOFS, Degrees Of Freedom for Signal, (Rodgers, 2000)) for ozone, and 2.5 to 4 for CO with band B2, 1.5 for CO with band B3. It should be noticed that one of this piece of information is located in the boundary layer. The accuracy of the retrieved profile leads to a final error of the tropospheric column of the order of 4 to 14% for ozone from B1, and 2 to 8% for CO from B2, depending on the geophysical situation. Fig. 6 shows the averaging kernels for SIFTI and the a priori and a posteriori variability of CO and O₃ profiles, computed with the 4A/OP radiative transfer code (Scott and Chédin 1981, Chaumat et al. 2007) for radiative transfer calculation, and with tools developed at CNES for the inverse model, based on optimal estimation (Rodgers, 2000). As compared to currently flying sensors, the error on the profile is reduced up to the surface, proving the interest of SIFTI for air quality.
SIFTI also offers promising retrievals of carbon monoxide in the troposphere thanks to the TIR/SWIR synergy. CO can be retrieved by combining the radiances spectra from the thermal and short-wave infrared domains. Fig. 7 shows that the TIR retrieval is more accurate than the SWIR retrieval, even close to the surface. However, combining both spectral domains improves the CO profile retrieval in the boundary layer: in that example, adding the SWIR band, the statistical error for the 0-1 km layer decreases from 23% to 16%.
The principle of static interferometry relies on a CNES patented concept: the moving mirror in classical Michelson interferometry is replaced by a stepped mirror. Temporal acquisition of the interferogram is replaced by spatial acquisition onto a detector matrix (see Fig. 8 and Fig. 9). The main advantage of static interferometry is its reliability, as there is no moving mirror and no dynamic perturbation.
Such a concept permits very high spectral resolution: the maximal optical path difference is given by the depth of the stepped mirrors (Fig. 10). For SIFTI, it is 8 cm optical, as compared to 2 cm for IASI, thus leading to a spectral resolution 4 times better. Facets are obtained by crossing the steps of two mirrors. In the manufacturing of the mirrors, the technology of molecular adherence allows as many facets as about one thousand in a 100 mm × 100 mm surface. The interferometric fringes are built on these facets, and are read by imaging them onto a 2D detector array. There is no over-sampling of the interferogram, which implies that the number of channels in the spectrum is limited to about one thousand too. The concept is thus limited to narrow spectral bands. However, for gas retrieval, it is well adapted. The first difficulty of the concept is the need for a very good knowledge of Optical path Difference (OPD) (a few nm) which implies on-board monitoring of the mirror position thanks to an algorithm or a laser. The second difficulty is the accurate radiometric inter-calibration of the matrix detectors. More details on the instrument might be found in Hébert et al. (2006).

Moreover, this concept also opens the way to a new processing strategy of the data: a direct retrieval of geophysical products from interferogram data, with an optimisation of the interferogram sampling. CO periodic line comb produces a periodic fringe pattern in the interferogram (Fig. 11). So, the idea is to acquire and to use only interesting Optical Path
Difference (OPD) samples with irregular steps in the scaled mirrors. As a theoretical simulation, an optimal selection of samples for SIFTI B2, based on information content, has been conducted: only 87 different OPD positions are selected (among thousands of possible positions), some of them several times, mainly where CO signature is strong (Fig. 11). The direct retrieval of gas profiles on the irregular optimised interferogram shows better performances than the retrieval from a regular interferogram, or its equivalent spectrum. For instance, we see on Fig. 12 that we obtain 4.1 DOFS for the retrieval from regular sampling, and 5.7 from the optimised sampling. To obtain the same performance (5.7 DOFS) with regular sampling, we should reduce the noise by a factor of 2.12. Conversely, if we decide to keep the performance constant (4.1 DOFS), an optimised interferometer requires only 220 interferogram samples (versus 971 in the regular case) which conducts to a simpler and smaller instrument.

Fig. 11: SIFTI band B2 interferogram (top), and position and occurrence of selected OPD (bottom) for interferogram retrieval with optimised sampling.

Fig. 12: performance of the CO retrieval (DOFS) as a function of the number of optimally selected interferogram OPD samples, from 0 to 971.
Conclusions

For a mission dedicated to air quality and pollution monitoring, an original drifting orbit leading to 5 revisits per day in the mid-latitudes and a global coverage has been proposed. The geometric requirements are driven by the need to maximise the number of useful observations. For this purpose, an “intelligent pointing” strategy, based on on-board processing of an imager, permits to avoid clouds. The SIFTI instrument, an infrared interferometer, thanks to its very high spectral resolution (0.125 cm\(^{-1}\) apodised) and its very low noise, provides high quality profiles for ozone and carbon monoxide. The accuracy of CO retrieval in the boundary layer can be improved with a combined SWIR/TIR retrieval. The instrument concept is a static interferometer, with stepped mirrors instead of moving mirrors, which is very reliable for space applications. A possible optimisation of the interferogram samples opens the way to higher quality profiles for CO.

We established here that infrared sounding is a must for pollution monitoring, as it can provide ozone and carbon monoxide concentrations, both fundamental molecules for air quality. Moreover, we have seen that it gives access not only to gas total column but also to vertical profiles, with information down to the surface. The orbit and geometric optimisation presented here, as well as the high performance instrument concept, should find a place in the way towards operational atmospheric chemistry, for instance as planned in the European Union Global Monitoring for Environment and Security (GMES) program.

References


### Introduction

The development of space-borne hyper-spectral IR sounders (AIRS/EOS-Aqua, IASI/MetOp) opens new opportunities for detecting the variations of atmospheric carbon dioxide (CO2) and methane (CH4) concentrations. The capabilities to retrieve atmospheric column-average CO2 mixing ratio and similar column-average CH4 mixing ratio (or CH4 columns) from satellite measurements is of significant importance in the context of global carbon cycle research, climate change studies and due to sparse network of ground-based CO2&CH4 observations. Bearing in mind these issues the main objectives of our research were as follows:

- Improvement of the technique for column-average CO2 mixing ratio ($Q_{CO2}$) retrieval in the upper troposphere from AIRS/EOS-Aqua data over Western Siberia;
- Validation of $Q_{CO2}$ retrievals against aircraft flask CO2 observations (over boreal zone);
- Development and testing of the novel technique for tropospheric CH4 column ($C_{ACH4}$) retrieval from IASI and AIRS data.

This paper presents at first an updated status of $Q_{CO2}$ retrieval scheme based on clear-sky or cloud-cleared AIRS inversion algorithm. The validation effort carried out with real AIRS data for two areas in the boreal zone of Western Siberia (Novosibirsk and Surgut regions) and for 10 months of year 2003 demonstrates the successful performance of proposed technique.

With respect to the CH4 column retrieval from AIRS and IASI data the approach has been developed based upon the application of iterative physical inversion algorithm to clear-sky AIRS or IASI data in the subsets of CH4 – dedicated super-channels (linear combinations of measurements in temperature- and CH4- dedicated channels). Using the data in super-channels reduces the effect of inaccurate temperature profile $T(p)$ knowledge on accuracy of $C_{ACH4}$ retrievals in sounding points. The performance of the retrieval algorithm is evaluated in the case study experiment involving datasets of IASI and AIRS data covering Kiruna (Sweden) region and complemented with quasi-synchronous and collocated ground based and radiosonde observations as well as with AIRS-based L2 retrievals.

### Methodology of $Q_{CO2}$ Retrieval from AIRS data

The sensitivity studies based on RTM SARTA simulations of clear-sky AIRS measurements (Strow et al., 2003) resulted in the selection of 2 subsets of CO2 dedicated channels (9 LW channels within the band 699-705 cm$^{-1}$; 6 SW channels within the band 1939-2107 cm$^{-1}$) with strong responses to CO2 variations and minimum sensitivity to main interfering factors, namely inaccurate knowledge of state vector components (including surface temperature and emissivity, atmospheric water vapor and ozone profiles, etc.).
Fig. 1, 2 demonstrate the CO2 Jacobians for LW and SW CO2-channels. The AIRS radiances in CO2-channels have maximum sensitivity to CO2 variations in the mid- to high-tropospheric layer and minimum sensitivity to variations of above interfering factors.

Fig. 1 CO2 Jacobians for LW CO2-channels

Fig. 2 CO2 Jacobians for SW CO2-channels

The improved technique for AIRS-based QCO2 retrieval developed in (Uspensky et al., 2007) and similar to (Chahine et al., 2005) can be summarized as follows:

- Clear-sky and cloud-cleared radiances (brightness temperatures $B_T^{obs}$) measured in CO2-dedicated channels are used for QCO2 retrieval;
- Forward calculations of synthetic brightness temperatures, $B_T^{calc}$, are performed using RTM SARTA with reference values $Q_{CO2}^{ref}$ (in the range 370-385 ppmv) and ancillary information (AMSU-based temperature profile $T(p)$ retrievals and AIRS L2 retrievals of other state vector components);
- Monthly averaged biases $〈B_T^{obs}-B_T^{calc}〉$ are specified beforehand for the Region of Interest (ROI);
- Estimating QCO2 is carried out using physical inversion algorithm, namely the Gauss-Newton iteration algorithm is applied separately to bias-corrected AIRS data in LW and SW CO2-channels in order to produce “independent” $Q_{CO2}(LW)$ and $Q_{CO2}(SW)$ retrievals;
- Spatial/temporal (median) filtering is performed for the clusters of $\{Q_{CO2}(LW)\}$ and $\{Q_{CO2}(SW)\}$ retrievals;
- The final monthly averaged estimate QCO2 (AIRS) is produced as a linear combination of filtered $Q_{CO2}(LW)$ and $Q_{CO2}(SW)$ values (if they are consistent to each other).

The performance of described retrieval technique has been evaluated in the seria of validation exercises for three ROIs, involving samples of real AIRS data.

**Validation exercises: CO2 retrievals over Siberian boreal zone and Kiruna region**

The series of retrieval experiments has been conducted for a sample of more than 600 granules of actual AIRS data that were downloaded together with AIRS L2 retrievals and AMSU-based $T(p)$ retrievals for pre-selected ROIs and time period between January and October 2003 (1-2 granules daily) from the site http://daac.gsfc.nasa.gov/data/dataset/AIRS/02_L2_Products/index.html. The $Q_{CO2}$(AIRS) retrievals are inter-compared with the results of air-borne measurements (Arshinov et al., 2005). The first region of air-borne surveys is located at the right bank of the southern part of the Ob Reservoir. The air-borne measurements of CO2 concentration at heights of 0.5-7.0 km (available are the data at heights of 1, 3, and 7 km) cover the region $54^\circ 08' - 54^\circ 33'$ N, $81^\circ 51' - 82^\circ 40'$ E., moreover the boreal area consists 90% of coniferous trees. Similar observations have been conducted also for the...
second ROI, namely, Surgut region (60-62°N, 70-75°E); available are the data at 1 and 7 km. Other
details regarding both ROIs (including images of both areas) can be found in (Uspensky et al., 2007).
The monthly averaged air-borne CO₂ observations have been compared to final \( Q_{\text{CO}_2}(\text{AIRS}) \).
Figure 3 presents the comparison of AIRS retrieved \( Q_{\text{CO}_2} \) with air-borne measurements for
Novosibirsk and Surgut regions.

![Comparison of AIRS retrieved QCO2 (column average m.r.) with airborne measurements. Jan-Oct 2003. QCO2ref=370 ppmv. Novosibirsk region](image)

**Fig. 3a Q\(_{\text{CO}_2}\) retrievals (Novosibirsk)**

Besides, in order to specify the most appropriate temporal match-up window for averaging, the \( Q_{\text{CO}_2} \)
retrieval experiment has been conducted for the same Surgut region with 2 weeks temporal match-up
window, see Fig. 4. As follows from Fig. 3b) and Fig. 4 comparison, it is possible to reduce sought
temporal window from 4 to 2 weeks without significant loss of \( Q_{\text{CO}_2} \) retrieval accuracy.

![Comparison of AIRS retrieved QCO2 (temporal match-up window one month) with airborne measurements. Jan-Oct 2003. QCO2ref=375 ppmv. Surgut region](image)

**Fig. 3a Q\(_{\text{CO}_2}\) retrievals (Surgut)**

The results of validation exercise performance for both ROIs can be summarized as follows:
The inversion of actual AIRS data for 2 areas (Western Siberia) enables to retrieve \( Q_{\text{CO}_2} \) values that
agree reasonably with seasonal trend of those identified from in-situ air-borne measurements and have
a precision of about 1% (comparing to air-borne measurements at 7 km). The temporal match-up
window between 2 weeks and 1 month is suitable for \( Q_{\text{CO}_2} \) retrievals averaging.

Along with described validation exercises the performance of above \( Q_{\text{CO}_2} \) retrieval algorithm
has been evaluated in a case study experiment involving AIRS data and respective AIRS L2 retrievals
covering Esrange (Kiruna, Sweden) area. This dataset has been compiled as complementary to dataset
including IASI/MetOp, IASI balloon-borne instrument measurements together with ground-based and
radiosonde observations. The last one was kindly provided by Dr Claude Camy-Peyret (Université Pierre et Marie Curie et CNRS Physics department, LPMAA, France), see (Payan et al., 2007). The results of experimental AIRS based $Q_{CO2}$ retrievals are presented in Table 1.

Table 1: Experimental retrieval of $Q_{CO2}$ from AIRS data 21-23 Feb. 2007, Esrange/Kiruna

<table>
<thead>
<tr>
<th>First guess, ppmv</th>
<th>SW channels</th>
<th>LW channels</th>
<th>SW+LW</th>
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<tbody>
<tr>
<td></td>
<td>Number of pixels</td>
<td>Std.d</td>
<td>$Q_{CO2}$</td>
</tr>
<tr>
<td>375</td>
<td>184</td>
<td>10,7</td>
<td>387,5</td>
</tr>
<tr>
<td>380</td>
<td>206</td>
<td>12,0</td>
<td>389,3</td>
</tr>
<tr>
<td>385</td>
<td>222</td>
<td>13,3</td>
<td>390,5</td>
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<td>13,8</td>
<td>391,1</td>
</tr>
<tr>
<td>395</td>
<td>219</td>
<td>13,6</td>
<td>391,4</td>
</tr>
</tbody>
</table>

The retrievals have been performed using various first guess for $Q_{CO2}$ (1-st column of Table 1). It is seen that the $Q_{CO2}$ estimate based on AIRS data in LW CO2-dedicated channels (columns 5-7) as well as “combined” $Q_{CO2}$ estimate (columns 8, 9) are sufficiently robust with respect to first guess changes. In spite of absence collocated “ground truth” $Q_{CO2}$ observations, the analysis of Table 1 enables to confirm the above conclusions regarding the performance of proposed $Q_{CO2}$ retrieval technique. The feasibility of $Q_{CO2}$ retrievals is also confirmed (indirectly) via comparison with IASI based $Q_{CO2}$ retrievals from (Payan et al., 2007). This conclusion can be treated as preliminary, accounting for rather limited samples of AIRS and IASI data used.

**IASI- and AIRS-based CH4 column retrievals: first results**

Sensitivity studies carried out with synthetic clear-sky IASI measurements enabled to select subset of 4 CH4-dedicated channels within the methane absorption band around 7.7 μm, see Fig.5. According Fig.5 the IASI measurements in 4 channels with wave to numbers 1332.5, 1341.75, 1346.75 and 1342.75 cm$^{-1}$ being the most sensitive to CH4 variations have reduced sensitivity to variations of water vapor (H2O) and ozone (O3) concentrations treated as main interfering factors. It allows to select these channels as CH4-dedicated. The plots of CH4-Jacobians for these channels (Fig.6) show maximum sensitivity to the CH4 variations in the troposphere with a peak around 10 km. This fact is also confirmed by the behavior of averaging kernels, presented at Fig. 7.

**Fig.5: Brightness temperature sensitivity to changes in CH4, O3, H2O concentration and temperature variations.**
The plots of averaging kernels obtained for CH4 column retrievals demonstrate strong sensitivity to the CH4 concentration in the layer between 7 and 15 km, see also (Turquety et al., 2004). Besides, in order to reduce the effect of profile T(p) uncertainties on the accuracy of CACH4 assessment four CH4-dedicated super-channels have been built. Fig. 8 presents the temperature Jacobians in selected IASI CH4-channels and in “conjugated” channels from 15 µm band. The similarity of temperature jacobians for 4 channel pairs enables to form 4 super-channels with temperature Jacobians close to zero and thus to reduce the sensitivity of “signals” in these super-channels to temperature variations.

Thus it is reasonable to form the following set of super-channels, namely:
I: 1332.50-706.50; II: 1341.75-715.25; III: 1342.75-741.25; IV: 1346.75-714.0 cm⁻¹.

Use of superchannels provides valuable decrease in noise level, especially in noise induced by inaccurate knowledge of temperature at sounding points. It is illustrated by Fig. 9: the contribution of CH4 variations to signal exceeds significantly those induced by T and H2O-variations.

The CH4 retrieval approach is based on the physical inversion and utilizes clear-sky IASI data in listed super-channels and a priori specified T- and water vapor profiles. Similar inversion algorithm is applied to AIRS data.

Fig. 6: CH4 Jacobians in selected IASI channels

Fig. 7: Averaging kernels for CH4 column retrievals (various atmospheric models)

Fig. 8: Temperature Jacobians in “conjugated” IASI channels(CH4 7.7 µm and CO2 15 µm absorption bands).
Case study experiment
The performance of above retrieval algorithm was evaluated in a case study experiment using the above described dataset for Esrange (Kiruna, Sweden) area. The examples of IASI and AIRS-based CH4 column retrievals are presented at Fig.10 (left and right panels respectively).

IASI data inversion. The collocated radiosonde observations (temperature and water vapor profiles) are used as ancillary information. The Gauss-Newton iteration algorithm was applied for the inversion of bias-corrected IASI data in four CH4-dedicated super-channels. The final residuals, i.e., differences between observed and calculated radiances are demonstrated at fig. 11 (not more than 3 iterations).

AIRS data inversion. The AIRS L2 retrievals (temperature, water vapor and ozone profiles together with surface temperature and emissivity) were used as ancillary information. The Gauss-Newton iteration algorithm was applied to bias-corrected AIRS data in four CH4-dedicated channels. Comparison of both kinds of CA CH4 retrievals demonstrates their closeness and it confirms indirectly the efficiency of proposed IASI&AIRS data inversion technique.
Fig. 11: First guess and final residuals for IASI spectra, crosses mark the IASI channels used for CH4 retrieval.

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References
Total ozone depletion due to tropical cyclones over Indian Ocean

Devendra Singh and Sanjiv Nair

We have analyzed the perturbations in the total ozone due to four severe Tropical Cyclones formed over Arabian Sea and Bay of Bengal. Total Ozone data derived from Total Ozone Mapping Spectrometer instrument aboard Earth Probe satellite was used for this study. The daily total ozone anomalies have been calculated for the life span of each tropical cyclone. Theses anomalies were observed local in character and moved with the tropical cyclone. Further, these anomalies have been found related to the intensification of the cyclonic system. In general, negative anomalies were observed to be more than 20 Dobson units at the time of maximum intensity of cyclones. The variations in daily total ozone anomalies, from development to intensification stage and then to decaying stage of each cyclone have brought out clearly the impact of tropical cyclone on the total ozone, which got depleted, considerably over the affected region.
From TOVS to ATOVS based ozone monitoring – implication for the quality and homogeneity

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Abstract

The satellite monitoring of the total ozone content over Poland has been performed with the use of NOAA/TOVS data since 1993. The total ozone amount is used for UV Index forecast as well as to analyse its changes over Poland. Meanwhile, the new generation of NOAA satellite with ATOVS instrument were launched implying the changes both, in type of data and software applied for ozone retrievals. Therefore, the quality of the total ozone amount derived from TOVS and ATOVS data for the period with simultaneous measurements, January 2006 – May 2007. The error of 12.2% for NOAA15 and 11.5% for NOAA-14 was obtained. Moreover, the seasonal variability of the quality of satellite derived total ozone amount was found. Change to NOAA-15 lead to decrease in error for summer and increase – for spring and winter, while for autumn no effect was found for autumn. Furthermore, effect of the transition from TOVS to ATOVS data on the total ozone series homogeneity was studied using Standard Normal Homogeneity Test. In general, the transition from NOAA-14 to NOAA-15 did not break the total ozone time series (since 1993) for the most months. However, for March, June and July the inhomogeneity was found in 2007. As it is the last year of the series, the analysis should be continued in order to confirm that result.

Introduction

Large worldwide total ozone depletion observed during the last two decades of the 20th century (Bojkov, 1999; Solomon, 1999) as well as the results of the EU research programs on stratospheric ozone depletion in the Arctic and mid-latitudes (Knudsen et al., 1998; Rex et al., 1997a, 1999b), have clearly shown the importance of ozone monitoring. The satellite data are the irreplaceable source of information related to the global ozone distribution.

Total ozone amount has been operationally derived from NOAA/TOVS data since 1993 in Satellite Remote Sensing Centre of Institute of Meteorology and Water Management, Krakow, Poland, and used for ozone monitoring over Poland. Its quality has been routinely checked by comparing with ground measurements. The existing ozone data series has been also homogenized using the Standard Normal Homogeneity Test (SNHT) (Lapeta at el., 2007).

Meanwhile, the new generation of NOAA satellite with ATOVS instrument were launched implying the changes both, in type of data and software applied for ozone retrievals. Therefore, the quality of the total ozone amount derived from TOVS and ATOVS data for the period with simultaneous measurements, January 2006 – May 2007, was studied and the results are presented below. Furthermore, effect of the transition from TOVS to ATOVS data on the total ozone series homogeneity is discussed.
In the first part of this paper, the applied method for ozone data retrievals both from NOAA/TOVS and ATOVS satellite data are described together with the results of the comparative analysis for total ozone amount derived from satellite data and ground measurements.

In the second part of the paper, the effect of the transition from TOVS to ATOVS data on the total ozone series homogeneity is studied using Standard Normal Homogeneity Test.

**Data**

To retrieve the total ozone amount from NOAA/TOVS 9.6 µm ozone band, a physical model (Xia-Lin Ma et al. 1984) has been applied. It includes an iterative scheme, in which the first guess of the ozone profile is constructed using regression relation between the ozone concentration and the brightness temperatures observed in HIRS carbon dioxide channels. Additionally, in order to make the first guess of the ozone profile sufficiently accurate, the ozone mixing ratio profile is moved up or down by \( \delta N \) levels calculated from the following relationships (Xia-Lin Ma et al. 1984):

\[
\delta N = 0.5 + 1.4 (T_{cal} - T_{obs}) \quad \text{for low latitudes, and}
\]
\[
\delta N = 0.2 + 1.8 (T_{cal} - T_{obs}) \quad \text{for middle latitudes,}
\]

(1)

where \( T_{cal} \) and \( T_{obs} \) are the brightness temperatures calculated from the ozone guess profile and observed in the ozone 9.6 µm.

The above algorithm was used for NOAA/TOVS data during the period of 1993-1999. Since 2000, the PC-TOVS software package based on the ITPP from Wisconsin University has been applied with the first guess ozone profile from Thermodynamic Initial Guess Retrieval (TIGR) database.

Since beginning of 2006, total ozone amount has been additionally derived from NOAA/ATOVS data using IAPP software from Wisconsin University. The software was run with the use of UK NWP model data and internal data for first guess ozone profile.

For all ozone retrievals the calculations have been performed for 3x3 individual HIRS field of view. Quality of total ozone amount derived from satellite data have been estimated using ground total ozone measurements from Polish Academy of Sciences station located in Belsk (21.0°E, 52.0°N).

**Quality analysis – monthly means**

The total ozone amount operationally calculated from NOAA/TOVS and NOAA/ATOVS was compared with the ground measurements for Belsk for monthly mean values. In order to reduce the influence of ozone diurnal course on the obtained results, the analysis was performed only for NOAA14 and NOAA 15 morning overpasses.

To select satellite ozone value for the station localization, the ozone distribution derived from satellite data have been converted into a regular grid with 0.25° step resolution by the kriging spatialisation algorithm. Then, the total ozone amount for the station has been calculated as the inverted distance weighted mean value estimated from four nearest grids. The example maps of total ozone amount over Europe obtained from NOAA/TOVS and ATOVS data for the 3rd of March 2008 are presented on the Fig. 1. Although, the time difference between NOAA-14 and NOAA-15 morning overpasses was 3.5 hours, the reasonably significant differences both in ozone distribution and values can be observed on the maps.
Fig. 1: Total ozone amount distribution obtained from NOAA14, 08:41 UTC (left panel) and NOAA 15, 05:04 UTC (right panel) data for 03.03.2007 using kriging interpolation algorithm.

On the Fig. 2, monthly means total ozone amount derived from NOAA-14, NOAA-15 satellite data and ground measurements are shown for the period of 2006-2007. One can easily see that the use of NOAA-15 data leads to the stronger underestimation of measured total ozone amount during spring and overestimation during winter, what results in smaller annual amplitude of total ozone amount calculated from NOAA/ATOVS data (blue curve) then from NOAA/TOVS and ground data (red and yellow curves, respectively).

Fig. 2: Total ozone amount derived from NOAA-14, NOAA-15 satellite data and measured Dobson spectroradiometer for Belsk station (21E, 52N) for the period of 2006-2007.
Statistical analysis performed for the seasons revealed that mean difference between satellite derived and measured total amount is of -27.4 DU for spring and 21.7 DU for winter for NOAA-15 and 1.1 DU and 3.4 DU respectively for NOAA-14. On the other hand, the difference obtained for summer for NOAA-15 is much smaller than for NOAA-14. For autumn the results obtained for both type of data are almost the same (Fig.3).

In order to obtain some quantitative information, mean total ozone amount derived from NOAA-15 and NOAA-14 satellite data, the values of mean difference, mean absolute difference, RMSE and percentage error (ratio of MAE and mean value of measured total ozone amount) have been calculated for the whole period. The results are presented in the Table 1. Although the mean difference obtained for NOAA-15 is smaller, the values obtained for other parameters are almost the same.

Tab.1: Results of statistical analysis obtained for NOAA14 and NOAA 15

<table>
<thead>
<tr>
<th></th>
<th>NOAA-15</th>
<th>NOAA-14</th>
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<tbody>
<tr>
<td>Mean [DU]</td>
<td>329.0</td>
<td>347.9</td>
</tr>
<tr>
<td>Mean Diff. [DU]</td>
<td>5.0</td>
<td>14.1</td>
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<tr>
<td>Mean Absolute Diff. [DU]</td>
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<td>RMSE [DU]</td>
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</tr>
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<td>Error %</td>
<td>12.3</td>
<td>11.5</td>
</tr>
</tbody>
</table>
**Homogeneity test**

The influence of the transition from TOVS to ATOS data on homogeneity of the monthly means of total ozone time series was analyzed using the homogeneous, TOVS derived ozone data for the period of 1993-2005 and NOAA-15 derived total ozone amount for the period of 2006-2007.

The SNHT test was applied to the 1993-2007 series of ozone data separately for each month. Ground measurements from Belsk were used as a reference data. The inhomogeneity in the series can be detected subjectively, on the base of SNHT values ($T_i$). The change points usually correspond to the well defined maximum of $T_i$ values. On the Fig. 4, the SNHT test values for the months, for which significant inhomogeneity in 2007 was found, are presented.

![Fig. 4: SNHT values for ‘satellite’ total ozone series for Belsk and for selected months.](image)

The test values obtained for all months are shown in the Table 2. Red color was used when $T_0$ value exceeded 95% of significance level (adjusted from 20 values around the change).

<table>
<thead>
<tr>
<th>Month</th>
<th>Change</th>
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<tbody>
<tr>
<td>Jan:</td>
<td>2005</td>
<td>3.96</td>
</tr>
<tr>
<td>Feb:</td>
<td>1999</td>
<td>2.49</td>
</tr>
<tr>
<td>Mar:</td>
<td>2007</td>
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Conclusions
The quality of the total ozone amount derived from TOVS and ATOVS data for the period with simultaneous measurements, January 2006 – May 2007, was studied using ground measurements from Polish Academy of Sciences station in Belsk. The quality of monthly means of total ozone amount derived from ATOVS (NOAA-15) is almost the same as the one obtained for NOAA-14: error of 12.2% for NOAA15 and 11.5% for NOAA-14. However, day to day variability of total ozone amount is significantly lower for NOAA-15 then for NOAA14 and ground measurements.
Seasonal variability in quality of total ozone amount derived from satellite data was found. Change to NOAA-15 lead to decrease in error for summer and increase – for spring and winter, while for autumn no effect was found for autumn. Finally, the spring increase in total ozone amount is not as clearly marked as for ground measurements and NOAA-14 data.
Furthermore, effect of the transition from TOVS to ATOVS data on the total ozone series homogeneity was analyzed. Standard Normal Homogeneity Test was used to check the influence of transition from NOAA-14 to NOAA-15 (starting from January 2006) on homogeneity of total ozone amount time series. In general, the transition from NOAA-14 to NOAA-15 did not break the total ozone time series (since 1993) for the most months. However, for March, June and July the inhomogeneity was found in 2007. As it is the last year of the series, the analysis should be continued in order to confirm that result.

Acknowledgments
The work was partly funded by grant of the Polish Ministry of Science and Higher Education COST/2/2006 and Polish Chief Inspectorate for Environmental Protection. Ground total ozone data were kindly provided by Institute of Geophysics, Polish Academy of Science. The homogeneity analysis was performed with the usage of the freeware version of the AnClim software (Stepanek, P. (2006): AnClim - software for time series analysis. Dept. of Geography, Fac. of Natural Sciences, MU, Brno. 1.47 MB.)

References


Preliminary Comparisons Between the CO Retrievals from AIRS and the CO CATT-BRAMS Model Estimations over the Amazon Region During the 2002 Dry-to-wet Season

Rodrigo Augusto Ferreira de Souza, Jurandir Ventura Rodrigues, Karla M. Longo, Saulo R. Freitas, Plínio C. Alvalá, Rudinei M. de Oliveira

The high concentration of aerosol particles and trace gases observed in the Amazon and Central Brazilian atmosphere during the dry season is associated with intense anthropogenic biomass burning activity. The biomass burning emissions have a strong impact on the tropospheric and stratospheric chemical composition and are an important agent of weather and climate change. Therefore, the estimation of the amounts inject into the atmosphere at regional as well as global scales is needed. During the past decade, trace gas abundance in the troposphere were obtained from sparsely distributed measurement sites, and observations were mostly confined to the surface. The advent of downward looking instruments to probe the troposphere from polar-orbiting satellites has increased our ability to access the impact of human activities on the chemical composition of the atmosphere and on the climate changes. In this work the CO retrievals from AIRS/AQUA are compared with estimations of CO using the Coupled Aerosol and Tracer Transport model to the Brazilian developments on the Regional Atmospheric Modeling System (CATT-BRAMS) for the dry-to-wet transition season of 2002 over the Amazon region. In general, the results showed a relatively good agreement between both estimates, particularly in the mid-troposphere.
Multi-satellite observation on upwelling after the passage of typhoon Hai-Tang in the southern East China Sea

Yi Chang, Ming-An Lee, Kung Hwa Wang

The serial remote sensing based imageries clearly revealed large scale of upwelling within large regional enhancement of chlorophyll-a (Chl-a) concentration in the southern East China Sea (ECS) after the passage of super typhoon Hai-Tang in July 2005. After the typhoon on July 22, the upwelling area (< 26°C) expanded rapidly to 9146 km2 on the shelf-break. The large increased upwelling persisted for more than a week. Ocean color images also revealed that high Chl-a concentration of >3.0 mg/m3 appeared in the shelf region, where the high Chl-a pattern matched the upwelling in terms of location and time. On the other hand, a large offshore SST cooling was also observed mainly to the right of typhoon track on July 20, it lasted in a period of 2-3 days. Utilization of AVHRR, MODIS, AMSRE and SeaWiFS, this paper provides clear and high-resolution evidence that typhoon significant increased upwelling and Chl-a concentration in the southern ECS. Key word: Remote sensing, upwelling, chlorophyll-a, southern East China Sea, typhoon Hai-Tang.
Retrieval of atmospheric water vapour profile using the Megha-Tropiques

Filipe Aires, Frédéric Bernardo, Hélène Brogniez, and Catherine Prigent

Megha-Tropiques (MT) is a French/Indian mission designed to study the energy and water cycle in the Tropics. Its launch date is expected to be March 2009. This CNES/ISRO platform possesses two microwave instruments: - a cross-track sounder, SAPHIR, for the retrieval of atmospheric water vapour (6 channels in the 183 GHz band); - and a conical scanning imager, MADRAS, designed mainly to study precipitation and cloud properties, with 9 channels (18.7, 23.8, 36.5, 89 and 157 GHz with vertical and horizontal polarizations, except for the 23.8). In this study, we combine Saphir and Madras observations for the retrieval of atmospheric water vapour over ocean and land and for clear sky. The statistical inversion scheme is developed using a synthetic data simulated with the RTTOV radiative transfer model. The atmospheric temperature profiles from the ECMWF forecast are used as auxiliary information. Furthermore, a microwave surface emissivity atlas is utilized over land to better constrain the surface contribution in surface sensitive channels. These auxiliary information are added to Madras and Saphir observations to feed a neural network retrieval scheme that estimates the atmospheric water vapour profile. The synergy of the two microwave instruments comes from the sounding abilities of Saphir added to the vertically integrated water vapour information derived from Madras. Together with the development of the retrieval scheme, an information content analysis is conducted. In particular, the vertical resolution is optimized with respect to the retrieval capability of Saphir. In parallel, we perform a sensitivity analysis with respect to the various sources of uncertainty, i.e. satellite observations or auxiliary information. The evaluation of the retrieval algorithm is performed using AMSR-E and HSB observations that have roughly the same viewing geometry than Saphir and Madras (cross-track for HSB; conical for AMSR-E) and provide similar observations of the atmosphere. Radiosonde measurements are also utilized.
The Use of HSB to Derive the Integrated Water Vapor Content: An Example Using the RACCI/LBA Experiment

Wagner Flauber Araújo Lima and Luiz Augusto Toledo Machado

This work presents the capability of the HSB (Humidity Sensor Brazil) channel in retrieving Integrated Water Vapor Content. The data analyses of this study have been carried out in two stages: firstly using simulations of the HSB channel brightness temperatures from RTTOV radiative model, and secondly, using data from the “RACCI/LBA” (Radiation, Cloud, and Climate Interactions/Large Scale Biosphere Atmospheric Experiment in Amazônia) experiment in Rondônia, during the period of September and October 2002. The results show the potential of the 183 ± 1, 3 e 7 GHz channels in retrieving middle and upper tropospheric water vapor for clear sky situations. The estimation of integrated water vapor contents in the atmosphere using HSB channels was not possible due to the absence of troposphere low level information, where most of the water vapor is concentrated. The 150 GHz channel, which has the maximum peak of its weight function next to the surface, is strongly influenced by the surface emissivity.
The NPOESS Aircraft Sounder Testbed-Microwave (NAST-M) passive microwave spectrometer suite was used to help validate the radiometers (AMSU and MHS) on the MetOp-2/A satellite. Underflights of MetOp-2/A were made by the WB-57 high-altitude research aircraft during the Joint Airborne IASI Validation Experiment (JAIVEx – Apr. 2007). Microwave data from other satellites (Aqua, NOAA-16, and NOAA-17) will also be presented. Also, NAST-M data is used to validate the parameter tuning in a scattering Radiative Transfer Algorithm (RTA) coupled with a cloud circulation model. The NAST-M instrument suite includes a total of four spectrometers, with three operating near the oxygen lines at 50–57, 118.75, and 424.76 GHz, and a fourth spectrometer centered on the water vapor absorption line at 183.31 GHz. The NAST-M 54-GHz spectrometer has five channels corresponding to the AMSU-A instrument, and the 183-GHz spectrometer has three channels corresponding to the MHS instrument (or AMSU-B). This enables radiance-to-radiance comparisons, which can circumvent potential pitfalls and modeling errors that can be introduced when simulating spaceborne radiances. All four of NAST-M’s feedhorns are co-located, and have 3-dB (full-width at half-maximum) beamwidths of 7.5°, which translates to ~2.5-km nominal pixel diameter at nadir incidence. The four feedhorns are directed at a single mirror that scans cross-track beneath the aircraft, spanning ± 65 degrees. The NAST-M sensor is mounted on an aircraft platform with a typical cruising altitude of 17-20 km, which results in a nominal swath width of 100 km. The high-altitude platform enables high spatial and temporal coincidence with satellite measurements, and NAST-M’s 100-km swath width provides complete coverage of both AMSU and MHS nadir footprints. The paper will detail the essential techniques used to correct for the difference in altitude and view angle between the satellite and aircraft sensors along with procedure for co-locating NAST-M measurements with satellite measurements. The radiance-to-radiance comparisons will be evaluated against a purely simulated validation technique. The RTA parameter tuning utilizes the MM5 regional-scale circulation model to generate atmospheric thermodynamic quantities (for example, humidity and hydrometeor profiles). These data are then input into the Rosenkranz multiple-stream initial-value RTA [Rosenkranz, 2005] to simulate at-sensor millimeter-wave radiances at a variety of viewing geometries. The simulated radiances are filtered and resampled to match the sensor resolution and orientation. While the parameters chosen in the
circulation model are important, the focus of the current work is the parameter selection in the RTA, and we aim to extend the work of Surussavadee and Staelin to higher spatial resolutions (from 15 km to 2 km) and frequencies (from 183 GHz to 425 GHz). The RTA parameters are optimized by co-locating the model data with observations from the NAST-M instrument and choosing the parameters for which the RMS deviation between the simulated and actual brightness temperatures is minimized. The optimization is performed numerically with parameter sweeps using the MIT Lincoln Laboratory LLGrid High Performance Computing Facility, which consists of approximately 1000 Xeon processors. Over a dozen storms consisting of over 5,000 precipitation-impacted pixels have been studied. Comparisons of the observed versus calculated brightness temperatures will be presented. This work was sponsored by the National Oceanic and Atmospheric Administration under Air Force contract FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and not necessarily endorsed by the United States Government.
Metop satellites are the European contribution to the space-based global observing system and to the joint European/US operational polar satellite system. Metop covers the mid-morning (9:30) orbit, whereas the US continues to cover the afternoon orbit with the NOAA satellites. Metop-A provides advanced observations of temperature and humidity profiles, wind, ozone and other trace gases. The instrumentation of Metop is a judicious balance between continuity of known instruments and novel observations, notably the hyperspectral thermal infrared observations with IASI and radio occultation measurements. The Metop instruments have a great potential to provide synergetic measurements. Some of the instruments are synchronized (IASI, AMSU, MHS) or co-registered (AVHRR via the Integrated IASI Imager). IASI is expected to provide trace gas information, as is also the GOME-2 instrument. By flying different instruments on the same platform a large potential exits to combine measurements from different instruments and improve products. An example could be Ozone vertical information with GOME/IASI, the combination of IASI/GRAS (high vertical sampling at high accuracy) and others. The poster will provide an overview on the EPS/Metop system and the payload, and illustrate the synergetic potential of the instruments.
Australian Bureau of Meteorology Satellite Data Exchange and Use

Gary Weymouth, Anthony Rea, David Griersmith, Ian Grant, Chris Tingwell, AP-RARS participants, other Bureau staff

The Australian Bureau of Meteorology has recently improved its use of locally-received ATOVS data in NWP, with significant positive impact. Additionally, the Bureau both supplies and receives Asia Pacific Regional ATOVS Retransmission Service (AP-RARS) data. This data also has shown positive impact on local and international NWP, and is produced using AAPP. The AP-RARS network has expanded, with stations added from New Zealand, Singapore, Japan (Siyowa in Antarctica), Korea and Hong Kong, in addition to stations in Australia, Japan and China. During 2008, additional AP-RARS stations are expected to include Townsville (Australia), Casey and Davis (Antarctica). Provision of AP-RARS data from Noumea and Tahiti has been announced for some future date, and data from Fiji, Honolulu, and either Guam or the Marshall Islands is under investigation. The WMO goal for ATOVS availability on the various RARS networks is 90% global coverage with less than 30 minutes latency. The Bureau is also implementing X-band reception sites in Melbourne (Crib Point, March 2008), Darwin (June 2008) and Casey (summer 2008/9). Satellite data should be received from terra, aqua, NPP, NPOESS, FY3 and possibly other satellites. One of the drivers of this program is to improve the timely availability of hyperspectral satellite data for NWP. The data is also expected to be used for oceanography and other purposes. GPS precipitable water estimates are in test production, while production and NWP use of GPS RO soundings are under investigation.
In response to the request of its users to revisit the dissemination strategy for IASI data, EUMETSAT plans to begin the dissemination of level 1 data (spectra) using principal component compression. The principal component scores will be calculated using a robust training set, and disseminated in near real time both globally via the GTS and via EUMETSAT’s DVBS multicast system, EUMETCast. The data will be encoded in BUFR and will comprise around 180 principal component scores per spectrum. Several technical issues are currently being addressed, such as the possible prior separation of the spectra into distinct bands, the distribution of the residuals and the exact number of scores to be used.
NOAA/NESDIS Updates on Operational Sounding Data Products and Services

A.K. Sharma

The National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Services (NOAA/NESDIS) has been a pioneer in producing and distributing atmospheric sounding data products as a part of its operation for operating a fleet of civilian, Polar Orbiting Environmental Satellites (POES) and providing users and researchers a suite of operational atmospheric and environmental data products. Sounding Data Products are being generated from the advance TIROS Operational Vertical Sounder (ATOVS), onboard NOAA polar orbiting satellites (NOAA-15, NOAA-16, NOAA-17, and NOAA-18), and Infrared Atmospheric Sounding Interferometer (IASI) onboard Meteorological Operational Satellite (MetOp-1). ATOVS consists of three instruments, Advanced Microwave Sounding Units (AMSU), AMSU-A and AMSU-B, and a High-resolution Infrared Radiation Sounders (HIRS) instrument. NOAA-18 launched in May 2005 contains the Advanced Very High Resolution Radiometer (AVHRR/3), HIRS/4, AMSU-A, and the Microwave Humidity Sounder (MHS) instruments. AMSU-B has been replaced by MHS for deriving the sounding data products on NOAA-18. HIRS/4 on NOAA-18 has not been stable and has encountered numerous problems to prevent using its data in ATOVS processing. A new data distribution technique, Data Distribution Server (DDS), has been employed at the NOAA/NESDIS Environmental Satellites Processing Center (ESPC) for distributing the soundings data. This presentation will include the discussion on the ESPC system architecture involving sounding data processing and distribution for Infrared Atmospheric Sounding Interferometer (IASI), improvements made for data quality measurements, pipeline processing and distribution via DDS, and user timeliness requirements envisioned from the next generation of satellites. There have been significant changes in the operational system due to system upgrades, algorithm updates, and value added data products and services. User requirements for data products and services for sounders like ATOVS and IASI would help us determine the products and services required from the next generation of sounders such as Cross-Track Infrared Sounder/ Advanced Technology Microwave Sounder (Cris/ATMS) as planned for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program and the future missions of the European Organization for the Exploitation of Meteorological (EUMSAT) satellites. The operational IASI systems producing level 2 data will also be discussed.
Operational Implementation of Integrated Microwave Retrieval System

Limin Zhao, Aiwu Li and Jiang Zhao

The MIRS is a state-of-the-art retrieval system developed to support POES, MetOp, DMSP, NPP/NPOESS programs at NESDIS in generating operational temperature, water vapor, and hydrological parameters from microwave sensors. It is based on an assimilation-type scheme and capable of optimally retrieving atmospheric and surface state parameters simultaneously. It provides enhancements to the NESDIS current operational surface and precipitation products from Microwave Surface and Precipitation Products System (MSPPS), and also generates temperature and moisture profiles in all weather and over all-surface conditions. The MIRS aims to produce the operational microwave sounding, surface and precipitation products from different sensors cross several satellites, so its products are being developed and implemented into operation through a multi-years stratified phase approach. Recently, the MIRS was successfully transitioned into operation at NESDIS. Its Phase-I and –II products from POES and MetOp were declared operational, and have been made available to both real-time users and climate users through NESDIS Environment Satellite Processing Center (ESPC) Data Distribution Sever (DDS) and Comprehensive Large Array-data Stewardship System (CLASS). In this presentation, we will discuss the transition of MIRS from research to operation, its operational implementation procedures, products validation, monitoring and dissemination. Detailed information on the operational MIRS, its products and their application in supporting NESDIS precipitation operation will also be presented.
Enhancements of the AIRS Eigenvector Regression Algorithm

Lihang Zhou, Zhaohui Cheng, Thomas King, Walter Wolf, Mitch Goldberg, Xingpin Liu Fengying Sun, Chris Barnet and Haibing Sun

The differences between observed and simulated AIRS spectra, acquired from validation campaigns, are very small (usually decimals of degree in brightness temperature); this encourages the development of a physically-based regression. The physical regression coefficients are derived by first acquiring an ensemble of truth data, simulating ensemble spectra with the latest AIRS science team rapid radiative transfer algorithm, and then generating the regression coefficients. The truth data is consist of a set of radiosonde/rocketsonde temperature and moisture profiles, collocated with forecast model fields as well as other routine observations. The training set is augmented with representative profiles of CO2 and other greenhouse gases. The physically-based algorithm is tested and validated on our global multi-years re-processing dataset. Results and comparisons with the current regression algorithm will be presented.
Global Coverage of Total Precipitable Water using the Microwave Integrated Retrieval System (MIRS)

S.-A. Boukabara, K. Garrett, C. Kongoli, B. Yan, P. Pellegrino, F. Weng and R. Ferraro

This study focuses on the performances of the total precipitable water (TPW) operational product, generated using the Microwave Integrated Retrieval System (MIRS) at NOAA/NESDIS. These retrievals are made operationally available over ocean and also, experimentally, over land, coast, sea ice and snow surfaces. MIRS is a 1DVAR inversion scheme that employs the Community Radiative Transfer Model (CRTM) as the forward operator. It solves simultaneously for the surface and the atmospheric parameters in a consistent fashion. The surface is represented by its temperature and emissivity spectrum. The main difference between retrieval over land and that over ocean is confined to the shape of the spectral constraint imposed on the emissivities being retrieved. This renders the retrieval of atmospheric profiles over different surfaces, trivial. The main challenge becomes simply the determination of the appropriate constraint for each type of surface background. Although MIRS retrieves the entire temperature and moisture profiles, we will focus in this study on the assessment of the TPW retrieval over all-surfaces, namely ocean, sea-ice, land, coast and snow. Note that the TPW is not retrieved independently in MIRS, but is rather a vertical integration of the retrieved moisture profile. The assessment of the performances is done using NOAA-18 and METOP-A AMSU/MHS data. The retrievals are compared to the NCEP Global Data Assimilation System (GDAS) outputs and to a network of radiosondes, encompassing a wide variety of meteorological situations. Specific comparisons over a one-year period, to data from three Atmospheric Radiation Measurement (ARM) sites (Southern Great Plains, Northern Alaska and Tropical Western pacific) are also presented. It is found that TPW accuracy over snow and sea-ice backgrounds is higher than that over non-frozen land surfaces, consistent with expectations determined in simulation. Over ocean, the MIRS retrievals are also compared to operational products, namely the Microwave Surface and Precipitation Products System (MSPPS). Visual inspections of TPW fields seem to indicate that MIRS is consistent with meteorology, with no apparent discontinuity of moist/dry fronts at the boundaries of surface backgrounds. This adds confidence that MIRS is functioning as expected and suggests that coastal retrievals might also be accurate. In this case, the retrieved surface emissivity spectrum handles the mixed terrain within the pixels, avoiding therefore a contamination of the TPW. The statistical performances are broken down by surface type.
CrlIS Radiance Simulations in Preparation for Near Real-Time Data Distribution

Haibing Sun, Kevin Zhang, Lihang Zhou, W. Wolf, T. King, C. Barnet, and M. Goldberg

A simulation system is under development to support pre-launch preparations for the Cross-Track Infrared Sounder (CrIS) NOAA Unique near real-time processing and distribution system. CrIS, a Michelson interferometer infrared sounder with over 1305 channels per spectrum, will fly on the NPOESS satellite series that is dedicated to the operational meteorology and climate monitoring. It will replace the AIRS and HIRS as the next generation operational infrared remote sensor to provide improved measurements of the temperature and moisture profiles in the atmosphere. The CrIS simulation system will emulate the instrumental and orbital characteristics of the CrIS instrument on NPOESS. The utilities of this system are: (1) to provide simulated observation radiances that support NOAA Unique product (cloud clearing and trace gases) development and testing, (2) to provide a robust data distribution environment for development and testing of the CrIS data sub-setting system, and (3), most importantly, to allow for a smooth transition of the CrIS NOAA Unique Product processing system from the development environment to the operational environment. Details of the simulation system shall be presented.
Serendipitous Characterization of the Microwave Sounding Unit During an Accidental Spacecraft Tumble

Thomas J. Kleespies

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E/RA2 Room 711 WWB, 5200 Auth Road, Camp Springs, MD 20746 USA

Abstract

The Microwave Sounding Unit has been flown on NOAA spacecraft since 1979. It has been used by a number of teams to attempt to determine decadal trends of atmospheric temperature, often with conflicting results. While a great deal of innovation has gone into refined post-launch calibration, considerable uncertainty remains, especially regarding asymmetry of the radiances. A pitch maneuver was performed on the NOAA-14 spacecraft in which the satellite remained in an inertial drift for one orbit. This permitted all of the instruments to view the flat cosmic background while in normal scanning mode, and thus identify and quantify cross-track asymmetries. Approximately seven weeks after the maneuver was executed, the NOAA-14 spacecraft suffered a hydrazine thruster failure. A locked valve apparently failed, releasing to space hydrazine which had remained in the line from early orbit operations, sending the spacecraft in a tumble. MSU data were collected during the tumble until the instruments were turned off to conserve power. The spacecraft was recovered and resumed normal station-keeping. These two events represent a unique opportunity to examine time variable cross-track asymmetry in the MSU. This paper will describe the events of the maneuver and tumble, and present an analysis of the cross-track asymmetry and its variability.

Introduction

The Microwave Sounding Unit (MSU) (Homan and Soltis, 1977) was first launched on the Television-InfraRed Observational Satellite - N (TIROS-N) in October 1978. It has subsequently flown on a series of NOAA polar orbiting spacecraft up to and including NOAA-14, and has provided a continuous record of observations for almost twenty-eight years. A number of atmospheric temperature time series analyses have been derived from these observations, notably those of Christy et al. (2000), Fu et al., (2006), Mears et al., (2003), and Vinnikov and Grody (2003). Considering the ongoing debate on the cause and extent of global warming, it is imperative that the MSU be characterized to the maximum possible extent. For example, Christy et al. (2000) use differences between the inner and outer scan positions to account for stratospheric emission when computing their T2LT product. A scan asymmetry would affect this product. This paper describes a pitch over maneuver (POM) that recently was performed on NOAA-14 in order to evaluate any earth scene cross-track asymmetry caused by antenna side lobes, and to validate the space calibration view. For reference, Figure 1 displays the NOAA-14 spacecraft and the location of the MSU with respect to the other instruments and satellite components. Table 1 gives the basic characteristics of the MSU.

History

Pitch maneuvers have been performed on NOAA spacecraft before. They were conducted on NOAA 2 and 3 to characterize the Improved Temperature Profile Radiometer, on NOAA 10 to characterize the Earth Radiation Budget, and most notably on NOAA 6 to examine the MSU for asymmetry. Unfortunately the original data from the NOAA 6 maneuver have been lost.

Methodology

The term “pitch maneuver” is a misnomer since during normal orbital operations, POES spacecraft pitch forward 360º each orbit so that the instruments on the nadir side continuously face the earth (Figure 2). For the POM, this pitch motion is stopped, and the spacecraft maintains inertial pointing in
the pitch direction. As the spacecraft orbits the earth, the horizon sets and all of the nominal earth viewing scenes now view deep space. At the other side of the orbit, the horizon rises from the other side, and the instruments re-acquire the earth view. After exactly one orbit, the normal pitch motion is resumed.

A long sequence of commands must be sent to the spacecraft to accomplish the POM. For example, since the spacecraft is in an inertial drift, the solar array must stop rotating in order for the panels to maintain sun orientation. The earth sensor array is disabled in order to put the spacecraft into the inertial drift. Thrusters are enabled in case the spacecraft tumbles and recovery is required to assist magnetic torque recovery or to dump momentum. Normal spacecraft redundancy actions are overridden. Thruster firings did occur at the end of the maneuver as the spacecraft recovered and returned to a nominal mode.

**Results of Pitch Maneuver**

One hundred thirty-nine scans were selected while the instrument was viewing deep space, on 10 August 2006, from 16h28m35s to 17h27m53s UTC. Viewing of deep space was determined when all eleven nominal earth scene views registered to within a few counts of the space calibration view. Since the instrument counts vary with instrument temperature, the calibration space view was subtracted from the nominal earth scene counts for each scan. The mean difference of counts was converted to antenna temperature differences by multiplying by the nominal slope of 0.12K/count, and are shown as a function of scan position in Figure 3. Channels 1 and 3 are vertically polarized and channels 2 and 4 are horizontally polarized at nadir. For reference, the scan diagram for the MSU is shown in Figure 4. Note that position 1 is in the direction of the spacecraft, position 6 is at nadir, and position 11 views away from the spacecraft and is closest to the space calibration view.

The corresponding values of the standard deviation of the difference show essentially random changes of about 0.01K from one scan position to the next. For brevity, these figures will not be presented in this letter.

Three points are worth noting:

The first point to note is that the nominal earth scene viewing space records different brightness temperatures than the space calibration view. This difference is greatest in channel 1 at nadir position 6 of about 0.5 K. The vertically polarized channels register colder than the space look, and the horizontally polarized channels register warmer than the space look. As shown in figure 4, the space look is 85.263º from nadir. The nominal half power (3dB) antenna beamwidth is 7.5º, which means that the edge of the nominal field of view is 89.013º from nadir. As can be seen in Figure 1, the MSU sits on top of its electronics enclosure, which itself is enclosed by a thermal blanket with a reflective surface. We hypothesize that a side lobe is viewing the thermal blanket while the instrument is in its space look. Note that the nominal channel polarization is at nadir, and the polarization vector rotates through the scan. This means that when viewing space, the nominal vertical polarization channels would be horizontal, and the nominal horizontal polarization channels would be vertical. Since the nominal vertical channels are colder and the nominal horizontal channels are warmer than the space look, this suggests radiation is scattered off the thermal blanket in such a way as to be horizontally polarized.

The second point is that there is a marked asymmetry in the nominal earth scene, and the characteristics of the asymmetry differ for the different polarizations. The vertically polarized channels display maximum difference from the space look near the nominal nadir position. The horizontally polarized channels on NOAA-14 tend to have a maximum in the lower scan positions, and a minimum in the higher scan positions. This suggests that the side lobes are sensing the spacecraft components and instruments in a manner that is polarization sensitive.

The third point is that position 1 reads higher values than position 2. It is clear that the instrument side lobes are sensing something on the spacecraft in scan position 1, perhaps the Earth Radiation Budget Experiment dummy payload which appears to be in line with the MSU scan.
Spacecraft Tumble

On 28 September 2006, a thruster on NOAA-14 released hydrazine gas, causing the spacecraft to tumble. Approximately two orbits of instrument data were collected by the onboard recorders until the instruments were turned off in order to manage power. Over the next few days the spacecraft was returned to normal operations and the instrument data were recovered. This anomaly provided a unique opportunity to evaluate whether the asymmetry found in the pitch maneuver changed during the ensuing seven weeks.

The MSU data were carefully screened to exclude any earth influence in the individual scene and calibration views. The average of each scene and space calibration views were then differenced in the same manner as for the pitch maneuver. The results are presented in Figure 5.

Two points are noticed in comparing Figure 5 to Figure 3:
First, channel 2 difference from space look is sensing about 0.15 K colder during the tumble than during the pitch. The other channels either have no change, or the difference from space look is positive (warmer).
Second, the absolute average of all scene positions is warmer during the tumble than during the pitch.

Since channels 2 and 4 have the same polarization, it is unknown why the change in their behavior is so different between the pitch and the tumble.

Summary

The National Oceanographic and Atmospheric Administration has successfully performed a POM on NOAA-14. The test showed that earth scene viewing space reads different values than the space calibration view does, that there is an asymmetry in the observations, and that scan position 1 is warmer than scan position 2. Data gleaned from a spacecraft tumble seven weeks later reveal that most channels’ earth scene sense warmer than the space look, but that channel 2 senses colder.

Acknowledgements

The views expressed in this publication are those of the author and do not necessarily represent an official position or policy of NOAA, the Department of Commerce, or the United States Government.

References


Figure 1: NOAA-14 spacecraft with locations of instruments and major components. The Earth Radiation Budget Experiment (ERBE) instruments are dummies on NOAA-14. From the viewpoint of the reader, the MSU reflector for channels 1 and 2 is on the right side of the instrument, and the reflector for channels 3 and 4 is on the left side of the instrument.

Figure 2: Schematic of spacecraft attitude in normal orbit, and during the pitch maneuver.
**Figure 3.** Mean antenna temperature difference of nominal earth scene view minus space calibration view, averaged over 139 scans viewing space, as a function of scan position. Channels 1 and 3 are vertically polarized, and channels 2 and 4 are horizontally polarized.

**Figure 4.** Schematic of MSU scan pattern. Positions 1 through 11 are earth scenes, with position 1 viewing in the direction of the spacecraft, and position 11 viewing away from the spacecraft. Position 6 is nadir. Position 12 is the cold space calibration view, and position 13 is the internal warm calibration target view. The velocity vector is out of the page.
Table 1. MSU Instrument Specifications

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<tr>
<td>Polarization at Nadir</td>
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<td>H</td>
<td>V</td>
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<tr>
<td>Integration time (seconds)</td>
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<td>1.84</td>
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A Geostationary Microwave Sounder for NASA and NOAA

Bjorn Lambrigtsen, Todd Gaier, Pekka Kangaslahti, Alan Tanner
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4800 Oak Grove Drive, Pasadena, CA 91109

Abstract

The Precipitation and All-weather Temperature and Humidity (PATH) mission is one of 15 Earth space missions that the U.S. National Research Council recently recommended that NASA undertake in the next decade. The PATH mission will place a microwave atmospheric sounder, operating in the same temperature and water vapor bands used by the low-earth-orbiting Advanced Microwave Sounding Units (AMSU), into geostationary orbit. The objective is to enable time-continuous observations of severe storms, tropical cyclones and atmospheric processes associated with the hydrologic cycle under all weather conditions. The ultimate goal is to improve models in these areas, provide initial conditions and assimilation data for improved forecasts, and develop long time series to support climate studies. Both NOAA and NASA have long sought to develop such a sensor, but it is only recently that new techniques have emerged that enable such a mission. The Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR) is a microwave sounder concept based on aperture synthesis that has been developed at the Jet Propulsion Laboratory. A small proof-of-concept prototype was completed in 2006 under the NASA Instrument Incubator Program, and this demonstrator proves that the aperture synthesis method is a feasible approach for attaining the very large aperture required for adequate spatial resolution. The performance of the prototype and projections to a full-scale space version indicate that GeoSTAR, unlike alternative approaches, can meet all measurement requirements. It is therefore now considered the baseline PATH payload and is expected to be implemented by NASA in the next decade. A near-term option is to fly GeoSTAR as a “Mission of opportunity” on one of the first two satellites in NOAA’s GOES-R series currently under development. Such a joint NASA-NOAA mission would satisfy important NASA research needs and serve as a fast-track “Research-to-operations” pathfinder mission for NOAA as well.

Overview

The National Research Council, an arm of the U.S. National Academies of Science, recently released a “decadal survey” of NASA and NOAA Earth space missions [1]. Among the 15 missions recommended for NASA to undertake was one called the “Precipitation and All-weather Temperature and Humidity” mission (PATH). A “MW array spectrometer” was identified as the recommended instrument payload for PATH. Such an instrument, called the Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR), is being developed at NASA’s Jet Propulsion Laboratory (JPL). Sponsored by the NASA Instrument Incubator Program a proof-of-concept prototype has been developed and tested at JPL, in partnership with the NASA Goddard Space Flight Center and the University of Michigan. This development has been closely coordination with the NOAA NESDIS Office of System Development to ensure that the GeoSTAR design will meet the needs and measurement requirements of NOAA as well. The prototype, a ground-based fully functional temperature sounder with capabilities similar to the Advanced Microwave Sounding Unit – currently the most advanced microwave sounder operating on polar-orbiting low-earth-orbiting (LEO) satellites, shows excellent performance and has provided the intended proof of concept. This represents a major breakthrough in remote sensing capabilities, since it makes it possible to deploy a microwave sounder as part of the Geostationary Operational Environmental Satellite (GOES) system – a long sought goal, since the GEO vantage point offers key advantages over LEO, such as a continuous view of the entire life cycle of storms and hurricanes. Due to the very large antenna aperture needed for a microwave sounder to provide the required spatial resolution, it has not been possible to develop such instruments for GEO. Only infrared sounders have been feasible, but they are severely hampered by clouds – which is not a problem for microwave sounders. GeoSTAR overcomes those difficulties by synthesizing a large aperture. This new concept was clearly viewed by the NRC as a very important break-
through. Plans for a PATH/GeoSTAR mission are now under development, and a mission study was recently completed by JPL for NASA. A similar study has been done for NOAA as well, and both conclude that GeoSTAR can meet all relevant measurement requirements. The emergence of a viable approach to implement a GEO microwave sounder is of particular interest to NOAA, which is currently developing the next generation of GOES satellites (named GOES-R after the first in the new series). This new system was intended to carry an advanced hyperspectral infrared sounder (the Hyperspectral Environmental Suite – HES), but HES was recently cancelled for the first two satellites (GOES-R and GOES-S). There remains a strong need for an atmospheric sounder, and the possibility of flying GeoSTAR on one of the first GOES-R satellites as a “Mission Of Opportunity” is now under investigation. A joint effort by NASA and NOAA, where NASA would provide the instrument and NOAA would provide the platform and launch, would be a compelling demonstration of a new “Research to operations” paradigm.

PATH will provide a number of measurements that are crucial for the monitoring and prediction of hurricanes and severe storms – including hemispheric 3-D temperature, humidity and cloud liquid water fields, rain rates and totals, tropospheric wind vectors, sea surface temperature, and parameters associated with deep convection and atmospheric instability – everywhere and all the time, even in the presence of clouds. These parameters will be derived from a continuous stream of 2-D radiometric “synoptic snapshots” covering the entire visible disc. With these capabilities, GeoSTAR will become a prime hurricane sensor, in addition to providing the basic sounding functions required by operational agencies for regional weather prediction and will in addition provide key observations needed for studies related to the hydrologic cycle. In particular, with GeoSTAR the diurnal cycle can be fully resolved, and atmospheric processes related to cloud dynamics and convection can be studied without the diurnal temporal sampling biases that are prevalent with polar-orbiting sun-synchronous satellite sensors. As has been demonstrated in LEO, microwave sounders are excellent tools for climate applications, with their superior stability and lack of sampling bias. Much of the technology risk of this new measurement concept has been retired with the prototype and related developments, but additional technology development as well as application studies are under way, funded by NASA and NOAA.

**PATH**

The primary objective of PATH is to provide continuous soundings and precipitation measurements under both clear and cloudy conditions, with very rapid refresh rates. Those observations will be used to improve and constrain atmospheric models, which is expected to lead to significant improvements in storm forecasts as well as improved understanding of atmospheric processes related to the hydrologic cycle.

The NRC in its report states that current numerical weather prediction models are widely recognized as having an inadequate representation of the processes of cloud formation, evolution and precipitation. They rely on simplistic parameterization schemes and an incomplete understanding of the underlying cloud microphysics to represent the most rapidly changing weather phenomena. The PATH measurements will impose powerful new constraints on, and are expected to lead to greatly improved models for boundary layer, cloud, and precipitation processes. The availability of continuous observations will also significantly mitigate the requirements on those models because they will be able to be frequently re-initialized by observations. The observations will also enable major scientific advances in the understanding of El Niño, monsoons, and the flow of tropical moisture to the U.S. The NRC report suggests that “accommodation of an all-weather sensor suite on future GOES GEO platforms is the most promising option in the next ten years”.

The PATH measurements require penetration well into clouds, and that requires temperature sounding in the 50-70 and 118 GHz oxygen absorption bands and water vapor sounding at the 183 GHz water vapor line. These bands are also suitable for precipitation observations. Although the report does not specify a particular payload design, numerous references make it clear that the study panel envisioned that this would be a mission based on the GeoSTAR concept and recognized that known alternative concepts would not be able to satisfy the measurement requirements. This is reflected by the report identifying a “MW array spectrometer” as the presumed payload.
GeoSTAR

GeoSTAR is a “MW array spectrometer” that will meet all the requirements of the PATH mission. The measurement concept was initially developed for the NASA New Millennium Program “EO-3” mission in 1999 [2]. Subsequently, a small proof-of-concept prototype was developed at JPL in 2003-2006 [3]. The performance of the prototype shows that the STAR approach is feasible and that a full-scale space version will perform as required. The design and test results are discussed by Tanner et al. [4].

GeoSTAR is a spatial interferometer that essentially measures the upwelling radiation emitted by the atmosphere in the spatial Fourier domain. This is accomplished by deploying a large number of individual microwave receivers arranged in a sparsely filled 2-D array. In the baseline configuration there are three linear arrays arranged in a “Y” shape, and the effective aperture is then essentially defined by the circle that circumscribes the “Y”. In this way it is possible to form the large effective aperture required for geostationary satellites, where the orbit altitude is nearly 50 times greater than for low-earth orbiting satellites and therefore requires an aperture that is also 50 times as large. This array configuration is illustrated in Fig. 1. All of the antennas are pointed in the same direction. A digital subsystem computes the complex cross-correlations between all receiver pairs in the array simultaneously. In the small-scale example of Fig. 1 there are 24 receivers, 276 complex correlations and 384 unique so-called uv-samples, which means that the spatial imaging field can be resolved into 384 “pixels”. Each receiver pair forms an interferometer, which measures a particular spatial harmonic of the brightness temperature image across the field of view. The spatial harmonic depends on the spacing between the antennas and the wavelength of the radiation being measured. The complex cross-correlation measured by an interferometer, called the visibility function (a term coined by radio astronomers, who have used the STAR approach for many years, such as in the Very Large Array operated by the National Radio Astronomy Observatory in New Mexico), is essentially the 2-dimensional Fourier transform of the brightness temperature. By sampling it over a range of spacings and azimuth directions one can reconstruct, or “synthesize,” an image by discrete Fourier transform. In Fig. 1, the left panel shows the distribution of receivers in the instrument’s aperture plane, and the right panel shows the resulting sampling points in spatial Fourier space i.e. in terms of spatial harmonics.

Fig. 2 shows the hexagonal imaging region (left panel) resulting from this star-shaped uv-sampling pattern imposed on the Fourier transform of the Earth brightness temperature field (right panel). As in all interferometric systems, there are “ghost” imaging hexagons adjacent to the primary one, and radiation originating from those areas is aliased into the primary area. However, in the GeoSTAR case this is not a problem since the space beyond the Earth disc is featureless and at a uniform 2.7 K temperature. (The sun and the moon will periodically be aliased into the imaging area, but those occurrences will be used to help calibrate the system.) As we discuss below, the primary imaging area can even be reduced somewhat to reduce the number of receiving elements needed to attain the required spatial resolution, and portions of the observations near the limb would then be contaminated by aliasing. That can be
tolerated, however, since accurate sounding is limited to relatively high elevation angles.

**Baseline PATH mission**

A preliminary PATH mission study was conducted for NASA in 2007, which concluded that all requirements discussed in the NRC Decadal Survey can be met with the GeoSTAR design, and mission cost is projected to be within 15% of NRC’s estimate. The study also showed that a PATH-GeoSTAR mission is feasible in terms of mass and power as well. Power consumption has been a matter of concern, since a full-size instrument will have nearly 1000 receivers and close to 1 million correlators – digital multipliers operating at 100 MHz or more. The state of technology is now such that this can be done with comfortable margins, and the mass and power requirements are currently estimated at less than 250 kg and 350 W, respectively. These numbers are expected to decline as the technology matures further.

The baseline GeoSTAR design consists of a dual collinear array, one with ~300 receivers in the 50-GHz band and one with ~600 receivers in the 183-GHz band. Each “arm” of the 50-GHz array is approximately 2 meters long. That results in a spatial resolution of 50 km for temperature sounding and 25 km for water vapor sounding – this compares with 50 and 15 km, respectively for the LEO AMSU system. Future versions are envisioned to have significantly higher spatial resolution, which can be achieved by adding receivers and thus extending the lengths of the array arms. Fig. 3 shows the array layout, which features provisions for redundancy near the center of the array, i.e. for the critical larger spatial scales (which represent most of the radiative energy). In general, an aperture synthesis system like this is quite fault tolerant: the loss of a receiver or correlator will create a gap in the uv sampling pattern shown in Fig. 1, but the consequence of that is usually merely a degradation of image quality. The redundant receivers (and redundant correlators) reduce the chance of such degradation. The visibility spectrum of the Earth is such that most of the energy is in the shorter baselines (i.e. larger spatial scales), and the loss of a receiver near the center of the array is therefore the most serious. This design therefore protects against the most serious type of loss.

Fig. 3 also illustrates the use of two receiver spacings; the spacing in the outer portion of the array is twice that in the inner portion, and the receiver horns are scaled correspondingly. This “dual-gain” design results in a more focused imaging and increases the effective antenna efficiency. This approach makes it possible to increase the radiometric sensitivity in the central region of interest. The basic element spacing is 4 wavelengths in this design, which results in an alias-free field of view that is slightly smaller than the Earth disc and also results in regions near the Earth limb that are affected by aliasing, as shown in Fig. 4. This is of minor consequence, however, since atmospheric profiles cannot be reliably “retrieved” at such small elevation angles.

The array shown in Fig. 3 has a total of 312 50-GHz receivers and 576 183-GHz receivers. Each receiver consumes 100-150 mW. The 50-GHz array requires about 150,000 correlator cells, each of which is a multiplier-accumulator operating at about 100 MHz. The 183-GHz array requires about 460,000 such cells. (These estimates are based on computing 4 visibility components per baseline, each of which produces two pairs of real and imaginary readings – this also results in a significant measure of redundancy.) Implemented as a 1-bit multiplier with accumulator on a 90-nm application-specific integrated circuit (ASIC), each cell will consume less than
10 µW. Power consumption of the entire 183-GHz correlator will then be less than 5 W. This is expected to decrease as newer IC technologies become available, which will continue to drive down overall GeoSTAR power consumption and make it possible to increase radiometric performance by operating several correlator systems in parallel and thus extending the per-channel integration time.

With the design described above, but using broad-band 1.5-bit correlators implemented with 65-nm ASICs and using recently developed technology that yields receiver temperatures below 300 K, we estimate a radiometric sensitivity in the 183-GHz band of about 1/3 K, similar to AMSU performance, for all channels every 15 minutes, which is adequate to meet or exceed all relevant measurement requirements.

Mission of opportunity

An intriguing possibility for implementing the PATH mission in the near term is to fly it as a Mission of Opportunity on one of the first satellites in the GOES-R series now being developed by NOAA. An infrared hyperspectral sounder, HES, had been planned as one of the primary payloads on GOES-R, but it was temporarily removed from the manifest due to programmatic risk. As a result, there will be unallocated space and resources (mass and power) on the first 2-3 GOES-R satellites – sufficient to accommodate GeoSTAR with only relatively minor redesign. There is therefore the possibility of implementing the PATH decadal-survey mission for NASA and provide an advanced geostationary sounder for NOAA, at greatly reduced overall mission cost. This is now being vigorously pursued and remains a realistic possibility. The launch of the first GOES-R satellite is planned for the end of 2014, and the second satellite is planned for two years later.

Measurements and applications

Table I lists the data products that PATH/GeoSTAR will provide. Most of these products are routinely generated from LEO systems with mature algorithms but with only the limited spatiotemporal sampling available from LEO orbit. The lower portion of the table (in italics) lists emerging new products, where algorithm development is currently under way.

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<th>Parameter</th>
<th>Horiz.</th>
<th>Vertical</th>
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<th>Accuracy</th>
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<td>Tb (50 GHz)</td>
<td>50 km</td>
<td>(6 ch’s)</td>
<td>3 min per ch</td>
<td>1/3 K</td>
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<tr>
<td>Tb (183 GHz)</td>
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<td>(4 ch’s)</td>
<td>5 min per ch</td>
<td>1/3 K</td>
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<td>20 min</td>
<td>2 K</td>
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<td>25 km</td>
<td>2-3 km</td>
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<td>25%</td>
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<td>Liquid water profile (L)</td>
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<td>3-4 km</td>
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<td>TC-core MSLP anomaly</td>
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<td>20 min</td>
<td>~ 5 mb</td>
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<td>SST</td>
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<td>Stability index</td>
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<td>20 min</td>
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<td>Wind vector</td>
<td>25 km</td>
<td>2-3 km</td>
<td>30 min</td>
<td>TBD</td>
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These observations and derived products will enable a wide range of analyses and applications:

Weather forecasting
- All-weather soundings, in cloudy and stormy scenes
- Full hemispheric soundings @<50/25 km every ~ 15-30 minutes (continuous)
- Synoptic rapid-update soundings
- Forecast error detection; 4DVAR applications

Hurricane & severe-storm diagnostics
- Location, intensity & vertical structure of deep convection
- NRT atmospheric instability; tornado precursor detection
- Intensification/weakening in NRT, frequently sampled
- Measure all H2O phases: vapor, liquid, ice, rain/snow
• Operational analysis, forecast verification
• Improved model microphysics

Rain
• Full hemisphere @ \( \leq 25 \) km every 15 minutes
• Directly measure storm and diurnal total rainfall: predict flooding events
• Snowfall, light rain, intense convective precipitation

Tropospheric wind profiling
• 1000-300 mb; very high temp. res.; in & below clouds
• Major forecast impact expected, esp. for hurricanes
• Air quality applications (pollution transport)

Climate research
• Stable & continuous MW observations
• Long term trends in T & q and storm statistics
• Fully resolved diurnal cycle
• ENSO; monsoon; tropical moisture flow into the US
• “Science continuity”; GeoSTAR \( \approx \) AMSU

Summary

The GeoSTAR concept and the related technology have been maturing rapidly. Test results from the prototype amount in effect to proof of concept, and this represents a major breakthrough in remote sensing capabilities. Continuing efforts to develop the technology further will enhance the system’s performance as well as retire technology risk, and it is anticipated that the concept will be mature enough that a space mission can be implemented in the 2014-2016 time frame – making a GOES-R/S “ride-share” mission feasible. The recent mission studies have shown that GeoSTAR is of only moderate size in terms of mass and power, and the cost is reasonable as well. The only major obstacle remaining will then be of a programmatic nature. It is likely that this will be overcome, and a GEO/MW mission is therefore likely within the next 10 years. This will add significantly to the nation’s remote sensing capabilities. The GeoSTAR observations are expected to have a significant forecast impact and will greatly benefit research related to the hydrologic cycle as well. In particular, the GeoSTAR observations will add much to our ability to observe, understand and predict severe storms and hurricanes, just as the need for such observations is becoming critical.

References


Acknowledgments

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration. The authors wish to acknowledge the contributions of Chris Ruf of U. Michigan and Jeff Piepmeier of the Goddard Space Flight Center and the invaluable support of Ramesh Kakar of NASA.

A Canadian satellite mission for continuous imaging of the northern latitudes

Louis Garand, Guennadi Kroupnik, Ron Buckingham, Alexander P. Thrischenko

The Polar Communications and Weather (PCW) mission of the Canadian Space Agency has the dual goal of providing communications and weather information pertaining to latitudes 50-90 N in continuous fashion from two satellites in a highly elliptical orbit. The presentation will focus on the meteorological aspect of the mission, its uniqueness and motivation. The main payload will be an advanced radiometer providing imagery with a refresh time of the order of 15 minutes. An industrial consortium is currently evaluating the various aspects of the mission based on user requirements defined by Environment Canada and other federal departments. PCW could be realized as early as 2013, either as a standalone Canadian mission or with international partners.
Examining the mid winter severe weather outbreak of 7 January 2008 using satellite data with McIDAS-V

Thomas Achtor, Kathleen Strabala, Jason Brunner

On 7 January 2008 a strong mid latitude cyclone swept across the midwest United States producing an outbreak of severe weather that resulted in 48 tornadoes spanning an area from southeast Wisconsin through Eastern Oklahoma. There were two tornadoes in southeast Wisconsin, an EF1 and an EF3 which damaged or destroyed 105 homes and injured 15 people. There had previously been only 1 tornado reported in Wisconsin’s history in the month of January (150+ years). This poster will review this very unusual severe weather event, and apply various satellite imager and sounder products, some which are available to forecasters in real time, to help identify key features of the event.
Sub-mm Wave Micromachined Free-Standing Frequency Selective Surfaces

Norman Grant

The spectral transmittance of a frequency selective surface (FSS), which consists of two free-standing arrays of short-circuited nested annular slots, is presented.

The FSS was designed to provide a minimum of 20 dB isolation between the frequency bands 316.5–325.5 and 349.5–358.5 GHz when the filter operates in the TE and TM plane sat 45° incidence.

Experimental results, which are in close agreement with the computed transmission coefficients, show that the maximum insertion loss is 0.9 dB, and the minimum cross-polar discrimination is at least 21 dB in the passbands.

The FSS yields virtually identical spectral responses in the two polarisation planes over the frequency range 315–359 GHz.
Author Index

Achter, Thomas (2) ................................................................................................................ 6, 428
Aires, Filipe .......................................................................................................................... 403
Andreoli, Rita Valéria .......................................................................................................... 346
Antonelli, Paolo (2) ............................................................................................................... 36, 363
Armante, Raymond ............................................................................................................ 372
Arriaga, Arlindo .................................................................................................................. 193
Atkinson, Nigel .................................................................................................................... 4
Auligne, Thomas ................................................................................................................ 189
Aumann, Hartmut H .......................................................................................................... 124
Baker, Nancy ...................................................................................................................... 360
Bastarz, Carlos ................................................................................................................... 316
Bell, William ...................................................................................................................... 166
Blackwell, William ........................................................................................................... 190
Blumstein, Denis ............................................................................................................... 17
Borbas, Eva ......................................................................................................................... 113
Bormann, Niels .................................................................................................................. 157
Bouchard, Aurélie ............................................................................................................. 332
Boukabara, Sid (2) ............................................................................................................ 215, 413
Cameron, James ............................................................................................................... 343
Candy, Brett (2) ................................................................................................................ 130, 325
Chang, Yi .......................................................................................................................... 402
Chammat, Laure (2) ......................................................................................................... 233, 303
Chédin, Alain .................................................................................................................... 374
Cheng, Zhaohui .................................................................................................................. 370
Chengli, Qi ......................................................................................................................... 106
Clerbaux, Cathy ................................................................................................................. 81
Collard, Andrew ................................................................................................................ 70
Costa, Simone .................................................................................................................... 283
Crevoisier, Cyril ............................................................................................................... 243
Derber, John ...................................................................................................................... 129
Dong, Peiming .................................................................................................................... 195
Duffourg, Fanny ................................................................................................................ 305
Elliot, Simon ...................................................................................................................... 409
Eyre, John ......................................................................................................................... 249
Fiedler, Lars ....................................................................................................................... 18
Garand, Louis (2) ............................................................................................................. 173, 427
Grant, Norman .................................................................................................................. 429
Griersmith, David ............................................................................................................. 250
Gomes Jr, Jairo .................................................................................................................. 317
Gumley, Liam ..................................................................................................................... 5
Han, Yong (2) ..................................................................................................................... 284, 293
Harris, Brett ...................................................................................................................... 181
Hilton, Fiona (2) ................................................................................................................. 55, 269
Huang, Allen ..................................................................................................................... 364
Huang, Bormin .................................................................................................................. 109
Jacquinet-Husson, Nicole ................................................................................................. 21
John, Viju .......................................................................................................................... 114
Kaifel, Anton ..................................................................................................................... 244
<table>
<thead>
<tr>
<th>Name</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kelley, Richard</td>
<td>14</td>
</tr>
<tr>
<td>Kim, Min-Jeong</td>
<td>205</td>
</tr>
<tr>
<td>Klaes, Dieter (2)</td>
<td>251, 407</td>
</tr>
<tr>
<td>Kleespies, Thomas (2)</td>
<td>103, 415</td>
</tr>
<tr>
<td>Krzeminski, Blazej</td>
<td>345</td>
</tr>
<tr>
<td>Lambrigtisen, Bjorn (2)</td>
<td>123, 421</td>
</tr>
<tr>
<td>Lapeta, Bozena</td>
<td>394</td>
</tr>
<tr>
<td>Larar, Allen</td>
<td>270</td>
</tr>
<tr>
<td>Lavanant, Lydie</td>
<td>192</td>
</tr>
<tr>
<td>Le Marshall, John</td>
<td>206</td>
</tr>
<tr>
<td>Leslie, R. Vincent</td>
<td>405</td>
</tr>
<tr>
<td>Li, Jun</td>
<td>110</td>
</tr>
<tr>
<td>Li, Xiaoping</td>
<td>304</td>
</tr>
<tr>
<td>Lima, Wagner</td>
<td>404</td>
</tr>
<tr>
<td>Lipton, Alan</td>
<td>107</td>
</tr>
<tr>
<td>Liu, Xu</td>
<td>53</td>
</tr>
<tr>
<td>Liu, Zhiquan</td>
<td>155</td>
</tr>
<tr>
<td>Lu, Qifeng (2)</td>
<td>133, 358</td>
</tr>
<tr>
<td>Ma, Gang</td>
<td>180</td>
</tr>
<tr>
<td>Mango, Stephen</td>
<td>263</td>
</tr>
<tr>
<td>Marguinaud, Philippe</td>
<td>302</td>
</tr>
<tr>
<td>Matricardi, Marco</td>
<td>91</td>
</tr>
<tr>
<td>Michel, Yann</td>
<td>342</td>
</tr>
<tr>
<td>Montroty, Remi</td>
<td>194</td>
</tr>
<tr>
<td>Newman, Stuart (2)</td>
<td>37, 271</td>
</tr>
<tr>
<td>Okamoto, Kozo (2)</td>
<td>145, 261</td>
</tr>
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<td>Overton, John</td>
<td>3</td>
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<tr>
<td>Pangaud, Thomas</td>
<td>347</td>
</tr>
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<td>Péquignot, Eric</td>
<td>112</td>
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<td>Peyridieu, Sophie</td>
<td>248</td>
</tr>
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<td>365</td>
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<td>54</td>
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<td>Prunet, Pascal</td>
<td>366</td>
</tr>
<tr>
<td>Rabier, Florence</td>
<td>131</td>
</tr>
<tr>
<td>Randriamampianina, Roger</td>
<td>324</td>
</tr>
<tr>
<td>Reale, Tony</td>
<td>242</td>
</tr>
<tr>
<td>Romano, Filomena</td>
<td>234</td>
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<td>Ruston, Benjamin</td>
<td>187</td>
</tr>
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<td>Sapucci, Luiz</td>
<td>344</td>
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<td>Saunders, Roger</td>
<td>83</td>
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<tr>
<td>Schlüssel, Peter</td>
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<tr>
<td>Schmit, Tim</td>
<td>247</td>
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<td>Schröder, Marc</td>
<td>122</td>
</tr>
<tr>
<td>Schwärz, Marc</td>
<td>71</td>
</tr>
<tr>
<td>Selbach, Nathalie</td>
<td>371</td>
</tr>
<tr>
<td>Sharma, A. K</td>
<td>410</td>
</tr>
<tr>
<td>Shi, Lei</td>
<td>115</td>
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<tr>
<td>Singh, Devendra</td>
<td>393</td>
</tr>
</tbody>
</table>