Assimilation of ATOVS retrievals and AMSU-A radiances at the Italian Weather Service: Current status and perspectives

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ABSTRACT
Since 2003 a variational assimilation system has been running at National Center for Aeronautic Meteorology and Climatology (CNMCA) of the Italian Air Force Weather Service in order to provide accurate and timely initial conditions for CNMCA operational NWP models (Bonavita and Torrisi, 2005). The objective analysis component currently ingests a variety of observation types, both of synoptic and a-synoptic nature: TEMP, PILOT, SYNOP, SHIP, BUOY, AMDAR, AIREP, AMV, WIND PROF, QUIKSCAT and ERS2 winds. The start of the EUMETSAT ATOVS Retransmission Service has given us the opportunity to receive sounder data from the NOAA polar orbiters’ constellation within the time limits imposed by the operational schedule of our data assimilation system. Two different strategies for incorporating satellite sounding data have been investigated. In the first one temperature retrieved profiles were generated from a selection of HIRS and AMSUA-B channels using the IASI 1D-VAR software available from EUMETSAT NWP SAF. These retrievals were then ingested from the objective analysis as pseudo-TEMP observations on standard pressure levels. The second approach has been to directly ingest the level1C AMSU-A radiances in the variational assimilation system, making use of the RTTOV fast radiative transfer model and its tangent linear component. The relative merits of the two strategies are discussed in light of current results and future application to hyper-spectral interferometers.

Motivation
The beginning of the EUMETSAT ATOVS Retransmission Service (EARS) has provided regional European Weather Services with the possibility of receiving sounder data from NOAA polar orbiters’ constellation with a timeliness and a geographical coverage suitable for the needs of European regional NWP applications. At CNMCA (Italian Weather Service) a variational data assimilation (DA) system has been in operations for the past two years, providing the initial conditions necessary for the integration of CNMCA NWP models. With the timely availability of ATOVS data, work has started to make use of the sounder information in the objective analysis step of the CNMCA DA system. The concurrent availability of the IASI 1D-VAR package from the EUMETSAT NWP SAF provided us with a relatively simple way of starting to make use of ATOVS data without the need to make extensive modification to the existing analysis code base. The idea was also to gain experience with both the data and the retrieval software in view of proceeding to the direct assimilation of radiances at a later stage. On the other hand the number of channels present in the next generation of hyperspectral sounders could also make retrievals’
assimilation an attractive option especially for objective analysis systems, like ours, whose computational expense increases quadratically with the number of ingested observations.

The need to incorporate HIRS channel data in the retrieval step considerably reduces the number of retrievals available for ingestion. Currently only clear Field Of View (FOV) pixels are presented to the IASI 1D-Var package. To try to make a better use of the ATOVS data, a new version of the CNMCA DA system has been set up which can accommodate the direct ingestion of radiances. In this release of the software, direct ingestion of AMSU-A channels has been introduced.

For both types of assimilation strategies observing system experiments (OSEs) have been performed (and are still going on) in order to gauge the impact of these new sources of data on CNMCA NWP analysis and forecast fields (Fig.1: Analysis and integration domain) and the relative merits of the two approaches.

The paper is structured as follows. The data assimilation system is first described, with particular emphasis on the objective analysis step. Then a detailed account of the observations used in the OSEs is given. A thorough description of the OSEs setup and their results is finally given, with a discussion of the operational implications and indications for future work.

**Data Assimilation System setup**

At the National Center for Aeronautic Meteorology and Climatology of the Italian Air Force (CNMCA) an intermittent, 6-hourly, data assimilation system based on a variational objective analysis scheme and the HRM prognostic model (Bonavita and Torrisi, 2005) is currently operational. A schematic representation of the 6-h intermittent data assimilation system of CNMCA is given in Fig.2.

Let $y$ be the column vector containing all the observations at the analysis time; $x$ the column vector of the state (prognostic) variables at the same time at the model grid points; $x_a$ and $x_b$ the analogous quantities for the analyzed and background fields; $H$ is the observation (or forward) operator, i.e. the operator that performs the transformation from the state variables on grid points to the observed variables at the observing locations; $P_b$ the forecast error covariance matrix; $R$ the observation error covariance matrix. Then the objective analysis component computes the maximum likelihood estimate of the atmospheric state ($x_a$) by minimization of the following cost function of the state vector $x$:

$$ J(x) = 0.5[y - H(x)]^T R^{-1} [y - H(x)] + 0.5[x - x_b]^T P_b^{-1} [x - x_b] $$  \hspace{1cm} (1)

i.e., minimizing a scalar distance of the analysis vector from both the observations and the first guess fields, based on their respective perceived accuracies. The CNMCA implementation solves the minimization problem in “observation space” (3D-PSAS algorithm, Cohn et al., 1998) through a parallel, preconditioned conjugate gradient descent method. A linear balance is imposed on the mass and wind fields through the use of the thermal wind constraint in spherical geometry. The correlation functions employed in the modeling of the forecast error covariance matrix $P_b$ are shown in Fig. 3,4 (for a detailed description, see Bonavita and Torrisi, 2005). Fast
gravity waves are then filtered out of the analysis fields through an adiabatic implicit nonlinear normal mode initialization step (Temperton and Roch, 1991).

The numerical model used to produce the first guess fields is the High-Resolution Regional Model (HRM) of CNMCA. The HRM is a modified version of the Deutscher Wetterdienst hydrostatic, primitive equations, EM/DM model (Majewski, 2001). The model is run on a Euro-Atlantic domain (Fig.1) at 0.25° horizontal grid spacing and 40 vertical levels extending up to 10 hPa.

The assimilation cycle is run with a 4-h data window around the analysis nominal time. Twice daily (at 00Z and 12 Z), an extended run (+72h) of the HRM model based on the assimilation cycle analysis is performed.

Observations

The new observation type ATOVS was added to the conventional datasets used operationally, which comprise TEMP, PILOT, WIND_PROFILER, SYNOP, SHIP and BUOY reports: QUIKSCAT and ERS2 Surface Winds, atmospheric motion vectors (AMV) from Meteosat geostationary satellite METEOSAT 5-8 and aircraft observations (both manual, AIREP, and automated, AMDAR, ACAR). As mentioned before, ATOVS data has been used in two different ways, to construct temperature retrievals and to directly ingest the AMSU-A subset of ATOVS radiances. Details are here given for both procedures.

1. RETRIEVALS’ Production and Assimilation

To obtain the temperature and humidity vertical profiles (retrievals), the forecast fields (+6 h) from the CNMCA Regional Model EURO-HRM and ATOVS level1d products from EARS are fed into IASI_1DVar, the EUMETSAT NWP-SAF package developed by the UK Met Office.

In figure 5 the block diagram of the full retrieval scheme implemented at CNMCA is shown.

Currently only clear FOVs (using the AVHRR cloud mask included in the level1d products) over sea are selected. Figure 6 shows 24 hours available data for 1st of July 2004.

As a necessary process before the ingestion of the radiances into the radiative transfer model, the bias correction is then applied in two steps:

- correction of the systematic error depending on the satellite view angle (scan bias);
- correction of the bias depending on the air-mass scanned by the sounder (air-mass bias).

The correction steps make use of coefficients derived by a long period (last 3 months, typically) of collected statistics of raw brightness temperatures. As regards the scan bias correction, the scheme introduced by Eyre in 1992 (Eyre, 1992) is applied, for each FOV separately. For the air-mass bias correction part, the original Eyre scheme which made use of AMSU-A channels 4 and 9 as predictors, has been recently replaced by the Harris and Kelly scheme (Harris and Kelly, 2001), based on the identification of air-mass by four “external”
predictors derived from four forecast fields: 1000-300 hPa and 200-50 hPa thickness, surface skin temperature and total column water vapor.

Figure 7 shows the time series of the raw and corrected brightness temperature (bias and rmse) for a selection of NOAA-15 and NOAA-16 ATOVS channels. This kind of plot is very useful to monitor the performance of the bias correction scheme and eventual anomalies in the instrumentation.

In figure 8 a comparison between the old and new air-mass bias correction scheme is shown. The improvement, observed in general for all ATOVS channels, is significant in particular for HIRS water vapor channels.

The temperature and specific humidity vertical profiles, produced in ASCII format by the IASI 1D-Var package, are then encoded in the standard binary format (BUFR), to be assimilated as “pseudo-TEMP” soundings in the CNMCA DA cycle.

Quality control is performed on the corrected brightness temperatures. Through comparison with accumulated statistics, a global quality index is computed and included into the BUFR message, to allow a selective use of the profiles in the assimilation phase.

2. AMSU-A radiances direct assimilation

AMSU-A radiances from channels 5-10 of NOAA 15-16-18 in level1C format are currently downloaded from EUMETSAT ftp servers and used in CNMCA DA objective analysis step. Currently only sea fovs are used, with a threshold surface temperature of 271.5 K to distinguish them from sea ice fovs. A rain contamination test is also applied, discarding fov observations where \( |T_{\text{obs}} - T_{\text{fg}}|_{\text{ch4}} > 1.5\text{K} \) (Gerard, 2003).

The fast radiative transfer model (RTM) used is RTTOV version 8.7 (Saunders and Brunel, 2005). RTTOV is employed both in forward mode to compute first guess radiances from 6 hour forecast profiles of temperature and water vapor, and in tangent linear mode to compute the Jacobian matrix \( H_{x_{\text{fg}}} \) of computed radiances with respect to forecast profiles.

A simple bias correction algorithm is also applied to the observed brightness temperatures to mainly take into account slight deficiencies in the RTM simulated temperatures. Average observation minus first guess temperature departures have been computed and stratified for satellite and scan position. These differences are subtracted out of observed brightness temperatures before their ingestion in the objective analysis. From figures 9-10 the method can be seen to be fairly effective in removing most of the observed systematic departures. Some non negligible residuals are still observed in some channels, especially for lateral scan positions. The affected observations are filtered out of the assimilation procedure.
Results

In order to gauge the impact of the new observation type two observing system experiments (OSEs) were performed.

The general experimental framework was as follows. Two parallel data assimilation cycles were run alongside the operational one. The first one making use of the ATOVS retrievals plus the operational observations, the second one directly using AMSU-A radiances on top of the other available observation types (TEMP, PILOT, SYNOP, SHIP, BUOY, AMDAR, AIREP, AMV, WIND PROF, QUIKSCAT and ERS2 winds). Once a day two extended EURO-HRM model runs to +48h from the 00Z analysis fields were performed. Forecasts fields have been verified against observations from the European upper air network and surface synoptic observations covering the whole integration domain (Fig. 11). Only land stations having height lower than 700 m and height mismatch with nearest grid point lower than 100 m have been retained. Temperature, dew point temperature and wind vector vertical profiles of mean error and RMSE at the standard pressure levels for 12, 24, 36, 48 forecast steps have been also calculated.

1. ATOVS Retrievals experiment

Results from a statistical comparison in the period 15 December 2004 – 20 January 2005 for the +48h EUROHRM forecasts are plotted in Fig 12. Blue and red lines represent scores for the runs with and without the ingestion of ATOVS retrievals data, respectively. No statistically significant differences are evident in the RMSE and ME vertical profiles of temperature, dew point and wind vector. This is not a very encouraging result. However there are at least two mitigating factors to take into account. First there has been a constant degradation in NOAA16 HIRS longwave channels quality since summer 2004, which was not reflected in the expected observation errors for those channels. This has undoubtedly led to some degradation of the ensuing retrievals.

More importantly, an unexpected feature of the IASI 1D-Var package was not fully appreciated until the end of January 2005. The package, at least in our operational configuration, produces and outputs a retrieval even in the case when the minimization step fails. The encoded profiles are those reached in the last stage of the failed minimization procedure. Needless to say, these spurious profiles have considerably contributed to the degradation of analysis and forecasts quality.

An indirect confirmation of this is given by figure 13. Here the mean difference and standard deviation of the observation increments of the ATOVS retrievals with respect to the t+6h EURO_HRM first guess temperatures are shown. Red lines refer to the situation before the two above mentioned problems were identified and tackled. Blue lines refer to a period (15-25 January 2005) after the correction of the bug. The better consistency between retrievals and forecasts give a clear indication that a considerable part of the previous signal was spurious. New verification experiments have confirmed this hypothesis.
2. AMSU-A radiances assimilation experiments

The statistical evaluation of the impact of AMSU-A radiance data and in the CNMCA NWP system was performed during the same period 15 December 2004 - 20 January 2005. The ME and RMSE vertical profiles of temperature, dew point and wind vector for forecasts T+48h are plotted in Fig. 14. Red lines represent skill scores for runs with only the operational dataset ingestion while blue lines give the scores with the additional ingestion of AMSU-A radiances winds, respectively.

The impact in the temperature field is generally neutral, though a closer inspection reveals hints of a positive influence at some middle and upper tropospheric levels. A clearer positive signal can be seen in the dew point scores for the 200 - 400 hPa layer, and in the wind vector error throughout much of the troposphere.

Problems to AMSU-A channels 9-14 of the NOAA16 during the later part of the impact experiment may also have partly affected the aggregate scores. The general trend, however, of a slight but measurable improvement in forecast quality is clear and is borne out by more recent results from ongoing experimentation.

Summary and Outlook

The present study has concentrated on gauging the impact of ATOVS radiances observations on a limited area NWP system. The data have been used in two different ways: Construction of temperature retrievals and their subsequent ingestion as pseudo TEMP observations; direct assimilation of AMSU-A radiances. Observing System Experiments (OSEs) have been performed for each method over the same period of time using the CNMCA data assimilation system. Objective verification against the European conventional observing network has been performed in order to assess their relative merits for NWP forecast skill.

The retrievals’ impact has been mostly neutral over the experiment time. In our opinion this methodology, even though not theoretically “optimal”, might be a practical tool to exploit the new hyperspectral sounders data in NWP data assimilation applications. We believe this view to hold in general but particularly so for data assimilation systems based on “observation-space” implementations of variational techniques, where computational costs grow quadratically with the observations’ number. The experimentation with the IASI-1Dvar package will continue, with a view to application to the IASI interferometer data. Under this respect, the amount of channels that will be available from the IASI instrument will be such that new automatic procedures to deal with data pre-processing and bias correction will have to be put in place. It would be highly desirable that part of this necessary infrastructure would be integrated in the IASI-1Dvar package itself. The absence of bias correction routines in the current version of the package is a serious shortcoming which has considerably delayed our operational implementation of the retrievals’ production chain.
The impact results of the direct assimilation of AMSU-A data have been clearer. A positive impact has been recorded for dew point and wind vector scores, while temperature impact seem to be mostly neutral or slightly positive. Experimentation will continue along the present lines in order to consolidate these results. Near future developments will involve extending the use of AMSU-A data over land and sea ice, as well as testing the module RTTOV_SCATT for radiances contaminated by rain.

LIST OF REFERENCES


Figure 1  Regional model (EURO-HRM) domain of integration.
Figure 2 Data Assimilation system at CNMCA
Figure 3  Isobaric correlation functions used in CNMCA 3D-PSAS.
Figure 4  Vertical correlation functions used in CNMCA 3D-PSAS.
Figure 5  1DVar retrieval scheme at CNMCA
Figure 6  Example of ATOVS available data
Figure 7  Brightness temperatures time series
Figure 8  Comparison between old and new air-mass bias correction scheme
Figure 9  Mean differences (before and after bias correction) and standard deviations of NOAA15 AMSU-A channels 5-10 brightness temperatures with respect to synthetic radiances from EURO_HRM t+6h forecast vertical profiles.
Figure 10  Mean differences (before and after bias correction) and standard deviations of NOAA15 AMSU-A channels 5-10 brightness temperatures with respect to synthetic radiances from EURO_HRM t+6h forecast vertical profiles.
Fig. 11  TEMP and SYNOP lowland stations used for verification.
Figure 12  Verification of IASI 1D-Var ATOVS retrievals impact on EURO_HRM t+48h forecast fields.
Figure 13  Mean differences (before and after bug correction) and standard deviations of NOAA15-6 retrieved temperature profiles with respect to EURO_HRM t+6h forecast vertical profiles.
Figure 14 Verification of AMSU-A radiances assimilation impact on EURO_HRM t+48h forecast fields.