

THE USE OF SATELLITE OBSERVATIONS IN NWP

The impact of satellite measurements on NWP began in the early '70s with the operational use of global satellite cloud imagery. Nowadays the impact is from active and passive radiances measurements from a multitude of satellite instruments together with Atmospheric Motion Vectors. Up to the mid '90s satellite the satellite impact was mostly in the Southern Hemisphere and Tropics but today the Northern Hemispheric skill very dependent on satellite measurements.

Graeme Kelly ECMWF

In 1972 the VPTR radiometer was added to the polar operational Satellite series beginning with NOAA 2.

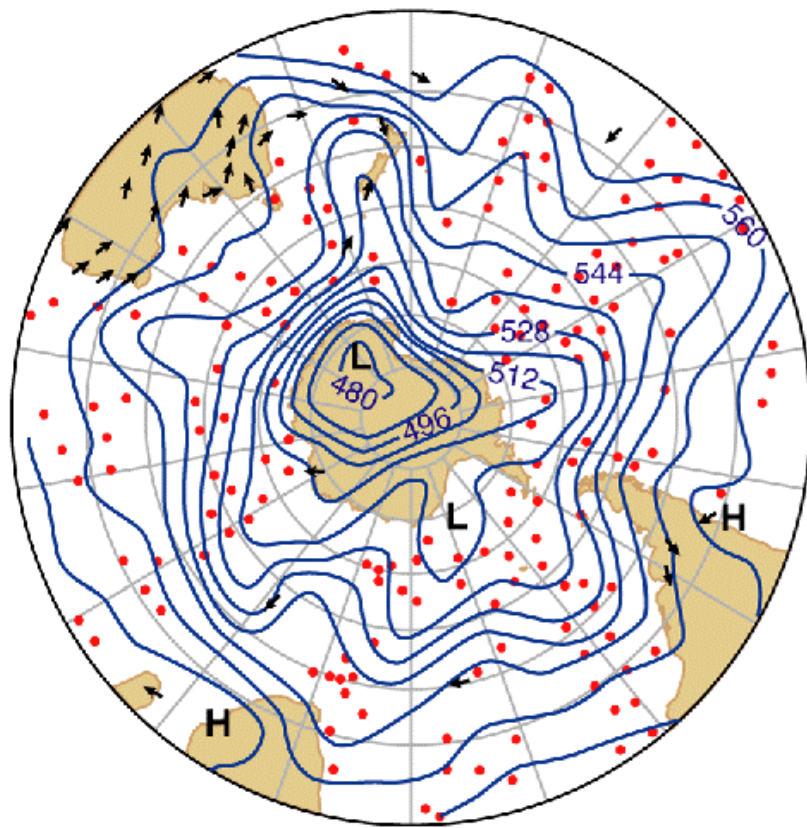
This instrument measured surface temperature (11 micron), 6 deep layer mean temperatures (15 micron band) and a upper level water vapour channel (18 micron band).

In 1974 VTPR cloud clear radiances were sent on GTS and regression retrieval method was developed (help of Bill Smith and Dave Wark) to provide vertical profiles of temperature and moisture for Southern Hemispheric numerical analysis.

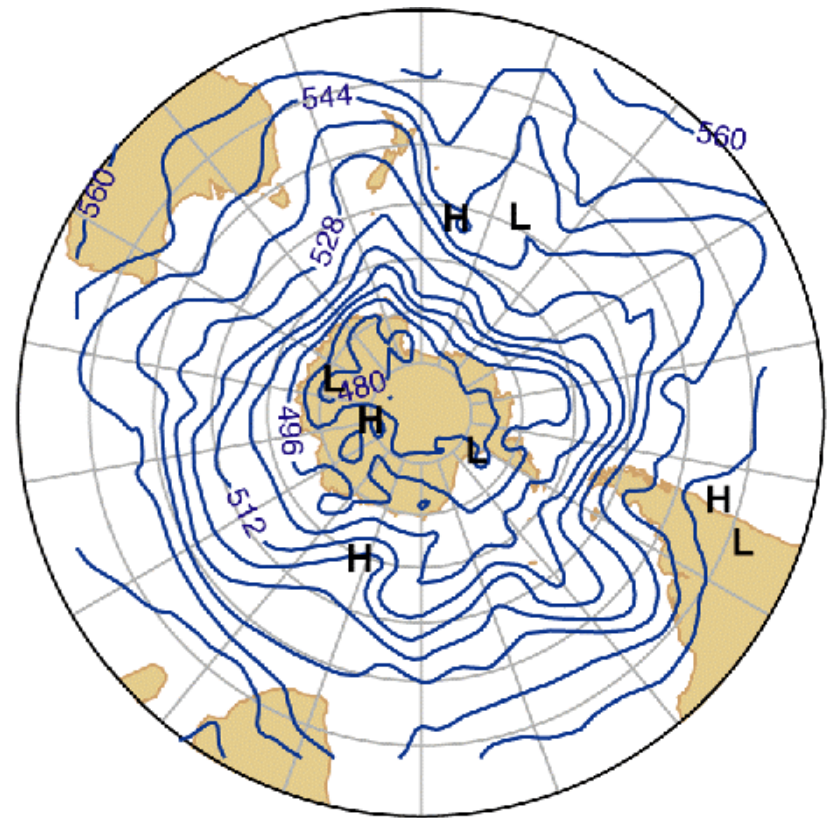
A cycling data assimilation was developed. (Kelly et al. 1978).

Up to this time the data assimilation was cold started each cycle with bogus observations.

The ERA 40 re-analysis using (3DVAR) assimilated these VTPR radiances.



1000 / 500 mb thickness VTPR analysis



1000 / 500 mb thickness ERA-40 analysis

It is interesting to compare the VTPR analysis from Kelly 1976 with the same case from ERA-40 analysis. This ERA 40 production was completed in April 2003 using a reduced resolution of the ECMWF operational assimilation system (TL159/L60 3DVAR).

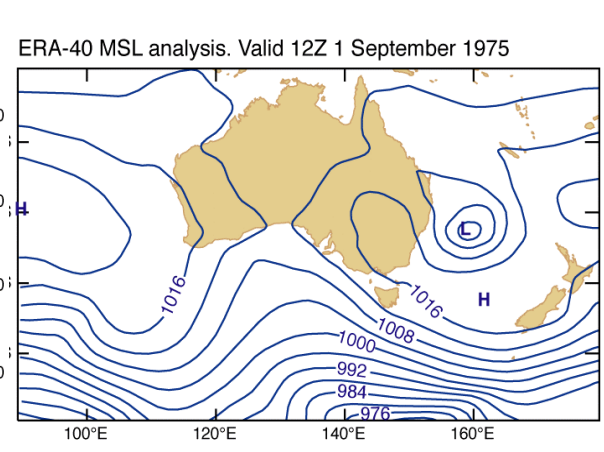
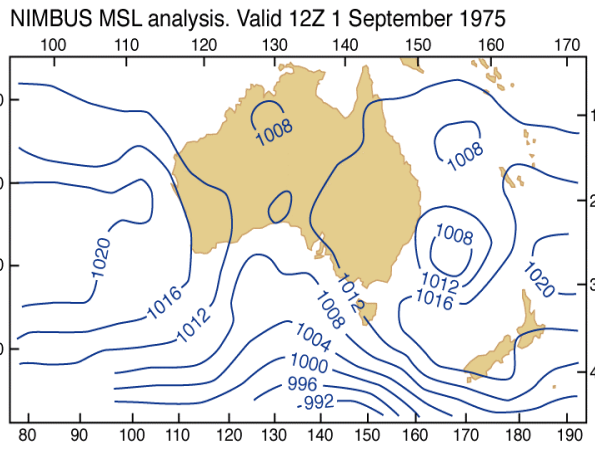
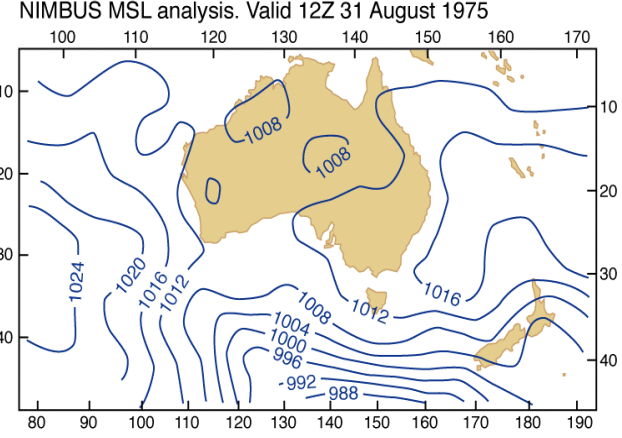
It is remarkable as to the closeness of these two analyses 27 years apart.

In 1977 two series of two parallel experiments were run using the BOM Operational Limited Area data assimilation system (kelly et al, 1978).

The control used conventional data, Australian Region PAOBs and THKLs (bogus for surface pressure and 1000/500 thickness).

In the second experiment the 1000/500 thickness PAOBs were replaced with thickness retrievals from NIMBUS 6 (HIRS and SCAMS).

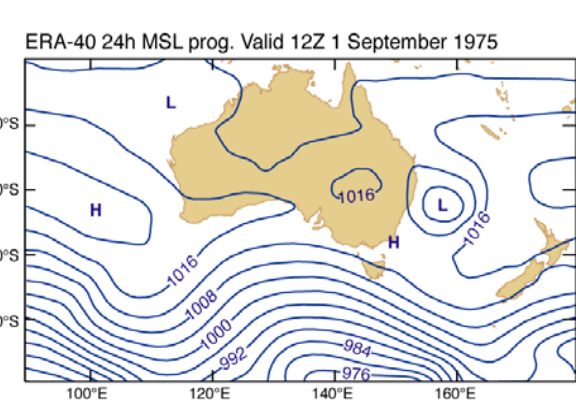
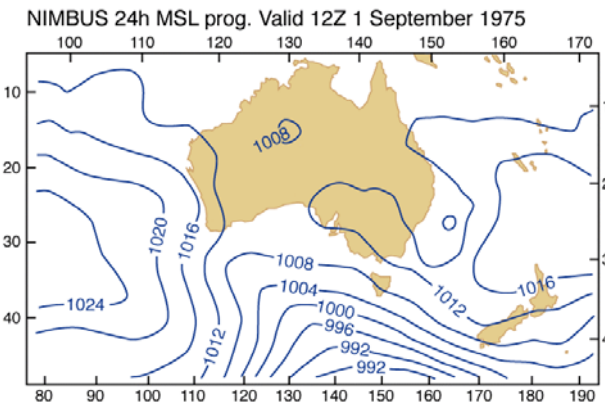
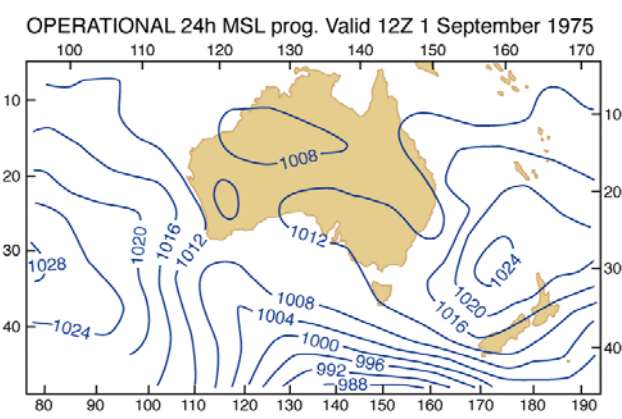
Again a comparison is shown with ERA40.



NIMBUS ANAL

NIMBUS (VER ANAL)

ERA40 (VER ANAL)



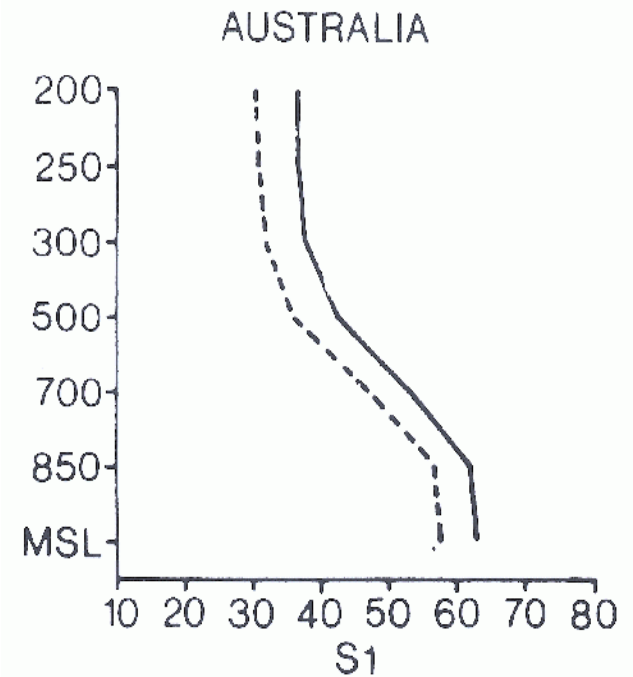
OPS 24 hour FC

NIMBUS 24 hour FC

ERA40 24 hour FC

Comparison of Operational, NIMBUS 6 and ERA40 analyses and 24 HR forecasts in September 1975.

S1 skill scores for Australian Region
14 cases (1 – 14 Sept 1975)
Solid operations
Dashed Nimbus 6 experiment



In 1978 a joint project began with CIMSS and BOM to develop this assimilation system (CRAS) using new types of satellite and conventional data. The first step was to port the system to the CRAY 1 at NCAR and change the grid to the North American Region.

Difficulties in using satellite retrievals in Numerical Analysis

The the '70s meteorological community asked for satellite retrievals to look like radiosondes with retrieved profiles of temperature and humidity be provided on standard pressure levels.

There was not a problem in early numerical analysis schemes (Cressman) which used a limited number of levels with thick layers.

As analysis methods improved (use of OI) and more analysis levels were added the error covariance of the satellite retrieval was required to use the data correctly. This is due to lack of vertical information in the radiance measurements.

The observation error covariance of a regression retrievals were difficult to compute as the fine vertical structure added from the prior information.

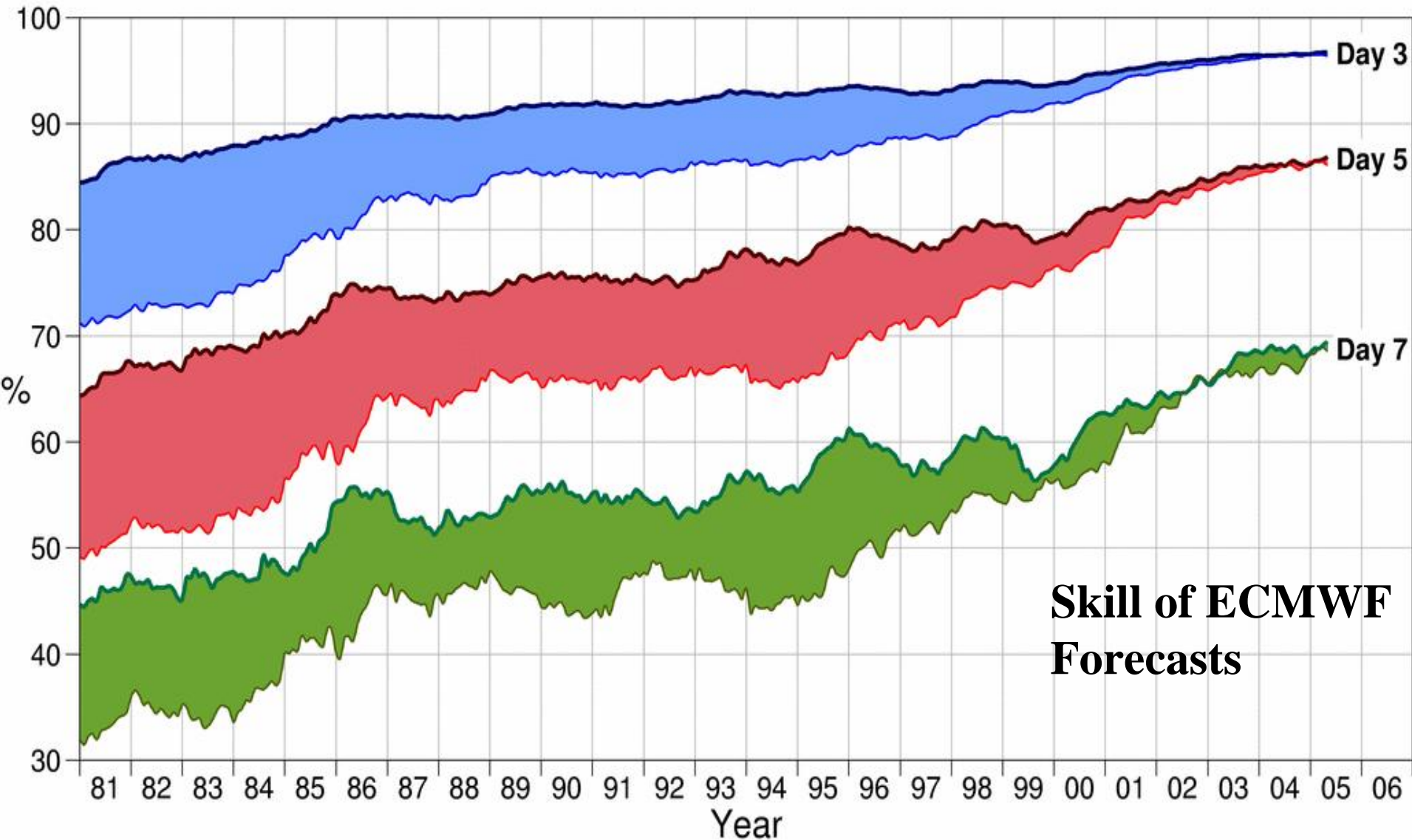
This too often lead to problems in the analysis and negative impact of satellite retrievals occurred in the Northern Hemisphere.

Variation methods were then developed to replace OI for numerical analysis in order to assimilate satellite radiances.

- **Important issues for the assimilation of satellite radiances**
- Biases:
 - Systematic errors must be removed before the assimilation (bias correction) (Harris and Kelly 2001)
 - Various sources of systematic errors:
 - Instrument error (calibration)
 - Radiative transfer error
 - Cloud/rain detection error
 - Background model error

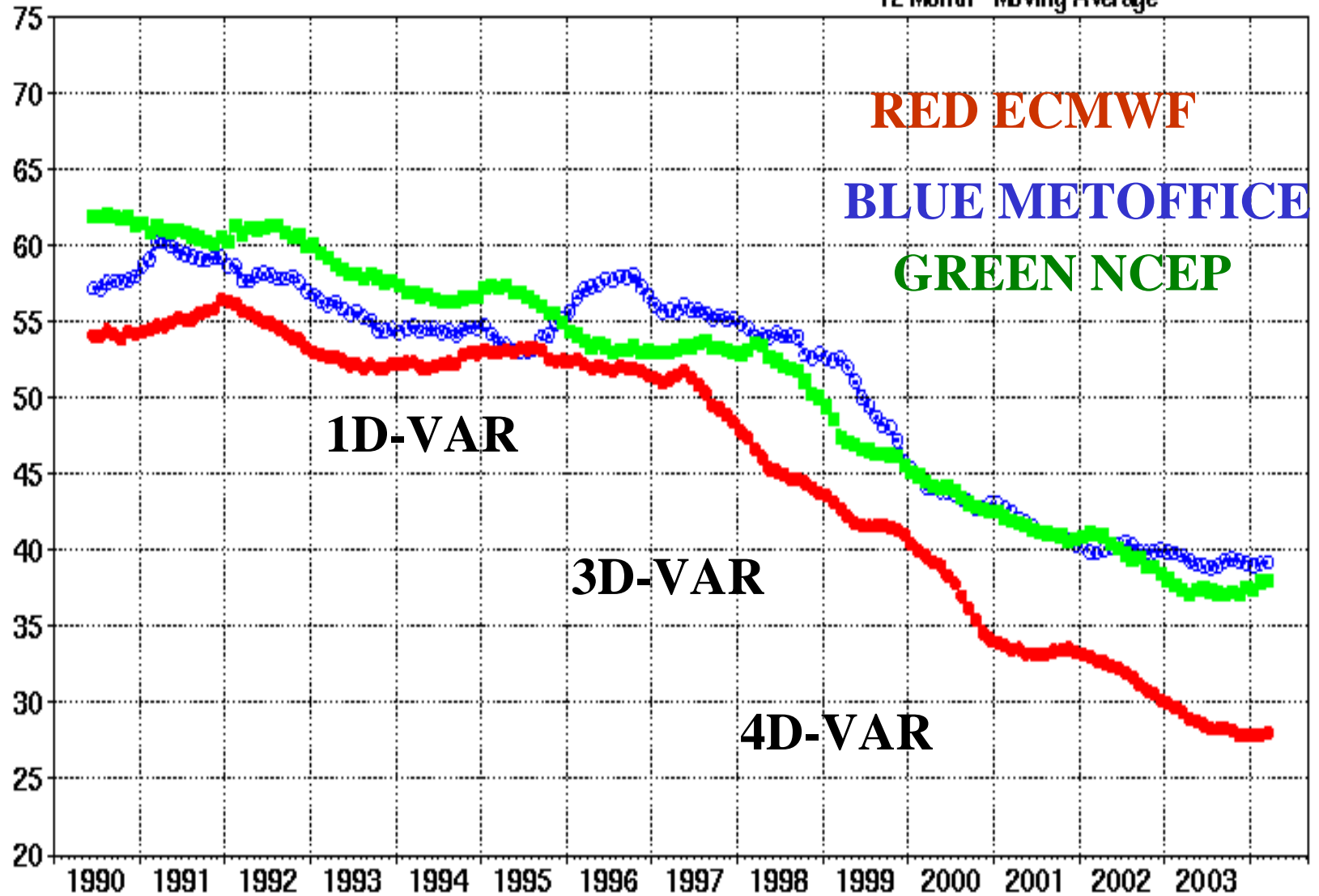
Anomaly correlation of 500hPa height forecasts

— Northern hemisphere — Southern hemisphere



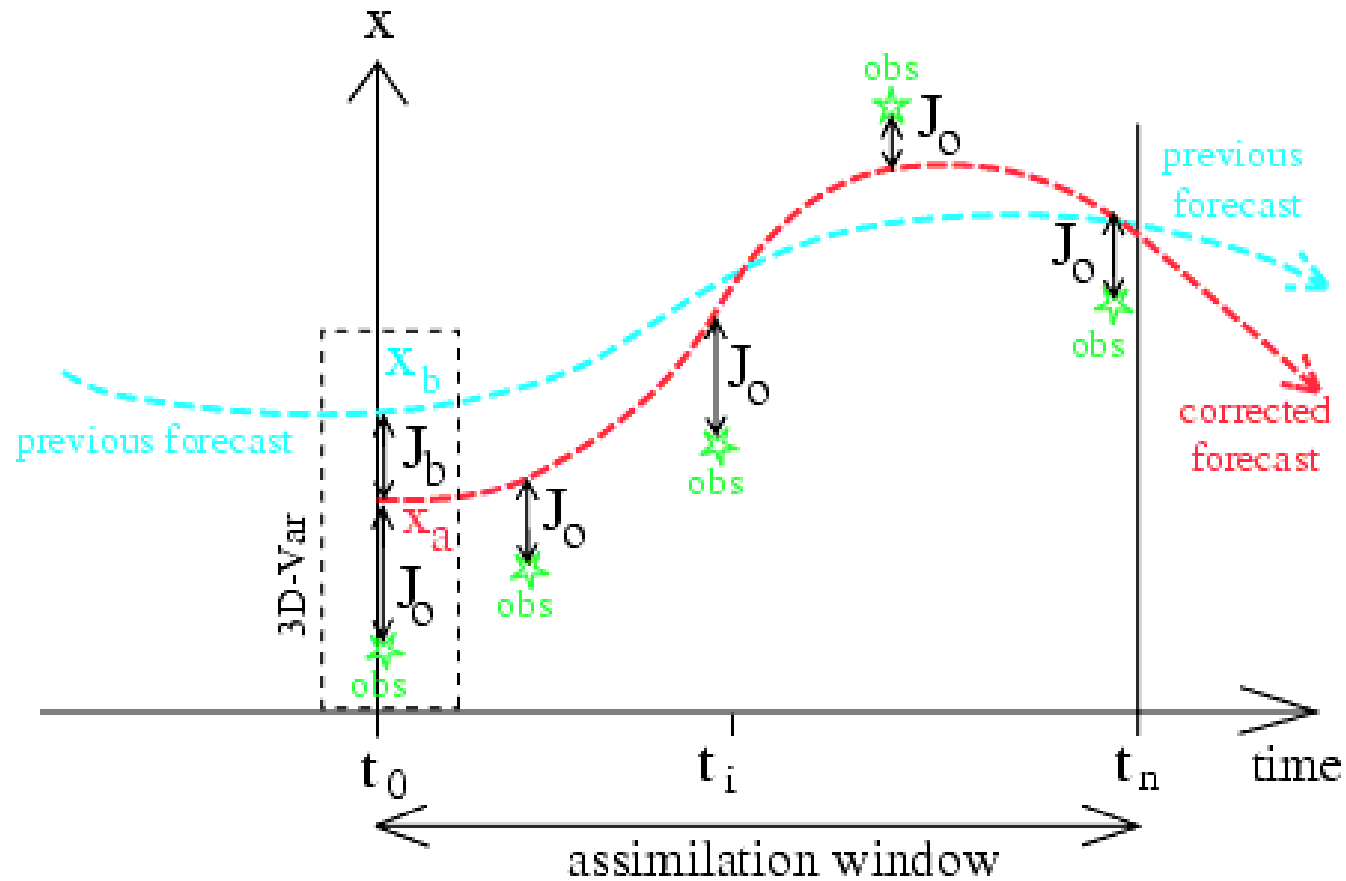
Southern Hemispheric 500 hPa RMS error (m) for Day 3

12 Month Moving Average



Conceptual difference between 3D-Var and 4D-Var

Analysis resolution at t_0 --- J_b is determined for a set of ensemble assimilations, and the statistics are not flow dependant and filter. Horizontal scales less than $\sim 120\text{km}$



Experiments in era40 system (Aug-Dec 1986)

4 experiments of four months of data assimilation were run to test 3D/4D VAR and effect of using an adaptive bias correction.

Resolution TL159/159

2 satellites NOAA 6 & NOAA 9

max 5 sensors 2 MSU 2 SSU 1 HIRS

- 1. 3dvar control stat**
- 2. 3dvar adaptive**
- 3. 4dvar control**
- 4. 4dvar adaptive**

Time series

FORECAST VERIFICATION 12UTC

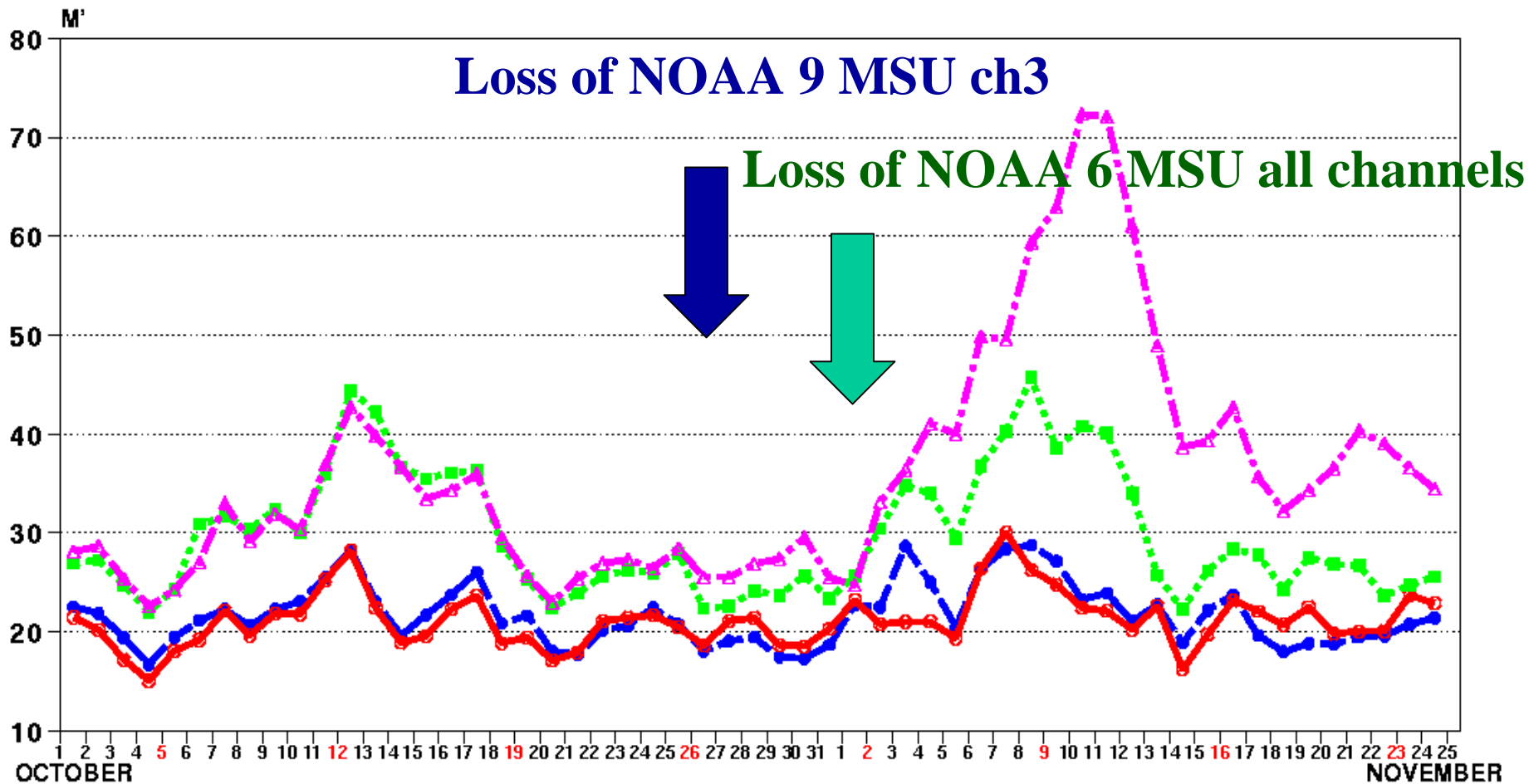
500hPa GEOPOTENTIAL

ROOT MEAN SQUARE ERROR

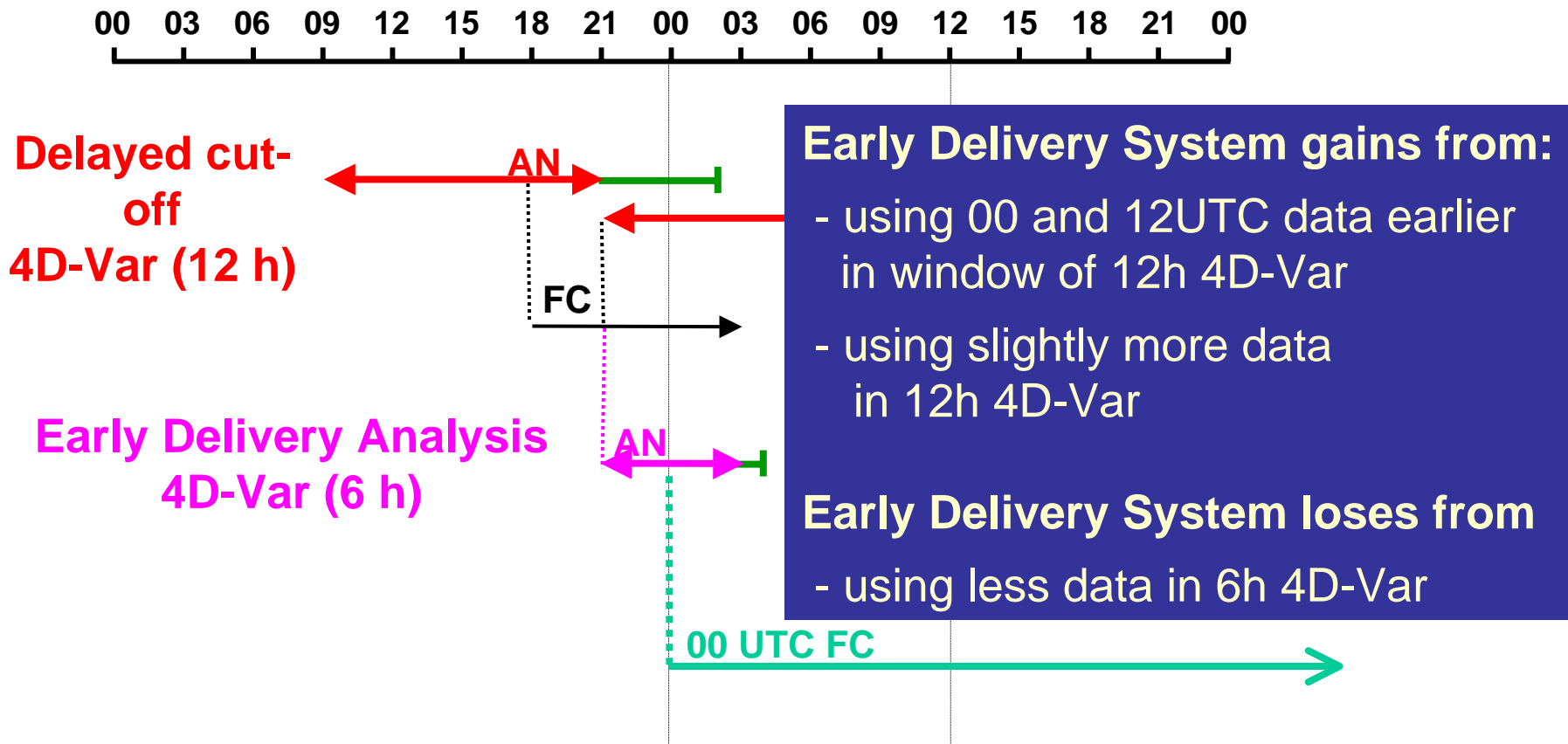
FORECAST

S.HEM LAT -90.000 TO -20.000 LON -180.000 TO 180.000

- 4d_adspc T+ 36
- 4d_stat T+ 36
- 3d_adsp T+ 36
- 3d_stat T+ 36



The Early Delivery From 29 June 2004 System

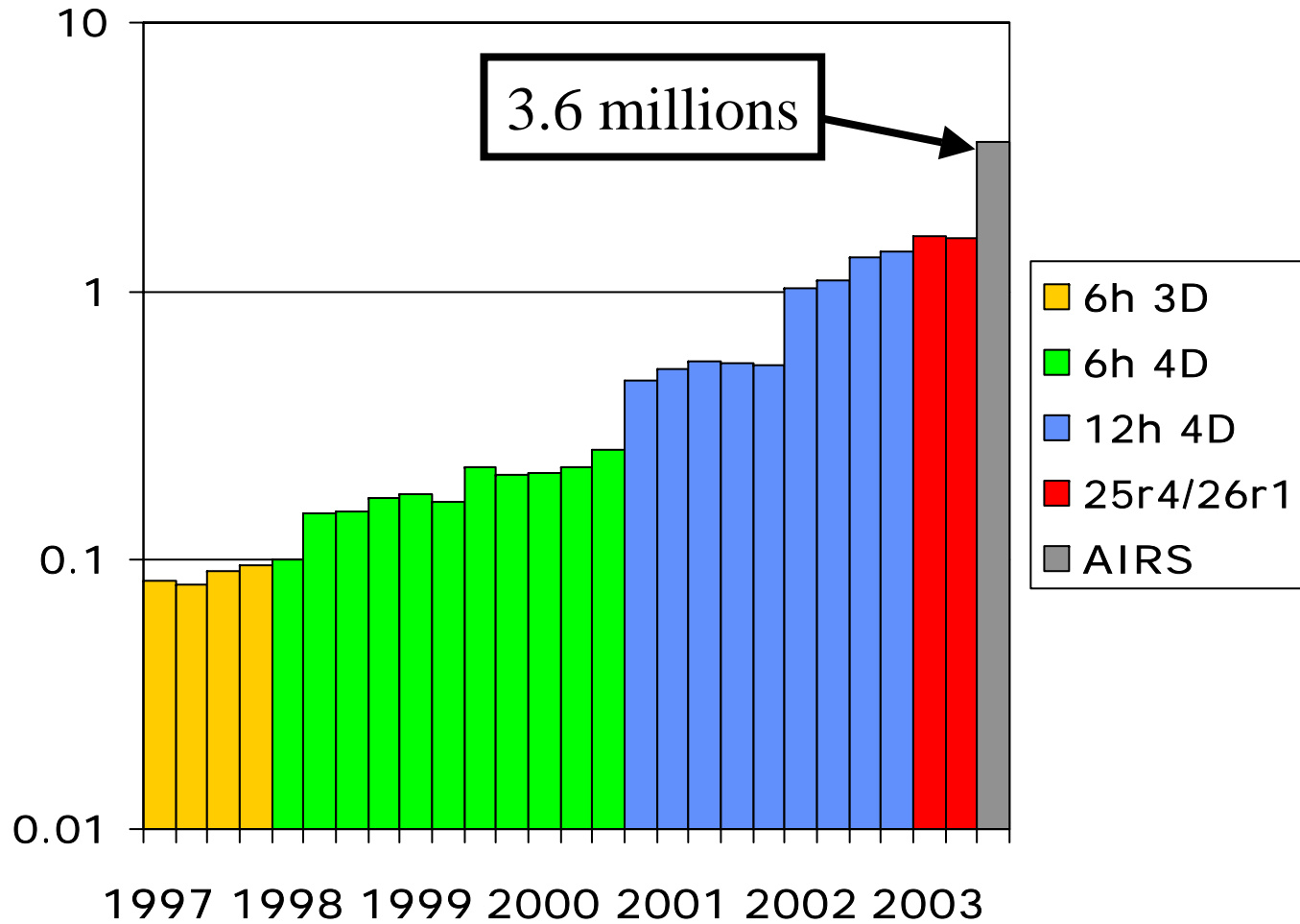


ECMWF operations since September 2004

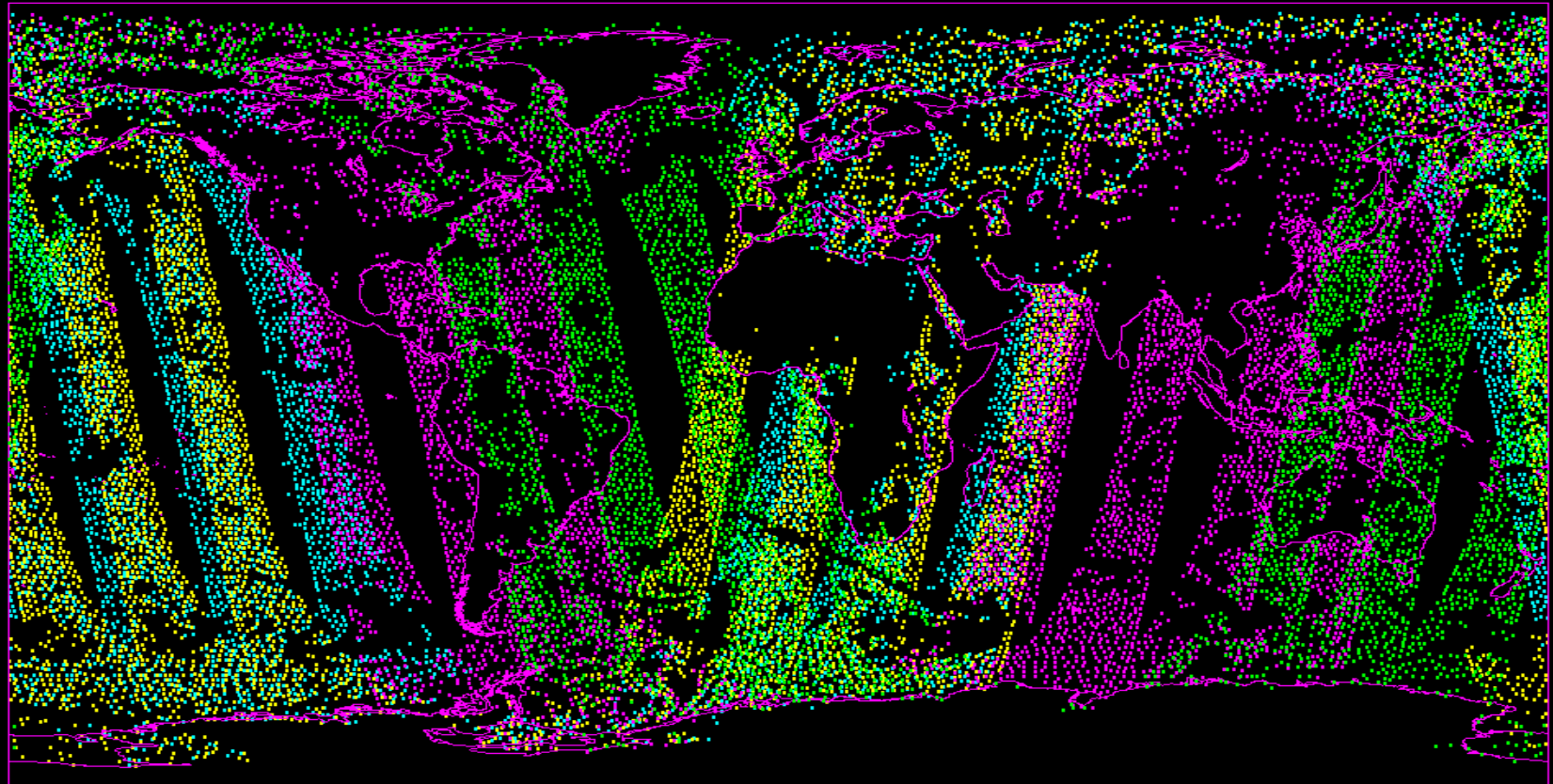
- **AQUA AIRS**
- **3xAMSUA (NOAA-15/16/17) + AQUA AMSUA**
- **3 SSMI (F-13/14/15)**
- **2xHIRS (NOAA-14/17)**
- **2xAMSU-B (NOAA-16/17)**
- **Radiances from 5xGEOS (Met-5/7 GOES-9/10/12)**
- **Winds from 5xGEOS (Met-5/7 GOES-9/10/12) and MODIS/TERRA**
- **SeaWinds from QuikSCAT**
- **ERS-2 Altimeter / SAR (limited coverage)**
- **SBUV (NOAA 16)**
- **ENVISAT OZONE (MIPAS+SCIAMACHY)**

28 satellite data sources

Number of observational data used in the ECMWF assimilation system (with AIRS)

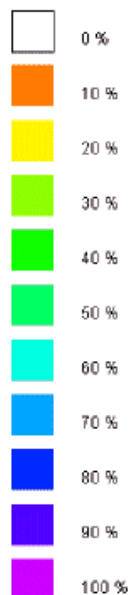
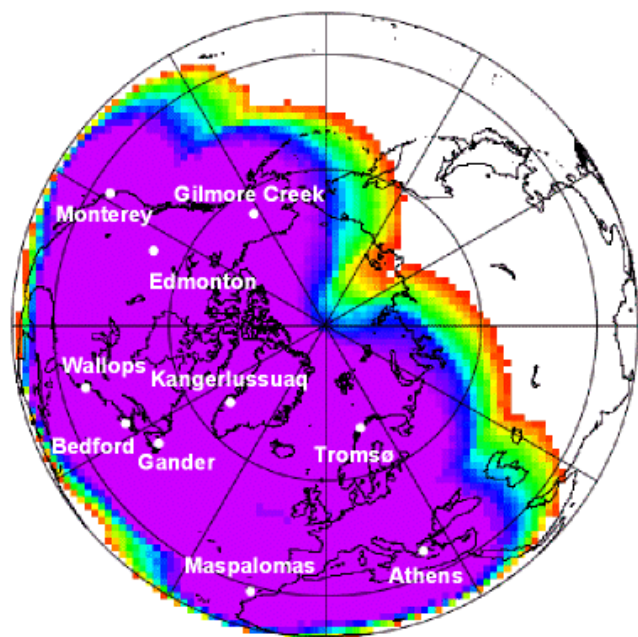


Data used for AMSU-A channel 6 in 4DVAR minimization for four satellites



CH08 F106-01
CH08 F106-01
CH08 F106-01

EUMETSAT ATOVS Retransmission Service (EARS)

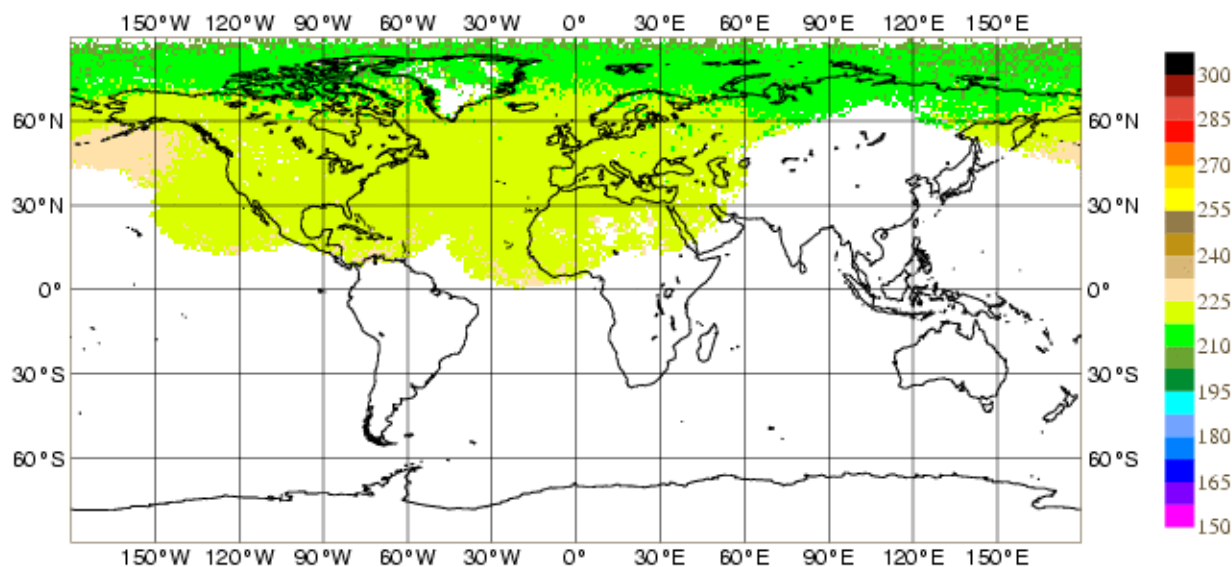


STATISTICS FOR RADIANCES (EARS) FROM NOAA-16 / AMSU-A - 07
MEAN OBSERVATION (USED)

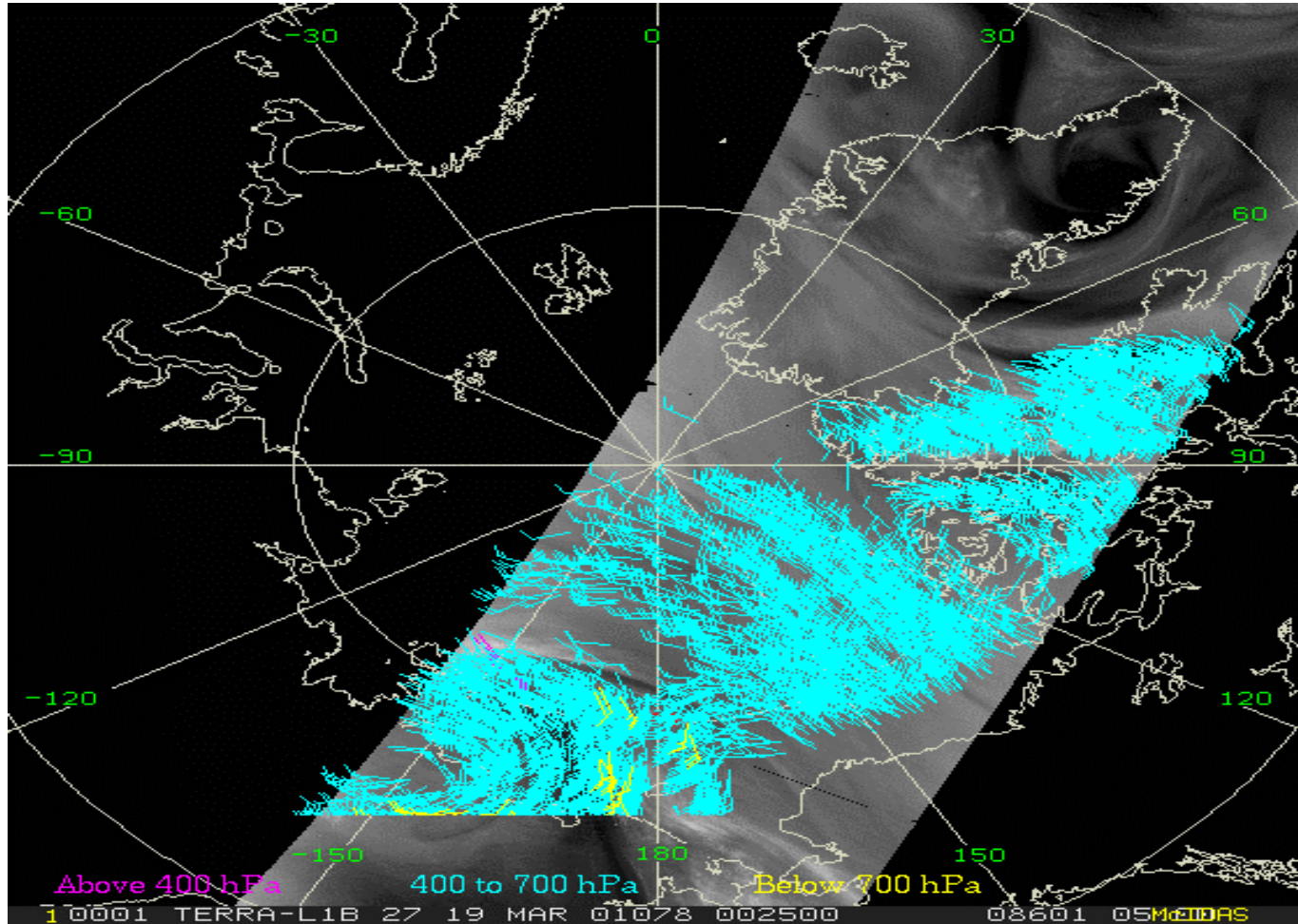
DATA PERIOD = 2004120100 - 2004122506 , HOUR = ALL

EXP = 0001

Min: 202.9 Max: 229.75 Mean: 219.74



Polar WV winds from MODIS



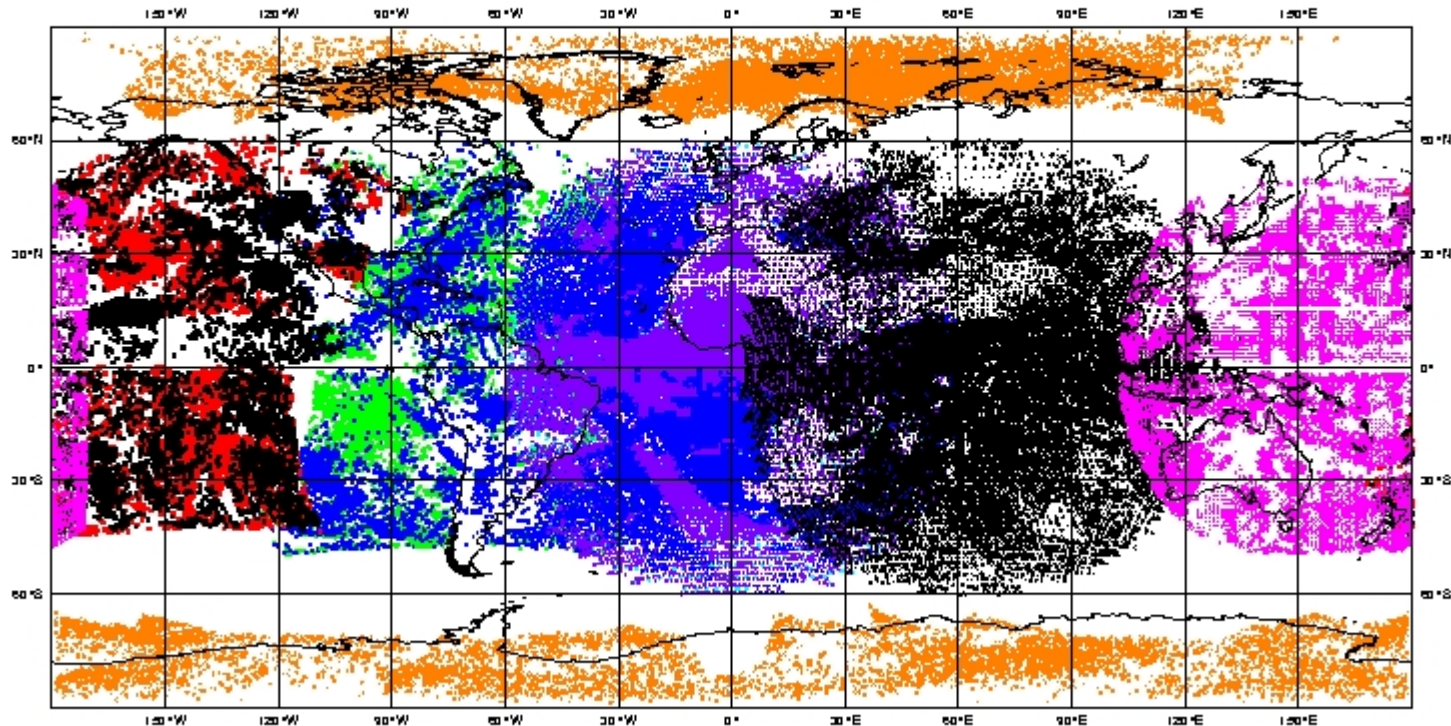
Source: P. Menzel, 2003

POLAR AND GEOSTATIONARY WINDS & RADIANCES

ECMWF Data Coverage (All obs) - SATOB

27/APR/2004; 12 UTC

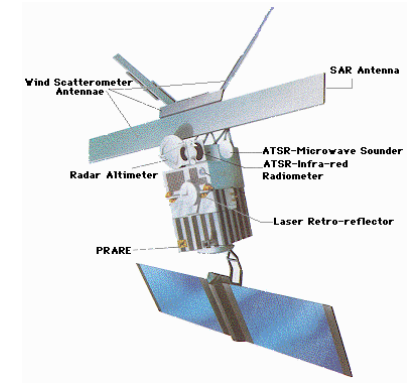
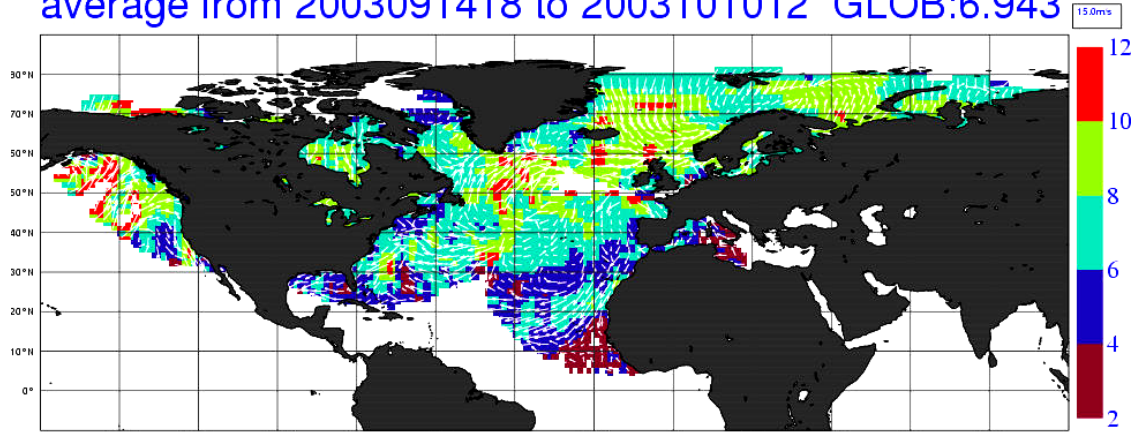
Total number of obs = 224958



SCAT Winds

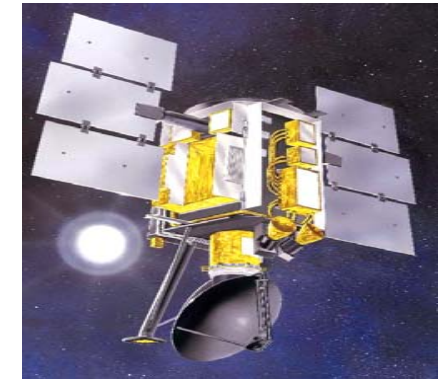
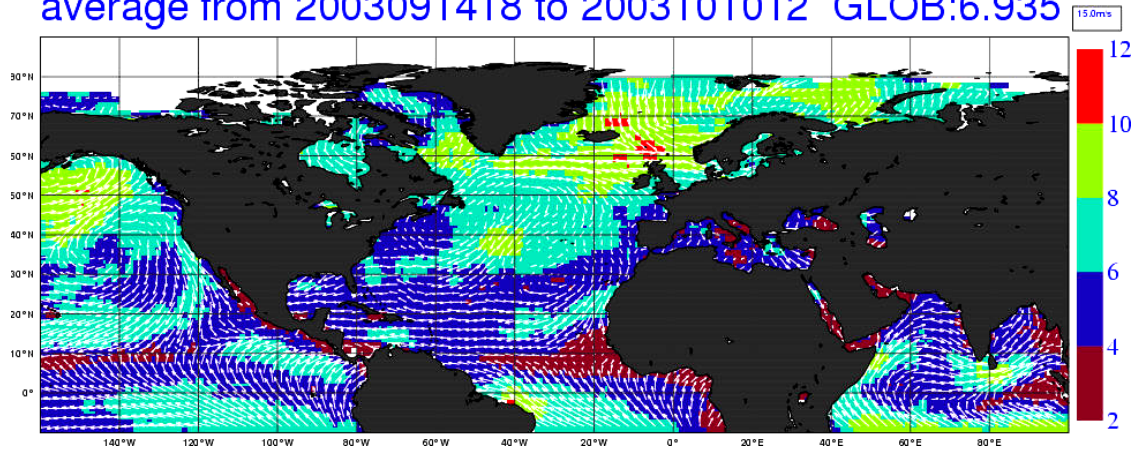
ECMWF FGAT at ERS-2 SCAT location

average from 2003091418 to 2003101012 GLOB:6.943



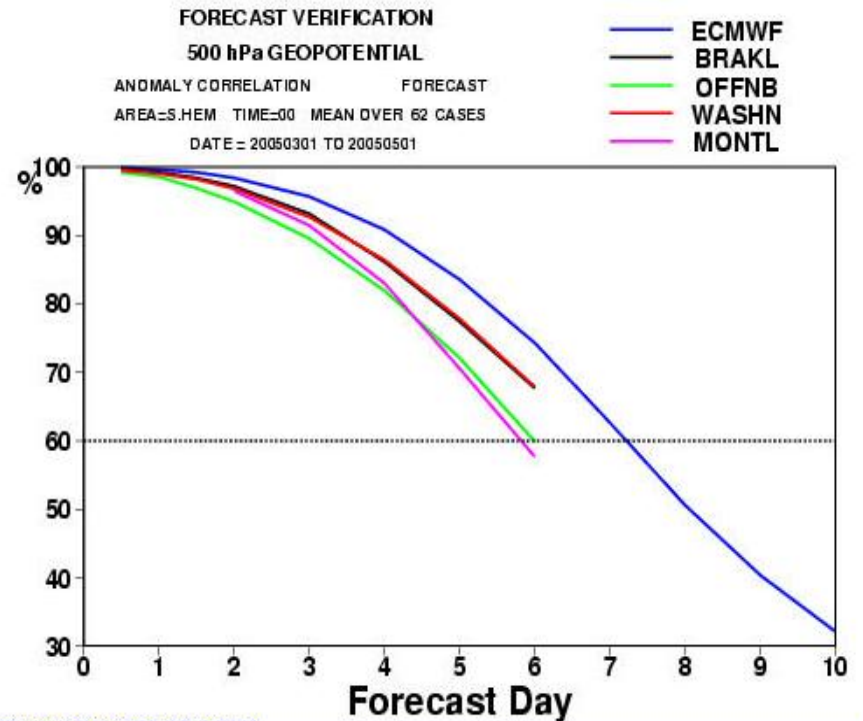
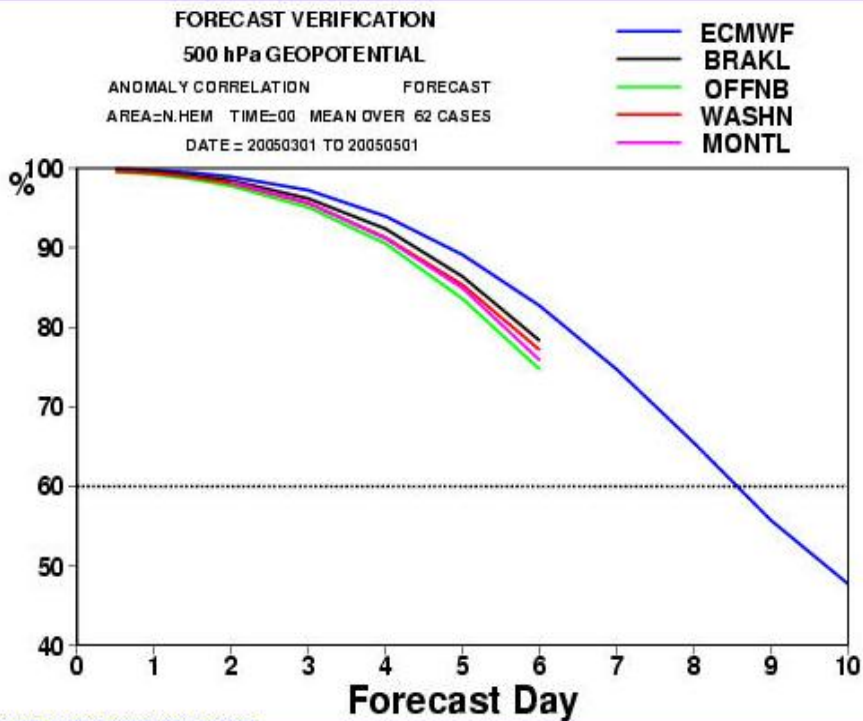
ECMWF FGAT at QuikSCAT location

average from 2003091418 to 2003101012 GLOB:6.935



Comparison other centres

April & May 2005



OSE's ECMWF (1997, 1999 and 2002)

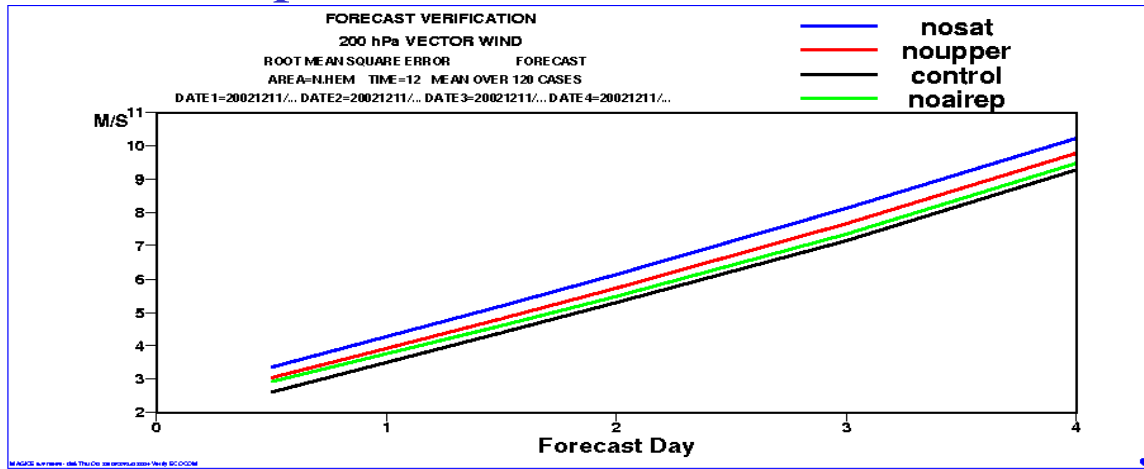
A series of OSE's were run with the current operational version (at the time) of the ecmwf system

**The 2002 OSE used :
(4dvar (TL511 40km) forecast model and
(TL159/511 120km) 4dvar analysis).**

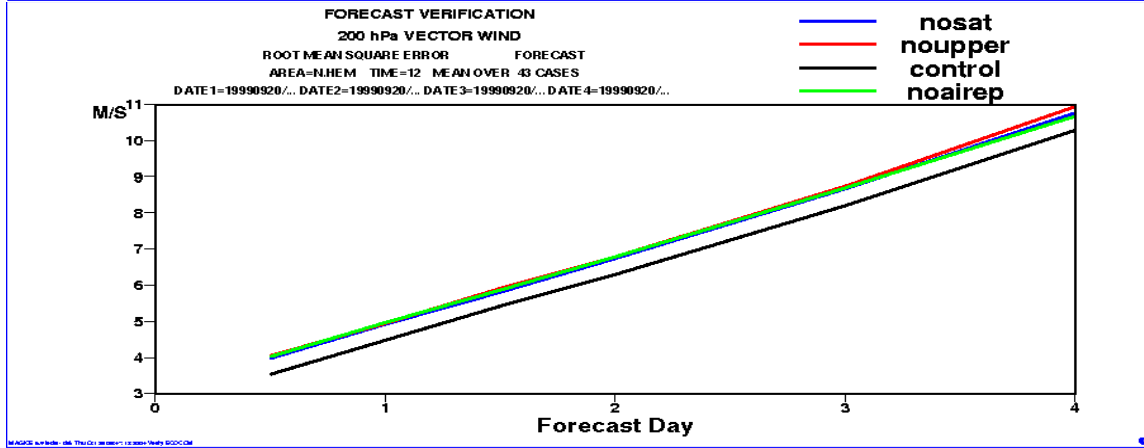
The number of cases:
1997 OSE 34 days (*Kelly 1998*)
1999 OSE 43 days (*Bouttier and Kelly 2001*)
2002 OSE 120 days (*Kelly 2004*)

Northern Hemispheric OSE's (RMS 200hPa vector wind)

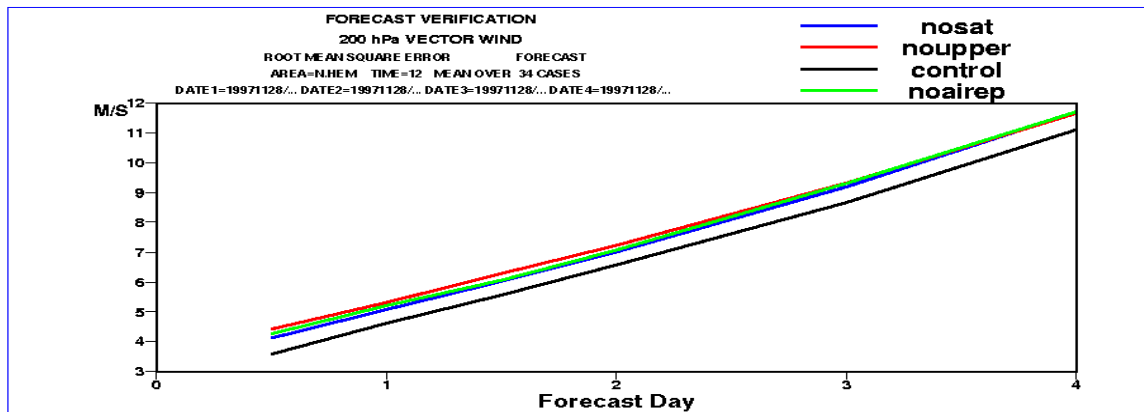
2002



1999

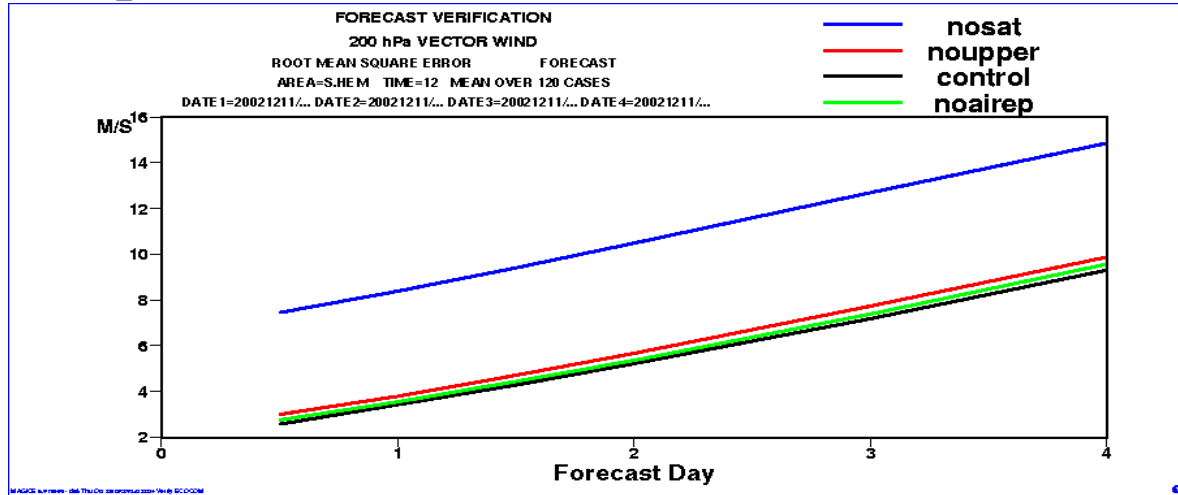


1997

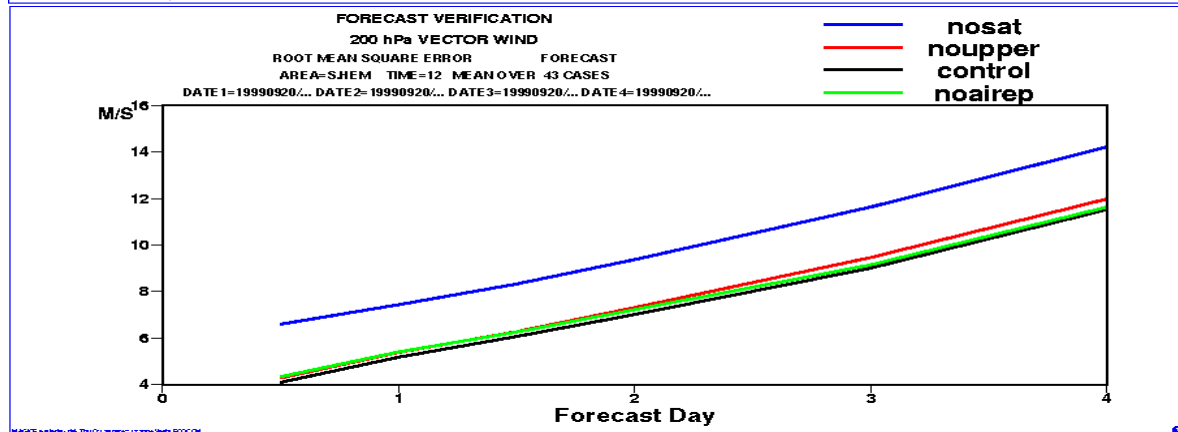


Tropical OSE's (RMS 200hPa vector wind)

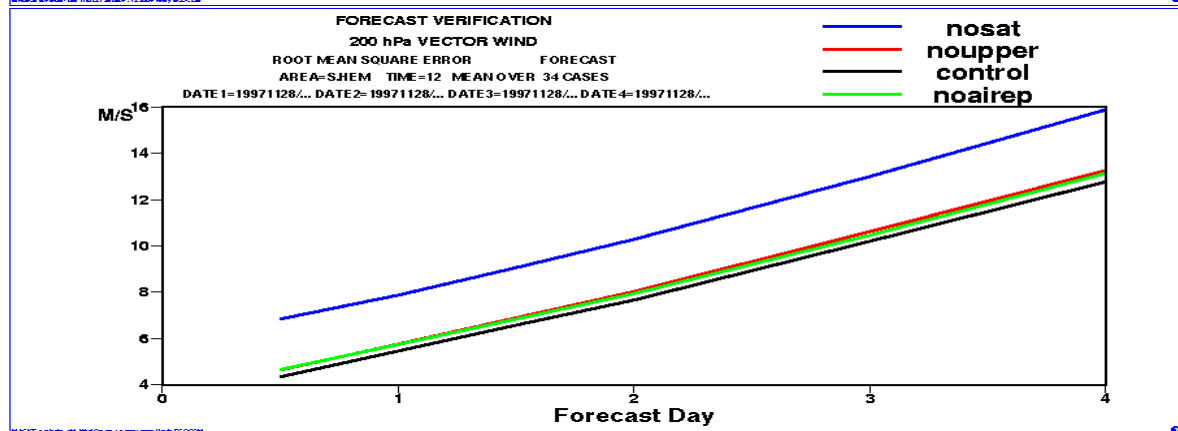
2002



1999

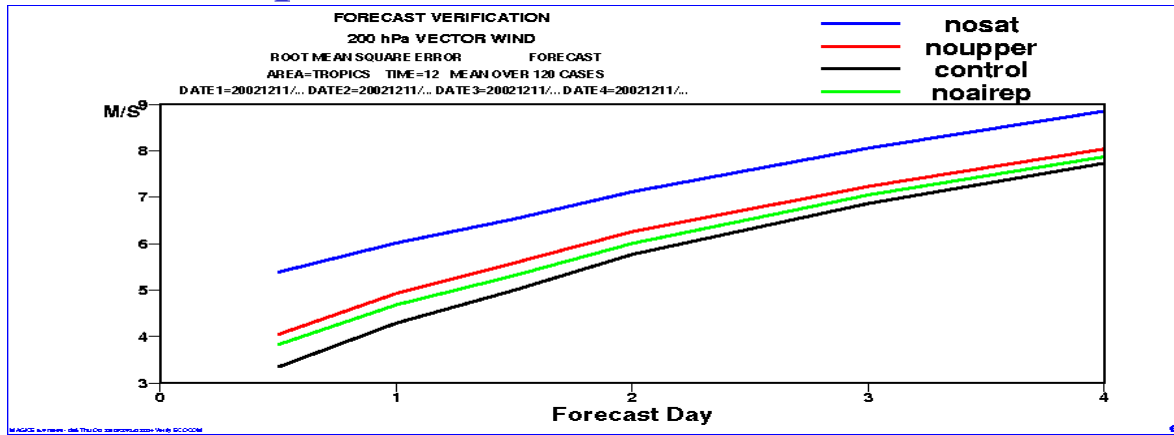


1997

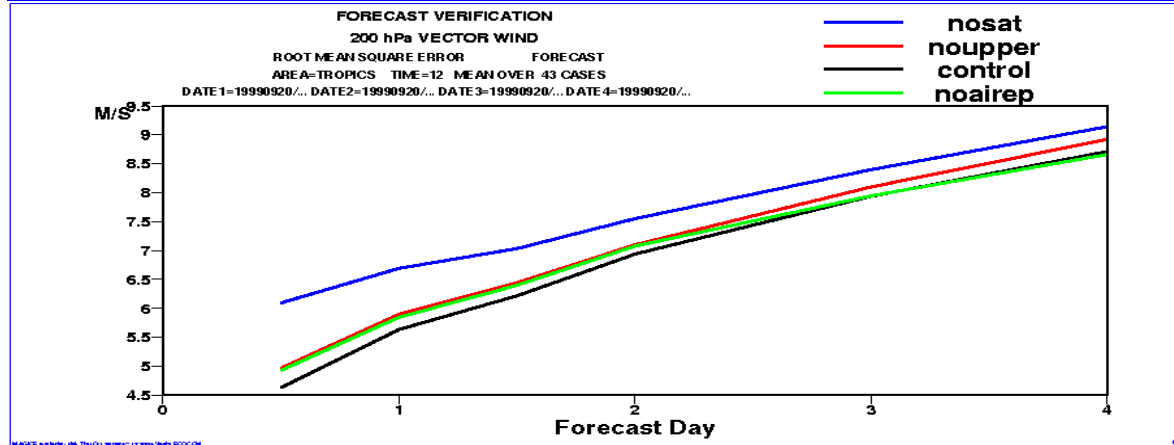


Southern Hemispheric OSE's (RMS 200hPa vector wind)

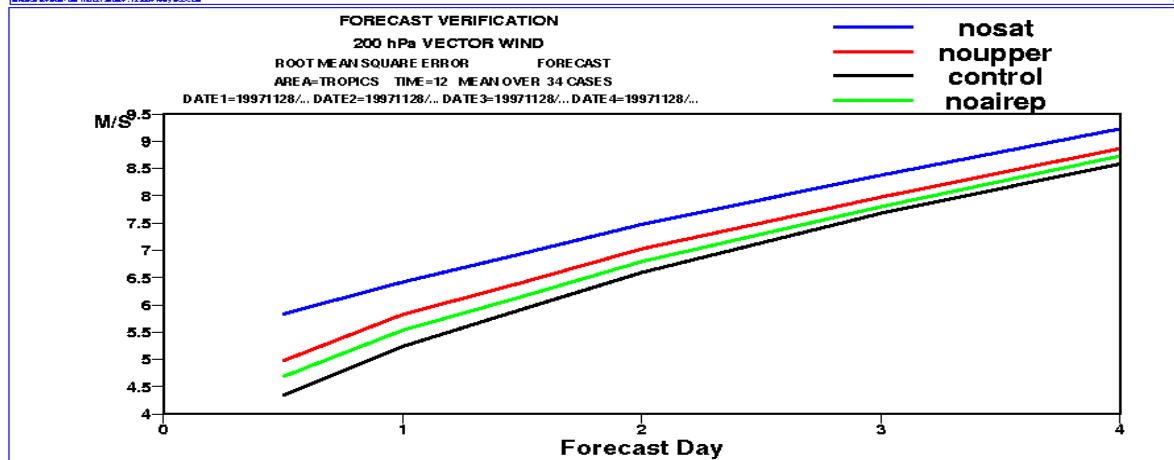
2002



1999



1997



Discussion of OSEs

Some important findings are:

The satellite data has more impact in the Northern Hemisphere than in previous OSE's even more than radiosondes and profilers combined.

In the four months of assimilation there are very few busts as defined by the anomaly correlation dropping less than 0.6 at day 4.

The Southern Hemispheric forecasts are almost as good as the Northern Hemispheric forecasts.

The short range RMS wind and temperature forecasts are of excellent quality and show the importance of satellite data.

Discussion from testing some satellite components.

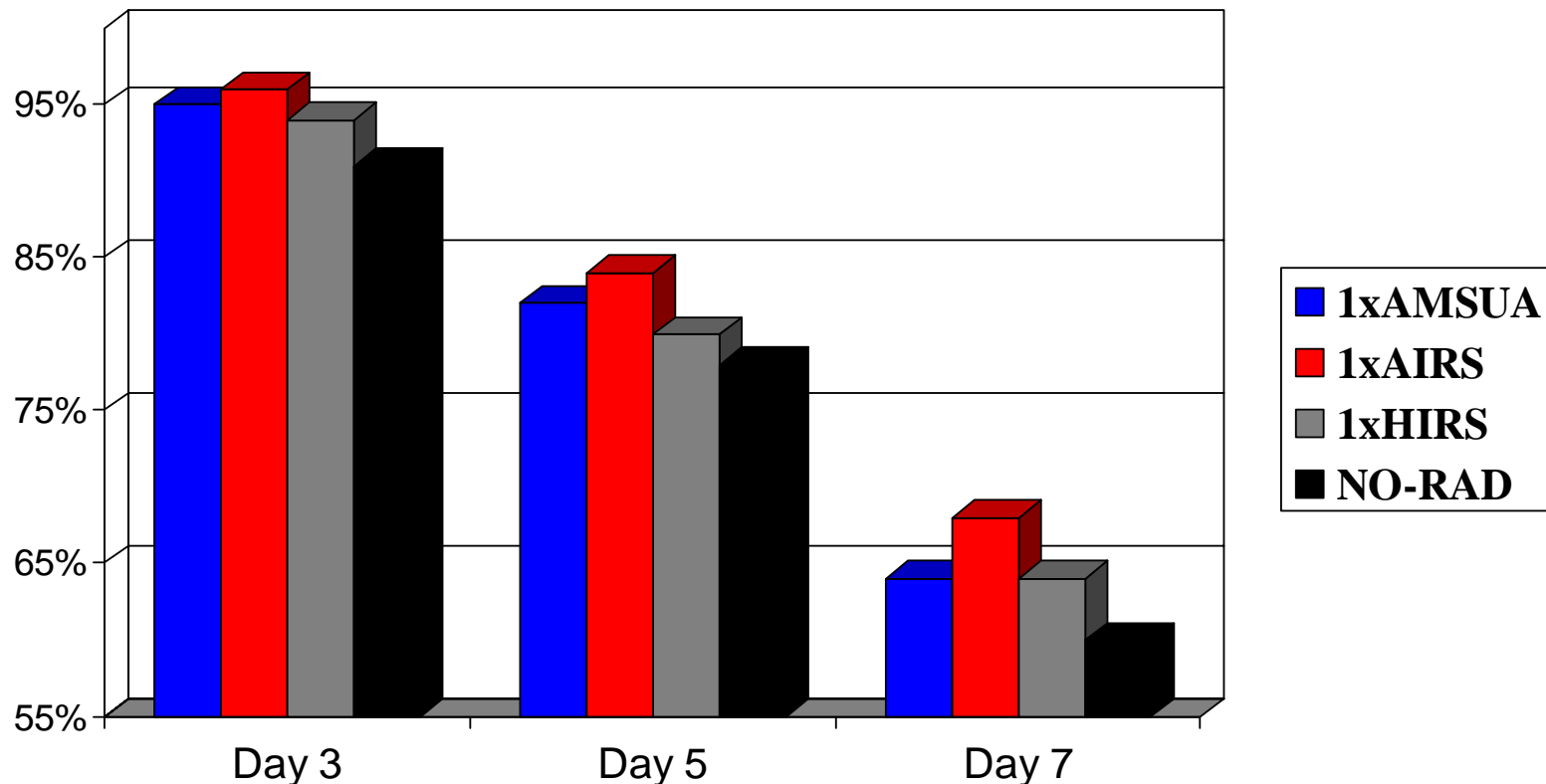
AMSUA plays an important role in the global observing system but removing all these instruments are not a complete disaster because of the system redundancy.

Addition of latest satellite instruments (GEO rads and a 'limited' AIRS) add little to current system but testing AIRS in a reduced satellite environment show some impact. This will allow a test-bed for improving AIRS usage.

Impact of individual sounding instruments on forecast quality

Anomaly correlation of 500hPa height for the **Southern Hemisphere** (average of 50 cases summer and winter 2003 verified with OPS analyses)

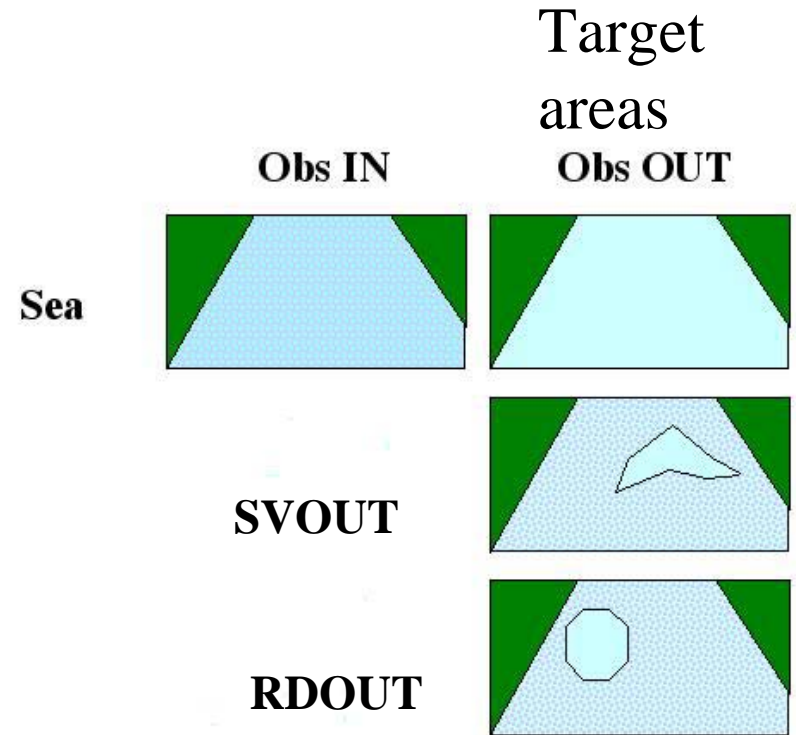
(NB: scores much more neutral in Northern Hemisphere)



Experiments removing all observations from target regions

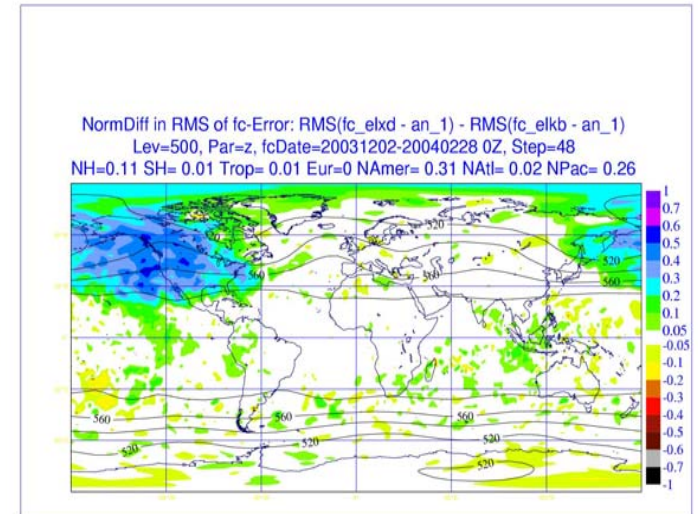
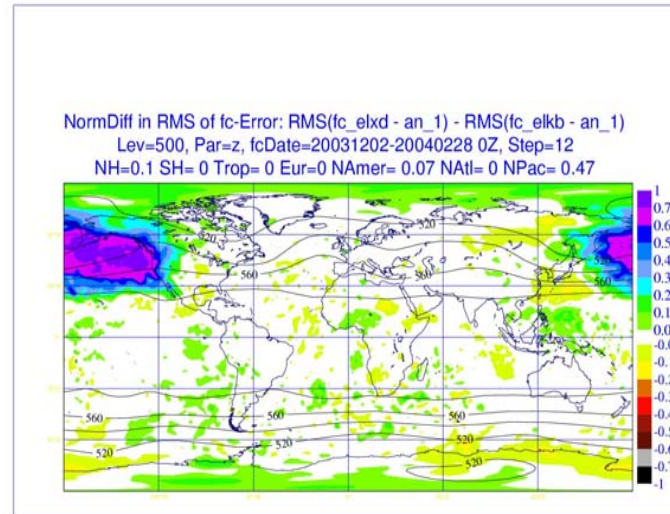
For the Pacific and the Atlantic oceans, four types of experiments will be discussed:

- **SeaIN:** control (all obs)
- **SeaOUT:** no obs in the ocean
- **SVOUT:** no obs in SV-target area
- **RDOUT:** no obs in random area

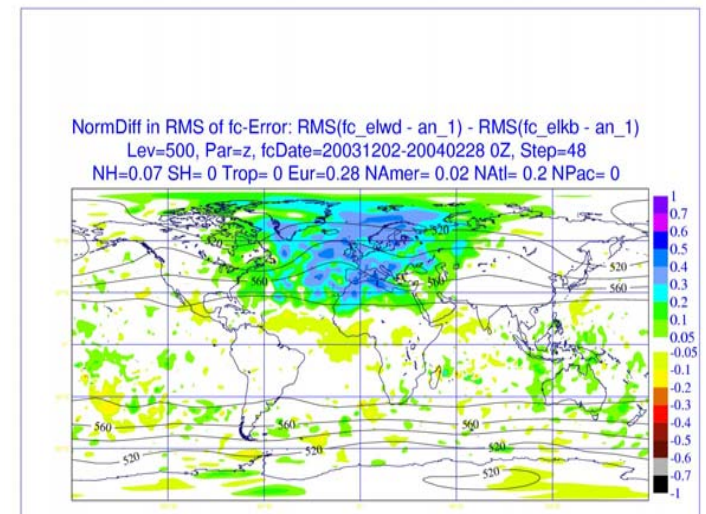
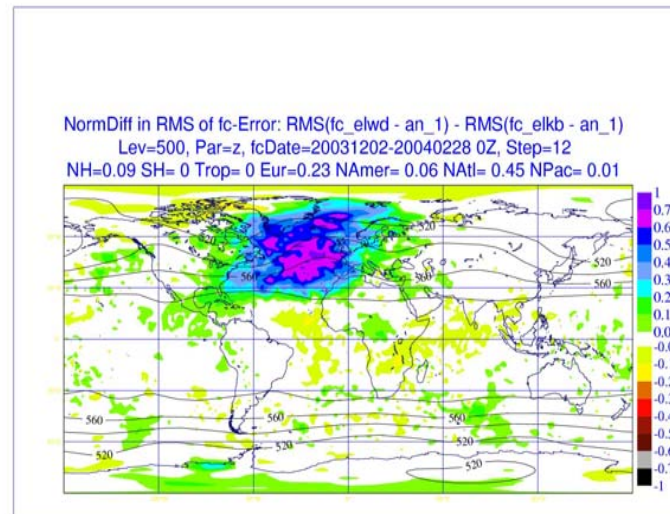


Influence of PAC- and ATL-obs on 12 hr and day 2 fcs – Z500

PAC-obs

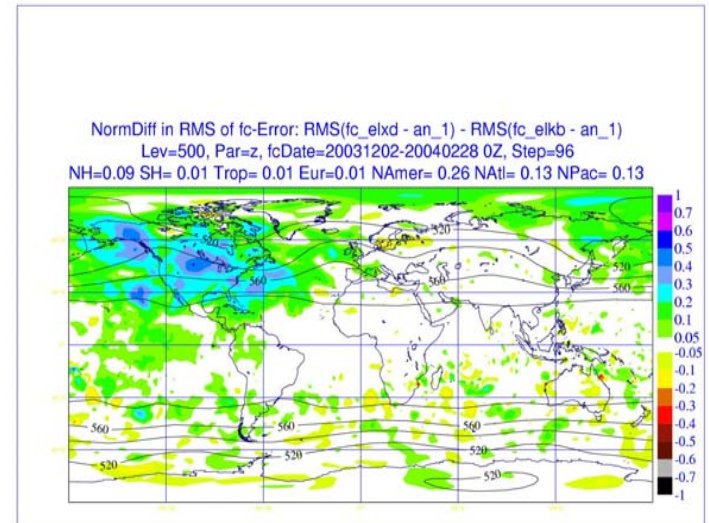
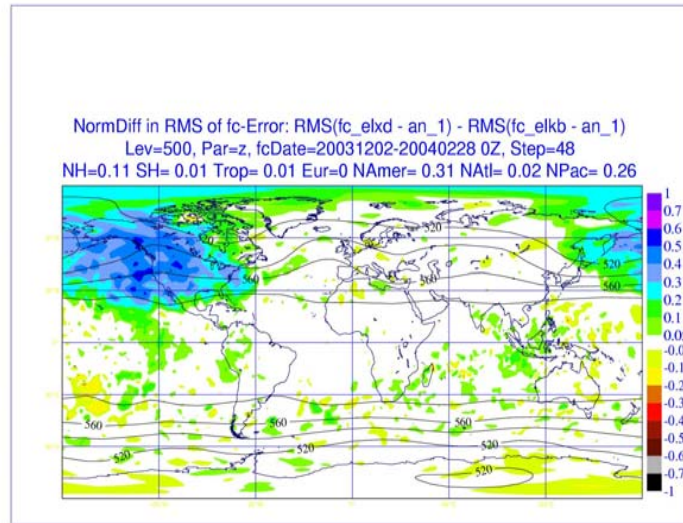


ATL-obs

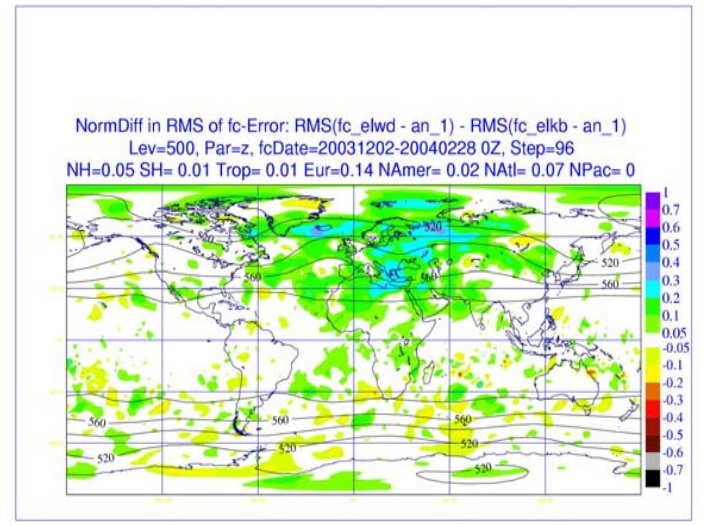
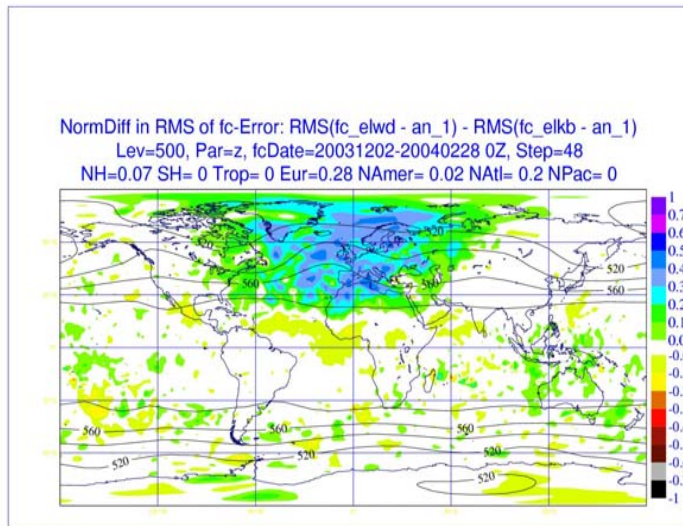


Influence of PAC- and ATL-obs on day 2 and day4 fcs – Z500

PAC-obs

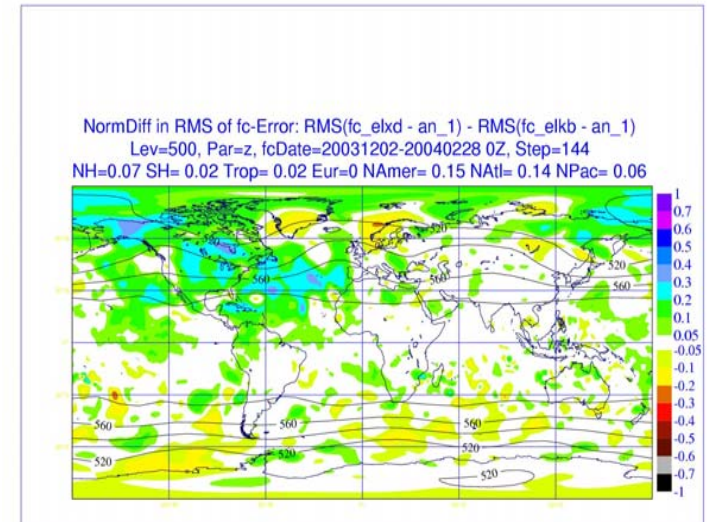
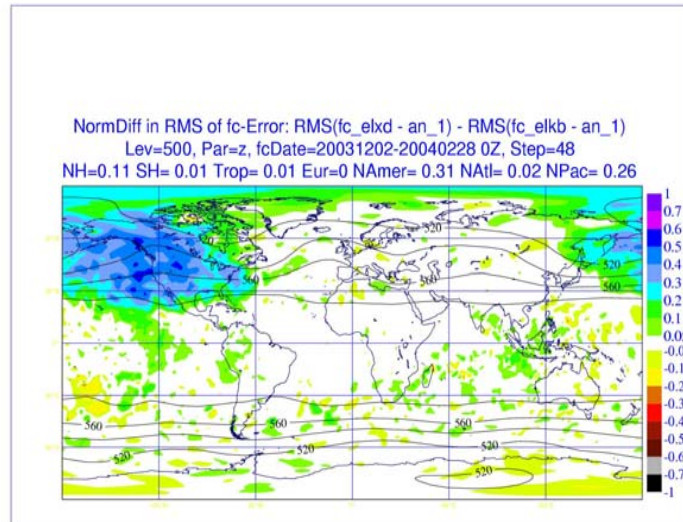


ATL-obs

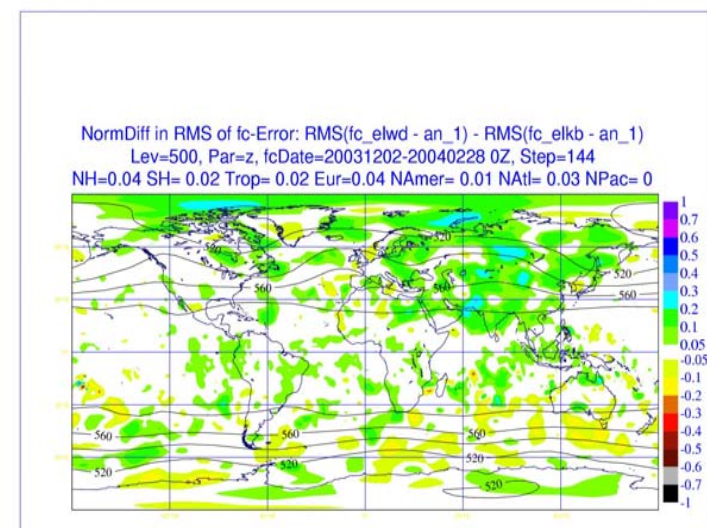
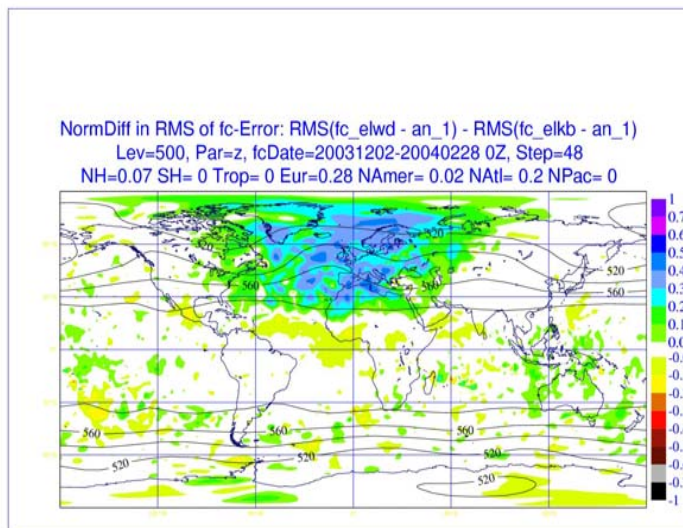


Influence of PAC- and ATL-obs on day 2 and day 6 fcs – Z500

PAC-obs

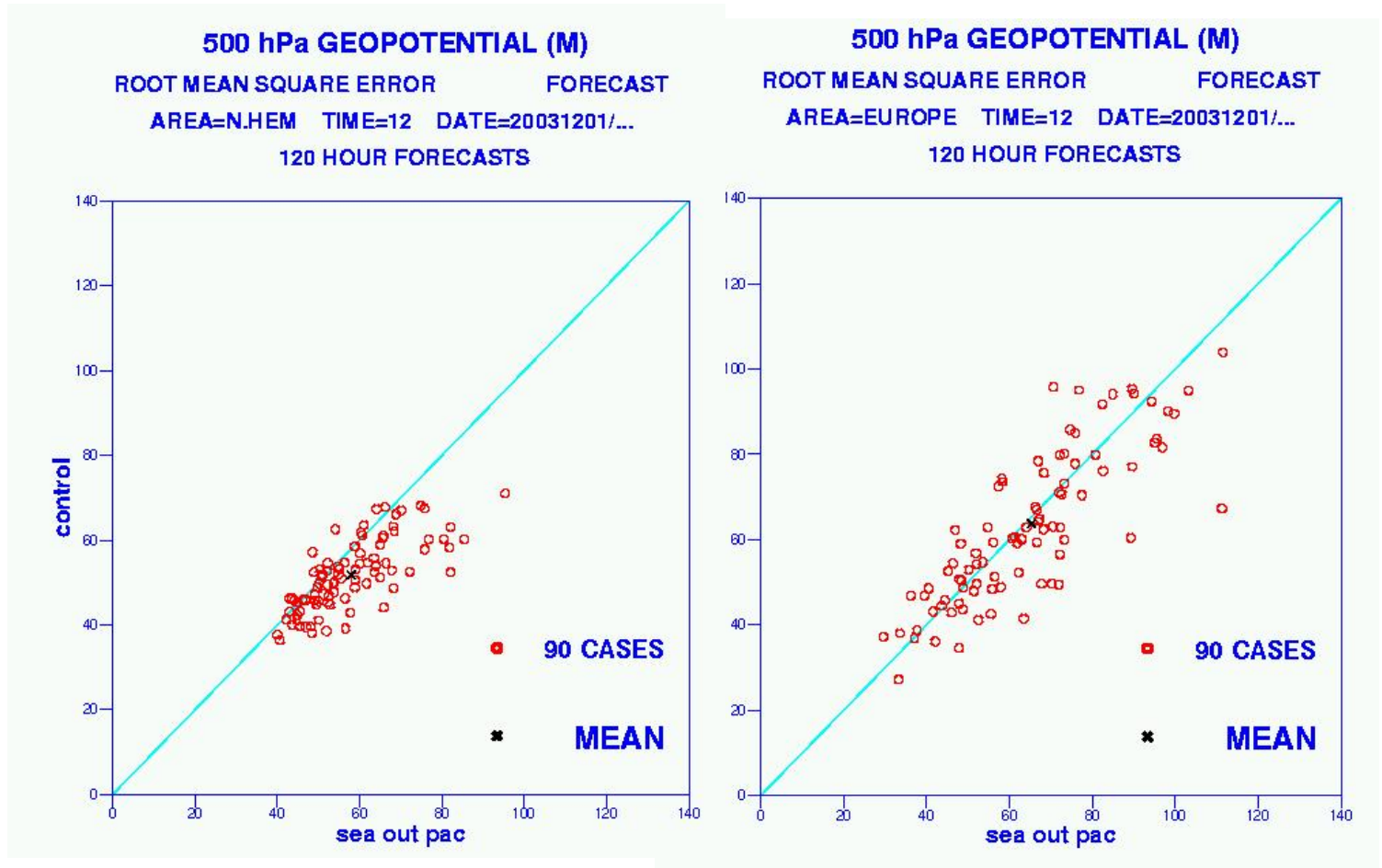


ATL-obs



Influence of removing PAC-obs on N A and Europe day 5

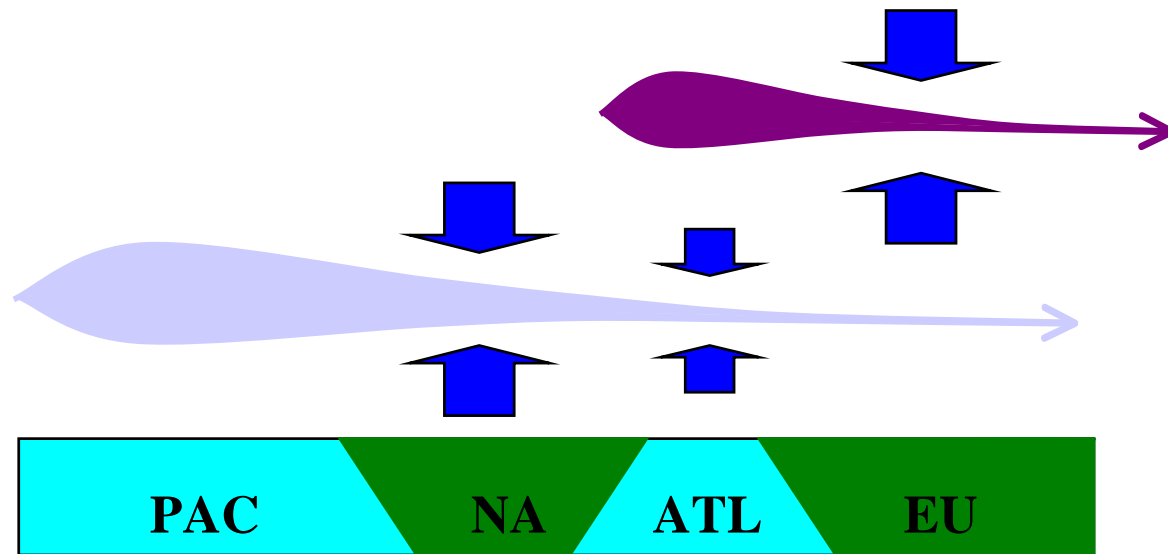
Influence of removing PAC-obs for day 5 forecasts over N H and Europe



Influence of ATL- and PAC-obs on fcs

These plots indicate that the impact of removing Atlantic data on Europe is smaller than the impact of removing Pacific data on North America. These indications are confirmed by the comparison of average RMSE computed over the different verification areas (NA, ATL, EU and NH).

The fact that the ATL-obs induced signal diminishes more quickly than the PAC-obs signal reflects the fact that the ATL initial signal is smaller (note that the ATL-SeaOUT area has ~25% less grid points than the ATL-SeaOUT area).

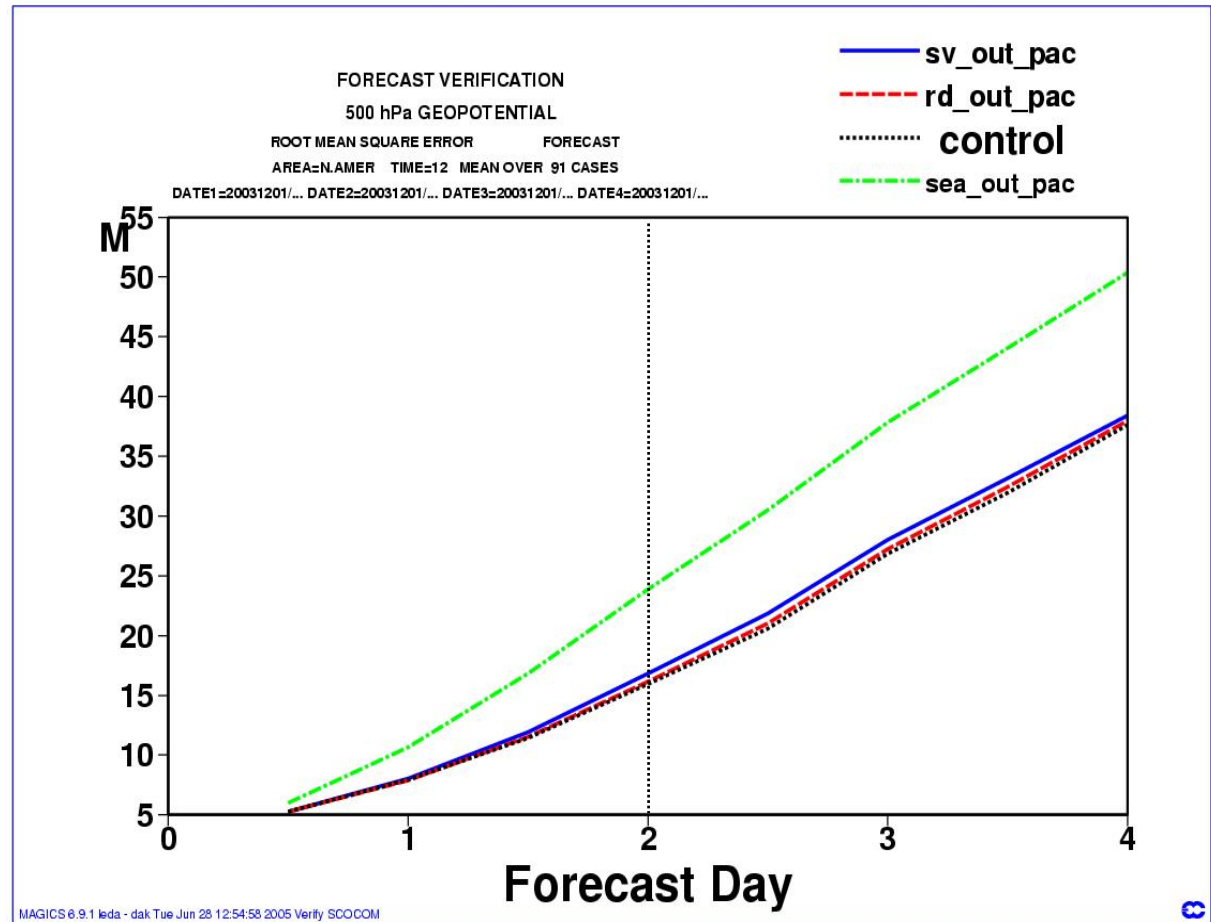


Influence of removing PAC-obs on North America Fcs, Z500

RMS error over NA of forecasts started from:

- **SeaOUT**
- **Control**
- **SVOUT**: no data only in the area defined by SVs (120 gp)
- **RDOUT**: no data only in a random area (120 gp)

Removing data in SV-target areas has a larger impact than removing data in random areas. The difference is statistically significant (2% lev) up to d3.

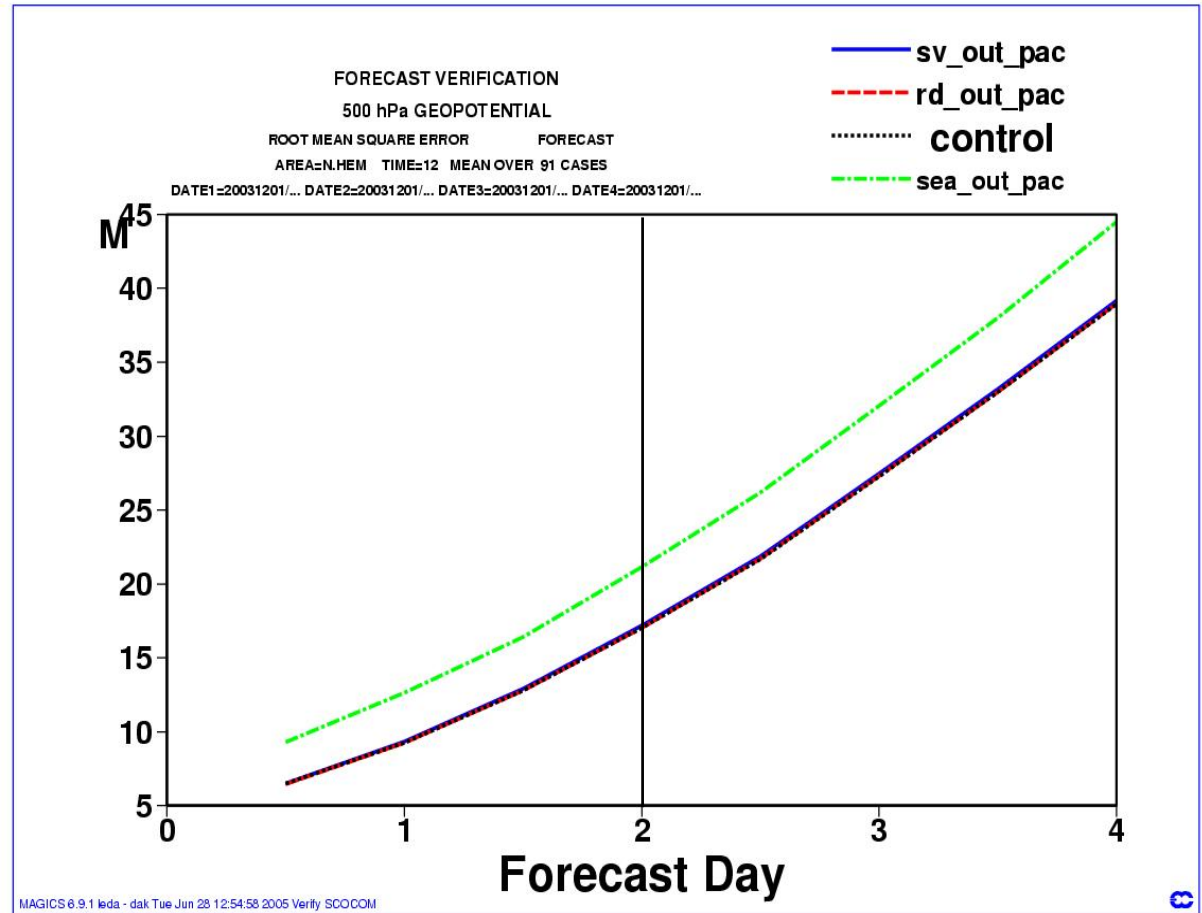


Influence of removing PAC-obs on N.Hem. Fcs Z500

RMS error over NH of
forecasts started
from:

- **SeaOUT**
- **Control**
- **SVOU**
- **RDOU**

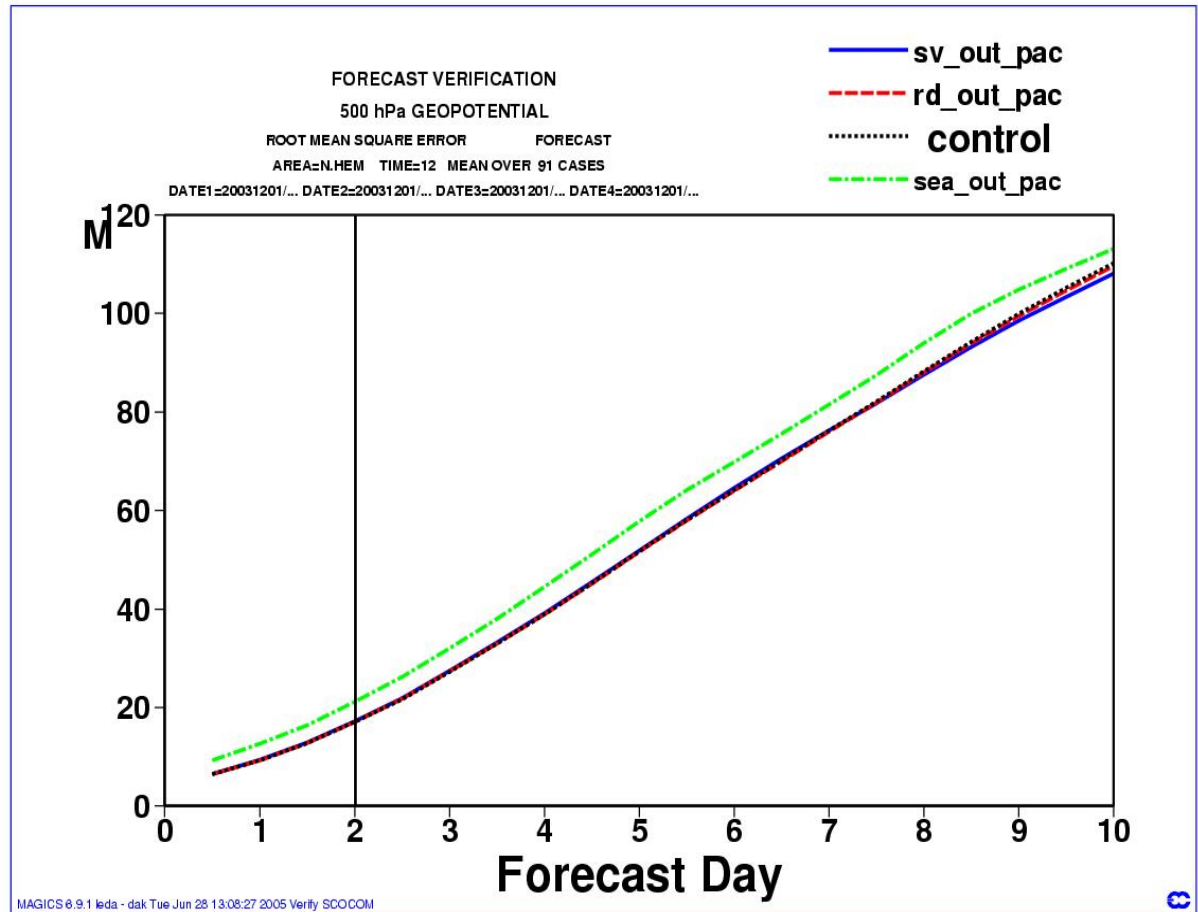
Removing data in SV-
target areas has a
larger impact than
removing data in
random areas. The
difference is
statistically
significant (% lev)
up to d3.



Influence of removing PAC-obs on N.Hem. Fcs, Z500

RMS error over
NH of forecasts
started from:

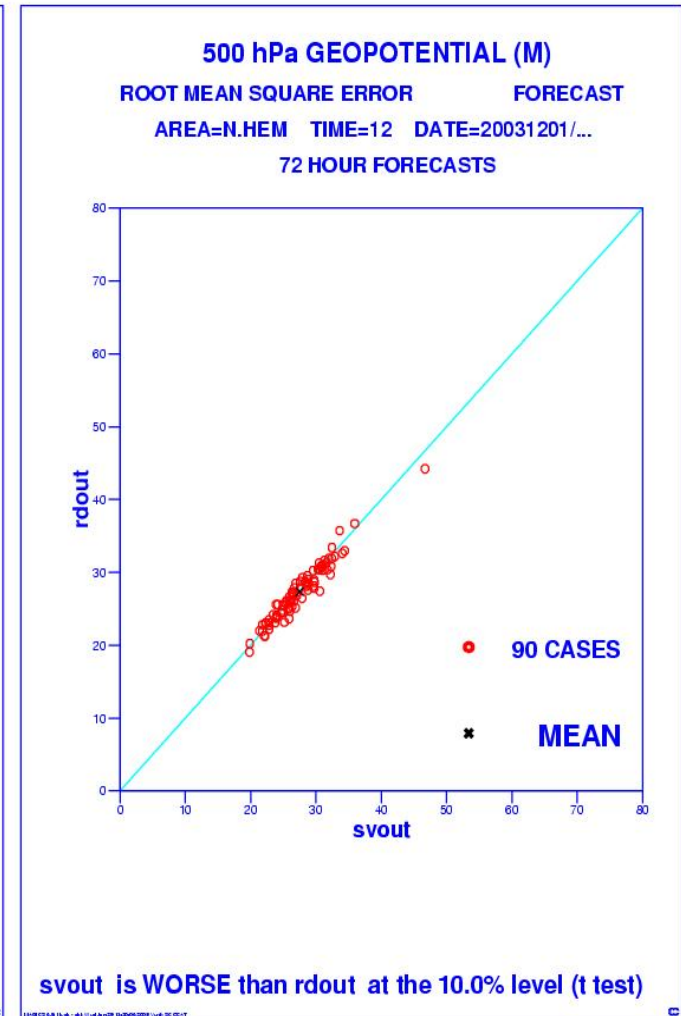
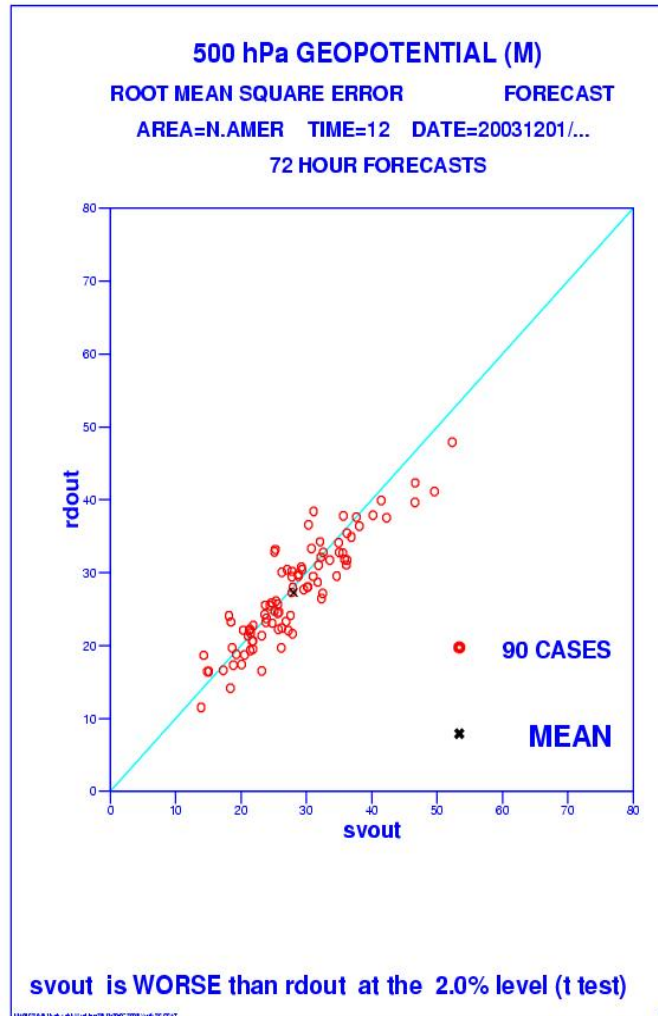
- **SeaOUT**
- **Control**
- **SVOUT**
- **RDOUT**



Influence of removing PAC-obs on North America/N. Hem. – RDOUT/SVOUT Day 3

Influence of removing PAC-obs for day 3 forecasts over North America and N. Hem.:

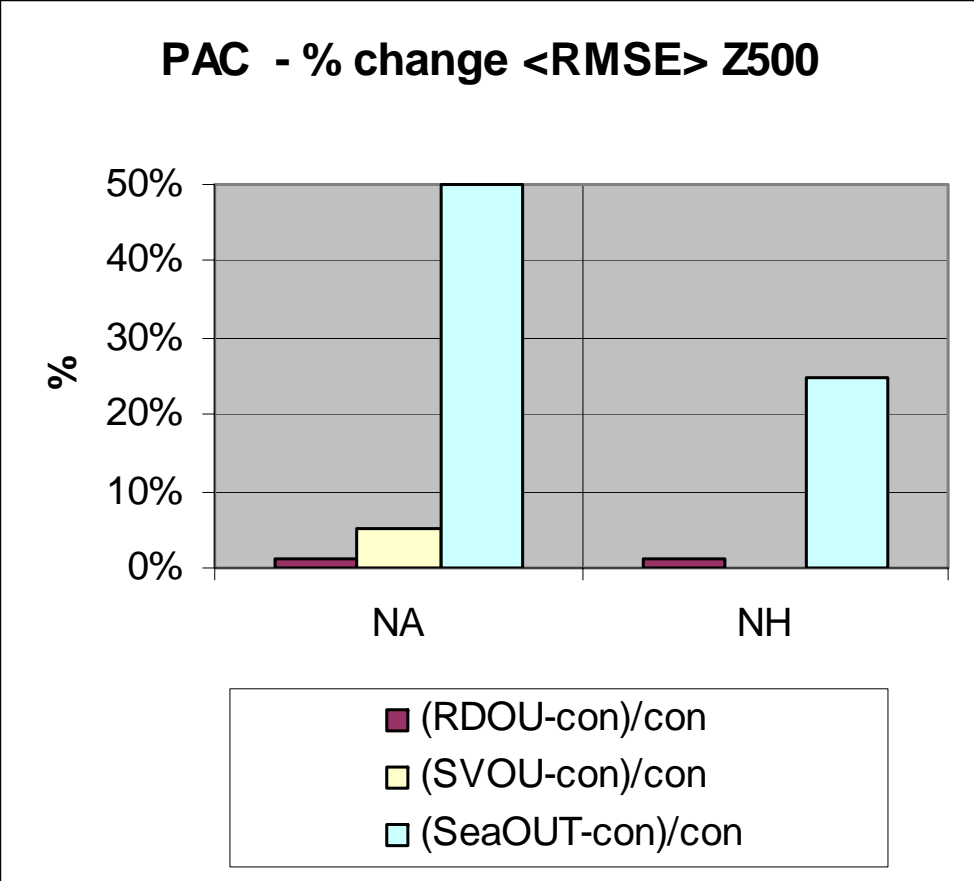
- **Observations taken in SV-based target areas have a higher value than random obs**
- **The difference is statistically significant also over NH**



Influence of removing PAC-obs on North Amer. and N. Hem. Fcs – Z500 day 2

Consider control as the baseline. Removing observations:

- In a random area (11.5% of SeaOUT gp) increases $\langle \text{RMSE}(d2) \rangle_{\text{NA}}$ by 1%
- In the SV-target area (11.5% of SeaOUT gp) increases $\langle \text{RMSE}(d2) \rangle_{\text{NA}}$ by 5%
- Over the whole SeaOUT area increases $\langle \text{RMSE}(d2) \rangle_{\text{NA}}$ by 50%



Summary of experiments removing all observations from target regions

- **The value of observations taken in the oceans is regionally dependent and depends strongly on the underlying observation system.**
- **Data denial experiments indicate that adding targeted observations in the Pacific is expected to have, on average, a rather small impact (~5%), and that adding targeted observations in the Atlantic may have, on average, an even smaller impact (~3%).**
- **The global observing system is very robust. Removing data in areas that covers 11-14% of the Pacific or Atlantic ocean has a small impact on the day 2 forecast error. Removing all Pacific data has a small impact over the forecasts over Europe.**

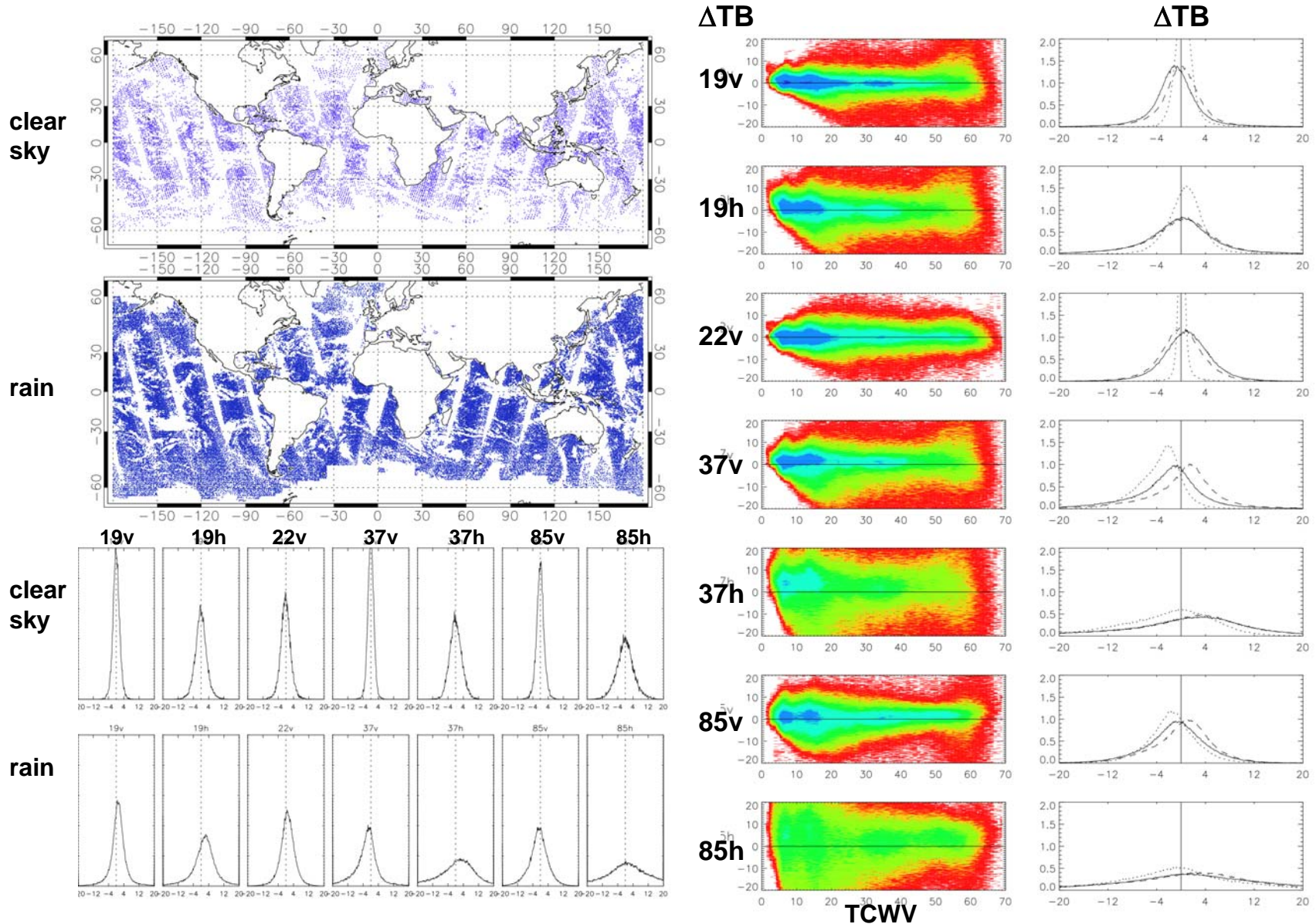
Summary of experiments removing all observations from target regions (cont.)

- **A possible reason for this lack of sensitivity may be due to the large scale nature of the analysis structure functions. Much more work is required in this area so that the background term are more flow dependant.**
- **Future plans include (a) assessing whether these conclusions are valid also for summer, and (b) investigating the relative impact on different observation types.**

1D/4D-Var and cloudy radiances

- In July 2005 ECMWF introduced into operations a pre-analysis 1DVAR (using moist physics and model tendencies) to assimilate cloudy SSMI radiances.
- The 1DVAR moisture profile used then used in 4DVAR.
- We are now working on a full 4DVAR version.

SSM/I clear-sky vs. rain FG-Departures (03/08/2004 00 UTC)

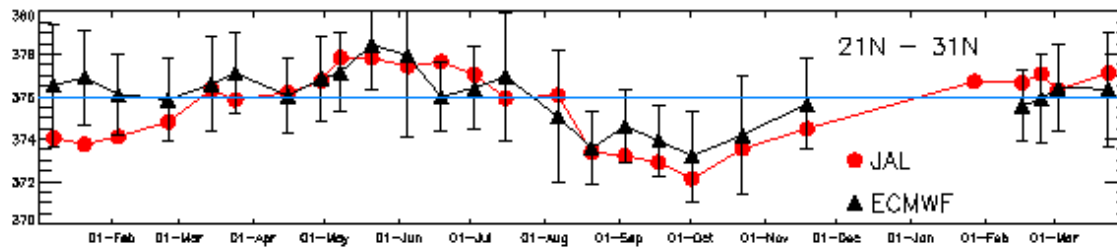


GEMS tasks at ECMWF

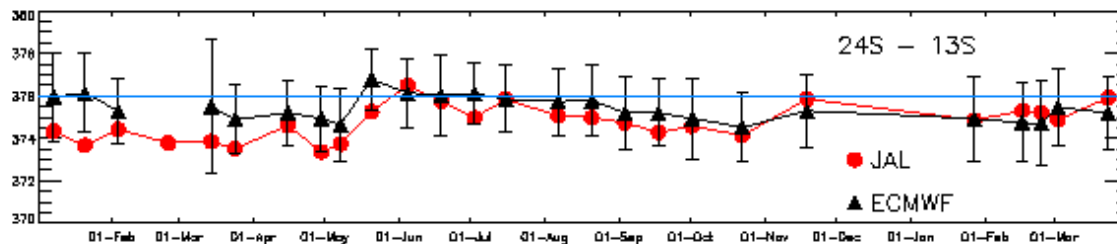
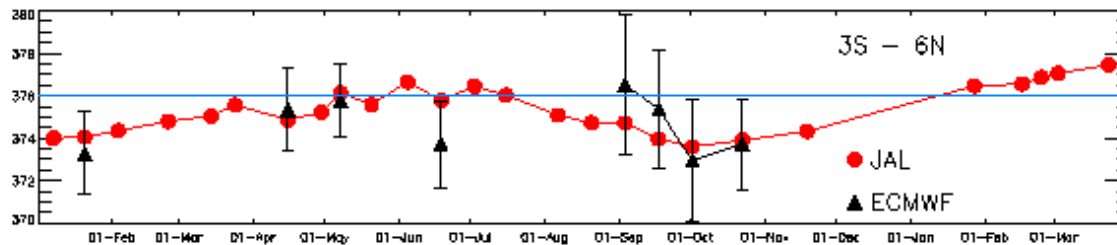
- **Greenhouse gases**
 - Start on CO₂, then CH₄, N₂O and CO
 - Develop modelling and data assimilation, and use analyses to infer sources and sinks for CO₂ and CH₄
- **Reactive gases**
 - Couple main forecast model with global CTMs
 - Carry O₃, NO₂, CO, SO₂ and CH₂O in main model and develop data assimilation
- **Aerosols**
 - Add to model, based on existing parameterizations
 - Develop assimilation of retrievals, then radiances
- Integrate above components, and run past periods
- Provide boundary conditions and technical support for regional air-quality prediction

CO₂ estimation

One year of AIRS radiances (Feb 03 to Mar 04) have now been analyzed inside the ECMWF 4DVAR and CO₂ estimates produced.



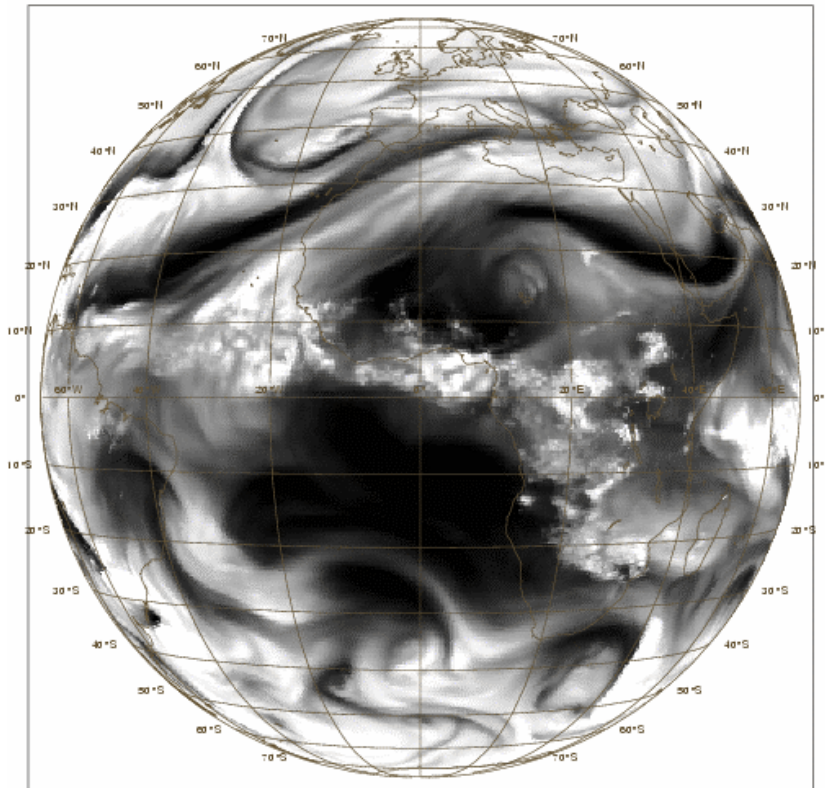
Zonal
column
estimates
(ppmv)



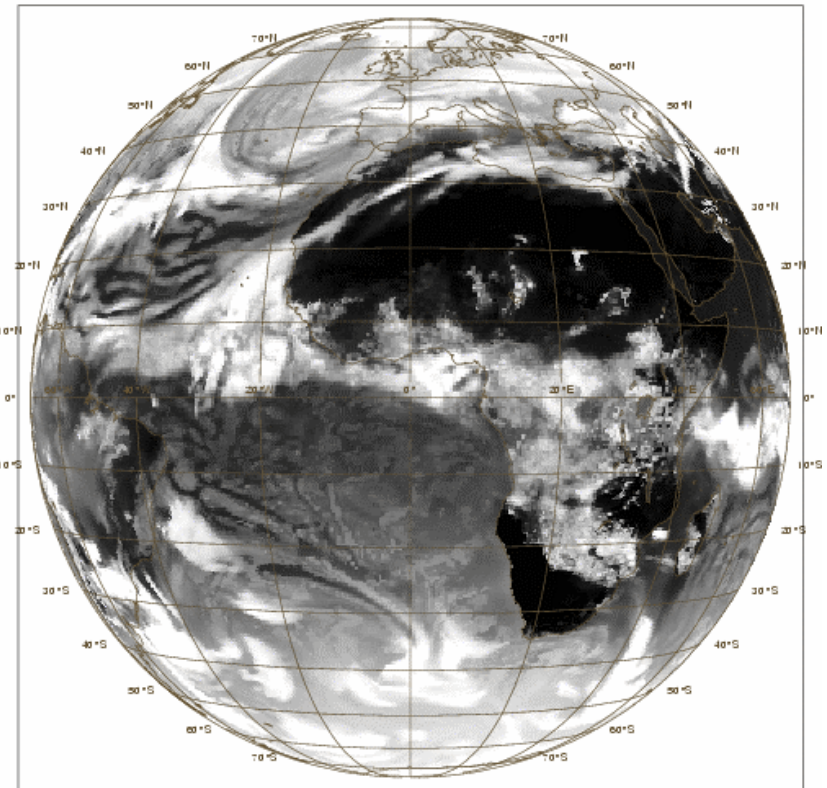
In general the agreement with the sparse validation data (JAL flight data) is quite good, although some periods need more study

Forecasted Imagery: 24-hour

Saturday 25 October 2003 12UTC ECMWF Forecast t+24 VT: Sunday 26 October 2003 12UTC
Satellite Image, Water vapour



Saturday 25 October 2003 12UTC ECMWF Forecast t+24 VT: Sunday 26 October 2003 12UTC
Satellite Image, First infrared band



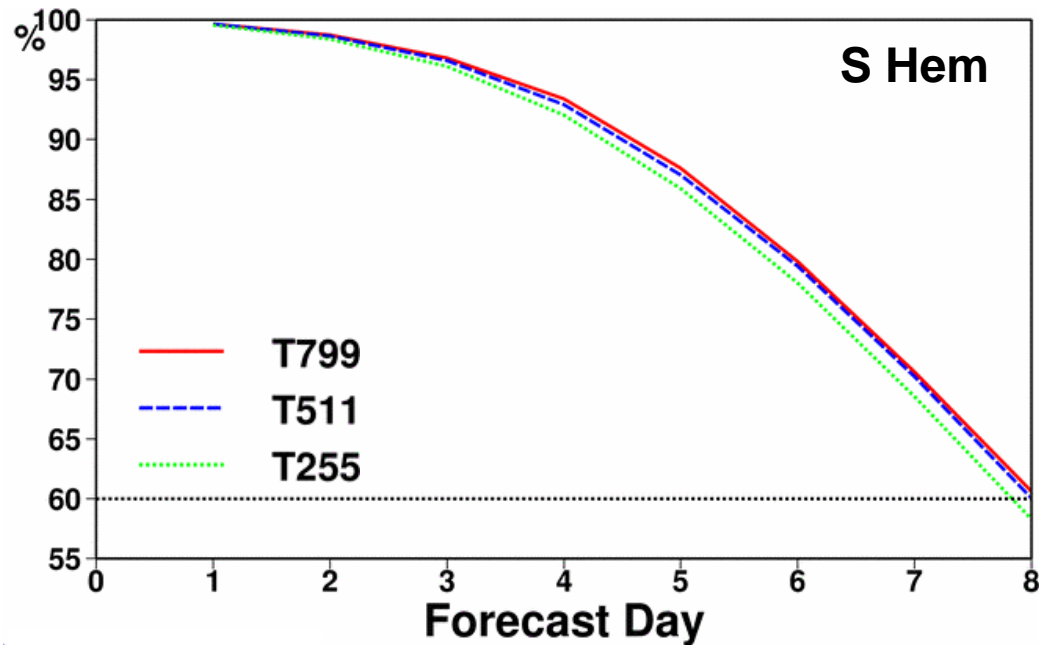
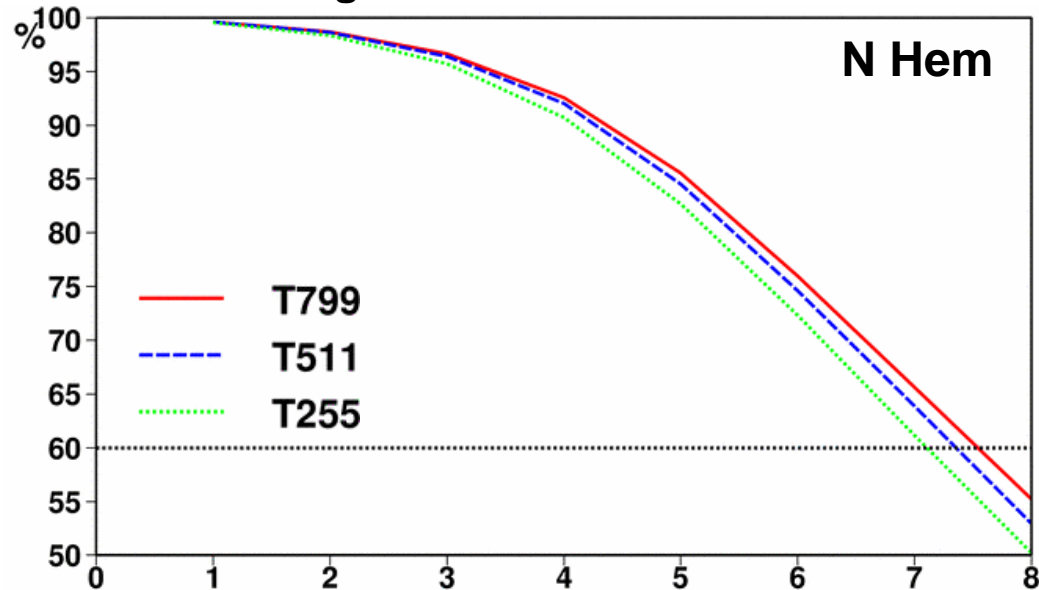
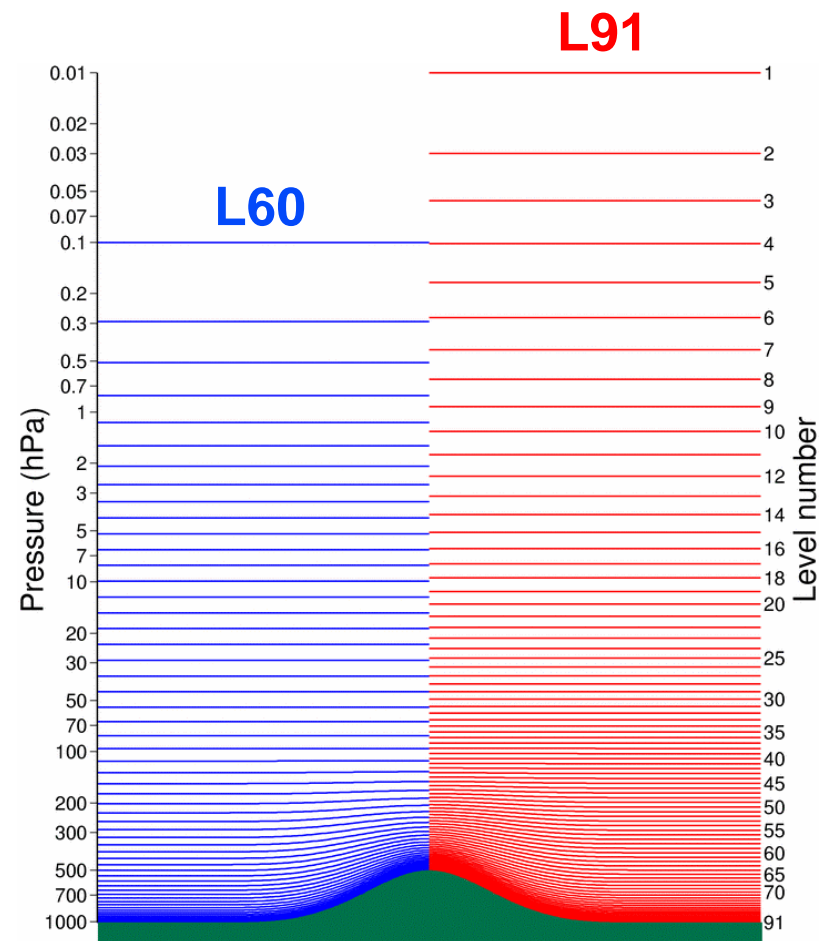
- WV and IR from forecast

Plans for 2005

- Higher vertical resolution
 -L91 for 4D-Var and deterministic forecast
 -L62 for EPS, seasonal and monthly forecasts
- T799 horizontal resolution in deterministic forecast and outer loops of 4D-Var with T255 inner loops (T319 for SVs?)
- Use of SSMIS and AMSR data
- Preparation for METOP (IASI in particular) and better exploitation of AIRS
 - Channel selection, cloud detection, monitoring,...
 - Environment monitoring

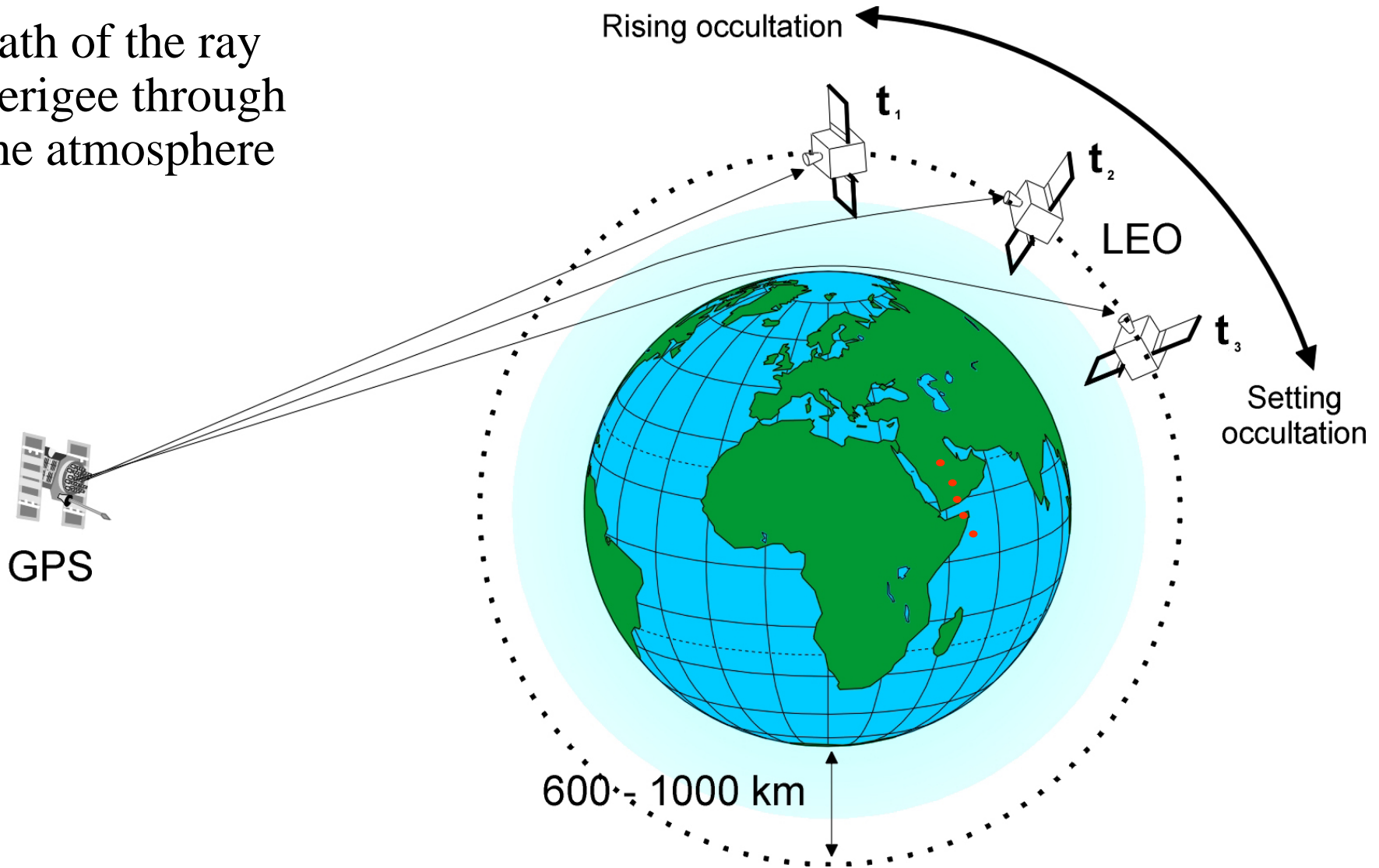
Increase in model and analysis resolution

Anomaly correlation of 500hPa height forecasts, 9 August – 13 November 2004



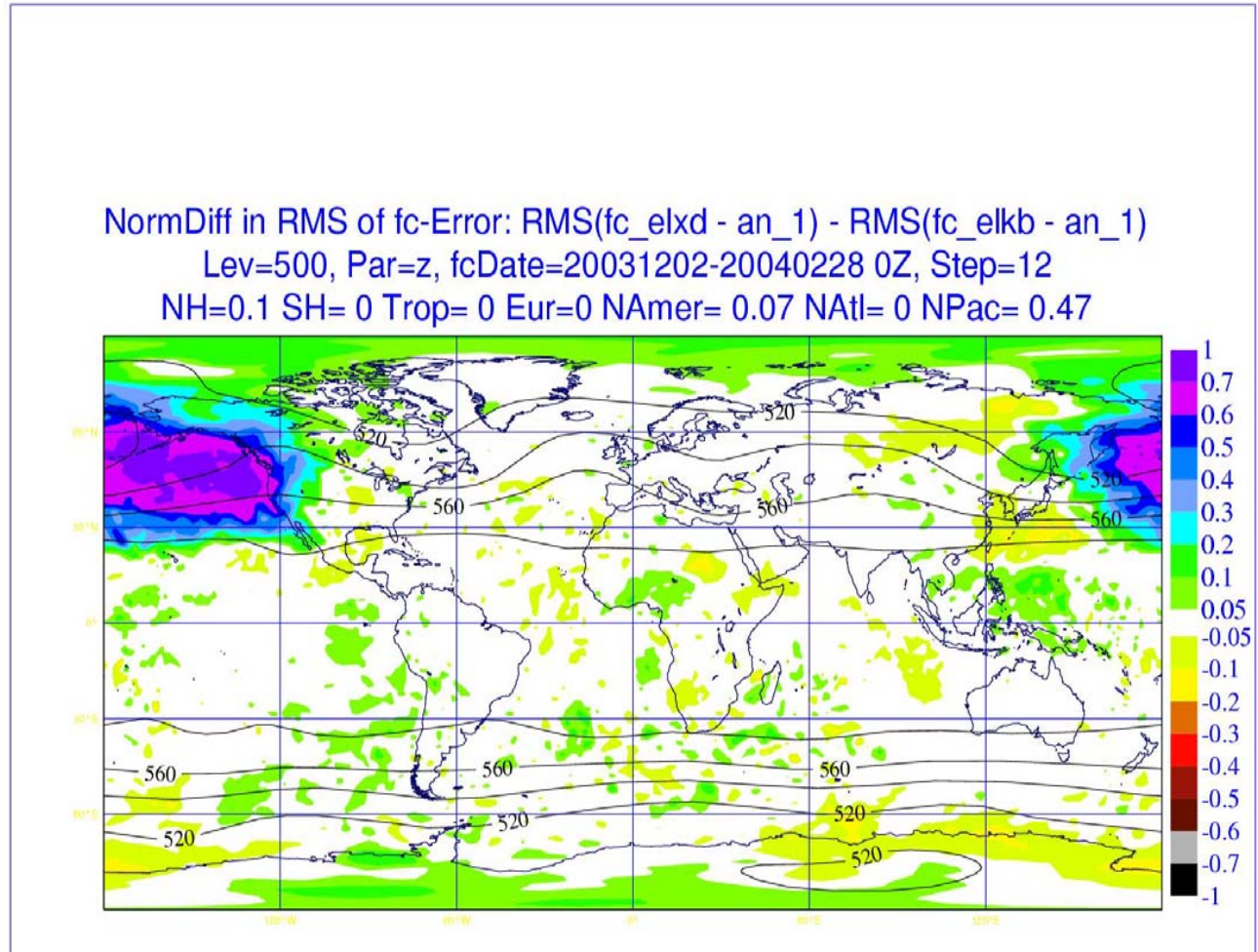
GPS radio occultation (CHAMP)

path of the ray
perigee through
the atmosphere



Influence of PAC-obs: signal

These plots
show the
difference
between
the
RMSE of
SeaOUT
and
control
from
t+12h to
t+168h.

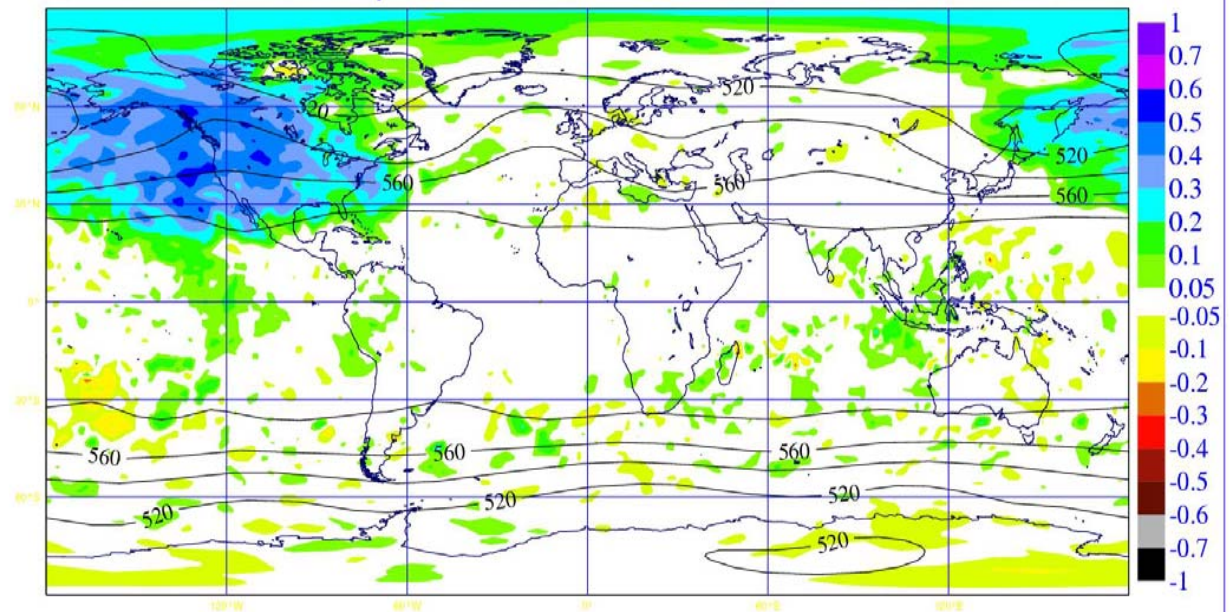


Note that
the
signal

Influence of PAC-obs: signal

pr

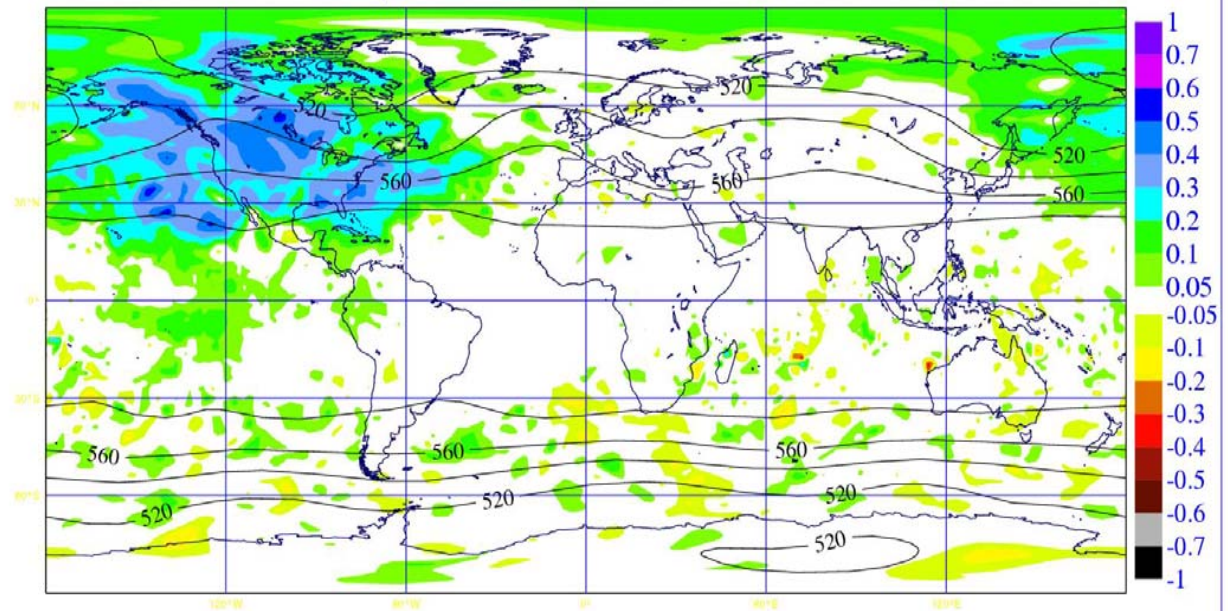
NormDiff in RMS of fc-Error: $\text{RMS}(\text{fc_elxd} - \text{an_1}) - \text{RMS}(\text{fc_elkb} - \text{an_1})$
Lev=500, Par=z, fcDate=20031202-20040228 0Z, Step=48
NH=0.11 SH= 0.01 Trop= 0.01 Eur=0 NAmer= 0.31 Natl= 0.02 NPac= 0.26



Influence of PAC-obs: signal

pr

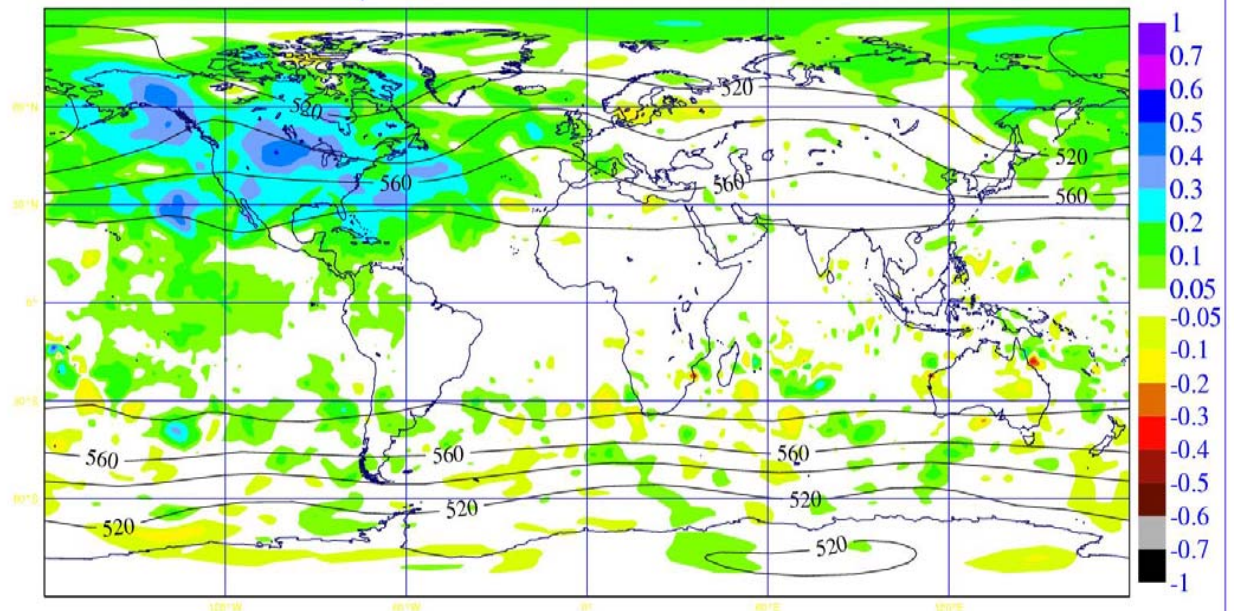
NormDiff in RMS of fc-Error: $\text{RMS}(\text{fc_elxd} - \text{an_1}) - \text{RMS}(\text{fc_elkb} - \text{an_1})$
Lev=500, Par=z, fcDate=20031202-20040228 0Z, Step=72
NH=0.11 SH= 0.01 Trop= 0.01 Eur=0 NAmer= 0.32 NATl= 0.09 NPac= 0.2



Influence of PAC-obs: signal

pr

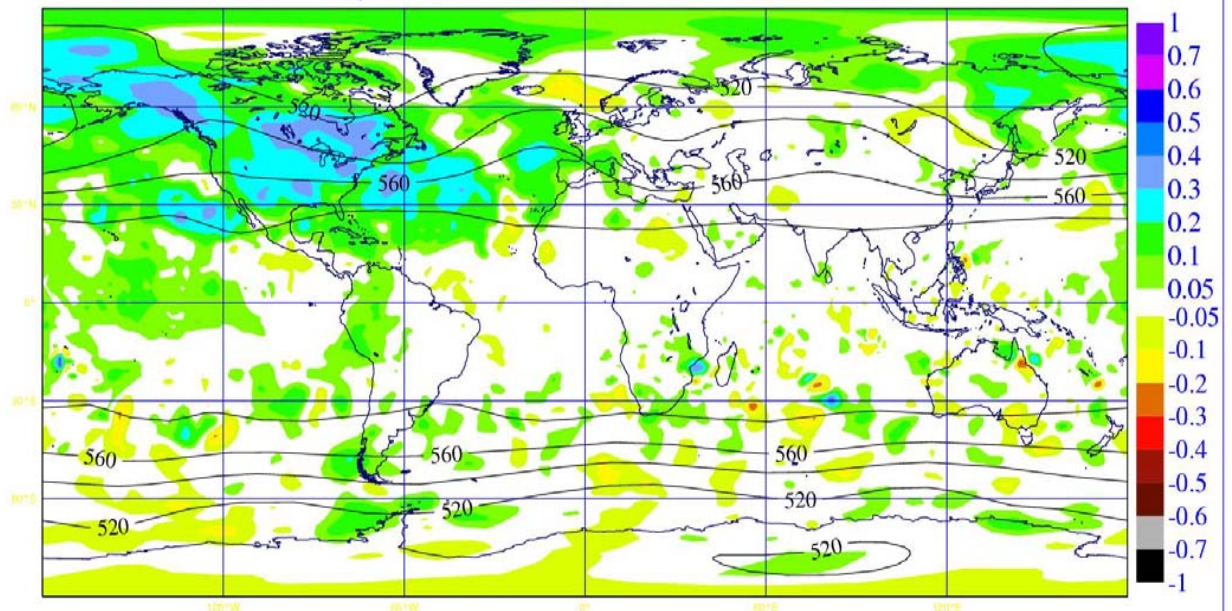
NormDiff in RMS of fc-Error: $\text{RMS}(\text{fc_elxd} - \text{an_1}) - \text{RMS}(\text{fc_elkb} - \text{an_1})$
Lev=500, Par=z, fcDate=20031202-20040228 OZ, Step=96
NH=0.09 SH= 0.01 Trop= 0.01 Eur=0.01 NAmer= 0.26 NATl= 0.13 NPac= 0.13



Influence of PAC-obs: signal

prc

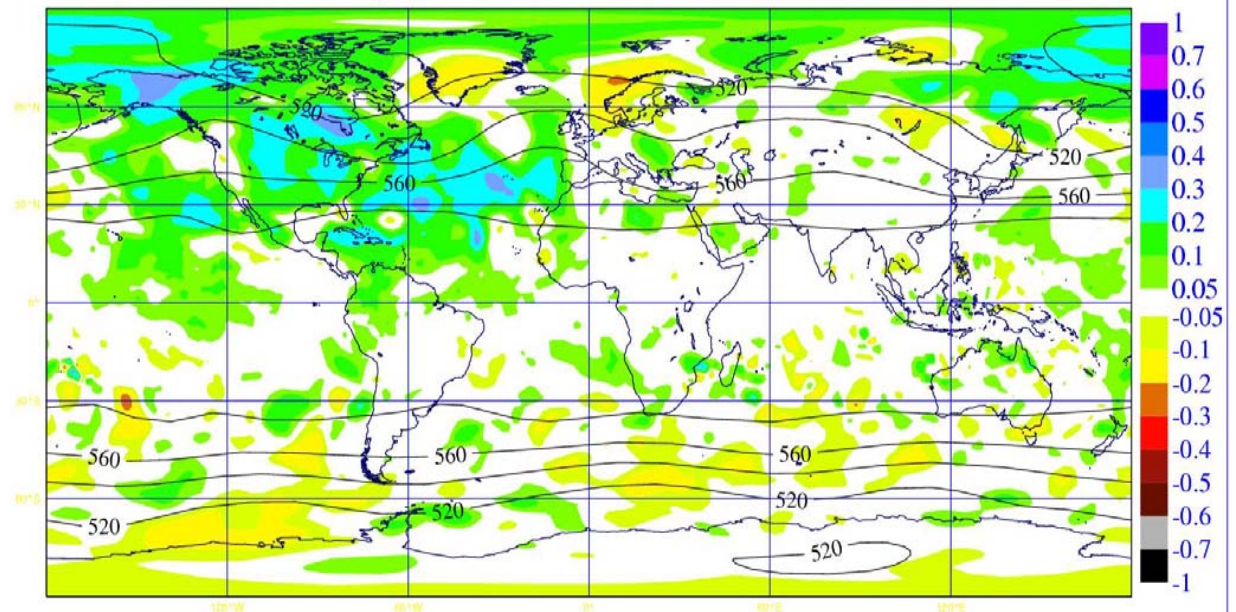
NormDiff in RMS of fc-Error: $\text{RMS}(\text{fc_elxd} - \text{an_1}) - \text{RMS}(\text{fc_elkb} - \text{an_1})$
Lev=500, Par=z, fcDate=20031202-20040228 0Z, Step=120
NH=0.08 SH= 0.01 Trop= 0.01 Eur=0.02 NAmer= 0.22 NATl= 0.14 NPac= 0.09



Influence of PAC-obs: signal

prc

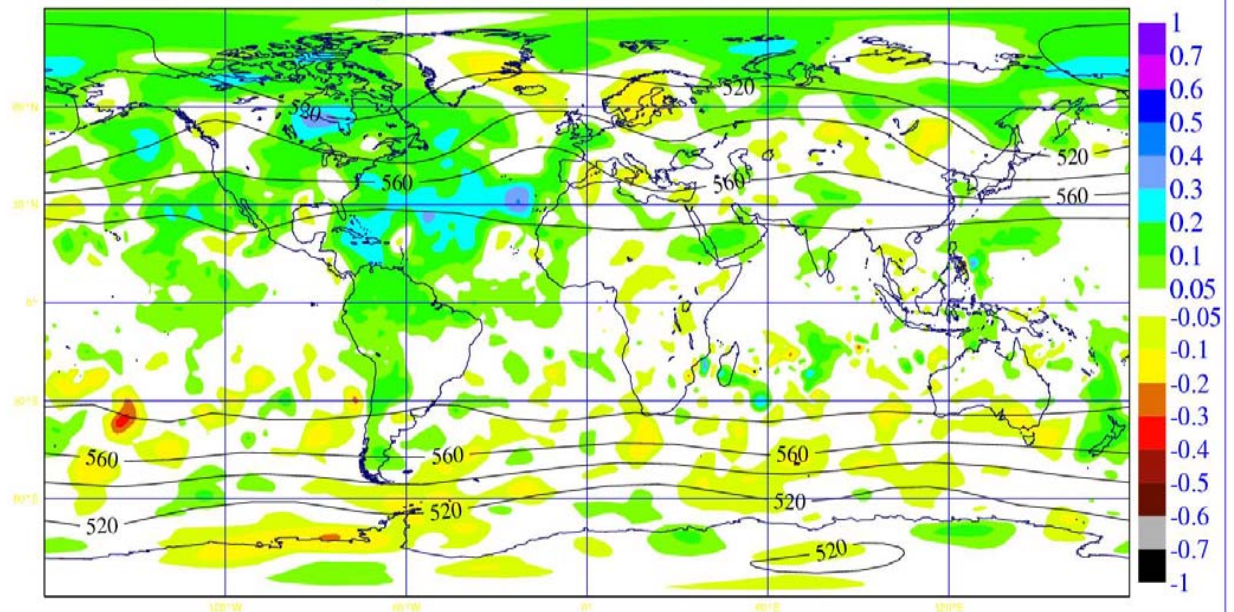
NormDiff in RMS of fc-Error: $\text{RMS}(\text{fc_elxd} - \text{an_1}) - \text{RMS}(\text{fc_elkb} - \text{an_1})$
Lev=500, Par=z, fcDate=20031202-20040228 OZ, Step=144
NH=0.07 SH= 0.02 Trop= 0.02 Eur=0 NAmer= 0.15 NATl= 0.14 NPac= 0.06



Influence of PAC-obs: signal

prc

NormDiff in RMS of fc-Error: $\text{RMS}(\text{fc_elxd} - \text{an_1}) - \text{RMS}(\text{fc_elkb} - \text{an_1})$
Lev=500, Par=z, fcDate=20031202-20040228 OZ, Step=168
NH=0.05 SH= 0.02 Trop= 0.02 Eur=0 NAmer= 0.09 NATl= 0.14 NPac= 0.04



Influence of PAC-obs on fcs: signal

These plots indicates that removing Pacific data has a large impact on the forecast errors over NA, but it also shows that the NA and the ATL data reduces the difference between the SeaOUT and the control analyses.

These indications are confirmed by the comparison of average RMSE computed over the different verification areas (NA, ATL, EU and NH).

