Weather (NWP) and composition analysis and forecasting – benefits of RO and satellite data

Sean Healy

Peter Bauer, Adrian Simmons, Paul Poli, Carla Cardinali and others ...

The EUMETSAT Network of Satellite Application Facilities

GRAS SAF

GRAS Meteorology

ECMWF

Outline

- Overview of the use and general impact of satellite measurements in numerical weather prediction at ECMWF.
- A more detailed look at the assimilation of GPS radio occultation measurements:
  - Assimilation approach adopted at ECMWF, information content, strengths weaknesses of technique.
- Outline the Monitoring Atmospheric Composition and Chemistry (MACC) project at ECMWF and show the impact of limb sounding measurements.
- Summary

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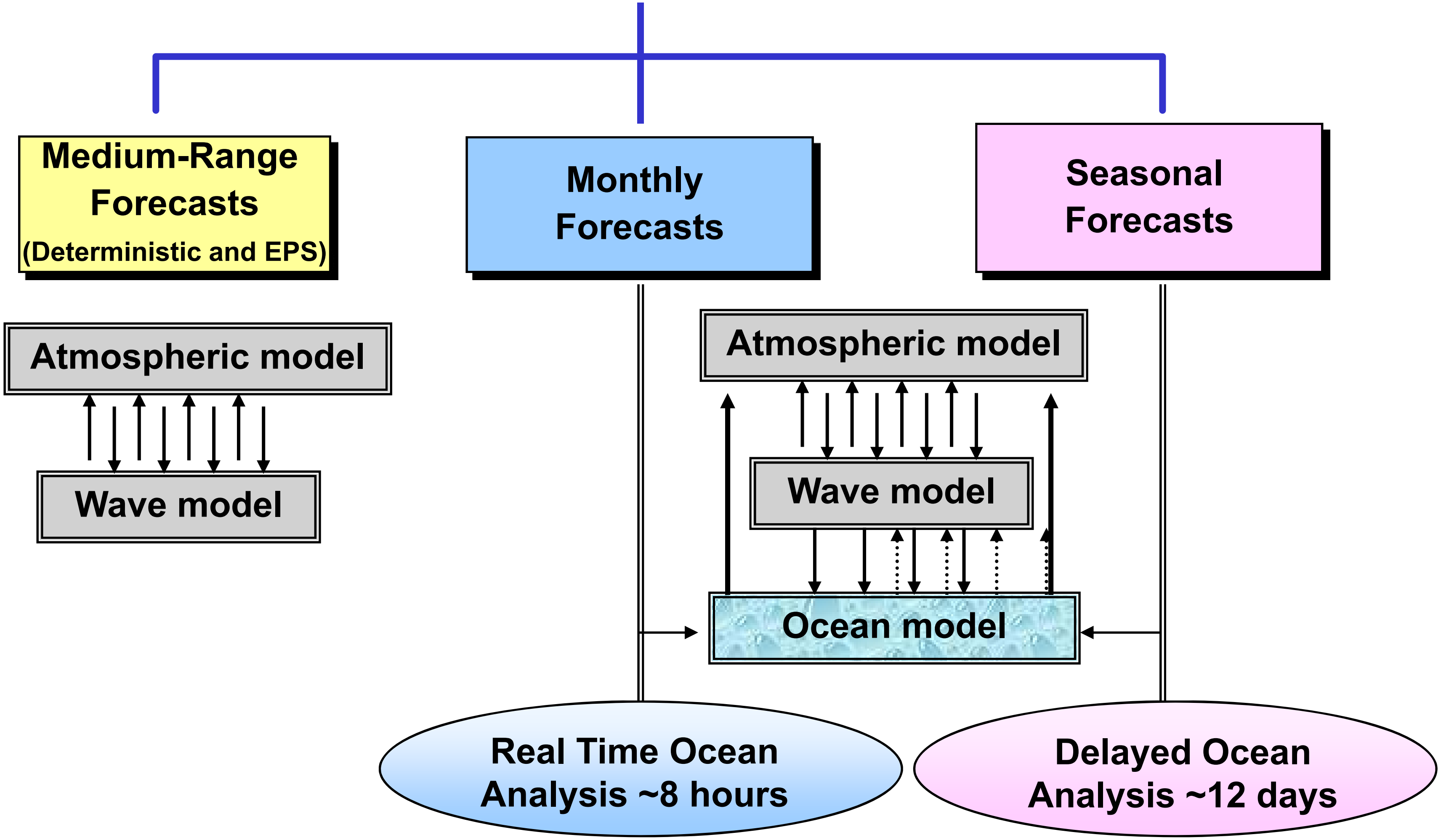
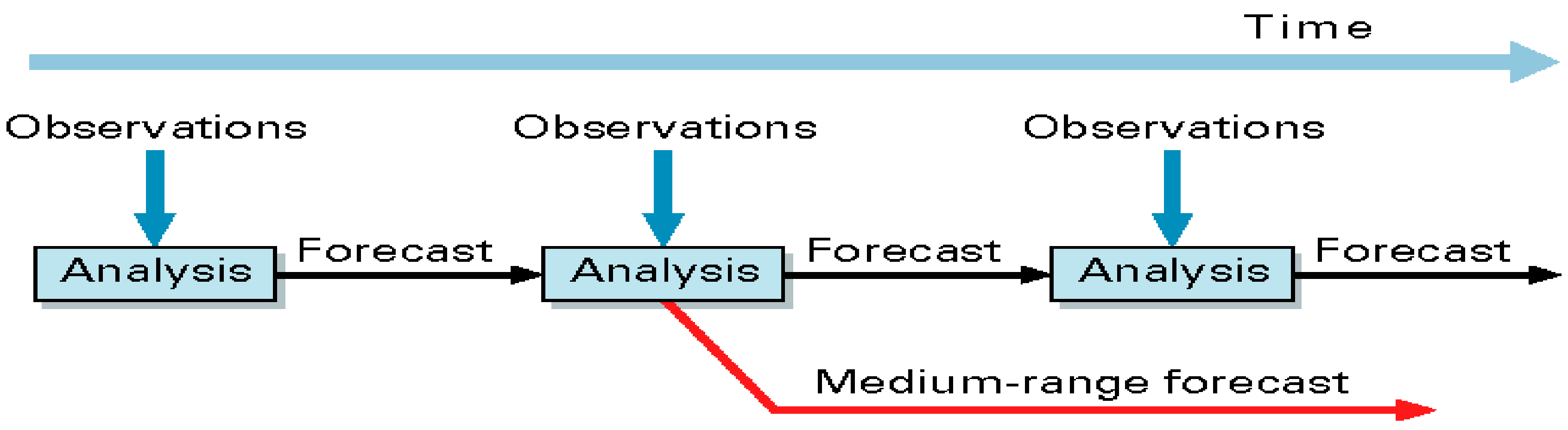
ECMWF forecasting systems



Data assimilation system (4D-Var)



- The observations are used to correct errors in the short forecast from the previous analysis time.
- Every 12 hours we assimilate ~9,000,000 observations to correct the 100,000,000 variables that define the model's virtual atmosphere.
- This is done by a careful 4-dimensional interpolation in space and time of the available observations; this operation takes as much computer power as the 10-day forecast.

Data sources: Conventional

SYNOP/SHIP/METAR:

- Meteorological/aeronautical land surface weather stations (2m-temperature, dew-point temperature, 10m-wind)
- Ships

→ temperature, dew-point temperature, wind (land: 2m, ships: 25m)

BUOYS:

- Moored buoys (TAO, PIRATA)
- Drifters

→ temperature, pressure, wind

TEMP/TEMPSHIP/DROPSONDES:

- Radiosondes
- ASAPs (commercial ships replacing stationary weather ships)
- Dropsondes released from aircrafts (NOAA, Met Office, tropical cyclones, experimental field campaigns, e.g., FASTEX, NORPEX)

→ temperature, humidity, pressure, wind *profiles*

PROFILERS:

- UHF/VHF Doppler radars (Europe, US, Japan)

→ wind *profiles*

Aircraft:

- AIREPS (manual reports from pilots)
- AMDARs, ACARs, etc. (automated readings)

→ temperature, pressure, wind *profiles*

ECMWF

Data sources: Satellites

Radiances (→ brightness temperature = level 1):
- AMSU-A on NOAA-15/18/19, AQUA, Metop
- AMSU-B/MHS on NOAA-18/19, Metop
- SSM/I on F-15, AMSR-E on Aqua
- HIRS on NOAA-17/19, Metop
- AIRS on AQUA, IASI on Metop
- MVIRI on Meteosat-7, SEVIRI on Meteosat-9, GOES-11/12, MTSAT-1R imagers

Bending angles (→ bending angle = level 1):
- COSMIC (6 satellites), GRAS on Metop

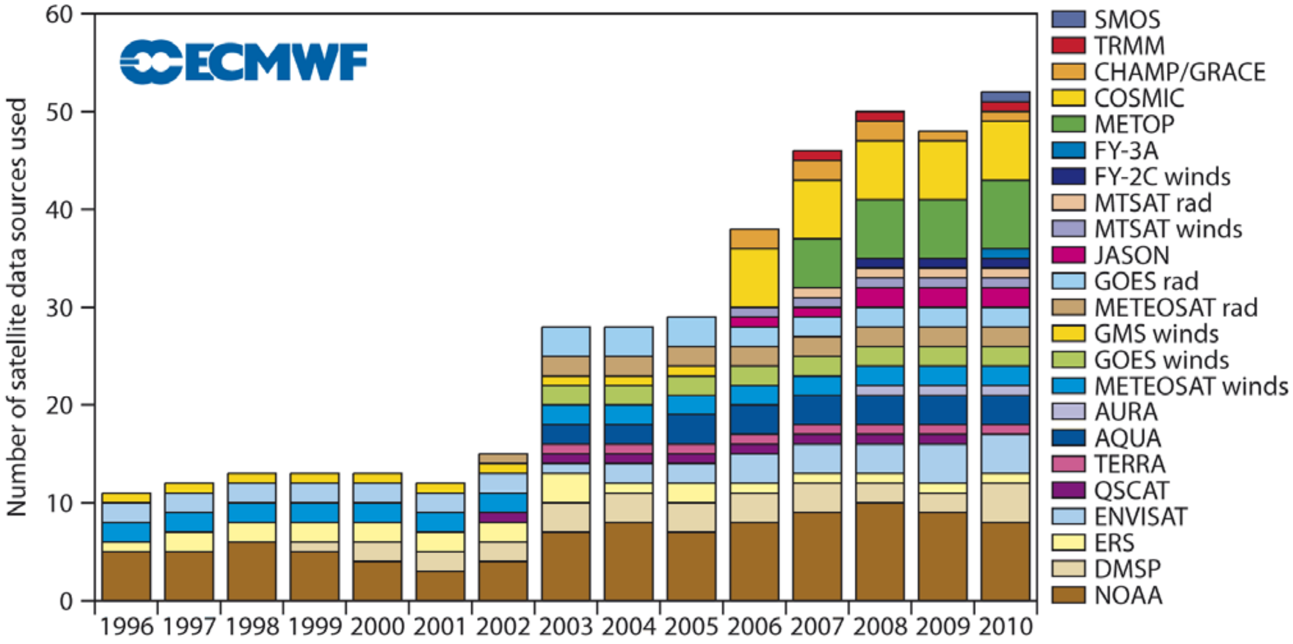
Ozone (→ total column ozone = level 2):
- Total column ozone from SBUV on NOAA-17/18, OMI on Aura, SCIAMACHY on Envisat

Atmospheric Motion Vectors (→ wind speed = level 2):
- Meteosat-7/9, GOES-11/12, MTSAT-1R, MODIS on Terra/Aqua

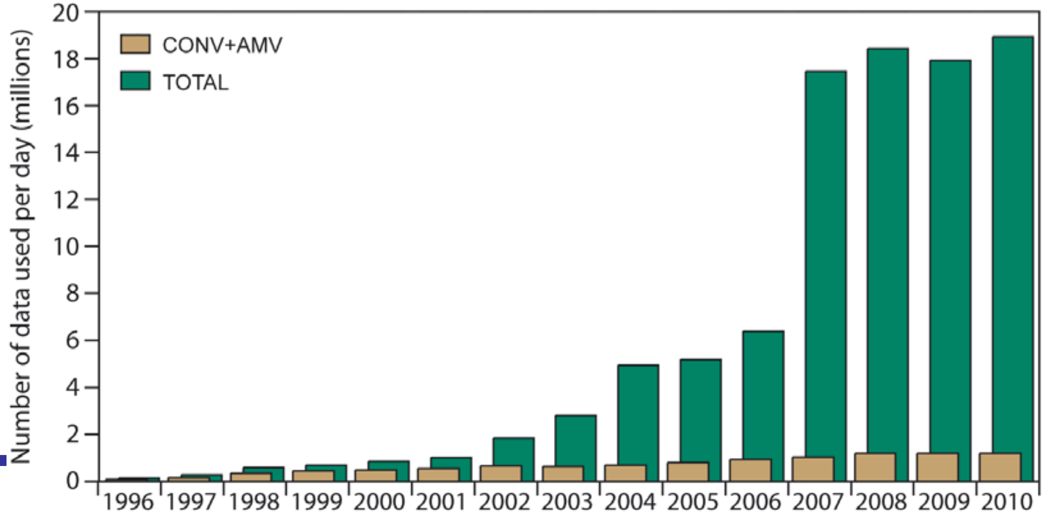
Sea surface parameters (→ wind speed and wave height = level 2):
- Near-surface wind speed from ERS-2 scatterometer, ASCAT on Metop
- Significant wave height from RA-2/ASAR on Envisat, Jason altimeters

Satellite observing system

Data types:



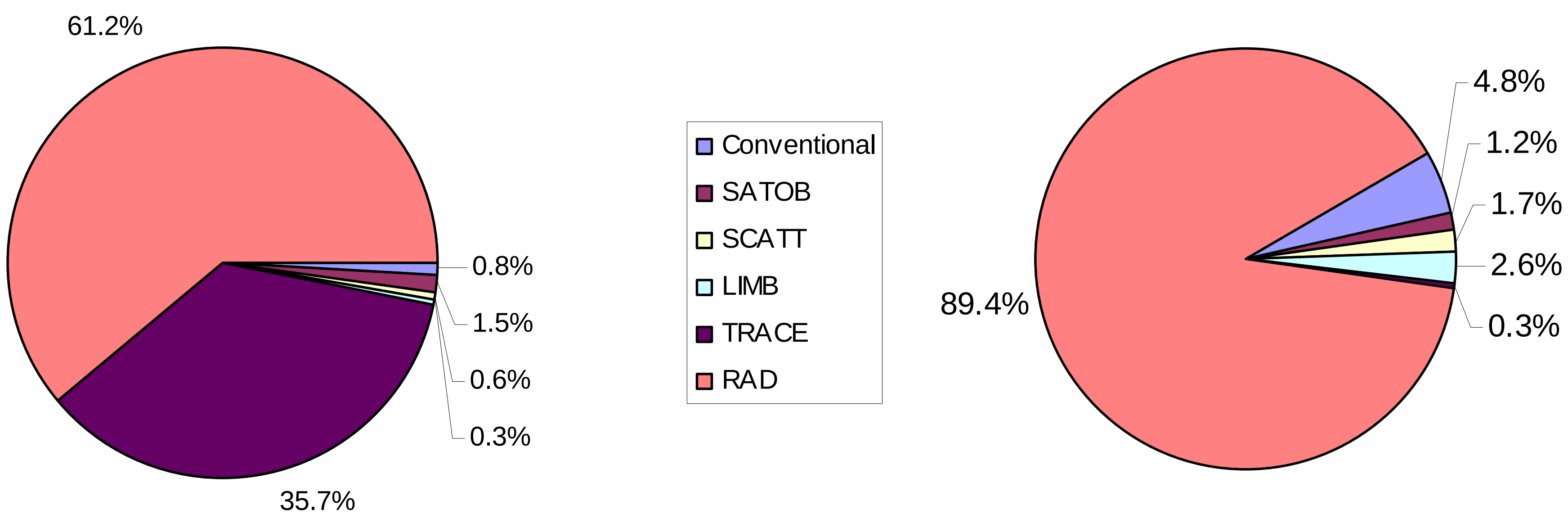
Data volume:



Data types

Screening
24/04/2008 00UTC

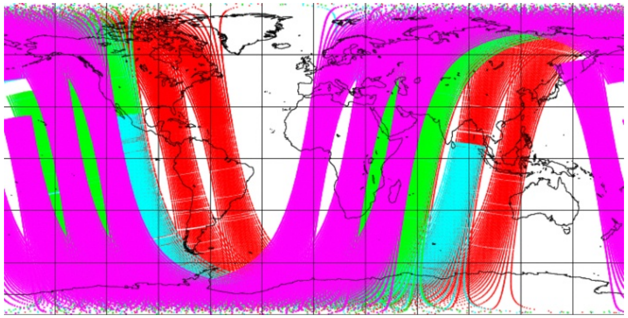
Assimilation
24/04/2008 00UTC



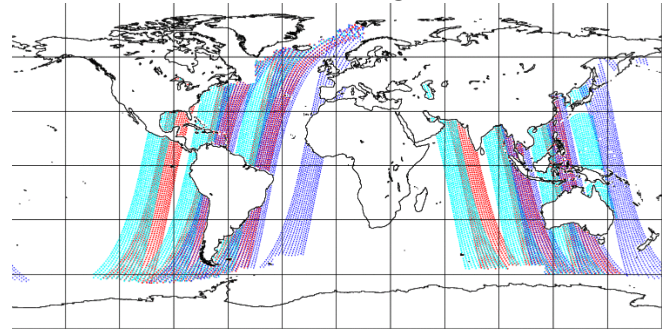
- Satellite data amounts to 99% in screening and 95% in assimilation.
- Radiance data dominates assimilation with 90%.
- Relative GPSRO (limb) data amount strongly increases between screening and assimilation while ozone data is largely reduced.

Example of satellite data coverage

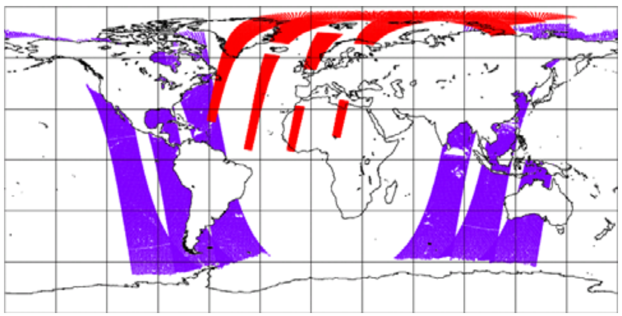
LEO Sounders



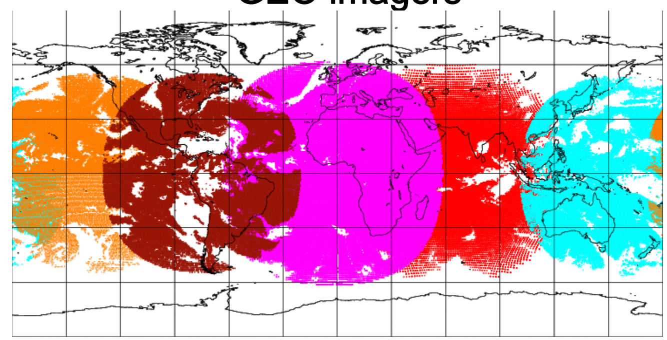
LEO Imagers



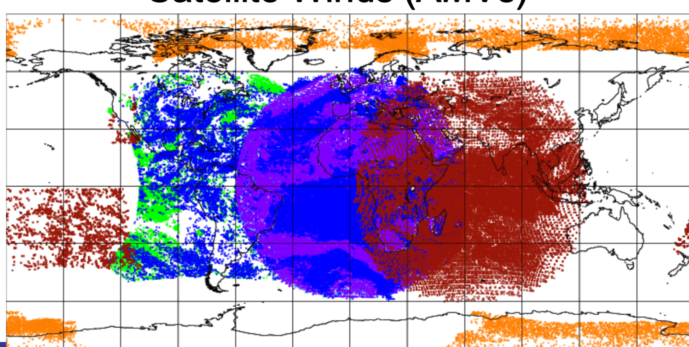
Scatterometers



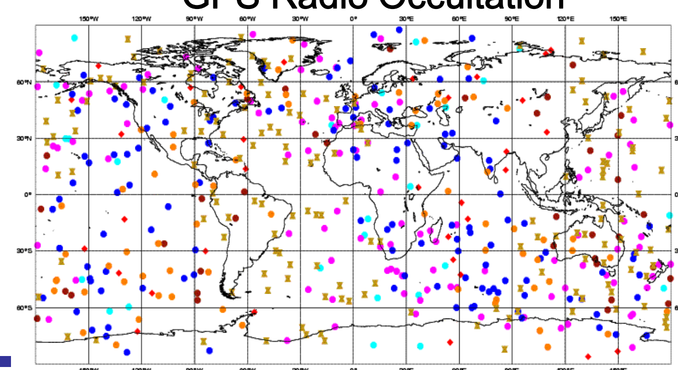
GEO imagers



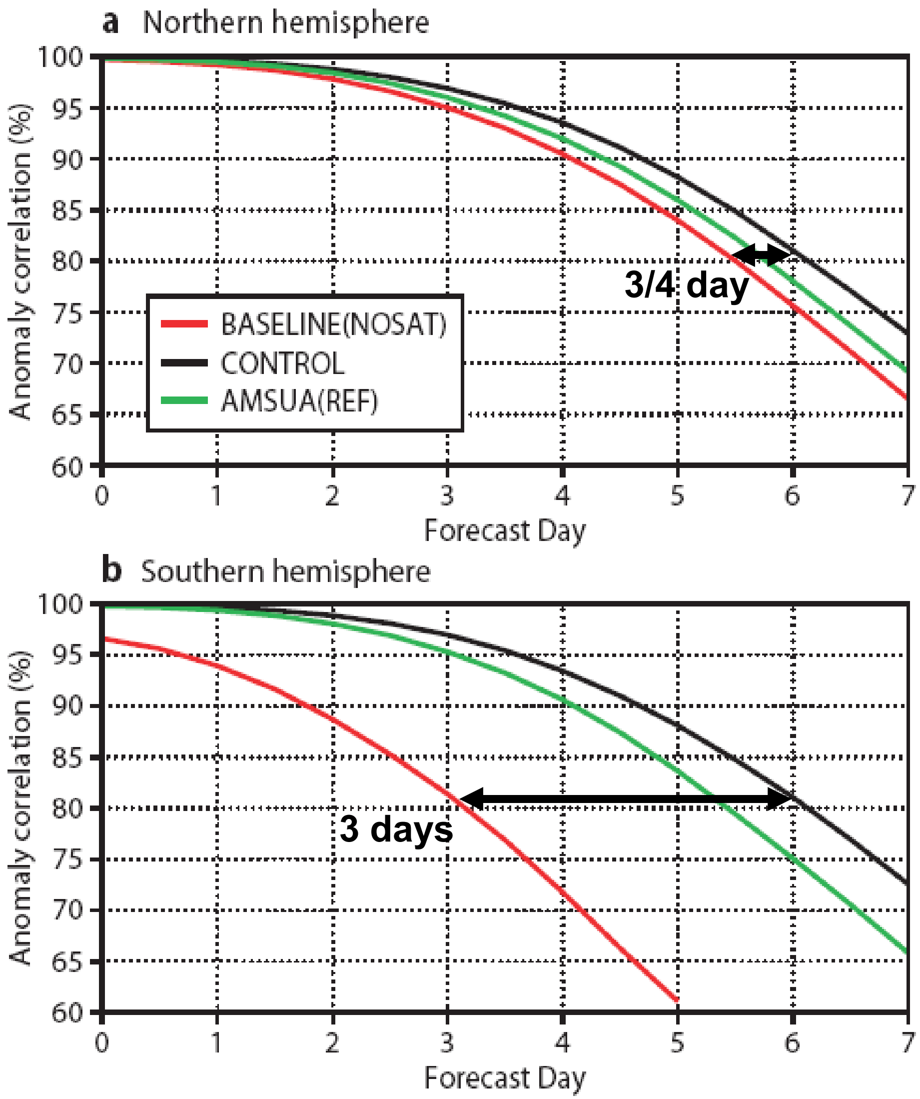
Satellite Winds (AMVs)



GPS Radio Occultation



Combined impact of all satellite data

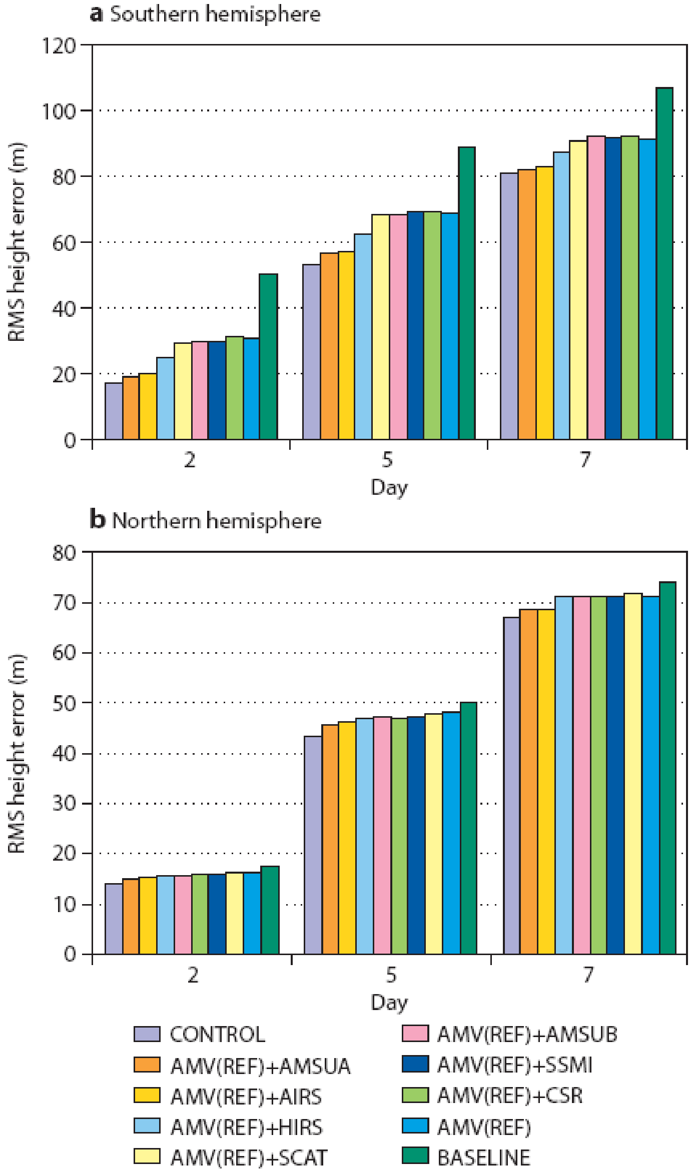


EUCOS Observing System Experiments (OSEs):

- 2007 ECMWF forecasting system,
- winter & summer season,
- different baseline systems:
  - no satellite data (NOSAT),
  - NOSAT + AMVs,
  - NOSAT + 1 AMSU-A,
- general impact of satellites,
- impact of individual systems,
- all conventional observations.

← 500 hPa *geopotential height* anomaly correlation

Individual impact of satellite data

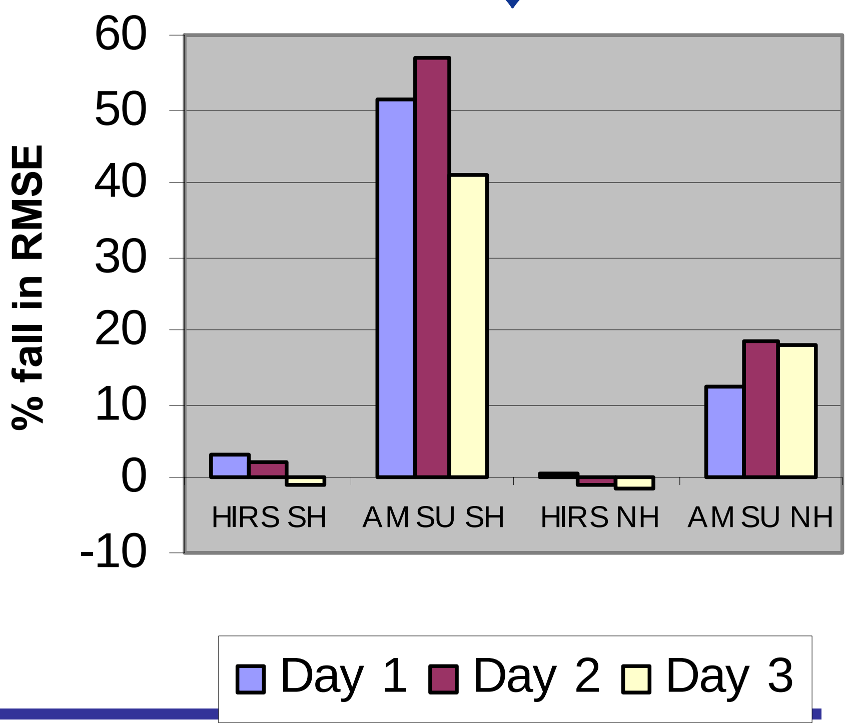


500 hPa *geopotential height* RMS error:

← 2007 ECMWF

2003 Met Office

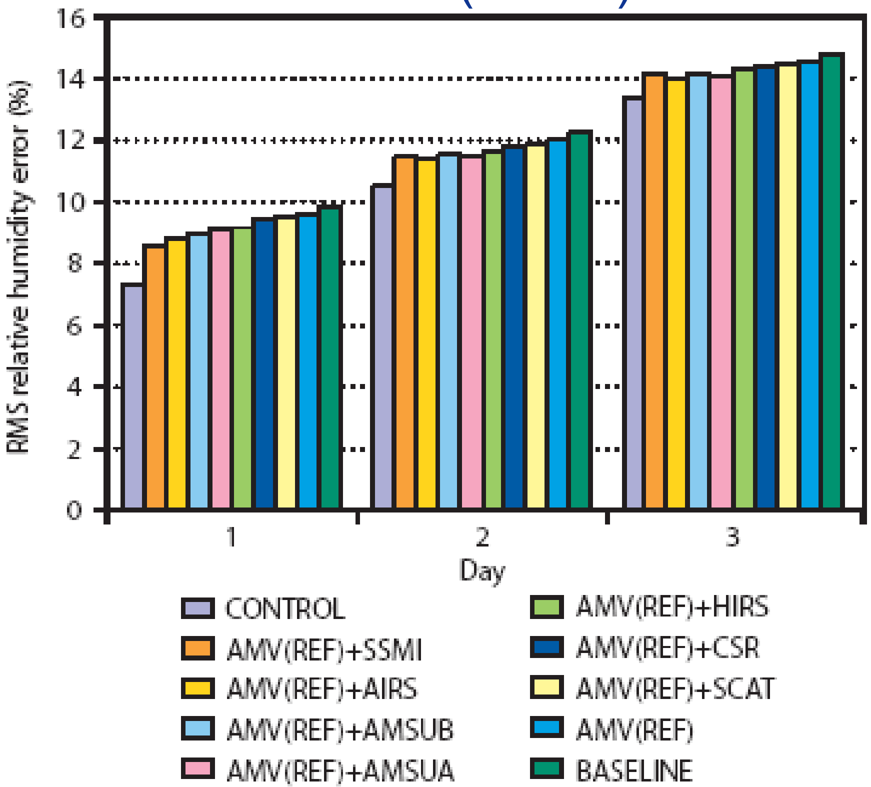
↓



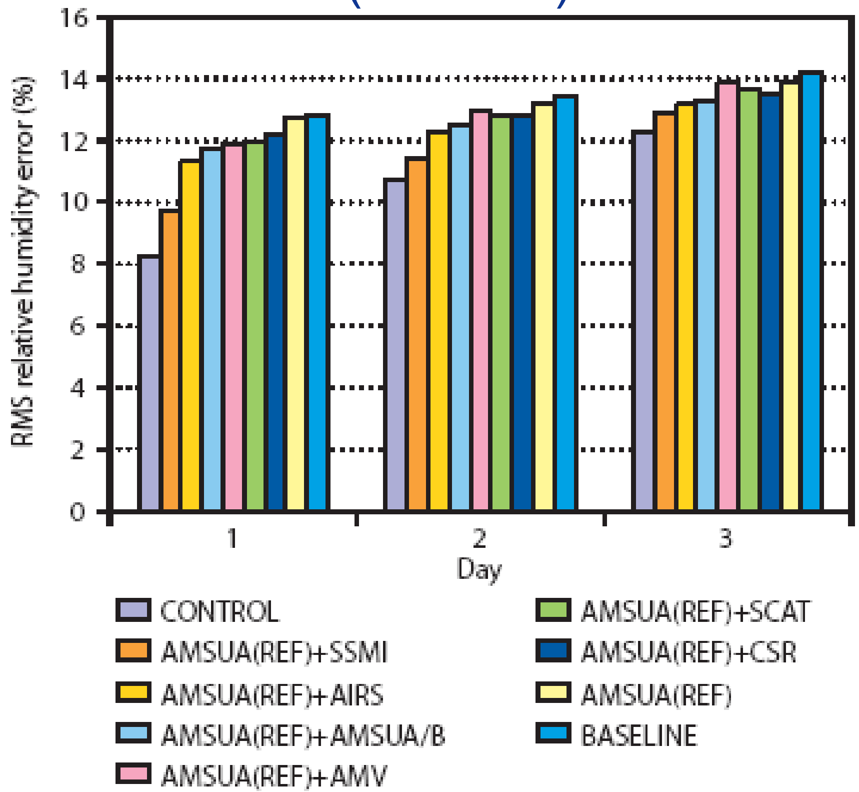
Individual impact of satellite data

850 hPa *relative humidity* RMS error

NOSAT + AMVs (winter)

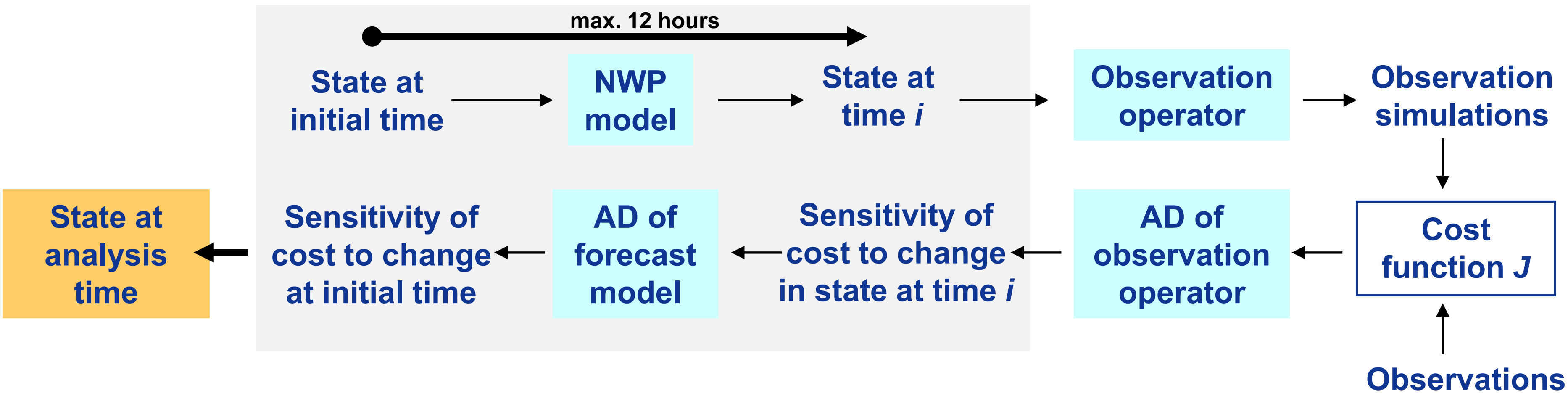


NOSAT + 1 AMSU-A (summer)

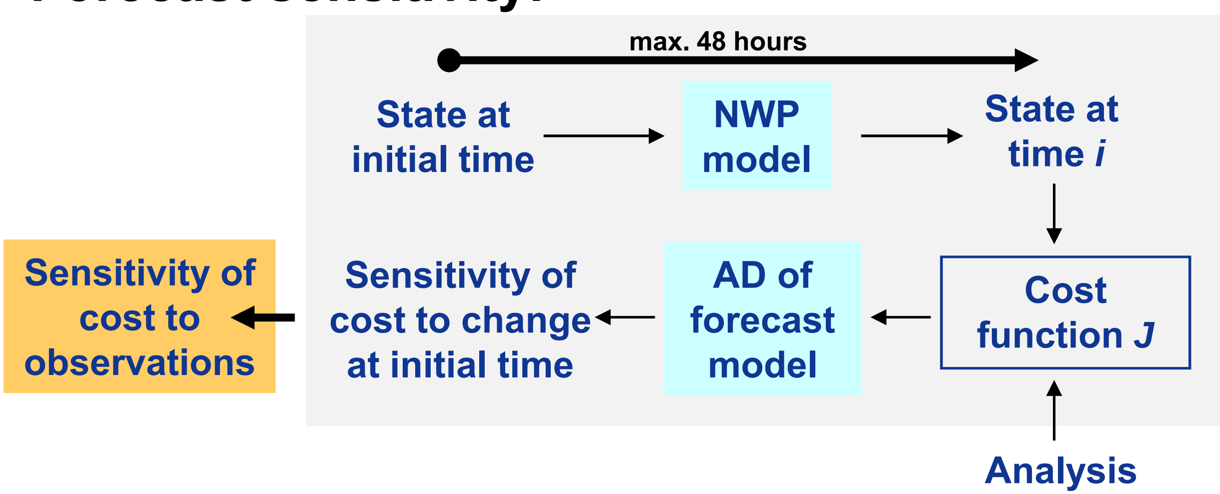


Advanced diagnostics

Data assimilation:



Forecast sensitivity:



Forecast sensitivity to observation: Equations

$$\frac{\partial J}{\partial \mathbf{y}} = \frac{\partial \mathbf{x}_a}{\partial \mathbf{y}} \frac{\partial J}{\partial \mathbf{x}_a}$$

J is a measure of the forecast error

Analysis solution

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{K}(\mathbf{y} - \mathbf{H}\mathbf{x}_b)$$

Forecast error sensitivity to the analysis

$$\frac{\partial J}{\partial \mathbf{x}_a}$$

Rabier F, *et al*. 1996.

Analysis sensitivity to observation and background

$$\frac{\partial \mathbf{x}_a}{\partial \mathbf{y}} = \mathbf{K}^T$$

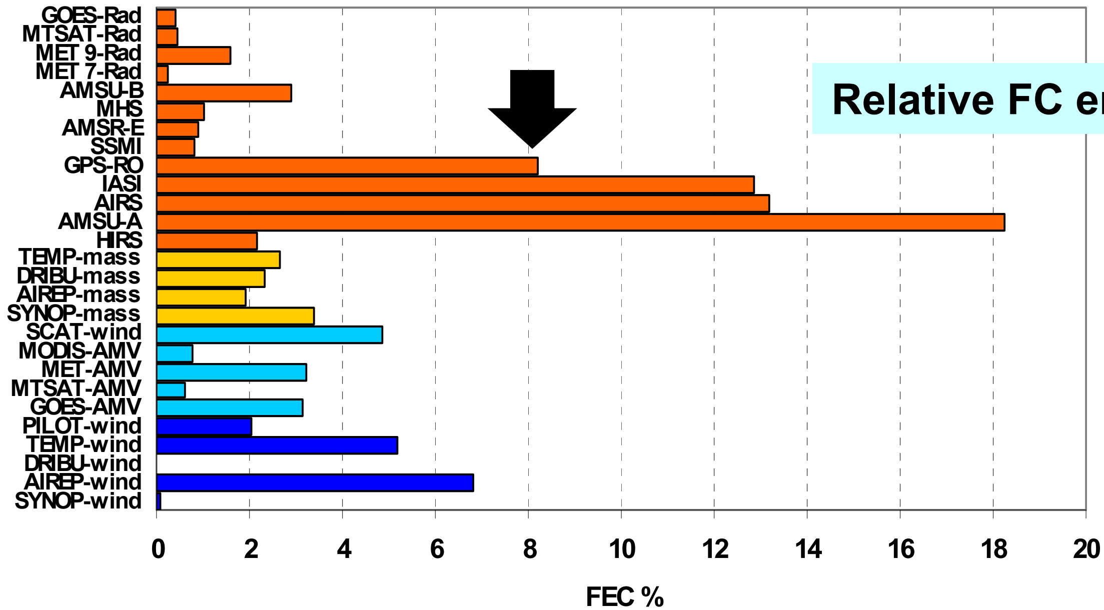
$$\frac{\partial J}{\partial \mathbf{y}} = \mathbf{R}^{-1}\mathbf{H}\mathbf{A}\frac{\partial J}{\partial \mathbf{x}_a}$$

$$\delta J = \frac{\partial J}{\partial \mathbf{y}}(\mathbf{y} - \mathbf{H}\mathbf{x}_b)$$

δy

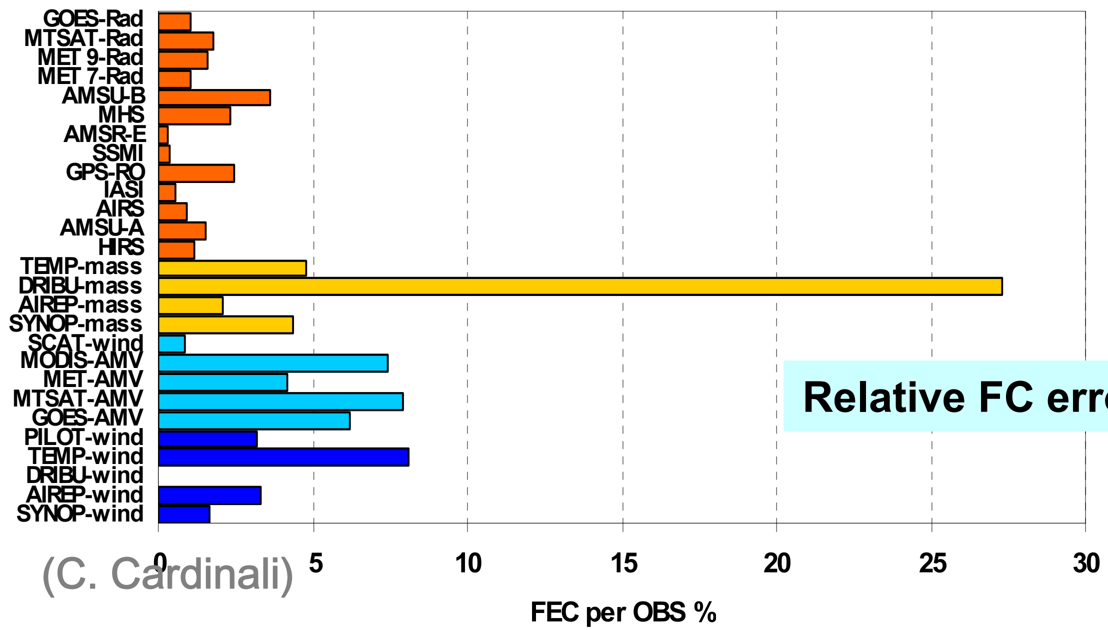
The tool provides information on the observation type, subtype, variable and level responsible for the forecast error variation

Advanced diagnostics



Relative FC error reduction per system

The *forecast sensitivity* (Cardinali, 2009, QJRMS, 135, 239-250) denotes the sensitivity of a forecast error metric (dry energy norm at 24 or 48-hour range) to the observations. The forecast sensitivity is determined by the sensitivity of the forecast error to the initial state, the innovation vector, and the Kalman gain.



Relative FC error reduction per observation

(C. Cardinali)

ECMWF

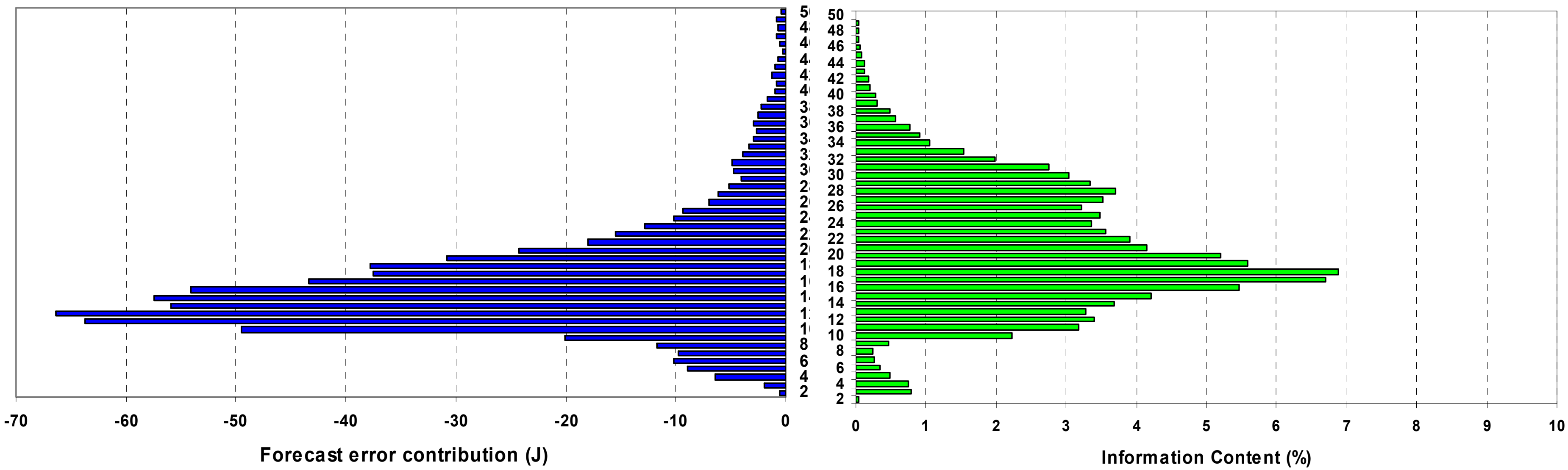
Advanced diagnostics

New diagnostic tools based on linearized model/operator employed in 4D-Var:

Sensitivity of forecast (errors) to observations: $$\frac{\partial J}{\partial \mathbf{y}} = \frac{\partial \mathbf{x}_a}{\partial \mathbf{y}} \frac{\partial J}{\partial \mathbf{x}_a}$$

$\rightarrow$ can also be quantified per observation (location).

GPSRO



Degrees of Freedom for Signal

(J = forecast error norm, y = observations, x_a = analysis state)

(C. Cardinali)

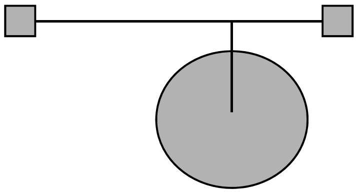
ECMWF

Use GPSRO measurements at ECMWF

- ECMWF has assimilated GPSRO bending angles operationally since December 12, 2006.
- Despite the relatively low observation numbers – in comparison with the number of radiances – the impact has been very good.
- Main impact on upper-tropospheric and lower/mid stratospheric temperatures.
  - GPSRO measurements are assimilated without bias correction, so they can correct model biases.
  - Very good vertical resolution, so they can correct errors in the null space of the radiance measurements.

Assimilation at ECMWF

- We assimilate bending angles with a 1D operator. We ignore the 2D nature of the measurement and integrate



$$\alpha(a) = -2a \int_a^{\infty} \frac{d \ln n / dx}{\sqrt{x^2 - a^2}} \, dx$$

- The forward model is quite simple:
  - evaluate geopotential heights of model levels
  - convert geopotential height to geometric height and radius values
  - evaluate the refractivity, N, on model levels from P,T and Q.
  - Integrate, assuming refractivity varies exponentially between model levels. (Solution in terms of the Gaussian error function).

Reason for choosing bending angle: Statistical Optimization

- The bending angles used in the Abel transform are the weighted average of the observed values and bending angle values **simulated** with a climatology or NWP model (eg, MSIS, CIRA or ECMWF!).

Simulated BA's

Observed BA's

$$\hat{\boldsymbol{\alpha}} = \boldsymbol{\alpha}_{\mathbf{b}} + \mathbf{B}(\mathbf{B}+\mathbf{O})^{-1}(\boldsymbol{\alpha} - \boldsymbol{\alpha}_{\mathbf{b}})$$

Error cov. matrix for simulated BA's

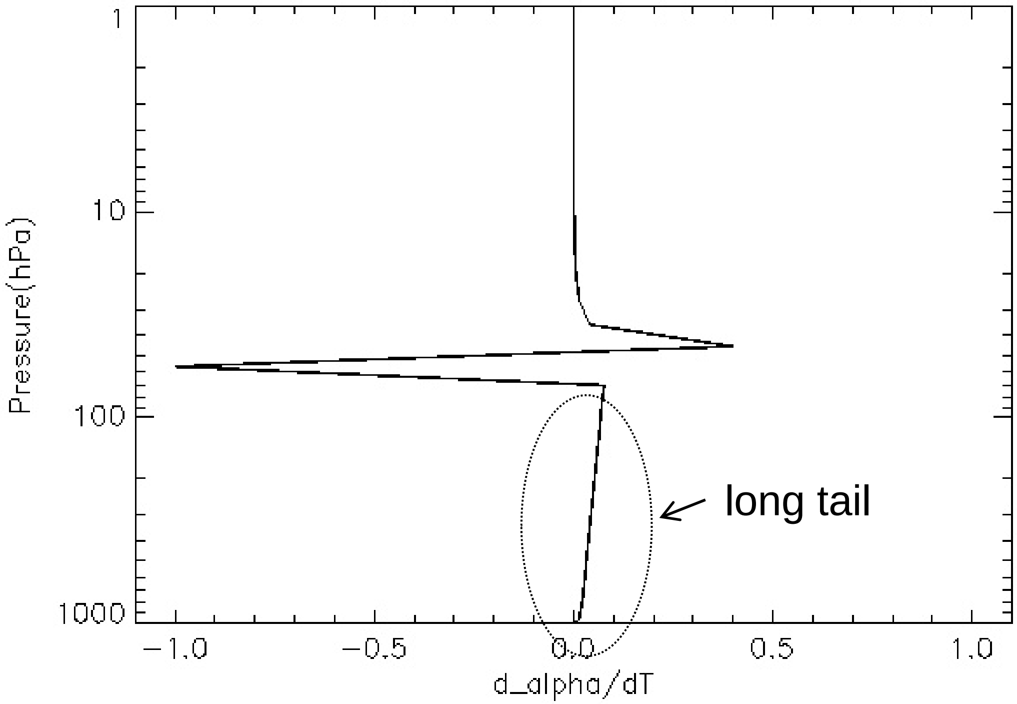
Error cov. matrix for observed BA's

statistically optimized bending angle.

$$N(x) = 10^6 \left[\exp\left(\frac{1}{\pi} \int_x^{\infty} \frac{\hat{\alpha}(a)}{\left(a^2 - x^2\right)} da \right) - 1 \right]$$

1D bending angle weighting function $\left(\frac{\partial \alpha}{\partial T}\right)$

(Normalised with the peak value)



(See Eyre, ECMWF Tech Memo. 199.)

Weighting function peaks at the levels above and below the ray tangent point. Bending related to vertical gradient of refractivity:

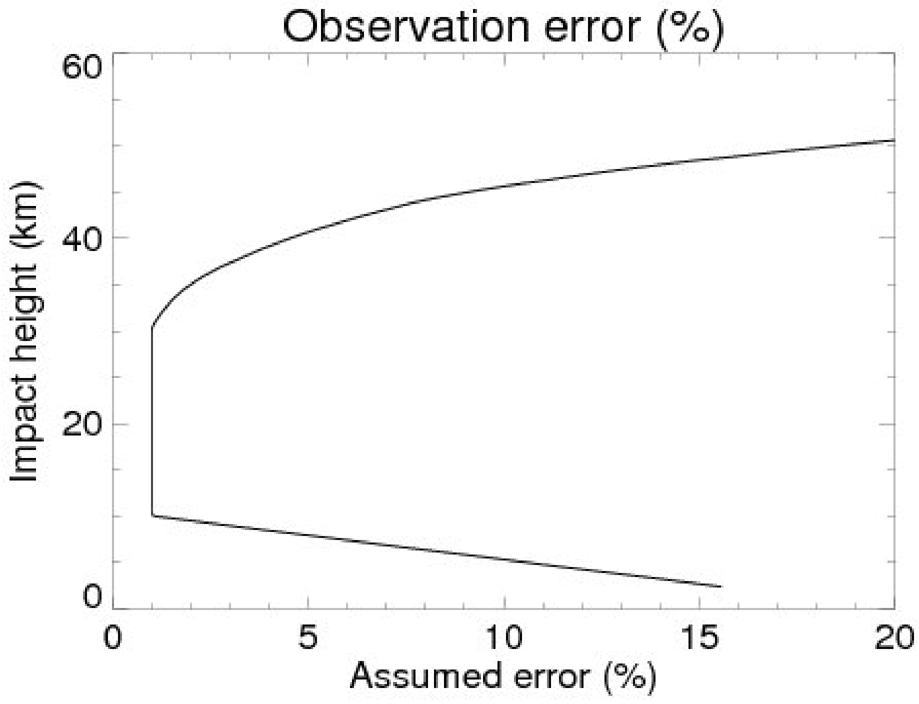
$$N = {c_1 P}/{T}$$

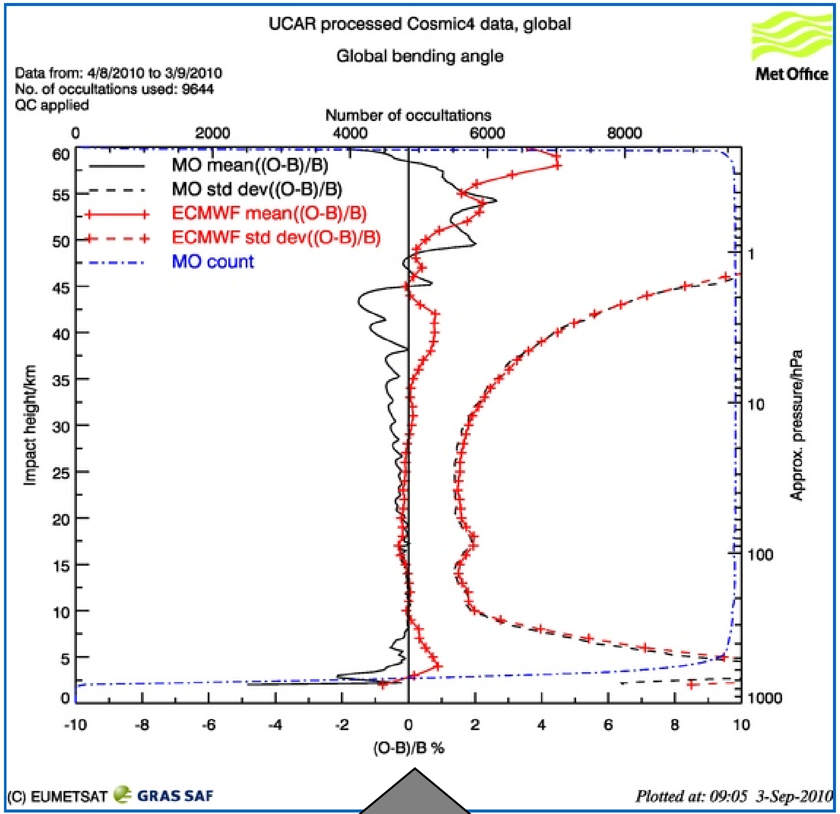
$$\Delta\alpha \propto (N_l - N_u)$$

Increase the T on the **lower level** – reduce the N gradient – less bending!

Increase the T on the **upper level** – increase N gradient more bending!

Assumed (global) observation errors and actual (o-b) departure statistics

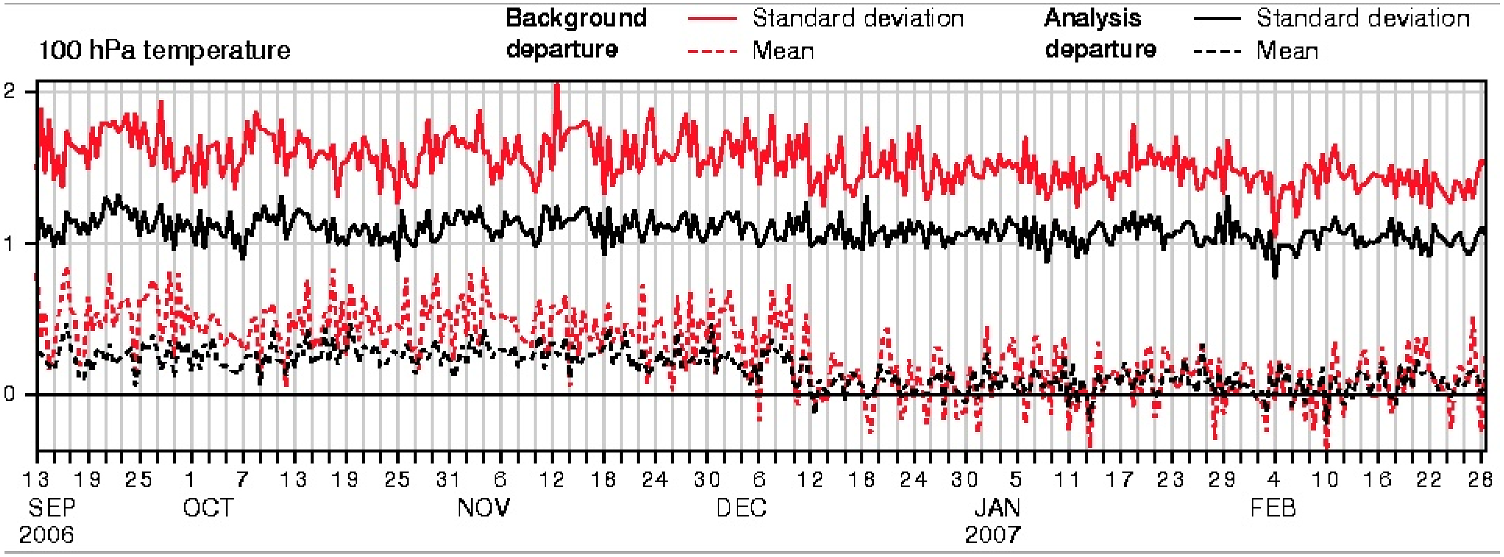




Consistent with o-b stats.

See http://www.grassaf.org/monitoring/

ECMWF operational short-range forecast fit to radiosonde temperature measurements (100 hPa, SH)



ECMWF started assimilating GPSRO data operationally on December 12, 2006.

Very clear improvements in stratospheric temperature biases – as expected from information content studies.

Other NWP centres (Met O, NCEP, EC) achieved similar results.

Results from recent observing system experiments (OSE's)

- **Observing system used in Control experiment**

Sounding:	Metop IASI/AMSU-A/MHS/HIRS + Aqua AMSUA/AIRS + NOAA-18 AMSU-A/MHS
Imaging:	DMSP F-13 + F-15
GEO sounding/imaging	all in
AMVs:	only GEO
Scatterometry	Metop ASCAT + only Quikscat
GPSRO	all in (reprocessed data by UCAR).
Ozone	Metop GOME-2 + NOAA-18 SBUV, NOAA-17 SBUV
TCWV	MERIS
Altimetry	all in
Conventional	all in

- Slightly weaker than full operations, but still a good observing system.

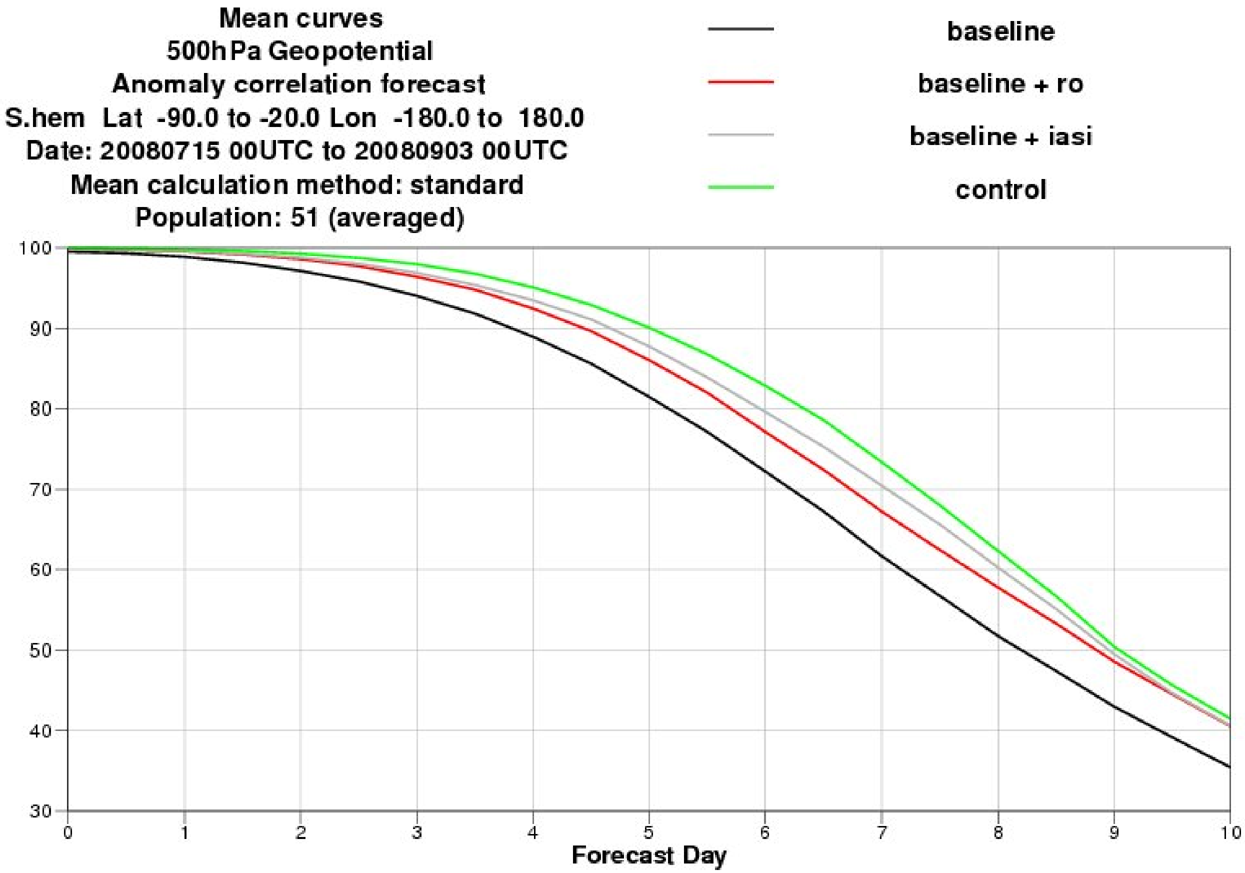
The baseline experiment for the same period

- **Baseline experiment**: Control minus all level 1b sounder radiances, all GPSRO measurements and all aircraft temperature measurements.

- Looked at:

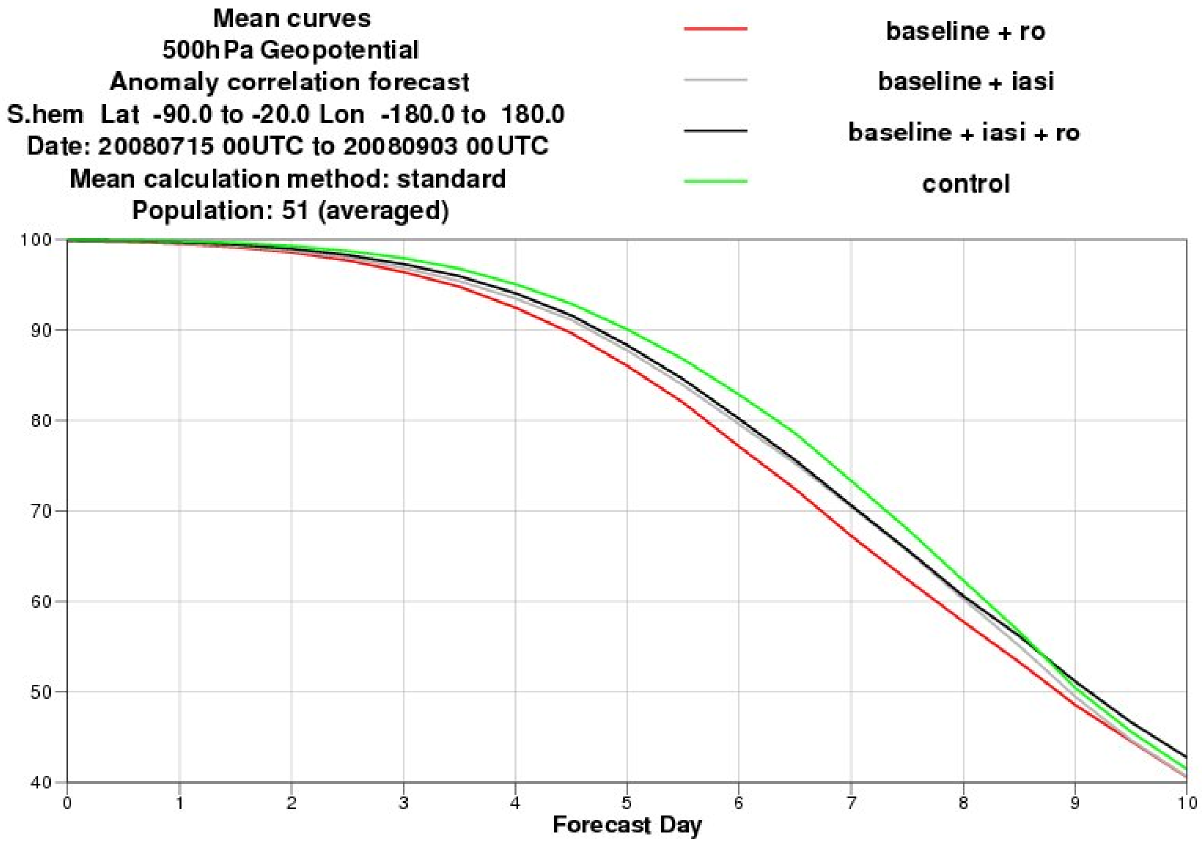
  – Baseline + GPSRO
  – Baseline + IASI
  – Baseline + IASI + GPSRO.

Comparison with IASI, relative to the baseline



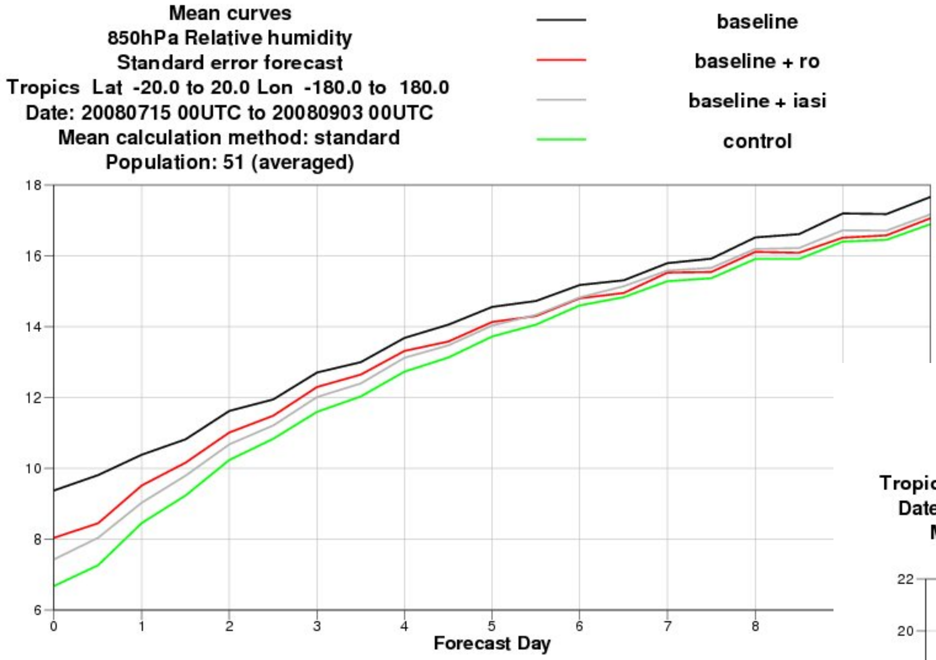
KEY QUESTION: How many GPSRO receivers do we need to equal or exceed IASI performance? Can we equal it?

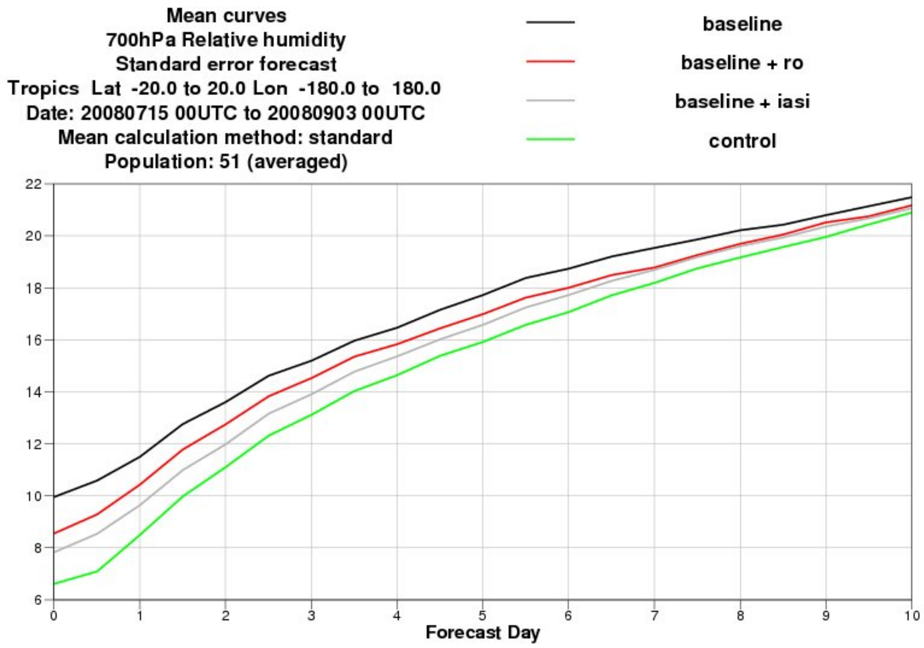
IASI + (GPS)RO impact



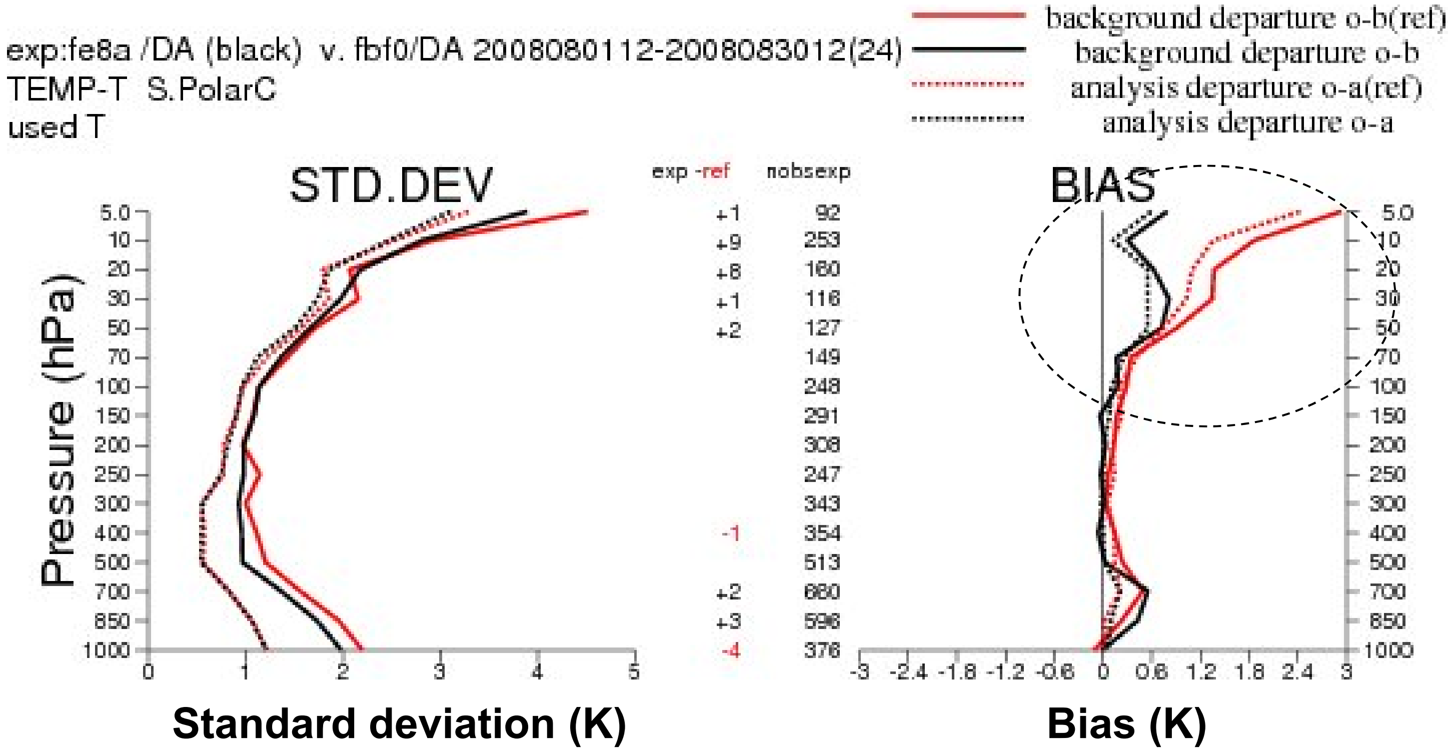
(baseline+iasi+ro) improvement relative to (baseline+iasi) statistically significant at 95% level day-1 to day-4.

Some indication of water vapour information content in the Tropics



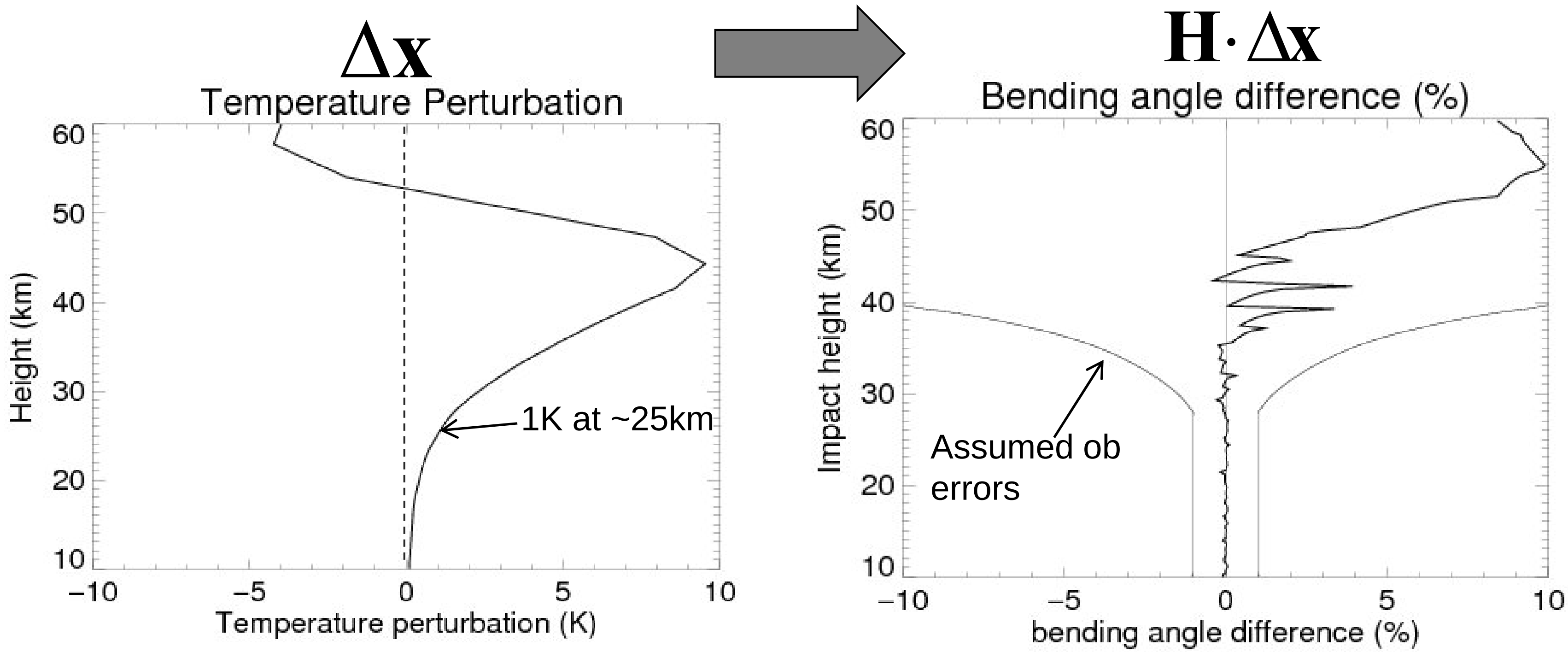


(IASI + RO) vs RO fit to radiosonde T



(IASI + RO) is producing much better stratospheric biases than just GPSRO generally, but most obvious at the S.Pole. Why is GPSRO not doing a better job? The GPSRO measurement has a “null space”.

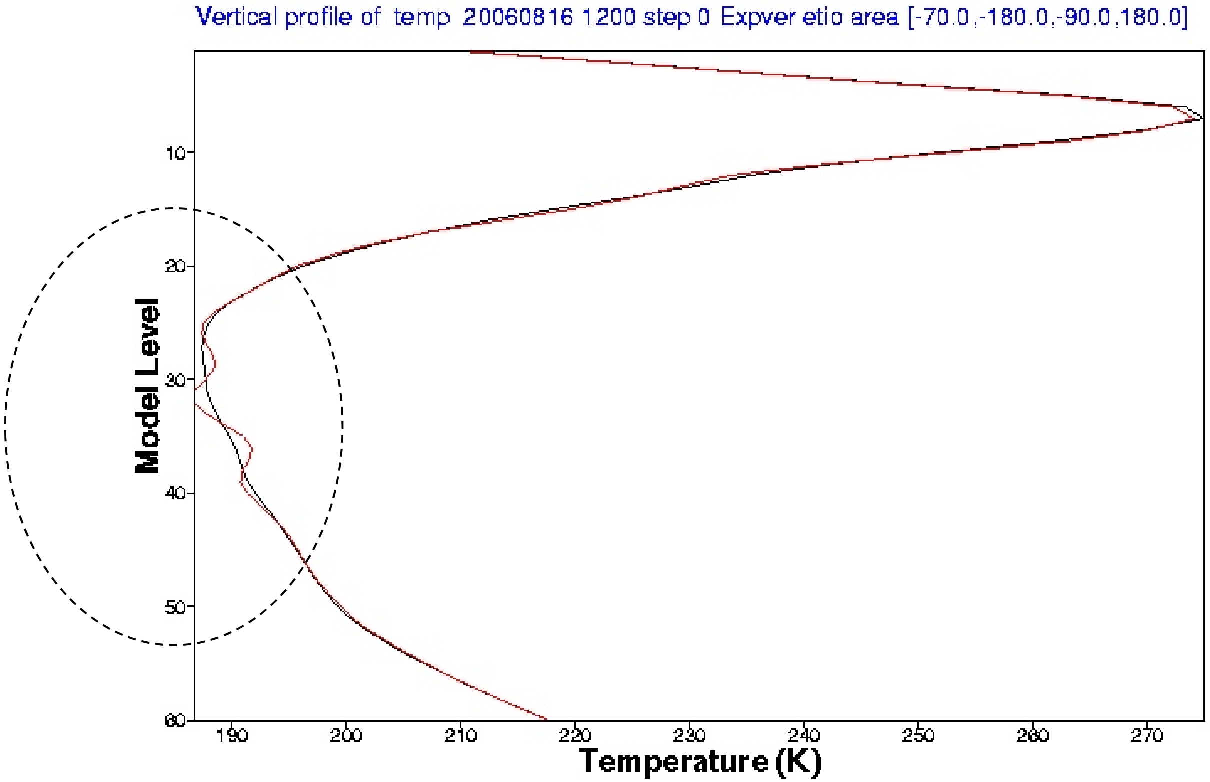
Null space – how does the temperature difference at the S.Pole propagate through the observation operator



The null space arises because the measurements are sensitive to density as function of height (~P(z)/T(z)). *A priori* information is required to split this into T(z) and P(z). We can define at temperature perturbation ΔT(P)~ε•1/P which is in the GPSRO null space. *Therefore, if the model background contains a bias of this form, the measurement can't see or correct it*.

ECMWF

The importance of GPSRO at S.Pole has been demonstrated previously



Red=control
Black=COSMIC

Assimilating GPSRO cured the "stratospheric ringing problem" in the mean ECMWF temperature analyses. These unphysical oscillations were in the null space of the radiance measurements. **Importance of complementary measurements**.

ERA-Interim reanalysis (http://www.ecmwf.int/research/era)

- Reanalyses apply modern data assimilation techniques to historical measurements to produce consistent, multi-decadal time series of meteorological parameters.

- **ERA-Interim covers the period 1989 – present day**:
  - The NWP system (Cycle 31r2) was operational at ECMWF in December 2006.
  - T255 resolution (~80 km).
  - 60 vertical levels (up to 65 km).
  - 4D-Var with a 12 hour assimilation window.
  - **Conventional observations**: surface, radio- and drop-sondes, aircraft, profilers.
  - **Satellite observations**: radiances (IR and MW sounder), **assimilated with a variational bias correction (VarBC)**, ozone, winds from imagery, scatterometers, **and 1st use of GPSRO measurements**.

GPSRO measurements used in ERA Interim

- CHAMP, May 2001 – May 2008: ~150 profiles per day. **Reprocessed by UCAR**.

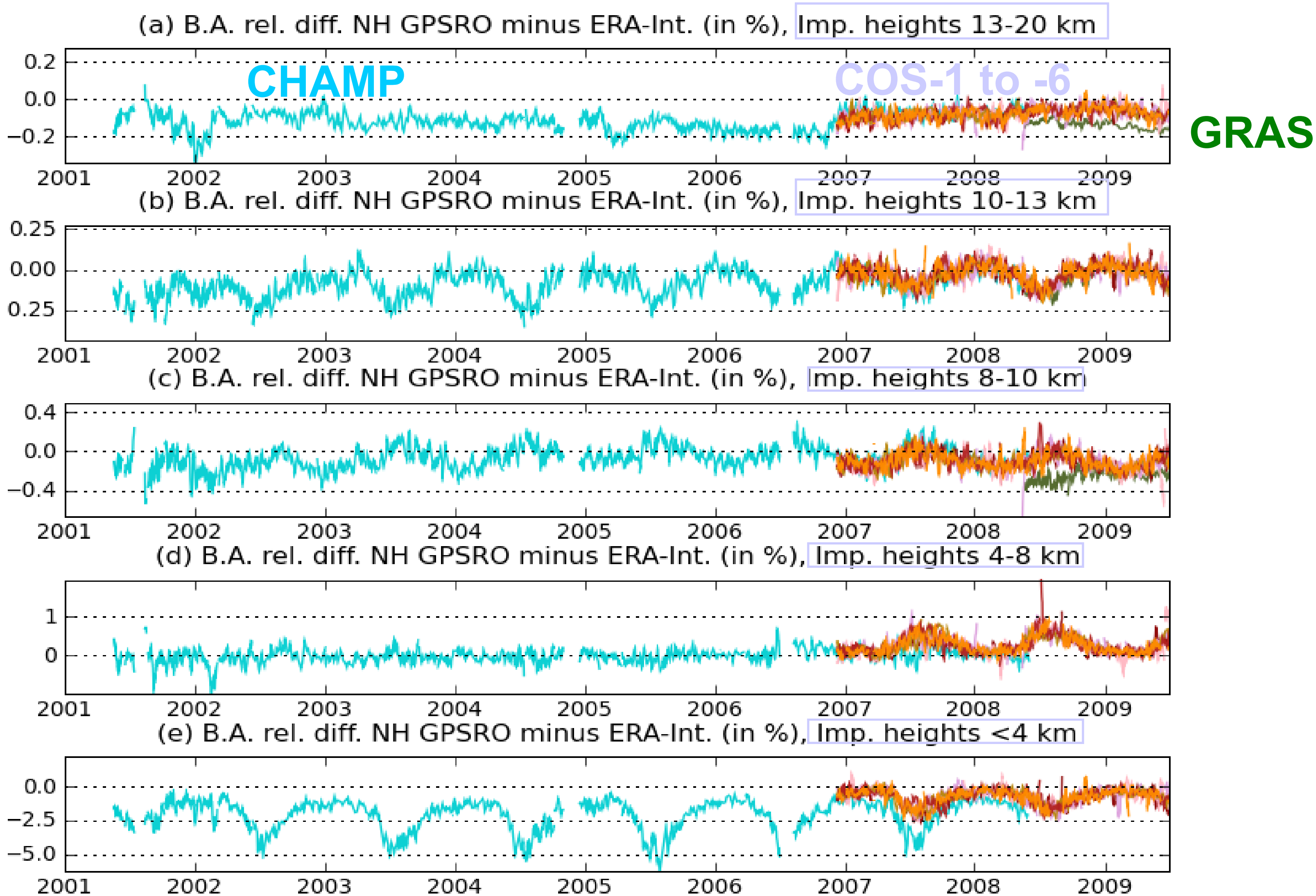
- COSMIC constellation, December 2006 – present day: ~1800-2000 profiles per day. **Near-real-time operational data used in NWP**.

- GRAS on MetOP-A, May 2008 – present day: ~650 profiles per day. **Near-real-time operational data used in NWP.**

CHAMP and COSMIC bending angle profiles assimilated from surface to 40 km. GRAS from 8 km to 40 km in NH/SH and 10 km to 40 km in Tropics.

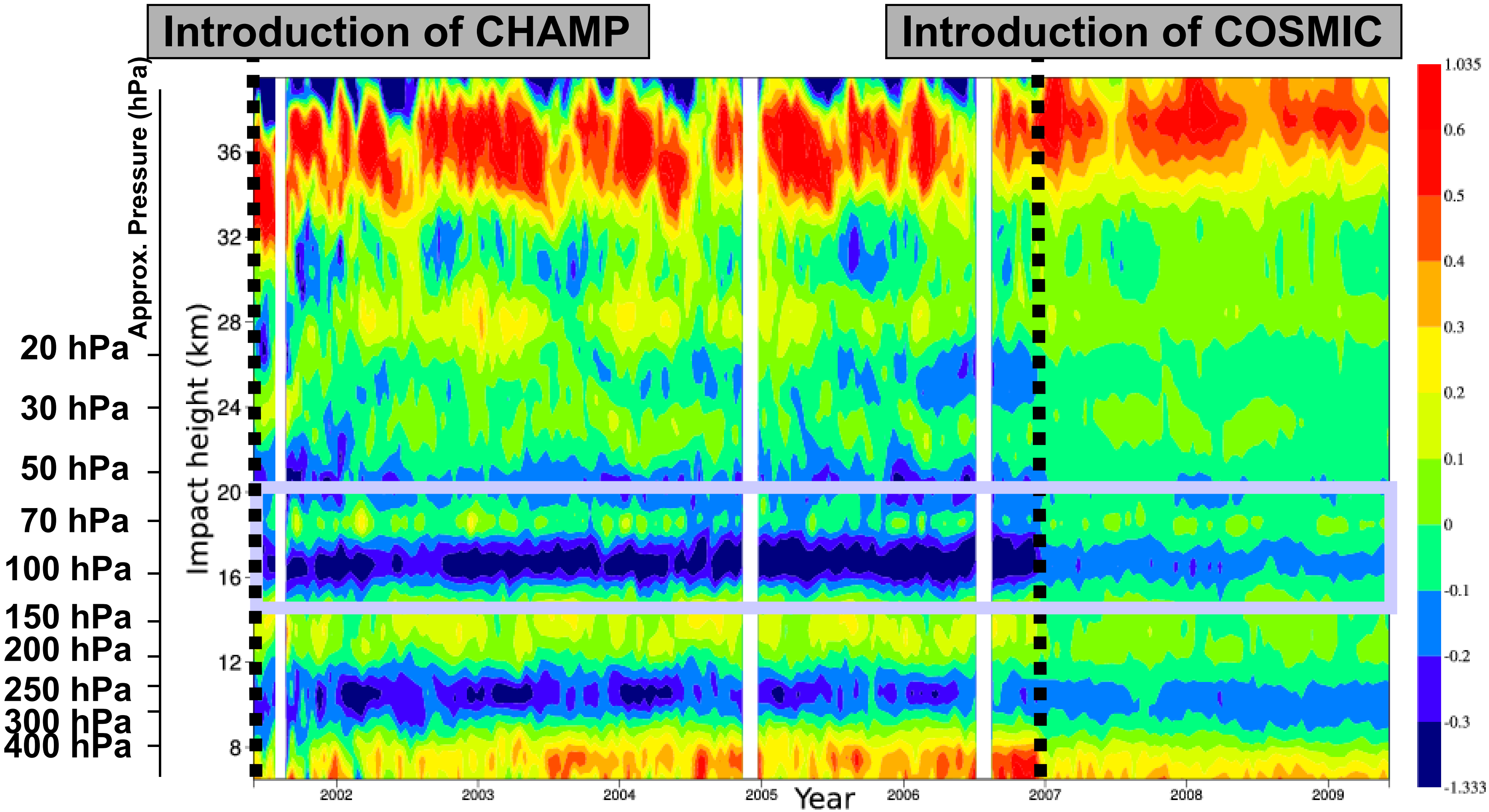
We assume the same error model for all GPSRO instruments and ignore vertical error correlations.

Time-series of mean RO differences as compared to ERA-Interim



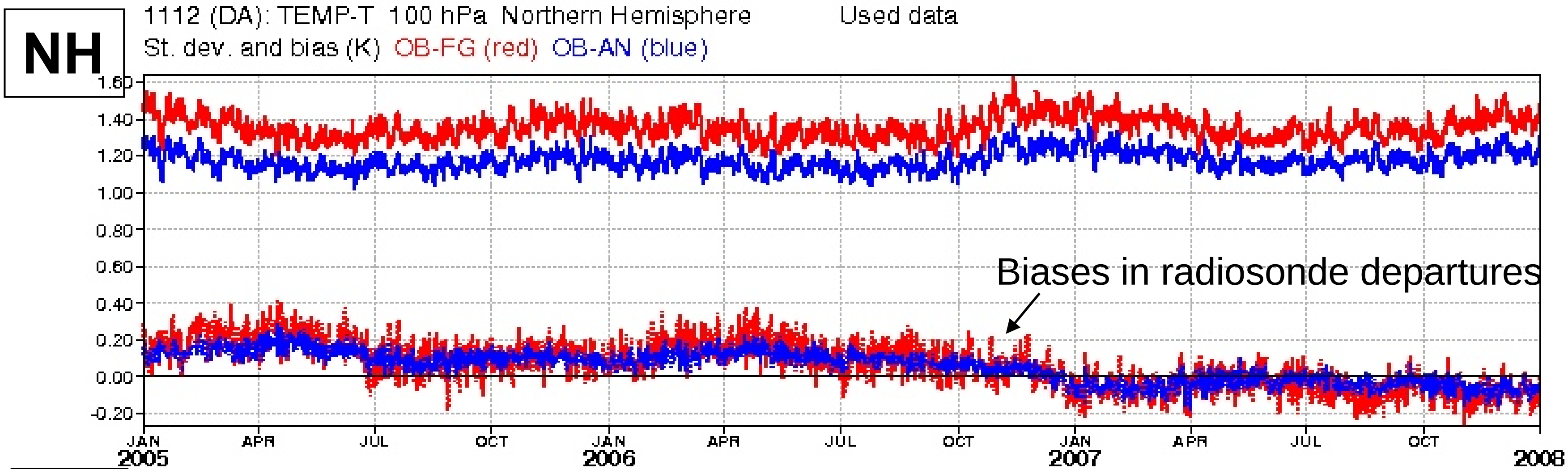
Small biases and reasonable consistency between various RO satellites/receivers

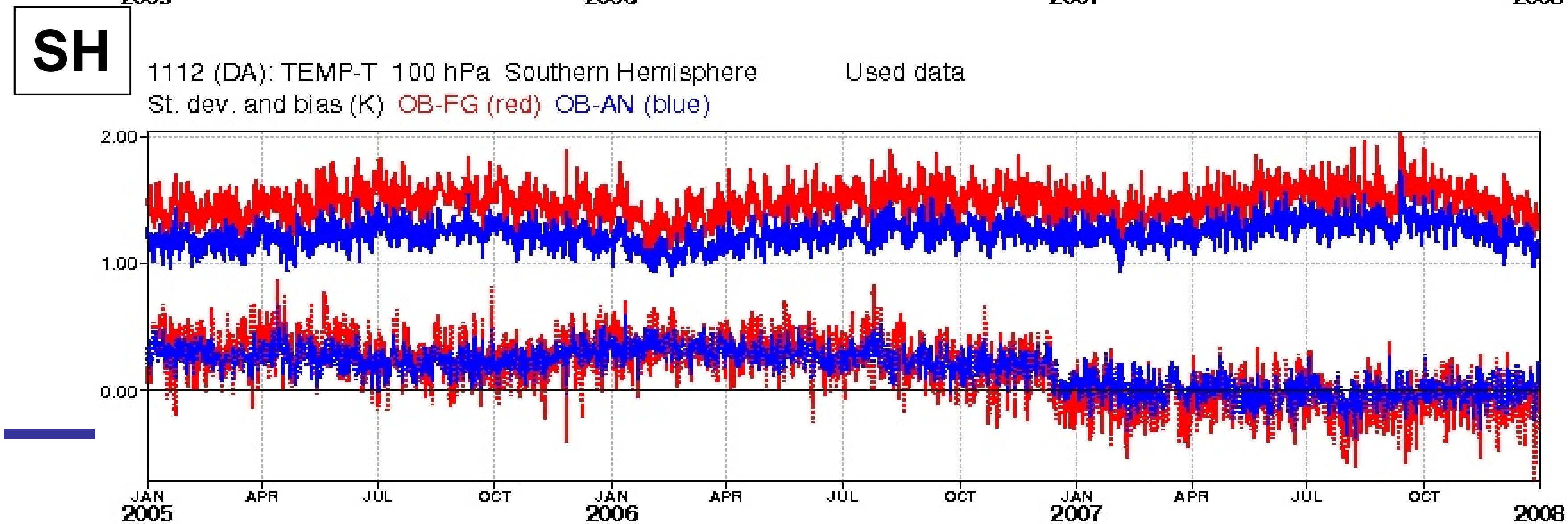
Mean differences between RO and ERA-Interim bending angles from a short-range forecast



ERA-Interim system and RO observing system show similar evolutions, except when additional RO data are introduced in a large number

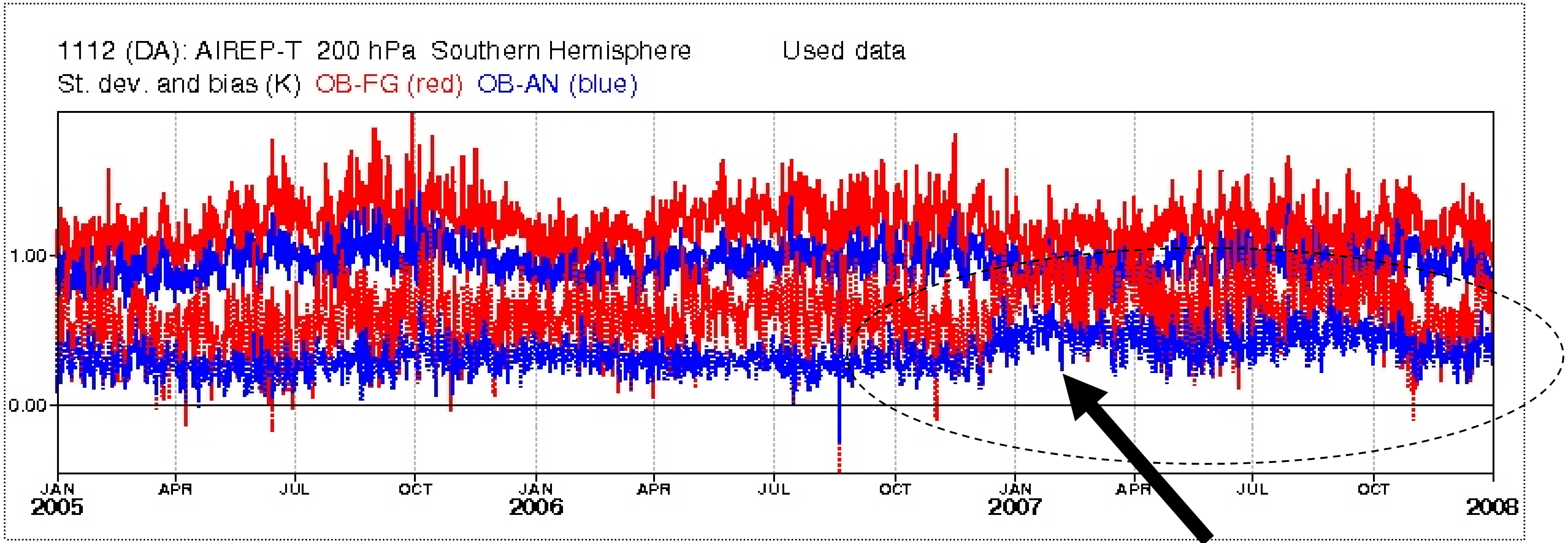
COSMIC introduced to ERA-Interim December 2006. Radiosonde T departures 100hPa





Fit to aircraft temperature measurements at 200 hPa in SH

SH



Noisy, but note the shift in bias post COSMIC.

Aircraft temperature are known to be biased warm (e.g., Ballish+Kumar BAMS, 2008) and they bias the analysis warm at 200 hPa. GPSRO measurements try to correct this bias in SH. Two "anchor" measurements are fighting!

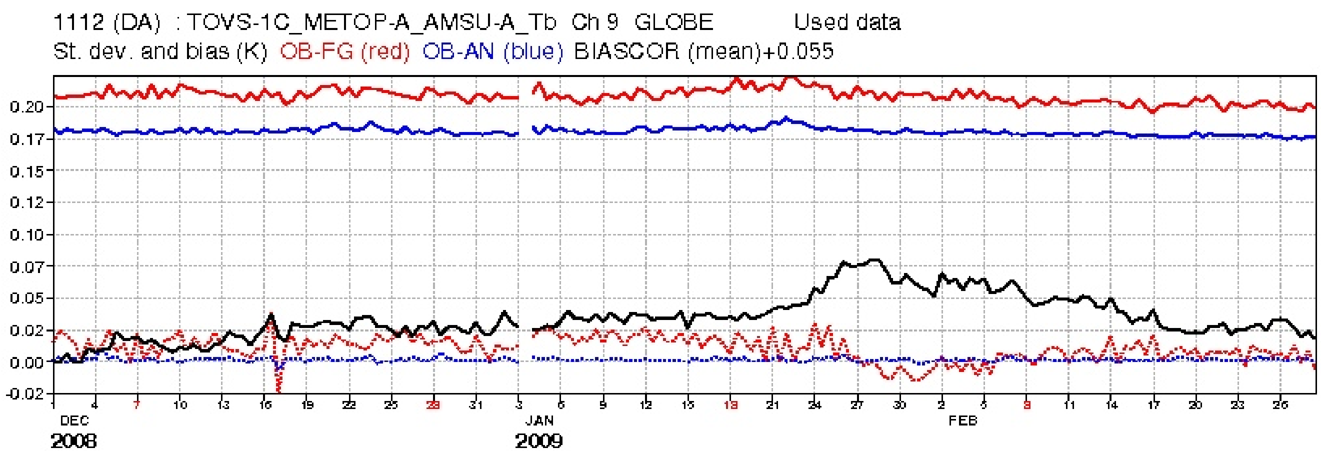
This is not possible in the NH, because the large number of aircraft temperature measurements swamp the GPSRO.

ECMWF

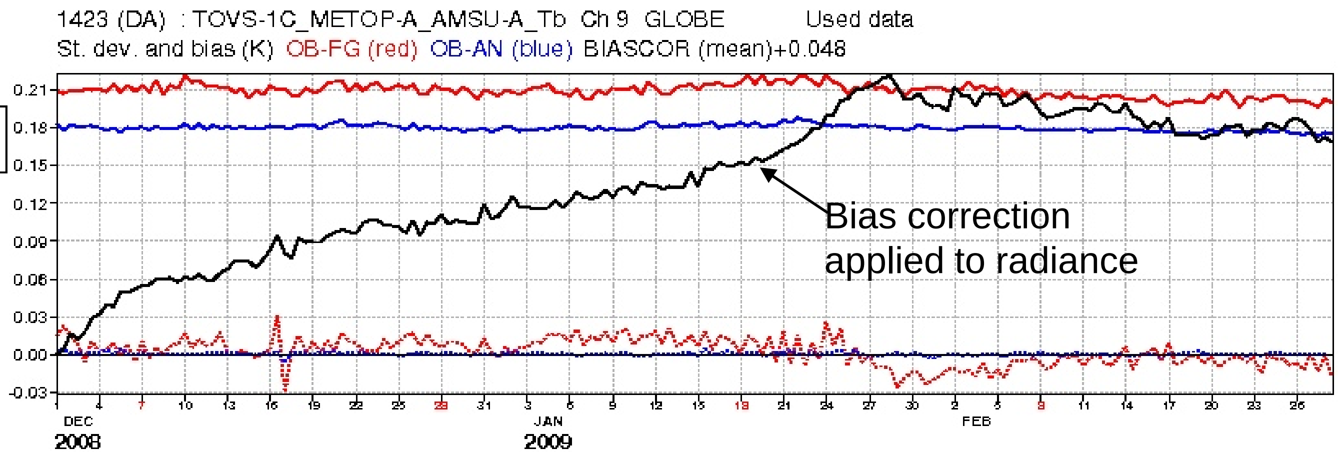
Recent experiment removing GPSRO from ERA-Interim Dec. 08, Jan-Feb 09

- Impact on bias correction. E.g., globally averaged MetOP-A, AMSU-A channel 9 bias correction.

GPSRO assimilated



No GPSRO



Core development of GMES atmospheric environmental services

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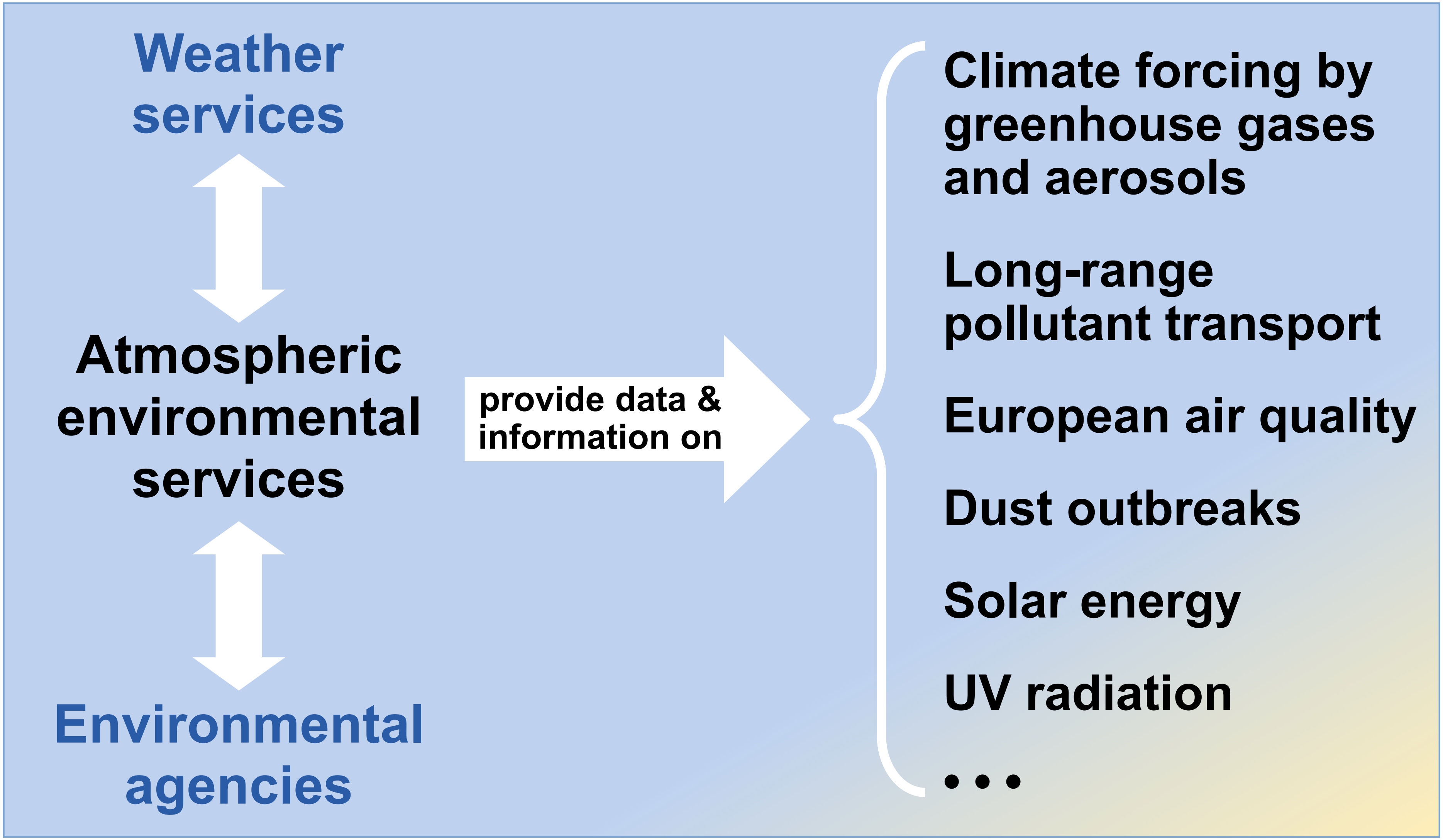
European Centre for Medium-Range Weather Forecasts

- **MACC is an EU FP7 project funded to:**
  - develop and establish pilot operation of core systems for monitoring and forecasting atmospheric composition
  - support the development of downstream services for specific sectors
  - bring systems to the point of full operational status as a GMES Service
- **MACC builds on:**
  - EU-funded FP6 project GEMS
  - ESA-funded GMES Service Element project PROMOTE
- **Partners comprise:**
  - 46 national entities from 18 European States
  - ECMWF and JRC
- **ECMWF is project coordinator**

Services related to the chemical and particulate content of the atmosphere



Global data assimilation

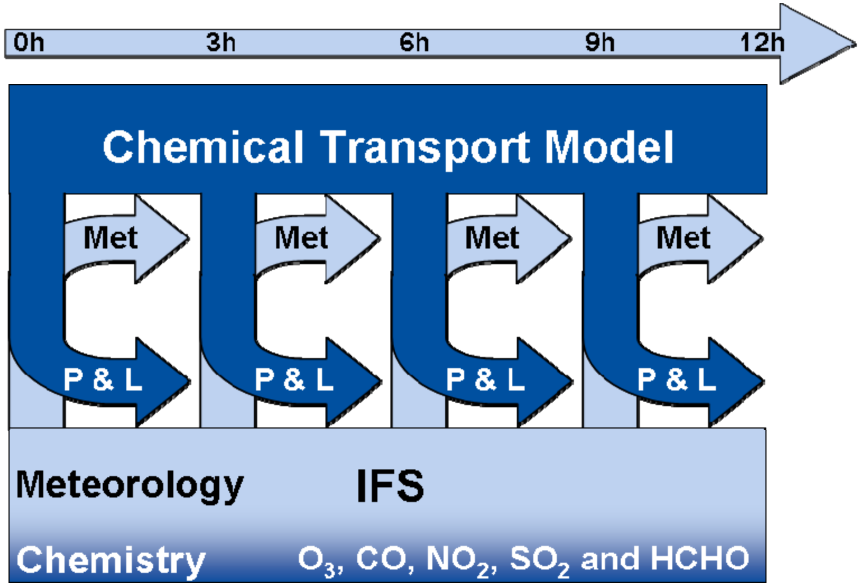
- **Based on ECMWF's "Integrated Forecasting System" - IFS**

- **CO_2 , CH_4 and aerosols have been incorporated in the IFS**
  and data assimilation has been developed for AIRS and IASI radiances, SCIAMACHY retrievals, MODIS aerosol optical depth, … GOSAT …

- **IFS also carries O_3, CO, NO_2, SO_2 and HCHO**

  Chemical production and loss come from a coupled CTM, either MOCAGE, MOZART or TM5

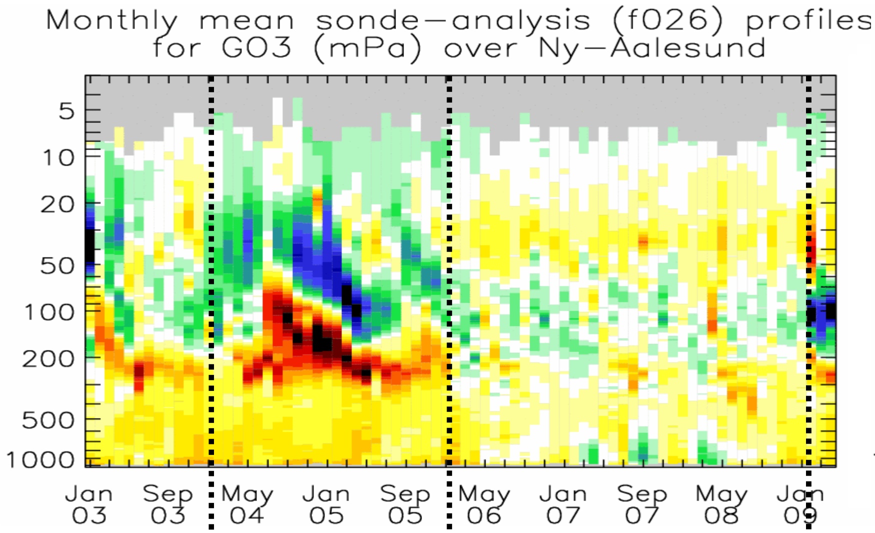
  Data for assimilation come from GOME, GOME-2, IASI, **MIPAS**, **MLS**, MOPITT, OMI, SBUV/2, SCIAMACHY, …

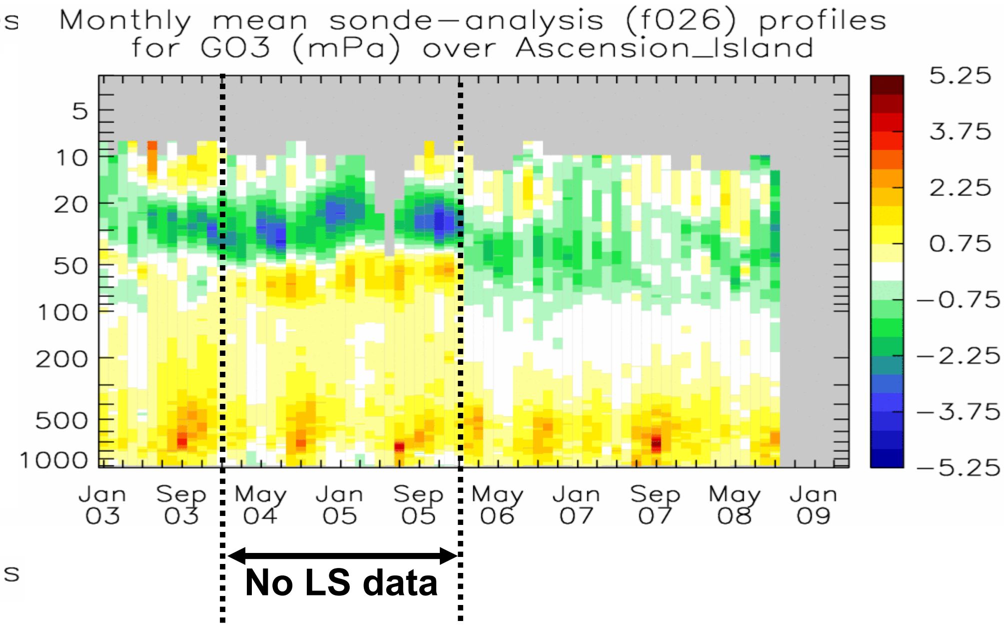


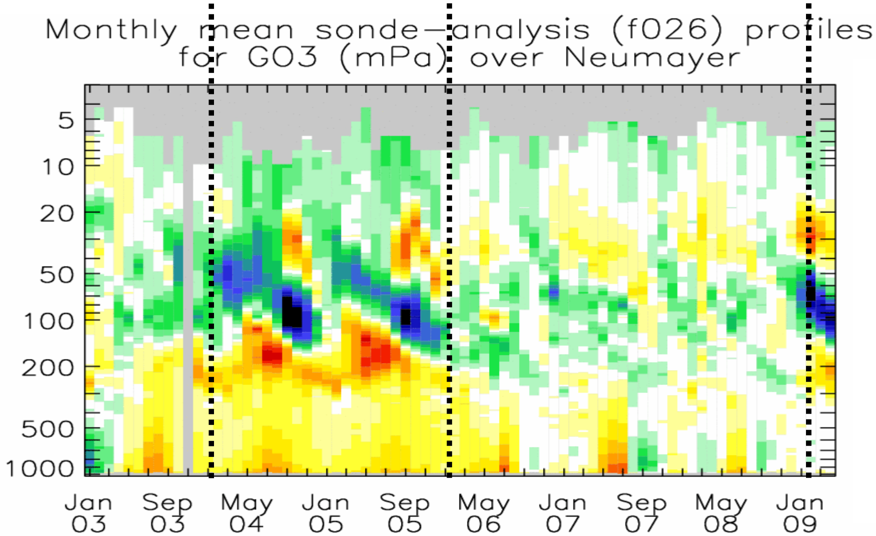
- **Chemistry modules are being built fully into IFS**

ECMWF

Validation against ozonesonde data







Limb-sounding data assimilated in 2003 (MIPAS) and 2006-2008 (MLS)

These data, especially MLS, are clearly beneficial

OMI data are used from July 2007

Comments relevant to proposed LEO-LEOmissions

- **GEMS and MACC have established assimilation of multiple sets of space-based data on atmospheric composition**

- **Space agency plans meet many longer-term data needs:**
  - Sentinels and Metop/Post-EPS, but also Japanese, US and other missions
  - reprocessing (ESA CCI, GSICS, SCOPE-CM, …) important for reanalysis

  but:

  - inadequacy of plans for Level-2 products is a concern
  - **plans for provision of sustained limb-sounding are lacking**

- ***In situ* data provision is important also:**
  - need for near-real-time availability, from European and global networks
  - need for sustained funding of several types of measurement

ECMWF

Summary

- Have tried to demonstrate the impact of satellite data in current NWP, and shown the importance of GPSRO measurements.

- Outlined how GPSRO measurements are used at ECMWF
  - GPSRO constellation has about 2/3rds of the impact of IASI for the SH Z500.
  - The GPSRO null space issue and the importance of complementary measurements.

- Results from reanalysis.

- Highlighted the importance of limb measurements in the MACC project. ATOMMS and ACCURATE missions.