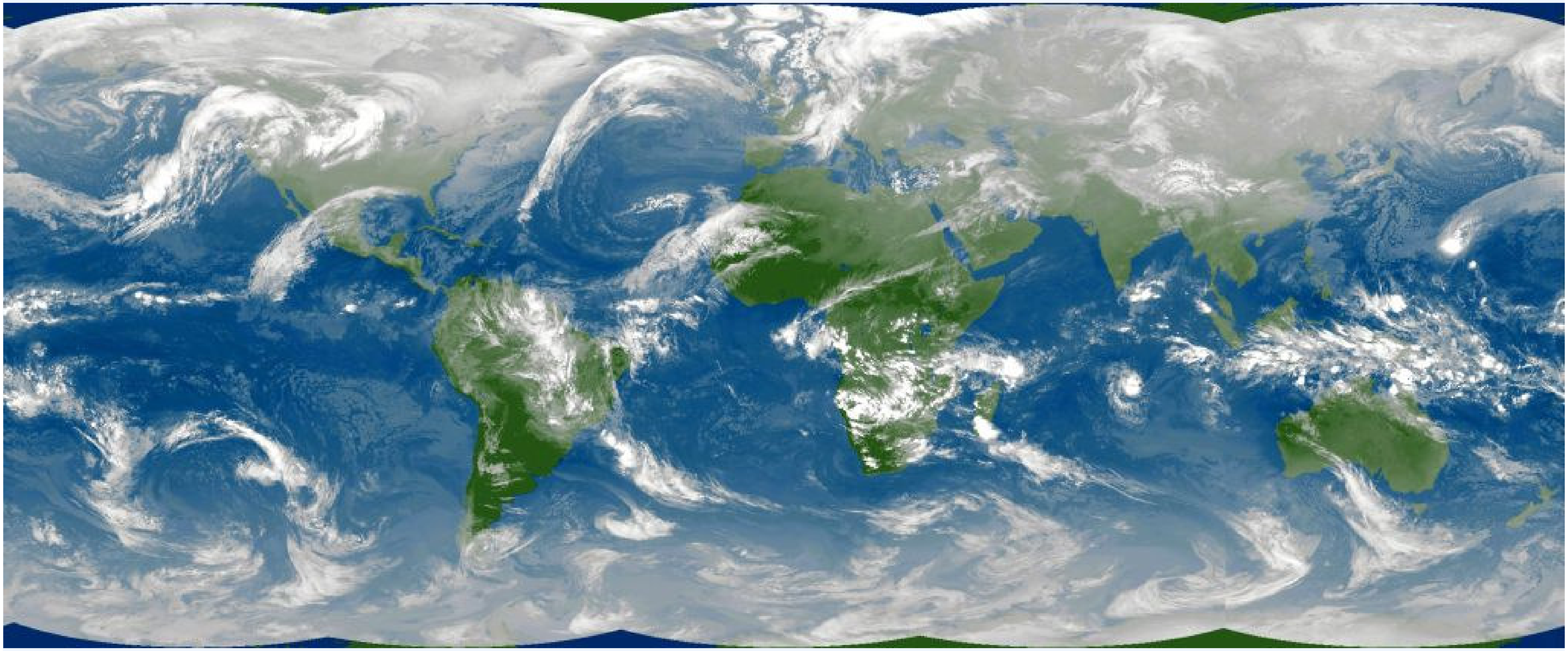
ECMWF Data Assimilation

Contribution from many people

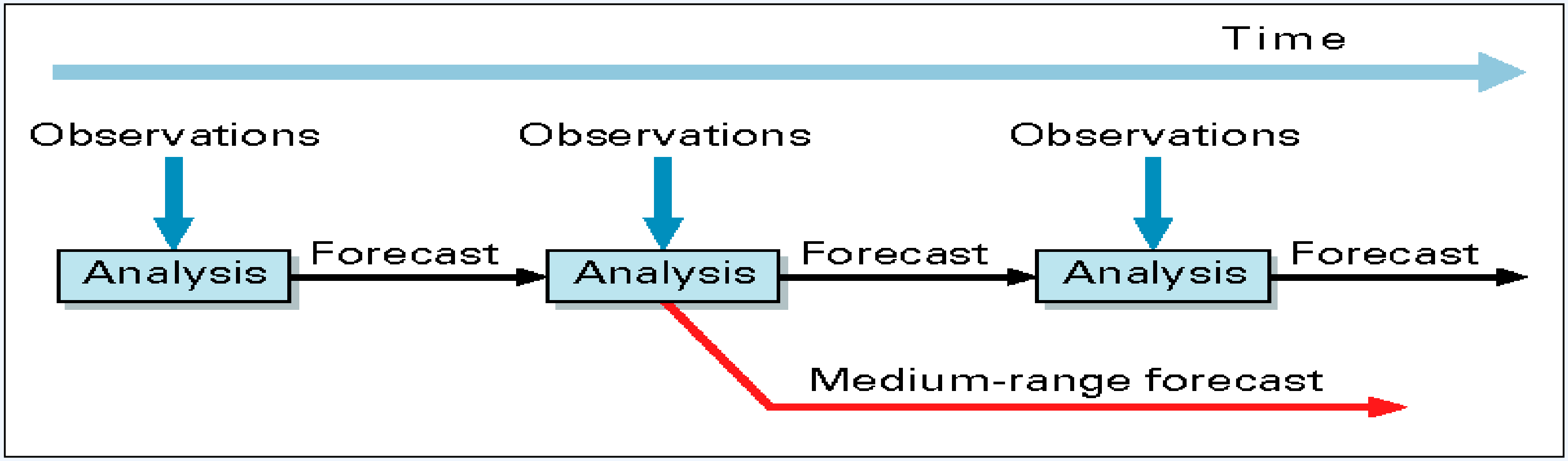


ECMWF

Fundamental challenges of ECMWF 4D-Var Assimilation System

- Incremental 4D-Var
- Linearized Physics
- Observation handling
- Assimilation of satellite data
- Model and Observation Bias
- Modelling Background Covariance

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 4 – 8,000,000 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.

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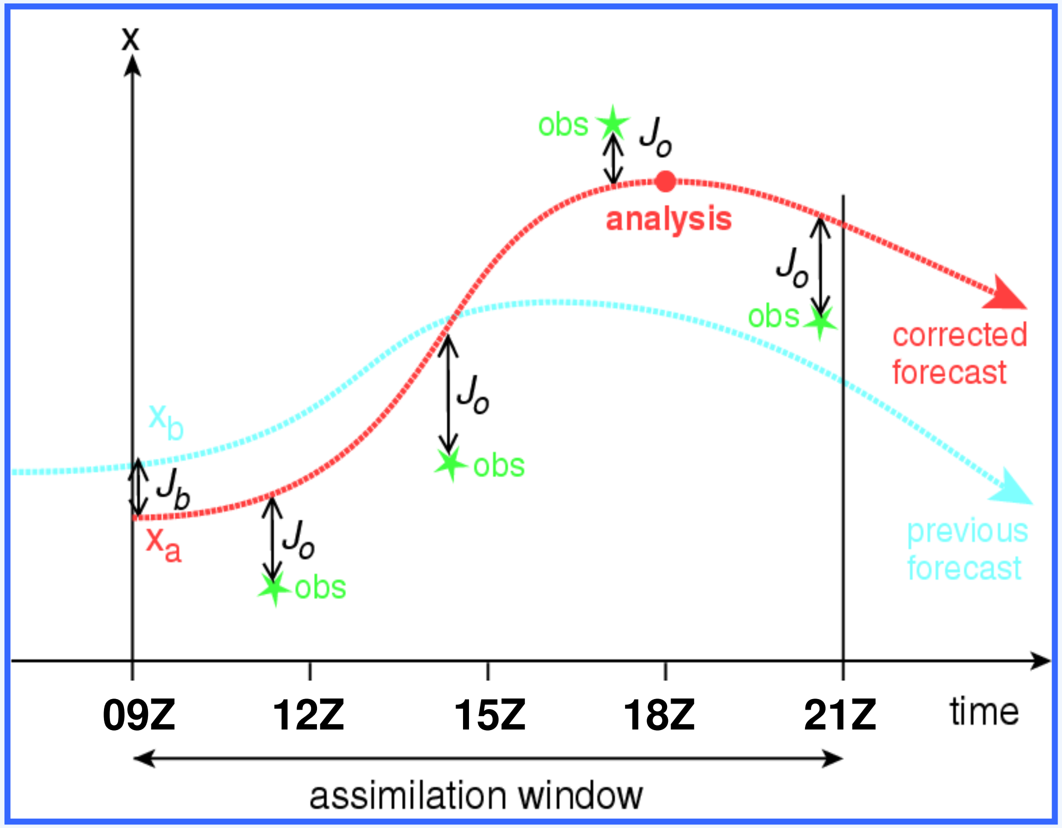
A few 4D-Var Characteristics

All observations within a 12-hour period are used simultaneously in one global (iterative) estimation problem

- Observation minus model differences are computed <u>at the observation time</u> using the full forecast model at T799 (25km) resolution
- 4D-Var finds the 12-hour forecast evolution that optimally fits the available observations. A linearized forecast model is used in the minimization process based on the adjoint method
- It does so by adjusting surface pressure, the upper-air fields of temperature, wind, specific humidity and ozone
- The analysis vector consists of ~10^8 elements at T255 resolution (80km)



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4D Variational Data Assimilation

- Model: $\mathcal{M}$,
- Observations: y,
- Background: x_b,
- Observation operator: $\mathcal{H}$,
- Cost function to minimise:

$$J(x) = \frac{1}{2}(x - x_b)^T B^{-1}(x - x_b) + \frac{1}{2}[y - \mathcal{H}(x)]^T R^{-1}[y - \mathcal{H}(x)] + J_c$$

- In discrete form:

$$\begin{aligned} J(x) &= \frac{1}{2}(x - x_b)^T B^{-1}(x - x_b) \\ &+ \frac{1}{2}\sum_{i=0}^{n}[y_i - \mathcal{H}_i(\mathcal{M}_i(x))]^T R_i^{-1}[y_i - \mathcal{H}_i(\mathcal{M}_i(x))] \end{aligned}$$

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Incremental 4D-Var

- The cost function is expressed in terms of increments with respect to the background state $\delta x = x - x_b$.
- $\mathcal{H}$ and $\mathcal{M}$ are linearised around $x_i = \mathcal{M}_i(x_0)$.

$$J(\delta x) = \frac{1}{2}\delta x^T B^{-1}\delta x + \frac{1}{2}\sum_{i=0}^{n}(H_i M_i \delta x - d_i)^T R_i^{-1}(H_i M_i \delta x - d_i)$$

where

- H_i and M_i are the linearised observation operator and model,
- $d_i = y_i - \mathcal{H}_i(\mathcal{M}_i(x_b))$ are the innovations.

- The innovations, which are the primary input to the assimilation, are always computed using the full observation operator and model to ensure the highest possible accuracy.

4D-Var incremental formulation

Courtier, Thépaut and Hollingsworth (1994)

In the incremental formulation the cost function J is expressed in terms of increments $\delta\mathbf{x}=\mathbf{x}-\mathbf{x}_b$ with respect to the background state at initial time.

H_i and M_i are the TL of $\mathcal{H}_i$ and $\mathcal{M}_i$ linearized around $x(t_i) = \mathcal{M}_i(x_b(t_0))$

$$\boxed{J(\delta x) = \delta x^T B^{-1} \delta x + \sum_{i=1}^{N} (H_i M_i \delta x - d_i)^T R^{-1} (H_i M_i \delta x - d_i)}$$

The i-summation is over N=25 ½-hour long time slots of the 12-hour assimilation period.

The innovations d_i are calculated using the non-linear operators, $\mathcal{H}_i$ and $\mathcal{M}_i$.

$$\boxed{d_i = y_i - \mathcal{H}_i(\mathcal{M}_i(x_b(t_0)))}$$

This ensures the highest possible accuracy for the calculation of the innovations $\boldsymbol{d}_i$ which are the primary input to the assimilation!

The Outer Iterations

After each minimisation at inner level:

- x is updated: $x_a^j = x_b + \delta x_j$,
- H_i and M_i are re-linearised around $x_i = \mathcal{M}_i(x_a^j)$,
- Innovations are re-calculated using the full nonlinear observation operator $\mathcal{H}$ and model $\mathcal{M}$:

$$d_i^j = y_i - \mathcal{H}_i(\mathcal{M}_i(x_a^j))$$

- Superscript j represents the **outer iteration**.
- The nonlinear model $\mathcal{M}$ remains at **T799** throughout.

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The Inner Iterations

- Tangent Linear approximation:

$$\mathcal{M}(x+\delta x) \approx \mathcal{M}(x) + M\delta x \quad \text{and} \quad \mathcal{H}(x+\delta x) \approx \mathcal{H}(x) + H\delta x$$

- Approximations to reduce cost: the tangent linear model (and its adjoint) is degraded with respect to the full model $\mathcal{M}$:
  - Lower resolution T255 instead of T799
  - Simplified physics (some processes are ignored),
  - Simpler dynamics (spectral instead of grid-point humidity).
- This results in **shorter control vector** and **cheaper TL and AD models** during the minimisation.

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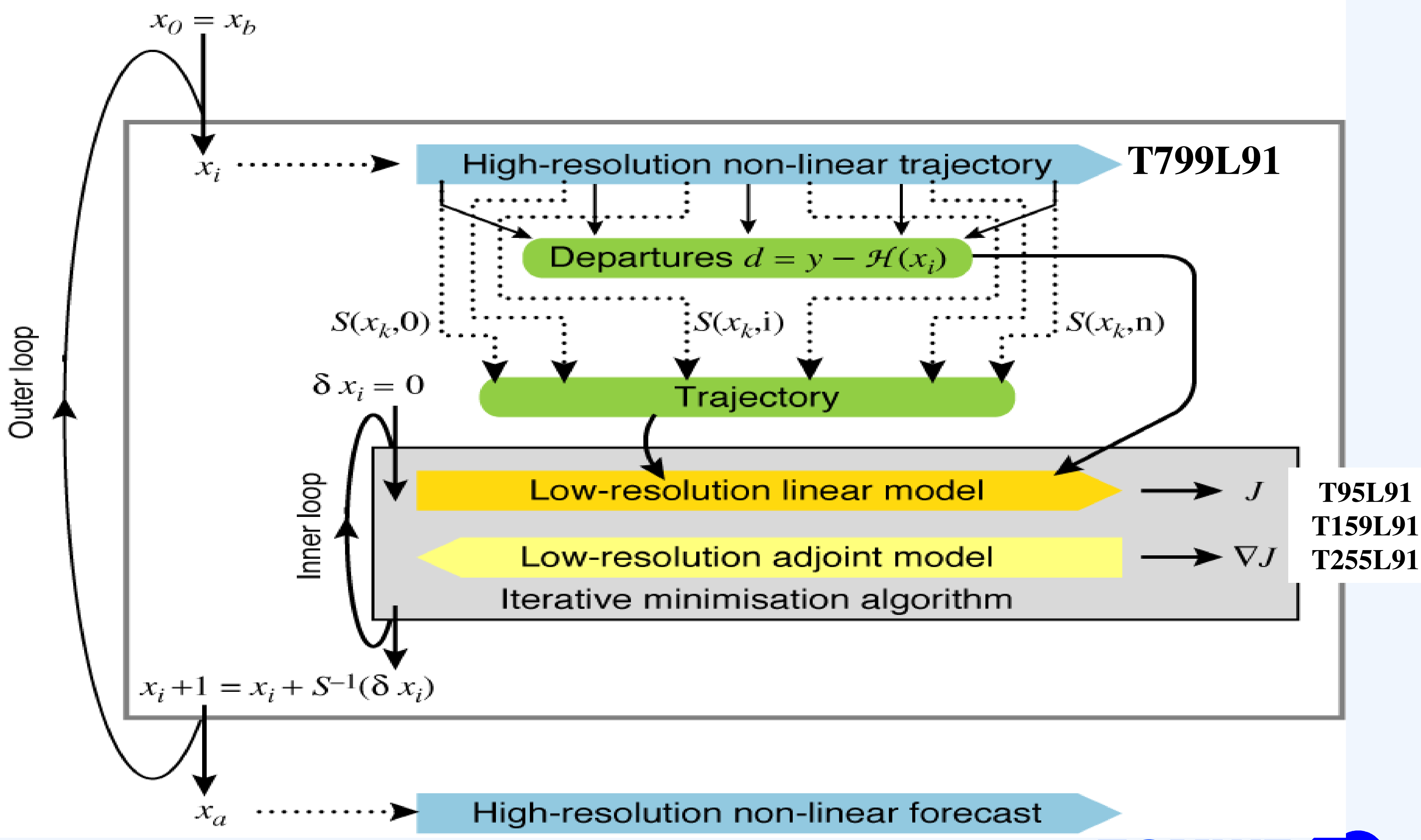
ECMWF 4D-Var procedure

Use all data in a 12-hour window (0900-2100 UTC for 1200 UTC analysis)

1. Group observations into ½ hour time slots
2. Run the T799 (25km) high resolution forecast from the previous analysis and compute "observation"- "model" differences
3. Adjust the model fields at the start of assimilation window (0900 UTC) so the 12-hour forecast better fits the observations. This is an iterative process using a lower resolution linearized model T95 (210km), T159 (125km) or T255 (80 km) and its adjoint model
4. Rerun the T799 high resolution model from the modified (improved) initial state and calculate new observation departures
5. The 3-4 loop in repeated three times to produce a good high resolution estimate of the atmospheric state – the result is the ECMWF analysis

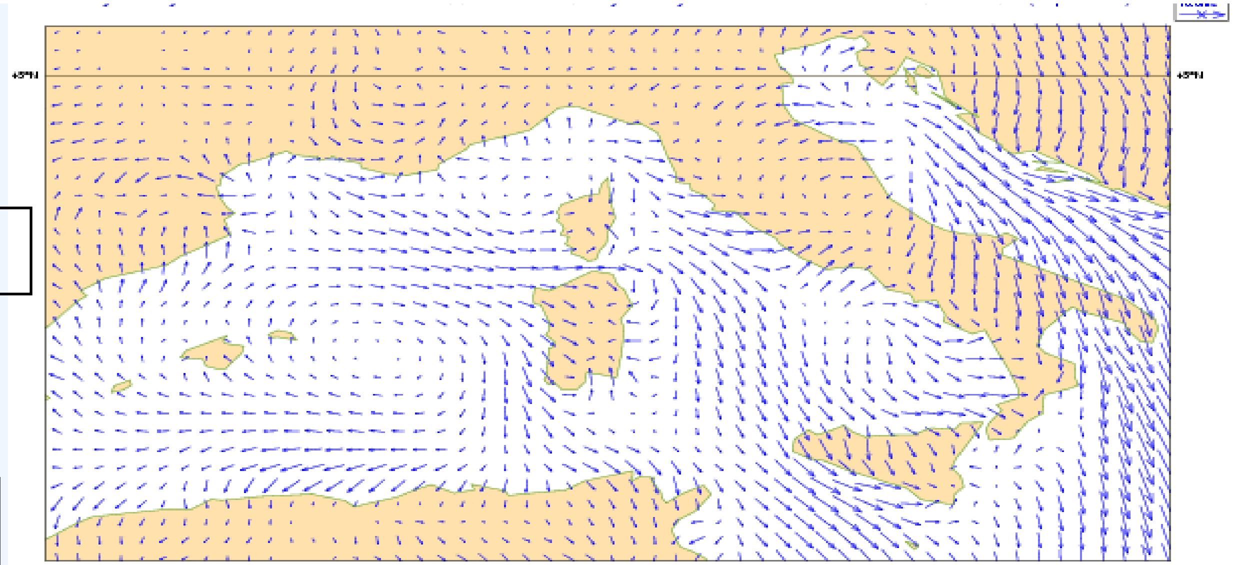
Multi-incremental quadratic 4D-Var at ECMWF



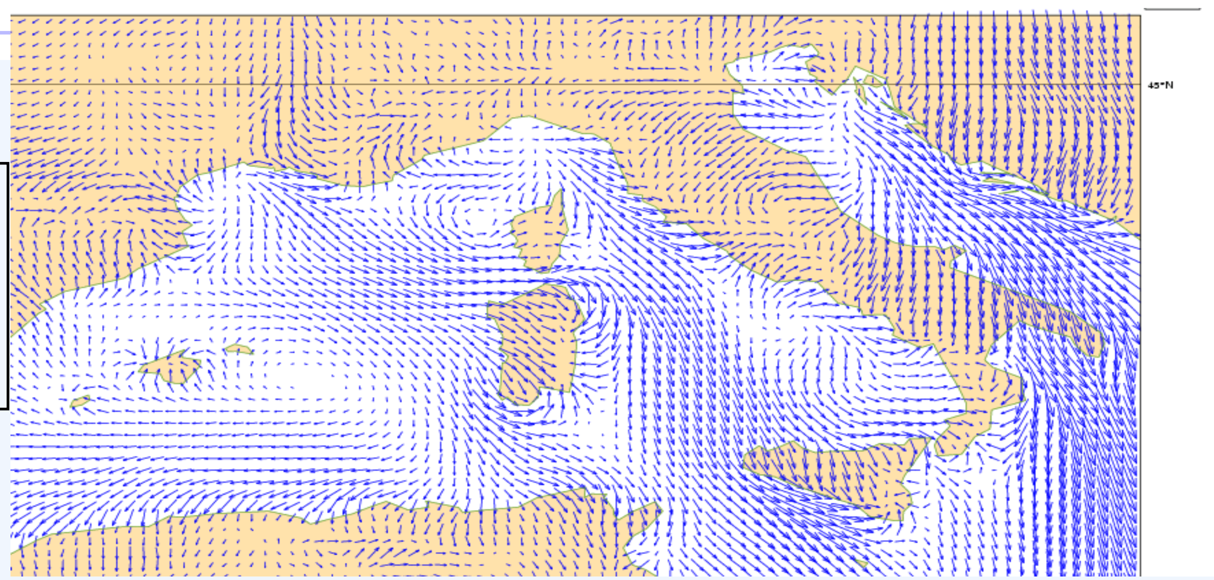
Outer loop forecast resolution is now T799

Important for accurate comparison against observations

T511 (40km)



10m winds



T799 (25km)

Since February 2006

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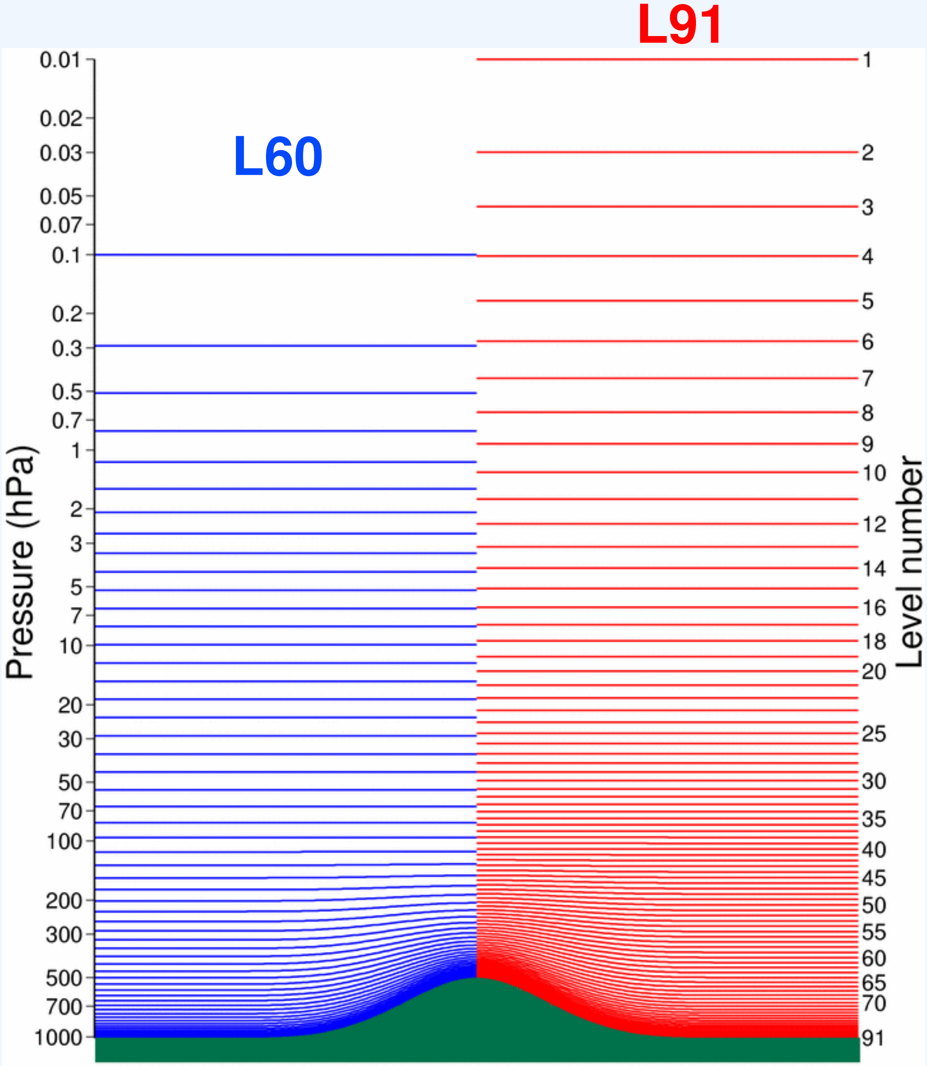
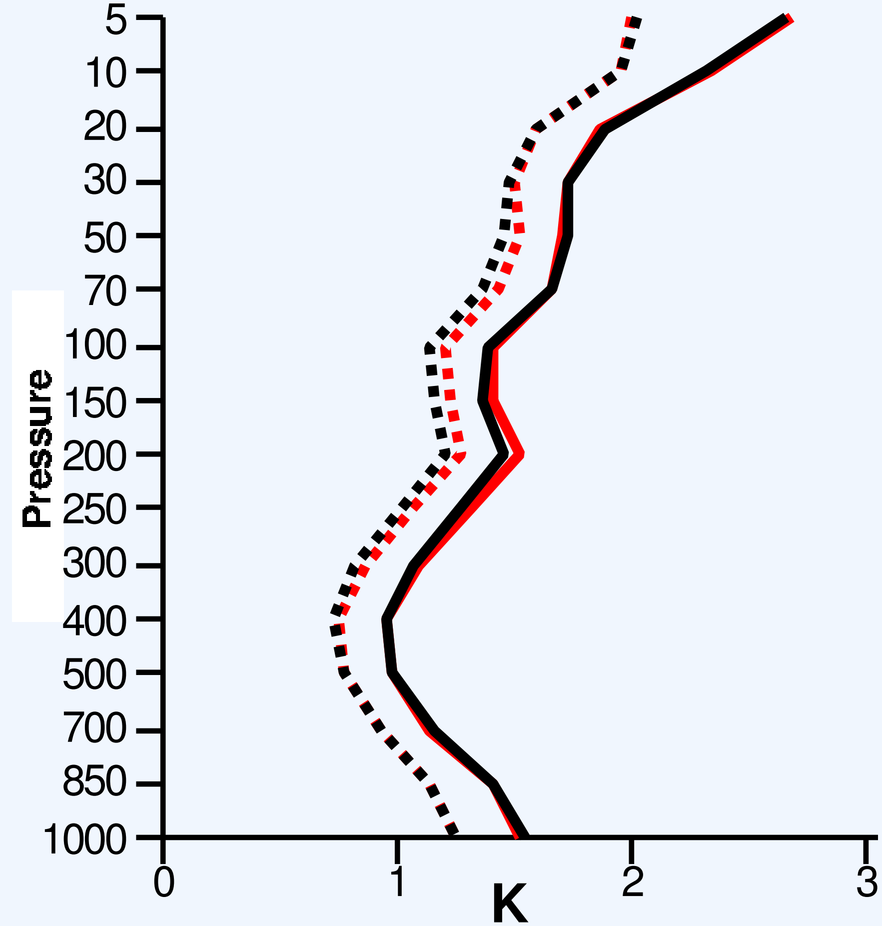
91-level vertical resolution from Feb 2006



Fit of L91 and L60 background and analysis to NH radiosonde T



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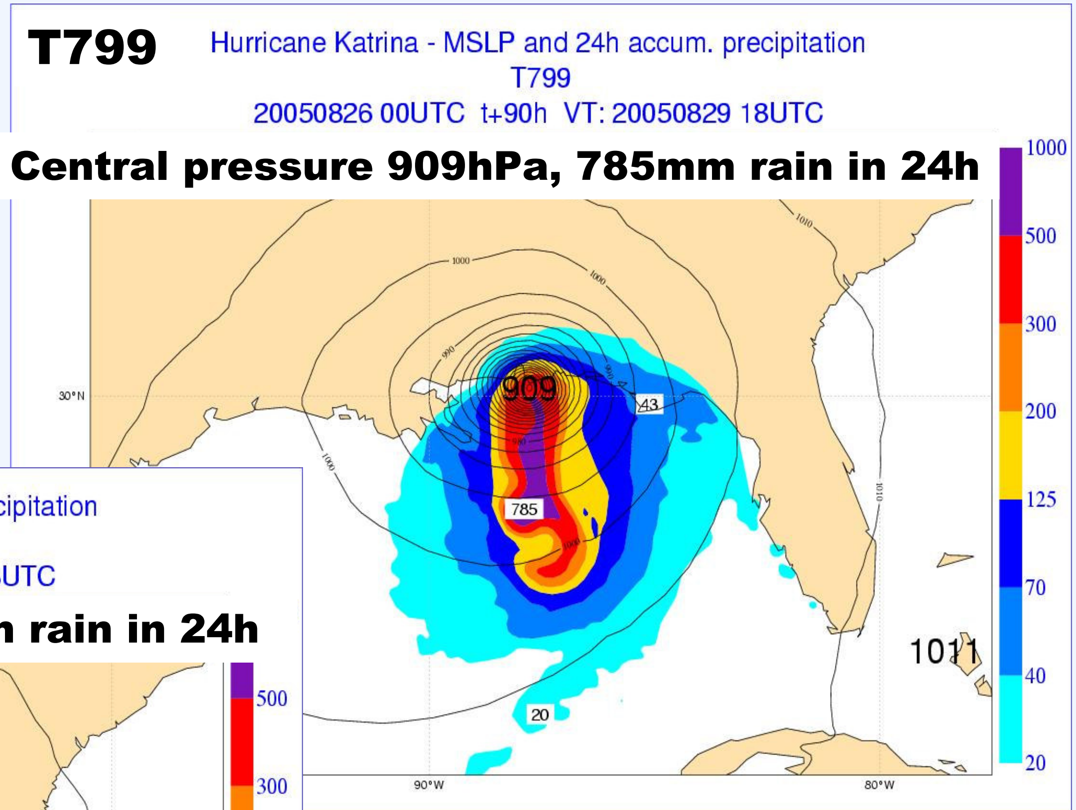
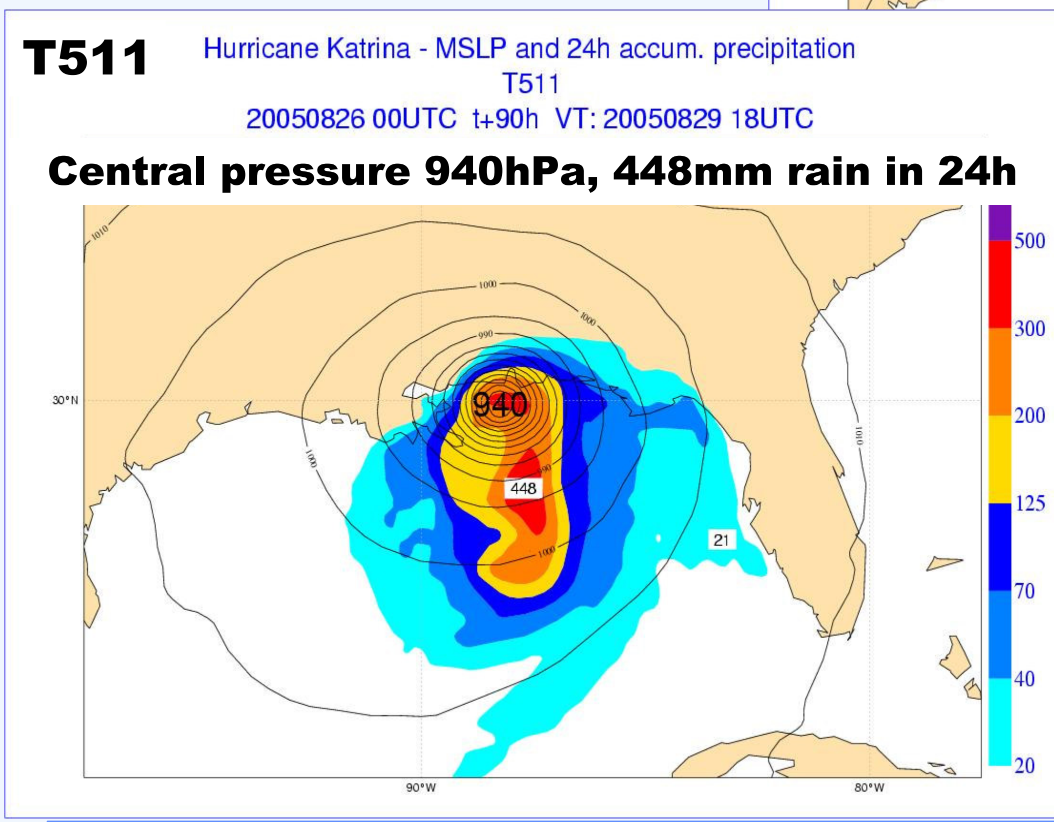
Katrina: 90h forecasts valid 18UTC 29 Aug T511 (40km) versus T799 (25km):



Central pressure 909hPa, 785mm rain in 24h



Central pressure 940hPa, 448mm rain in 24h

Model resolution is important, especially for extreme events

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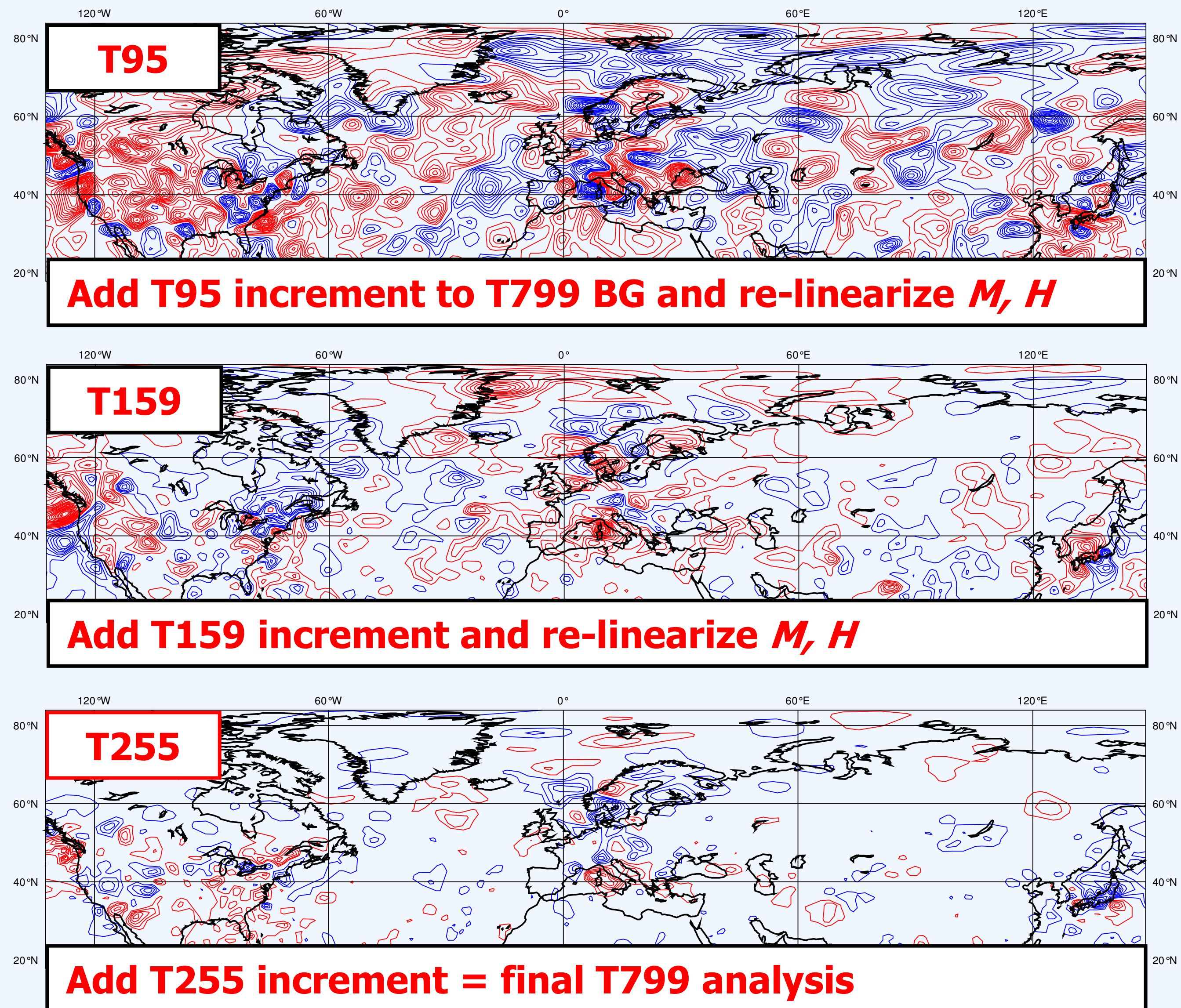
4D-Var with three inner loop: efficient, accurate and allows non-linearity

- **M.Level 80 (900 hPa) temperature analysis increments for each of the three minimizations.**
- **Decreasing amplitudes T95>T159>T255.**
- **Small corrections added at T255 where data density is highest.**
- **Model and observ. operators are re-linearized twice.**



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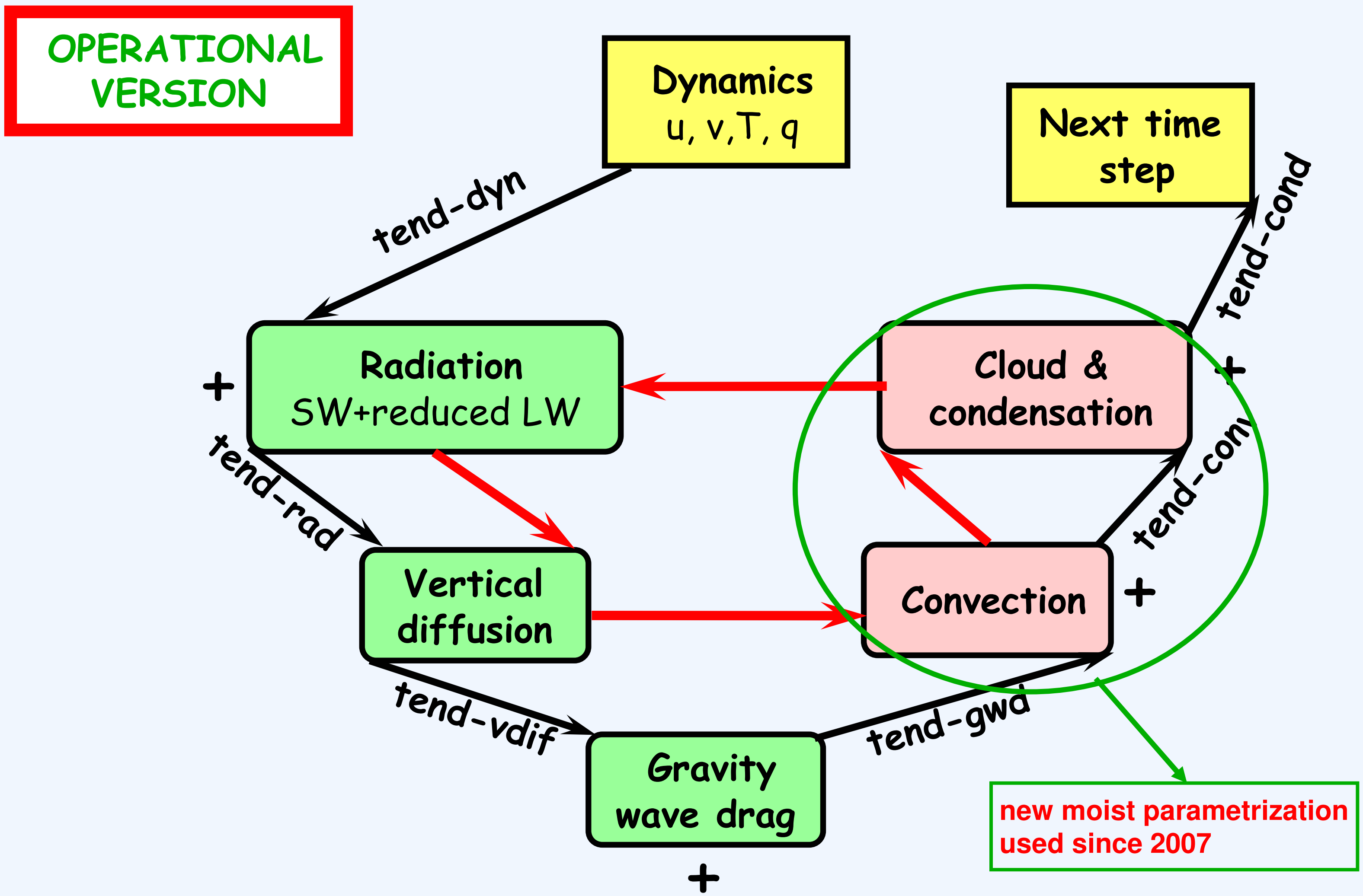
ECMWF LINEARIZED PHYSICS



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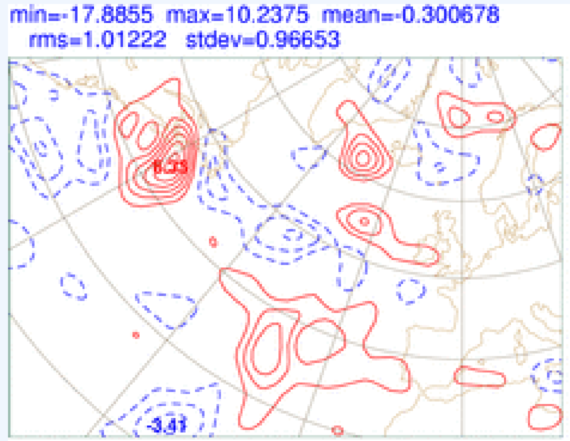
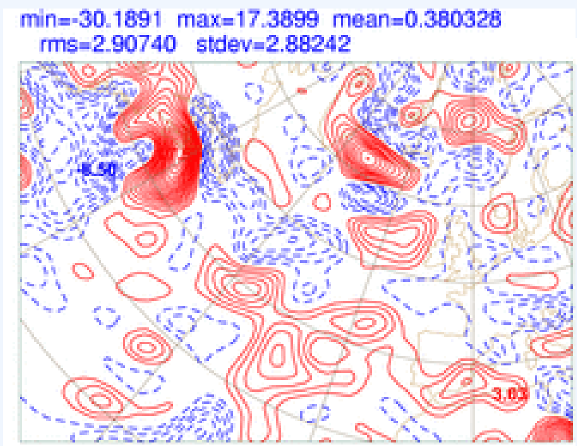
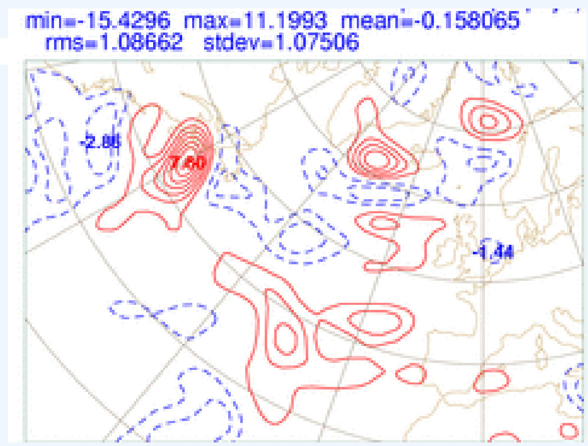
Zonal wind increments at model level ~ 1000 hPa [24-hour integration]

FD



TL_{ADIAB}





TL_{WSPHYS}

FD = Finite Difference **TL_{ADIAB} = adiabatic TL model**

TL_{WSPHYS} = TL model with the whole set of simplified physics

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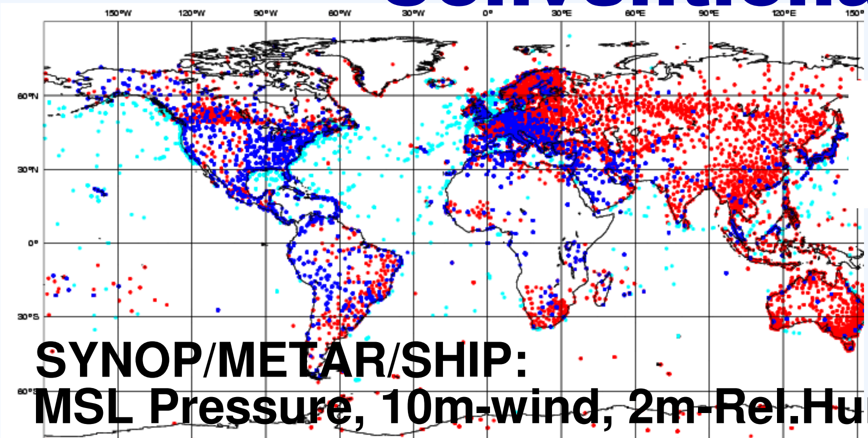
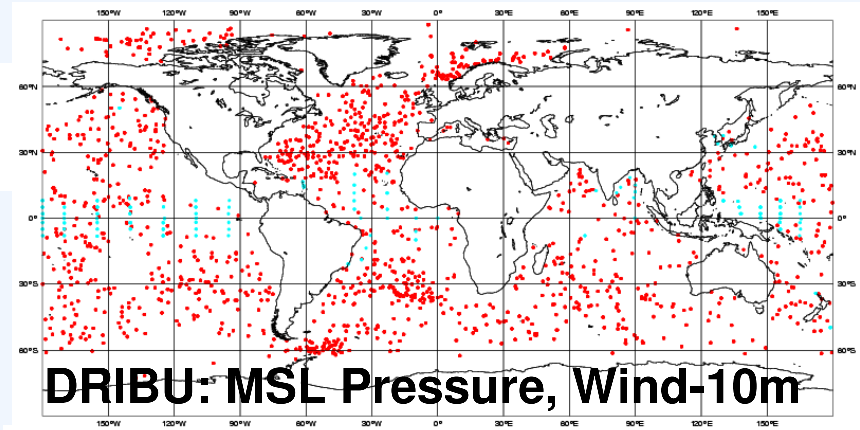
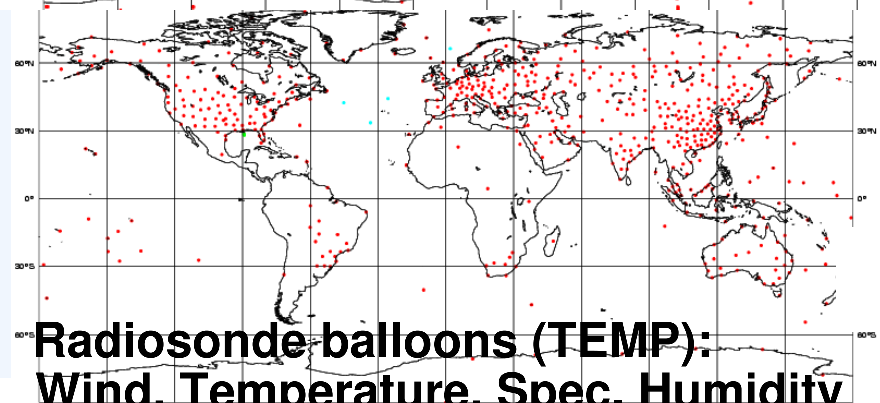
Conventional observations used



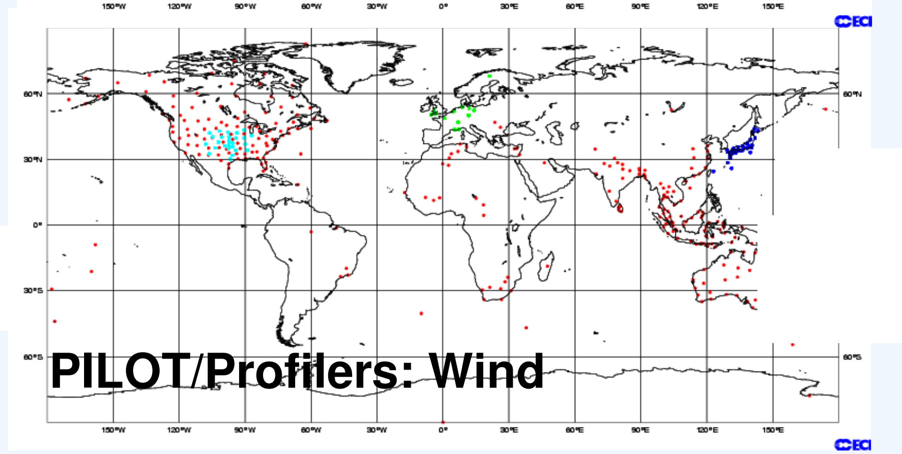
SYNOP/METAR/SHIP:
MSL Pressure, 10m-wind, 2m-Rel.Hum.



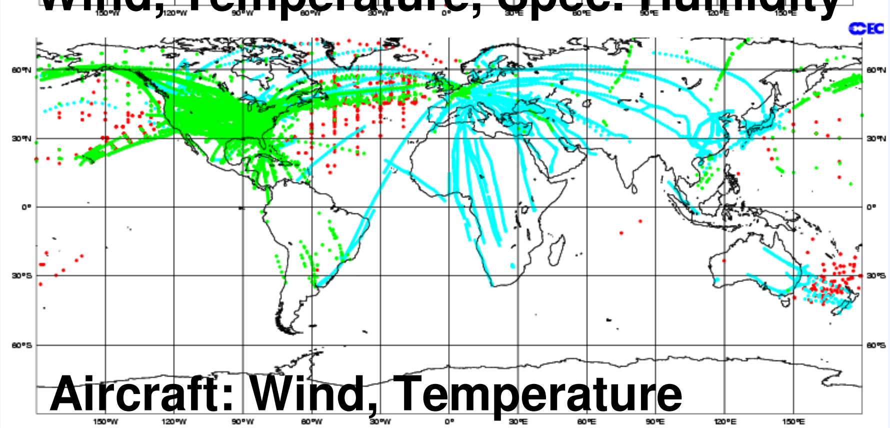
DRIBU: MSL Pressure, Wind-10m



Radiosonde balloons (TEMP):
Wind, Temperature, Spec. Humidity



PILOT/Profilers: Wind



Aircraft: Wind, Temperature

Note: We only use a limited number of the observed variables; especially over land.

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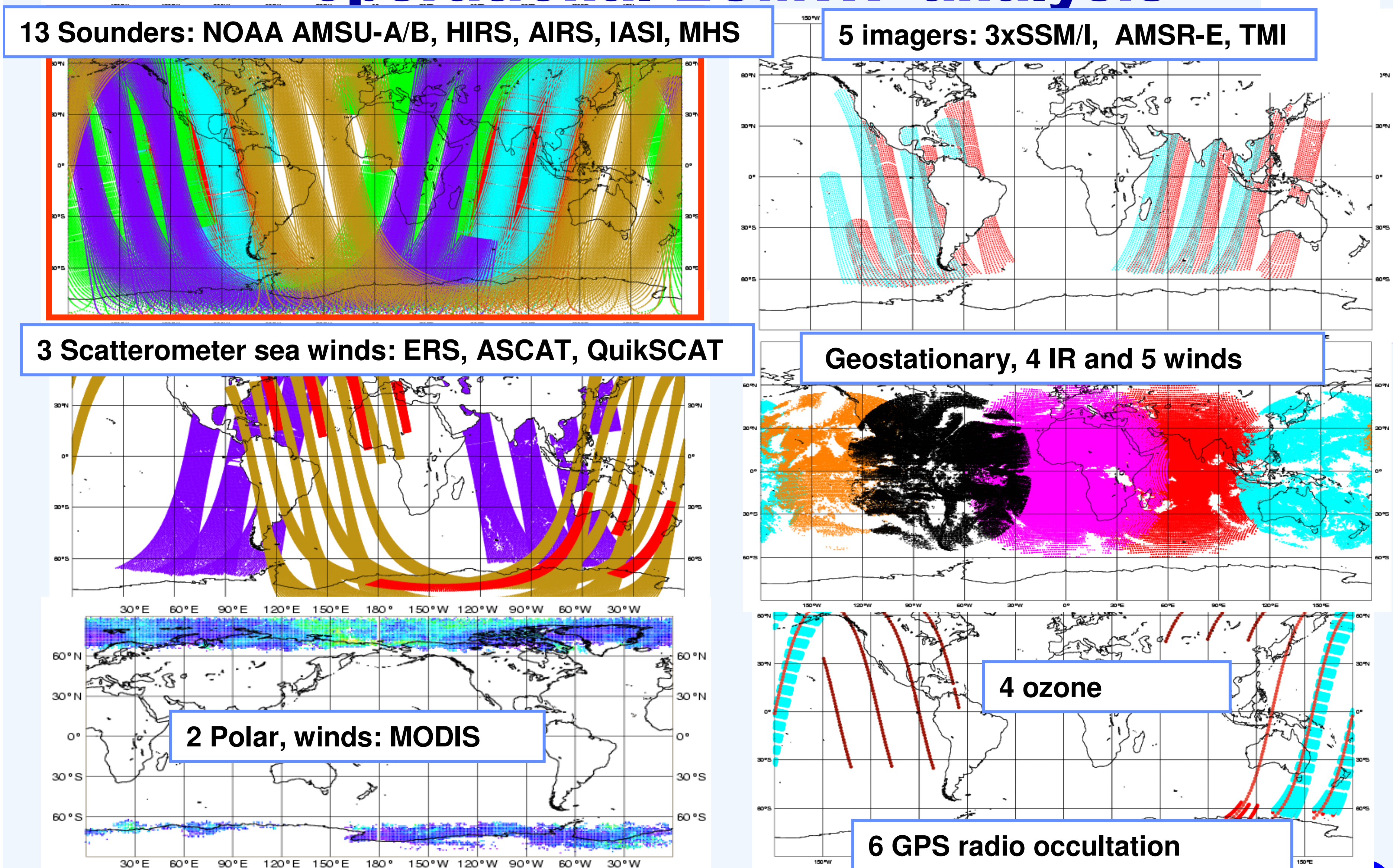
Satellite data sources used in the operational ECMWF analysis



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Data extraction

- Check out duplicate reports
- Ship tracks check
- Hydrostatic check

Thinning

- Data not used to avoid over-sampling and correlated errors
- Even so departures from background and analysis are generated and usage flags also

Blacklisting

- Data skipped due to systematic bad performance or due to different considerations (e.g. data being assessed in passive mode)
- Departures and flags available for further assessment

Model/4D-Var dependent QC

- First guess based rejections
- VarQC rejections

Used data → **Increments**

Analysis

Observation data count for one 12h 4D-Var cycle 0900-2100UTC 3 March 2008

Screened			Assimilated		
• Synop:	450,000	0.3%	• Synop:	64,000	0.7%
• Aircraft:	434,000	0.3%	• Aircraft:	215,000	2.4%
• Dribu:	24,000	0.02%	• Dribu:	7,000	0.1%
• Temp:	153,000	0.1%	• Temp:	76,000	0.8%
• Pilot:	86,000	0.1%	• Pilot:	39,000	0.4%
• AMV's:	2,535,000	1.6%	• AMV's:	125,000	1.4%
• Radiance data:	150,663,000	96.9%	• Radiance data:	8,207,000	91.0%
• Scat:	835,000	0.5%	• Scat:	149,000	1.7%
• GPS radio occult.	271,000	0.2%	• GPS radio occult.	137,000	1.5%
TOTAL:	155,448,000	100.00%	TOTAL:	9,018,000	100.00%

99% of screened data is from satellites

96% of assimilated data is from satellites

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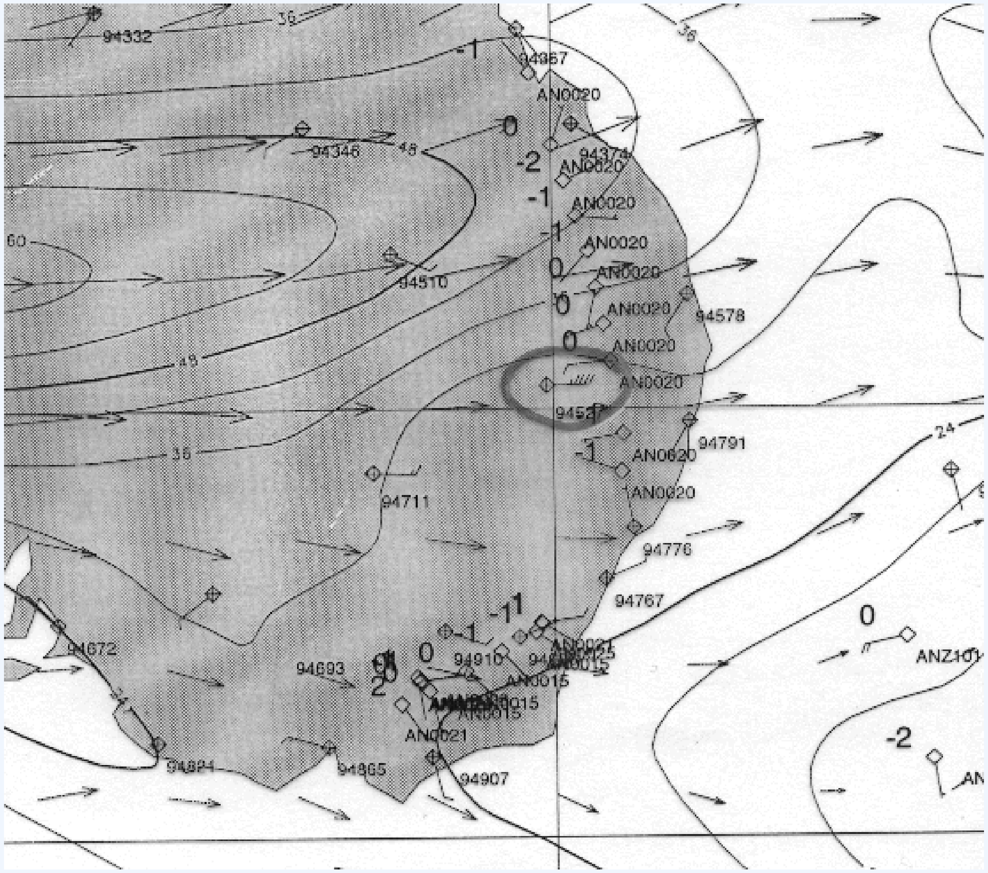
Quality control: Good example



In the quality control procedure all data from different data types are simultaneously checked. In this Australian example the presence of AIRCRAFT data has led to the rejection of a PILOT wind.

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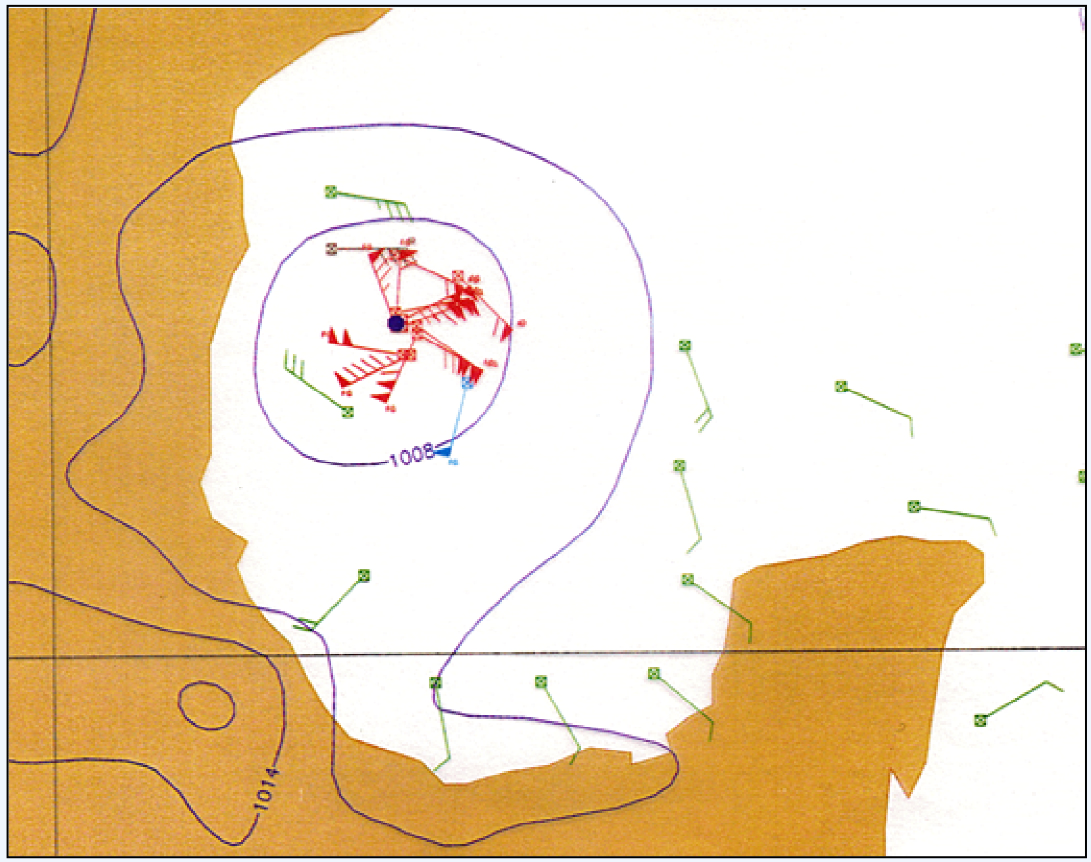
Quality control: Bad example
Tropical Cyclone

Observations of intense and small-scale features may be rejected although the measurements are correct.

The problem occurs when the resolution of the analysis system (as determined by the B-matrix) is insufficient.



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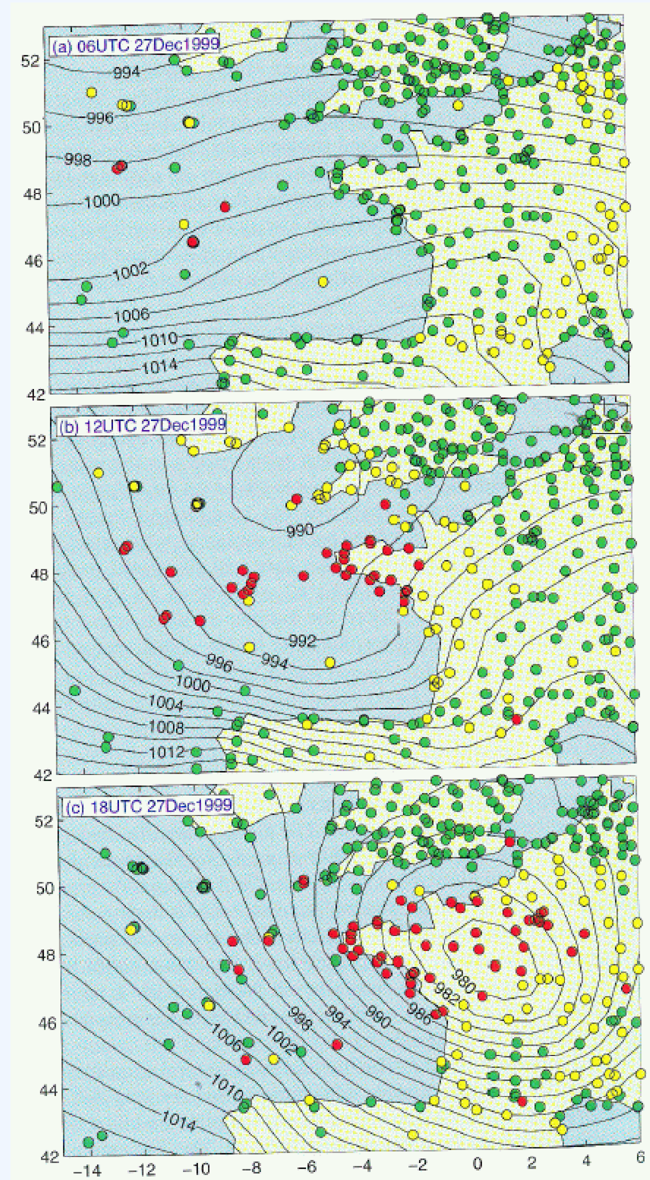
Quality control: Bad example
Extreme event -
The 'French Storm', 27 Dec 1999

Observations of intense and small-scale features may be rejected although the measurements are correct.



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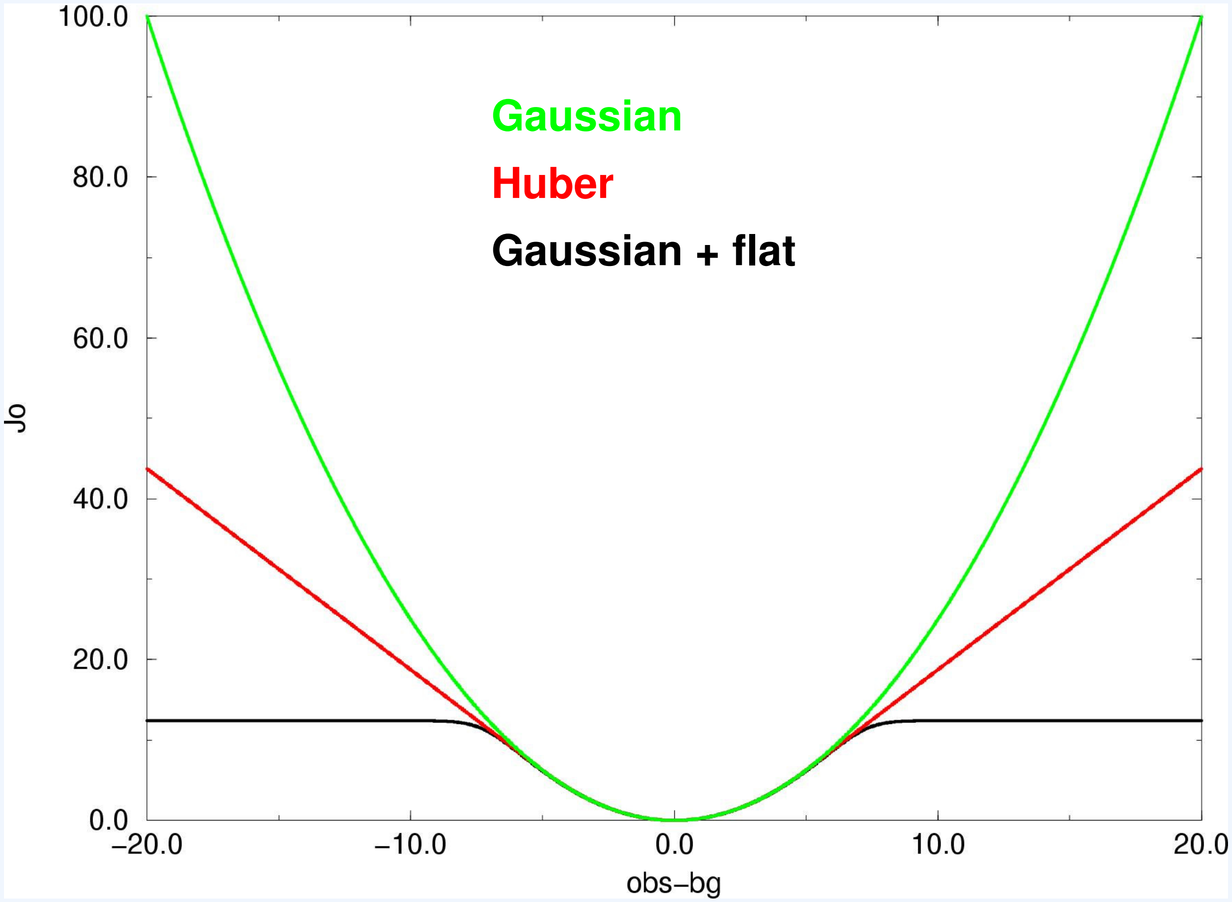
The Huber-norm –



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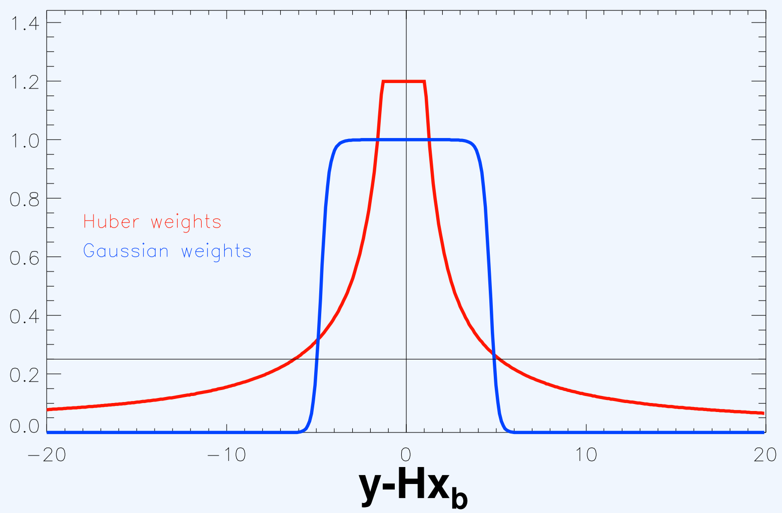
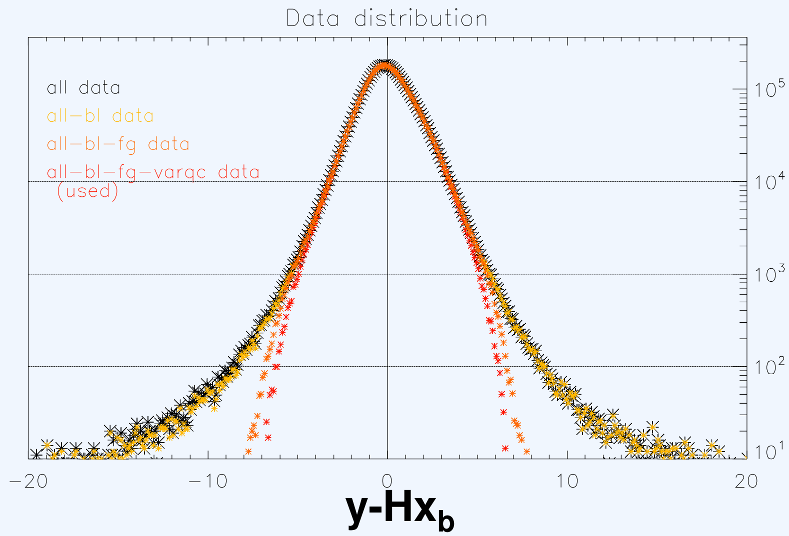
Comparing optimal observation weights
Huber-norm (red) vs. Gaussian+flat (blue)

North Hemisphere Temperature from Radiosonde





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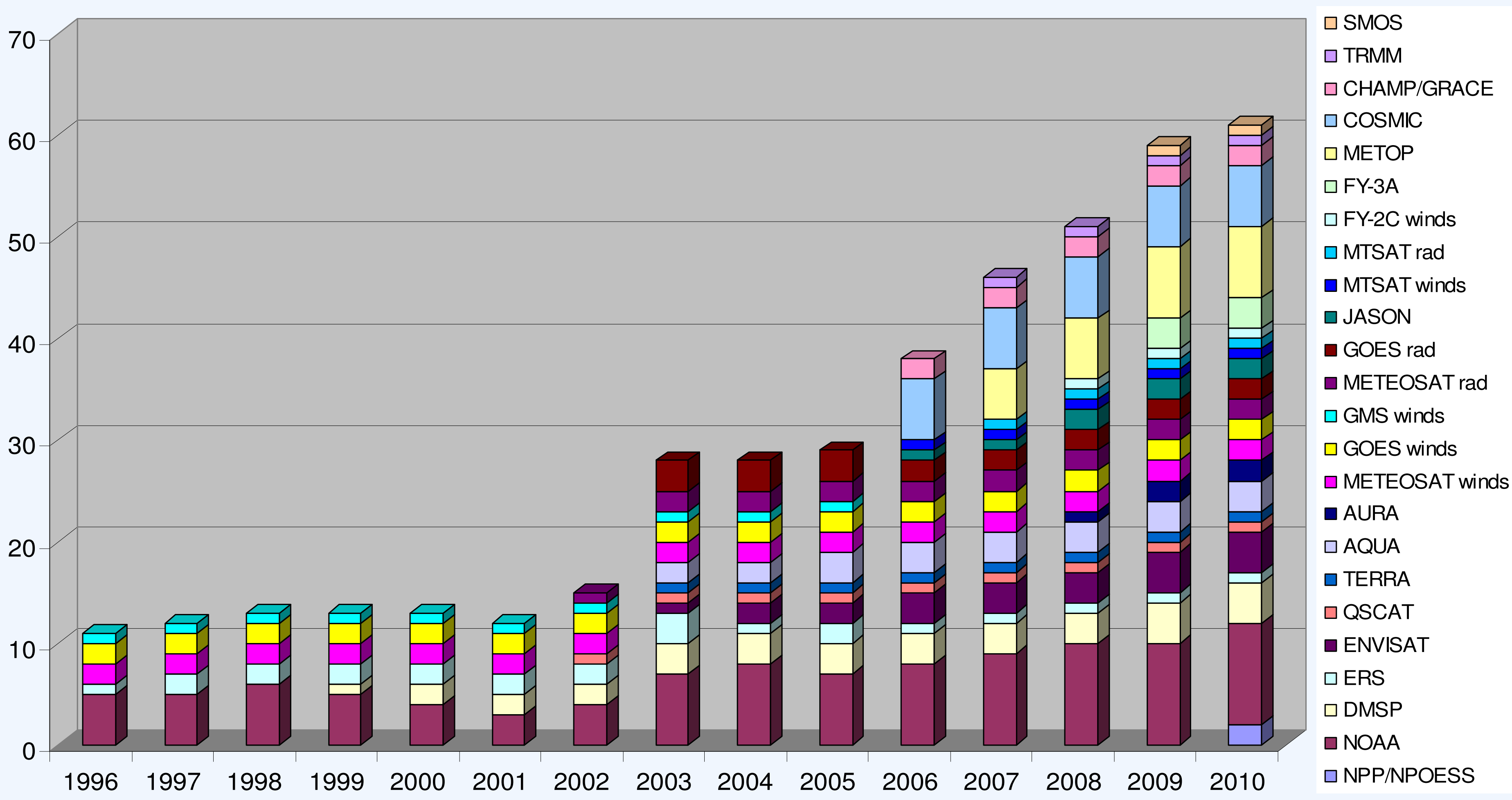
Satellite observing system



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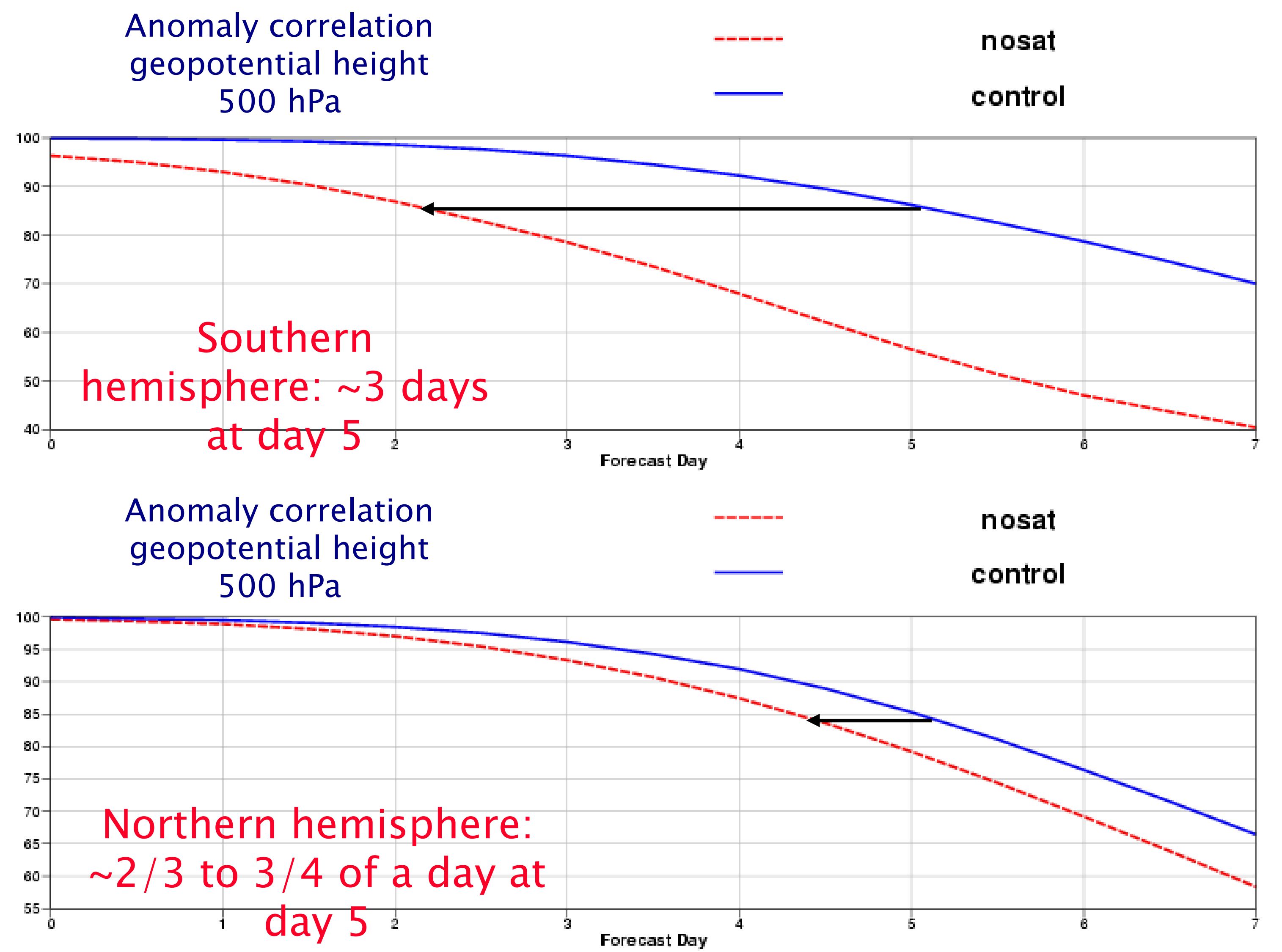
Combined impact of all satellite data



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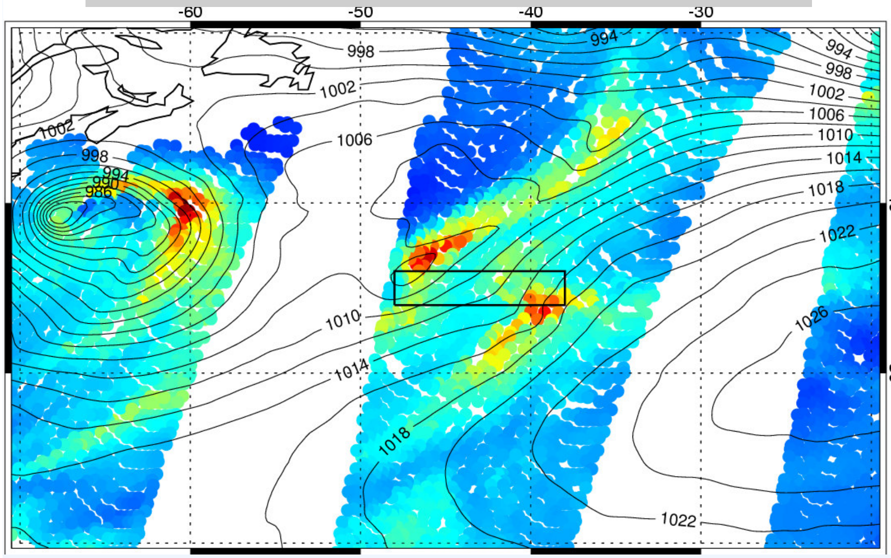
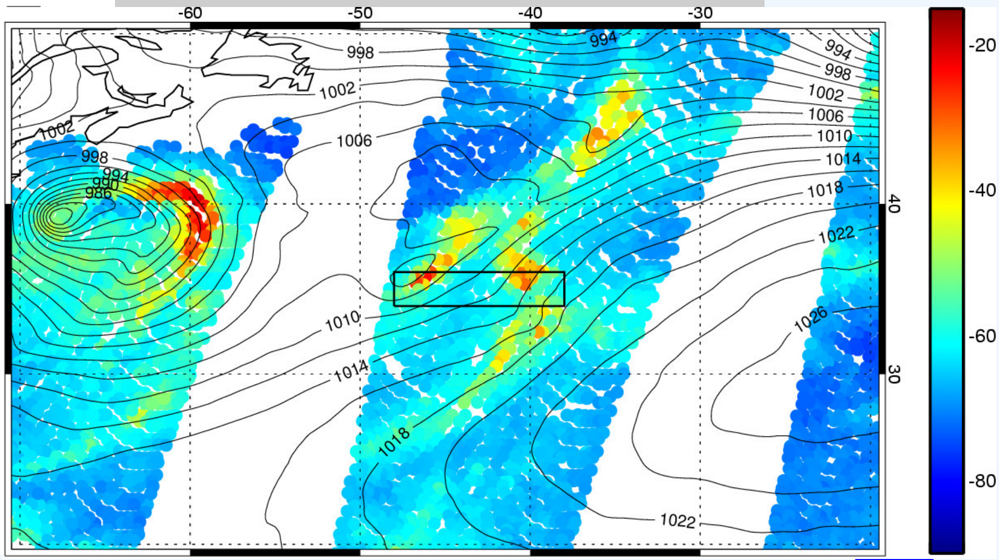
Assimilation of rain-affected microwave radiances

- Assimilation of rain-affected SSM/I radiances in 1D+4D-Var active since June 2005.
- Main difficulties: inaccurate moist physics parameterizations (location/intensity), formulation of observation errors, bias correction, linearity.
- Major improvements accomplished in 2007 and SSMIS, TMI, AMSR-E data included.
- Direct 4D-Var radiance assimilation envisaged for 2008.

4D-Var first guess SSM/I ΔTb 19v-19h [K]



SSM/I observational ΔTb 19v-19h [K]



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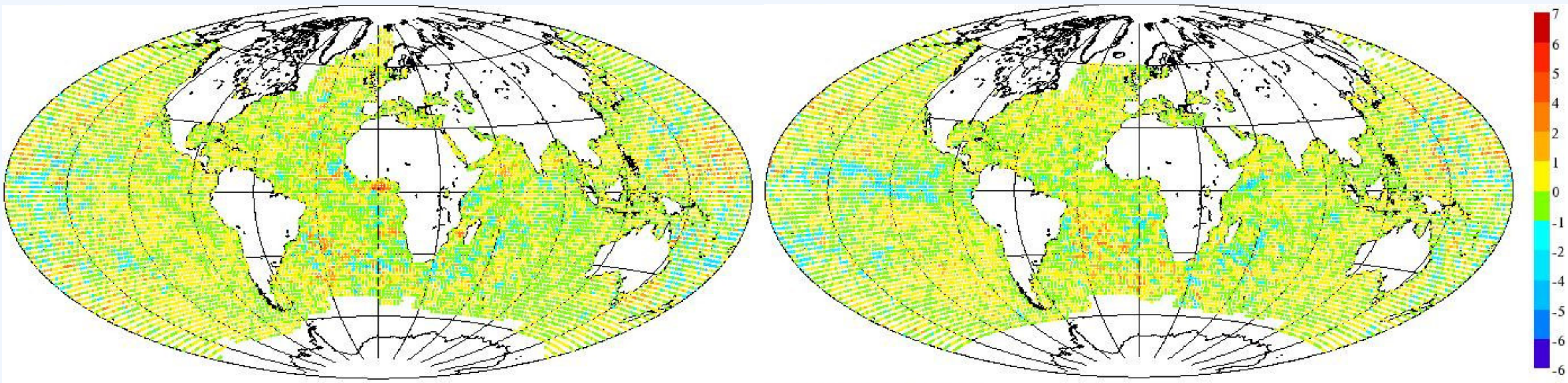
Forecast sensitivity to observations in analysis

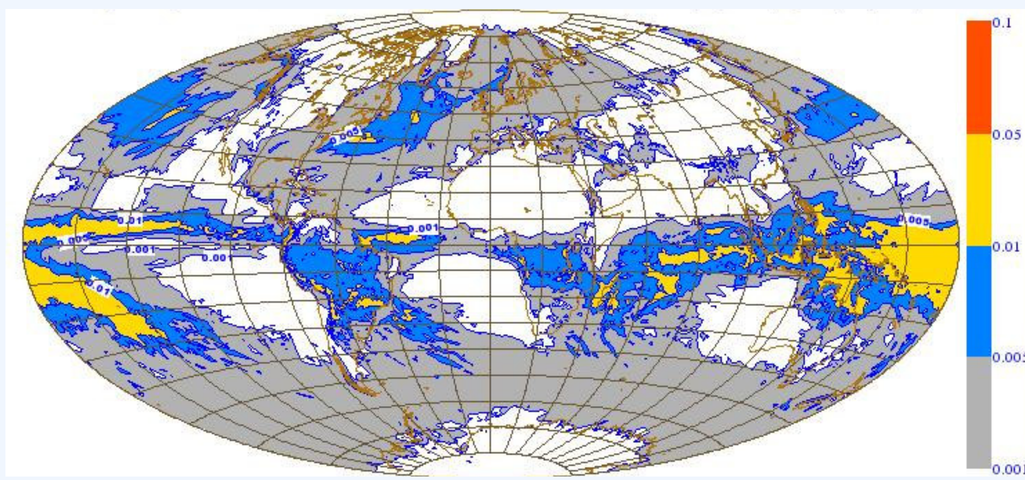
CY32R1, T511L60, 20070105-20070212

SSM/I clear-sky, winter SSM/I clouds/rain, winter



Mean 36-12h precipitation forecast initialized at 12 UTC

[J/kg]



[10^{-3} mm]

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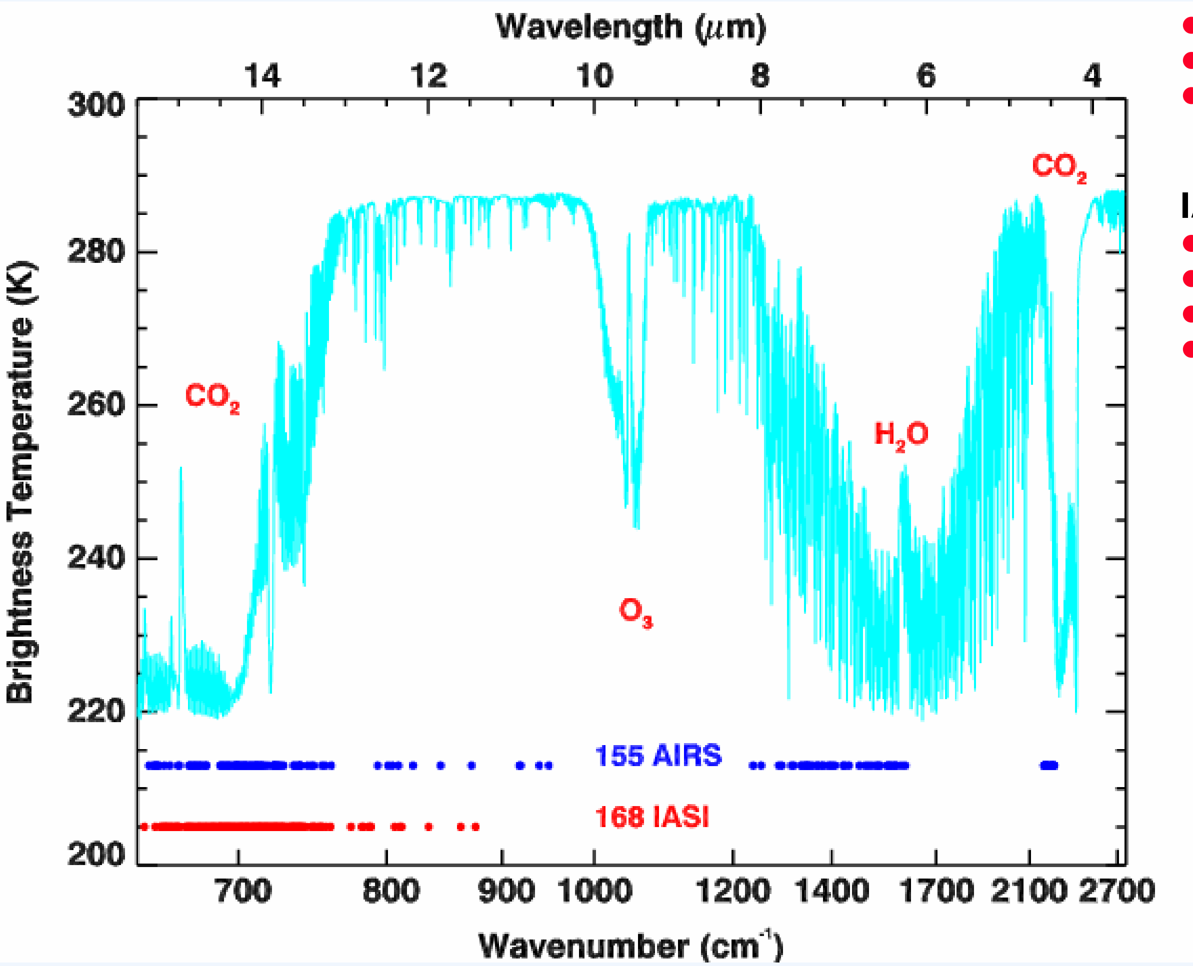
Advanced infrared sounders: AIRS and IASI

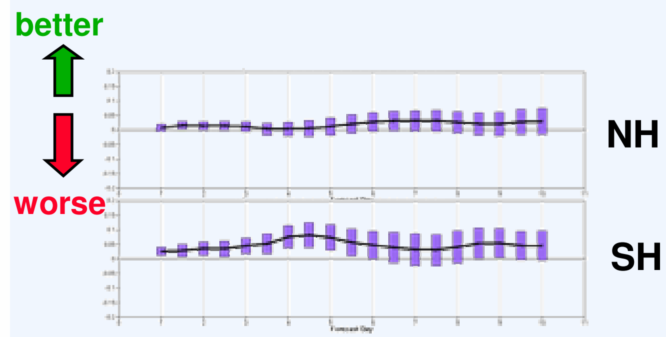


AIRS

- Operational at ECMWF since October 2003.
- 324 channels received.
- Up to 155 channels may be assimilated (CO_2 and H_2O bands).

IASI

- Operational at ECMWF since June 2007.
- 8461 channels received
- 366 Channels routinely monitored.
- Up to 168 channels may be assimilated (CO_2 band only).



500 hPa geopotential anomaly correlation
(56 cases, spring 2007, normalized RMSE difference, own analysi

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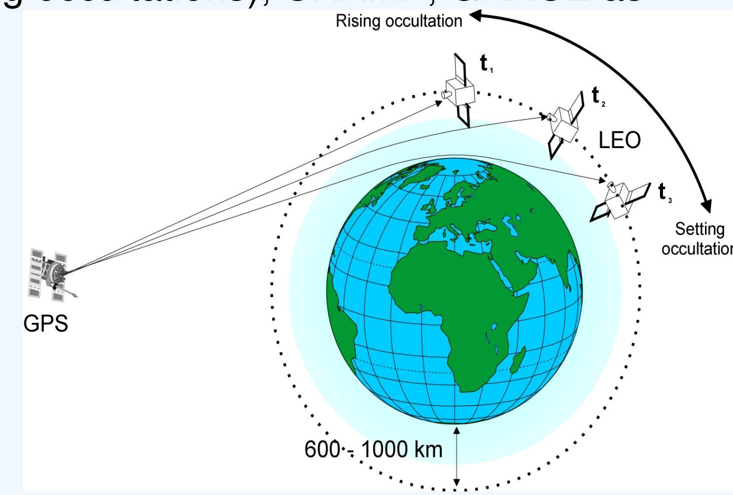
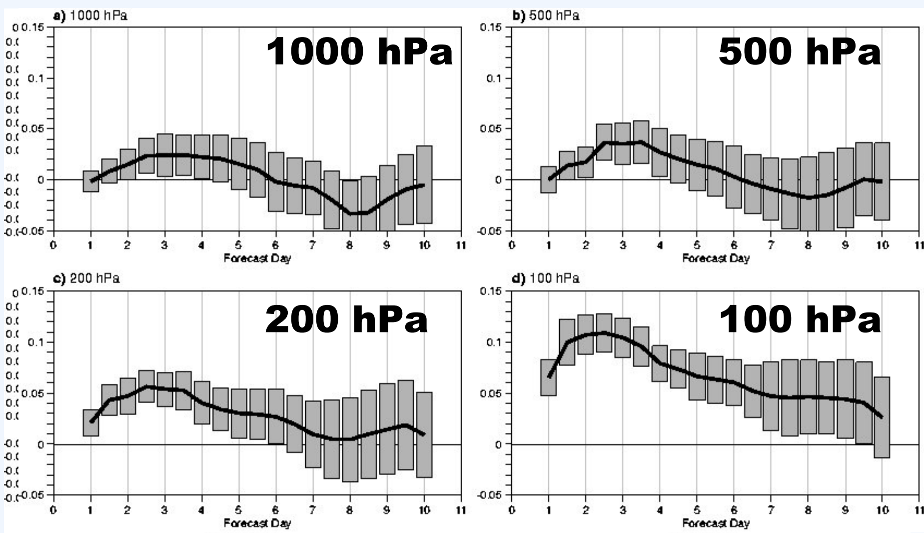
Assimilation of GPS radio occultation data

- COSMIC bending angles assimilated (both rising and setting occultations), CHAMP, GRACE as back-up, GRAS being monitored.
- GPSRO data reveals a warm bias of aircraft observations.
- Substantial improvement of stratospheric T-biases.
- METOP GRAS data assimilated since May 2008.
- COSMIC-2 follow-on?

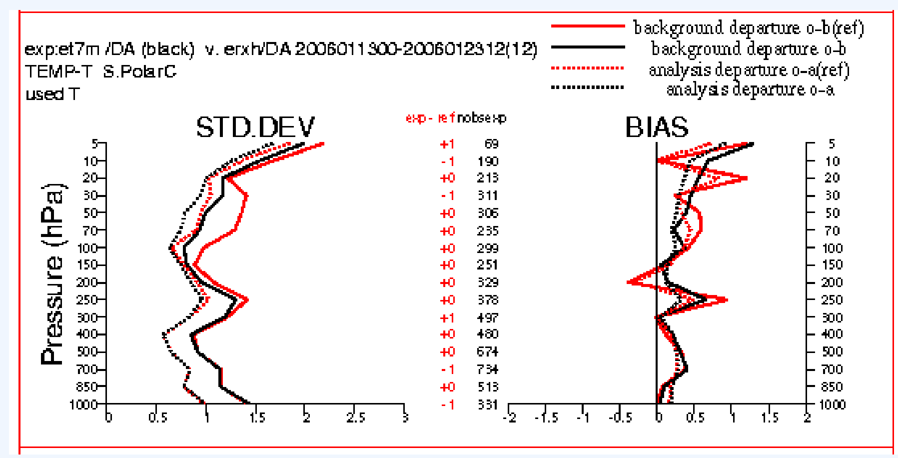


Southern Hemisphere scores

(normalized AC differences)



Improved fit to radiosonde data



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Recent revisions to observation usage

- Use AMSU-B on NOAA-16, 17 and 18, AMSU-A on NOAA-18 and 20
- Operational assimilation of 155 EOS-1/AIRS channels
- Operational assimilation of 168 METOP/IASI channels
- Radiances from Meteosat-5 (India), GOES-9 (Japan) and 12 (replaces GOES-8) and Meteosat-8
- Atmosp. feature track. winds from GOES-12, Meteosat-8, MTSAT-1R
- Use MODIS winds from AQUA satellite
- Use of SCIAMACHY and more SBUV ozone retrievals
- METAR surface pressure data active
- Increase use of radiosonde humidity in upper troposphere
- Use GPS radio occultation data (COSMIC)

Recent revisions to the assimilation system

- Increased resolution from T511/T159 L60 to T799/T255 L91
- Now three outer loop: T799 outer with T95/T159/T255 inner loop
- Use grid-point humidity and ozone in 4D-Var analysis
- More advanced Tangent Linear physics scheme in 4D-Var
- Wavelet Jb formulation has been implemented
- Jb statistics from latest ensemble data assimilation
- New humidity analysis using a normalized control variable
- Assimilation of “Cloudy and rainy radiances”
- Variational bias correction of satellite radiances
- Adaptive bias correction for radiosondes and SYNOP pressure data

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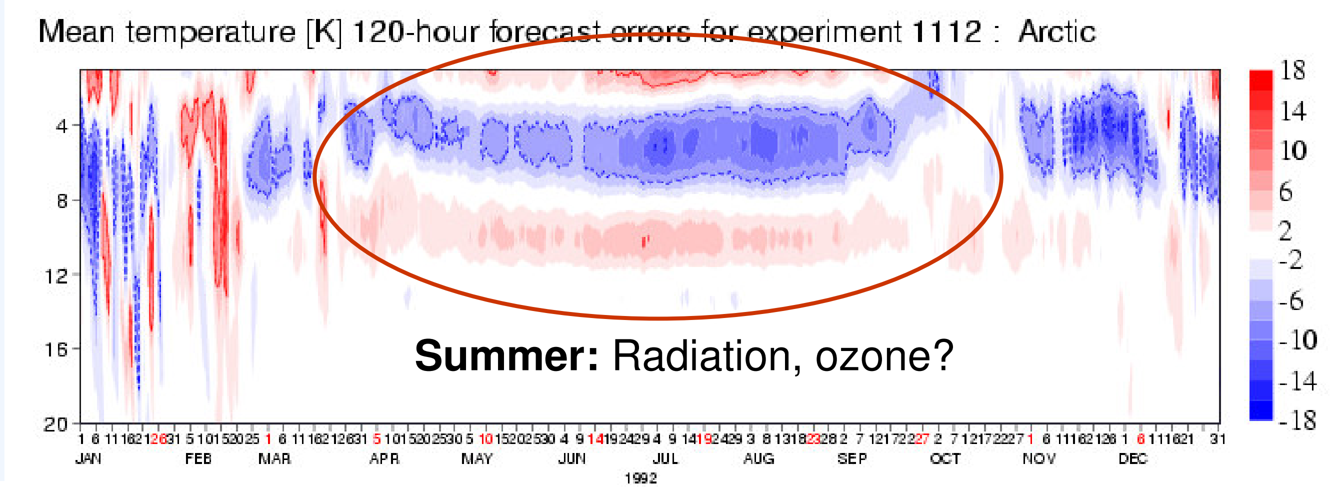
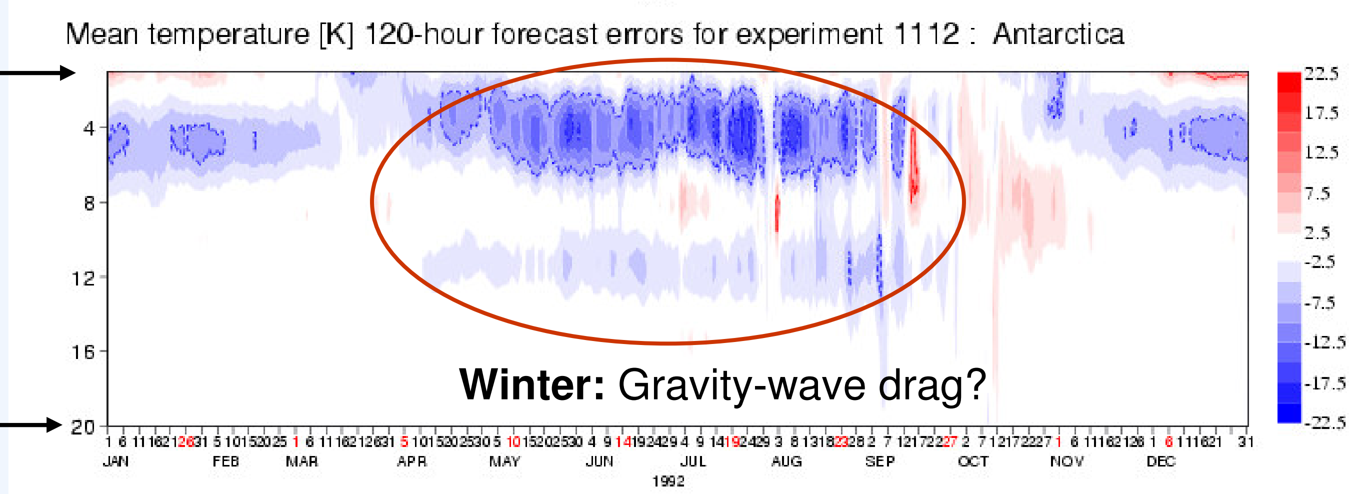
Model bias:

upper-stratospheric model errors variation

T255L60 model currently used for ERA-Interim



0.1hPa (65km)

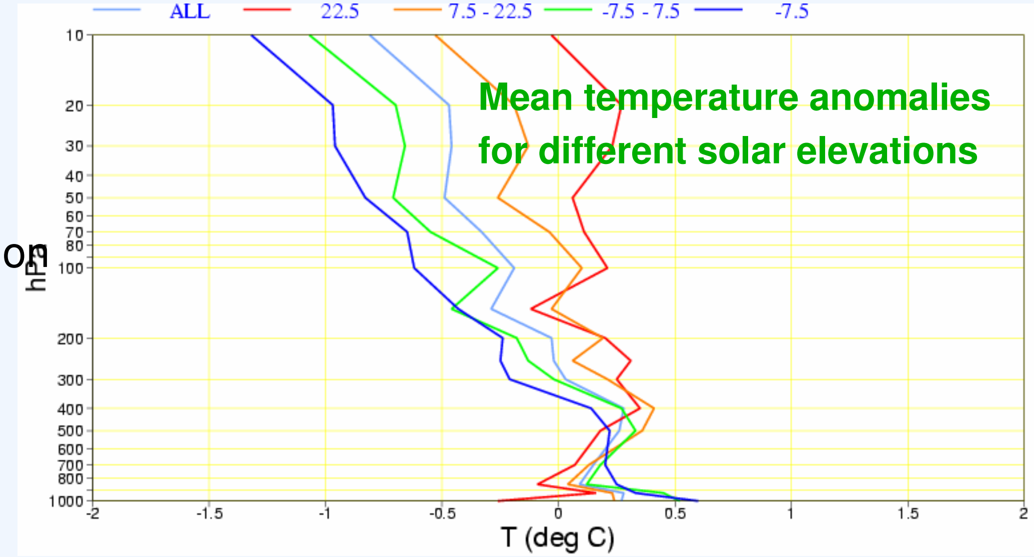


20hPa (22km)

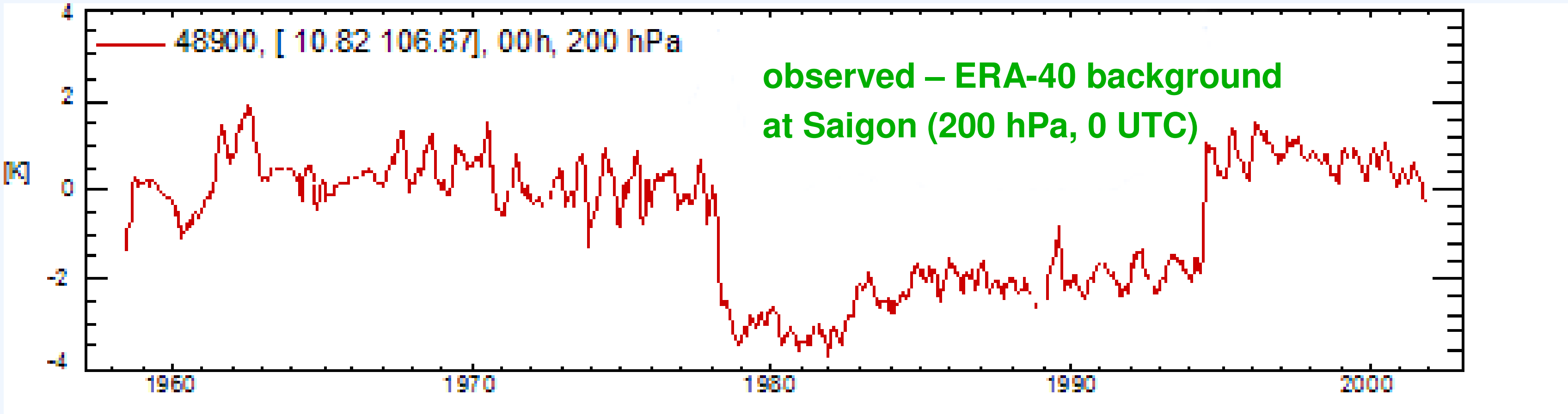
ECMWF

Observation bias:
Radiosonde temperature observations

Daytime warm bias due to radiative heating of the temperature sensor (depends on solar elevation and equipment type)



Bias changes due to change of equipment

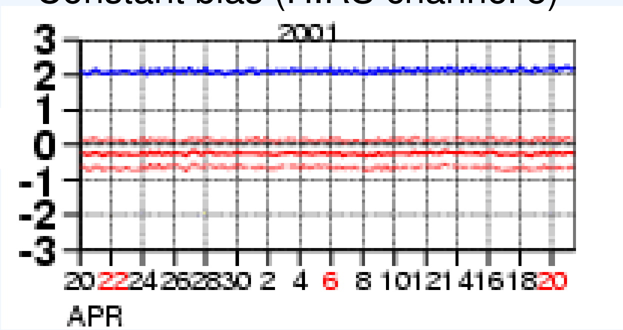


ECMWF

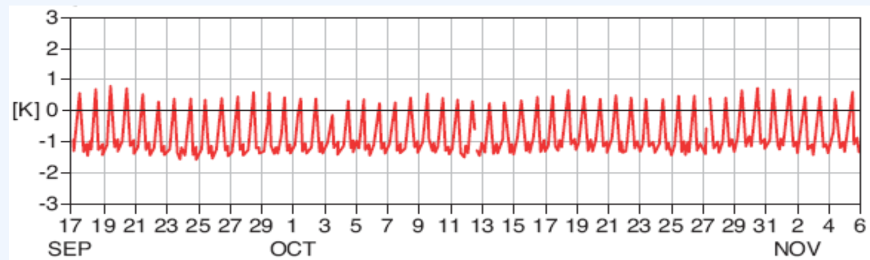
Observation bias:
Satellite radiances

Monitoring the background departures (averaged in time and/or space):

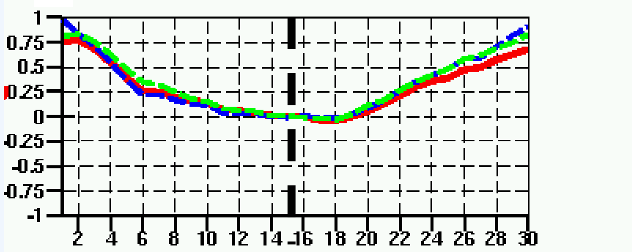
Constant bias (HIRS channel 5)



Diurnal bias variation in a geostationary satellite

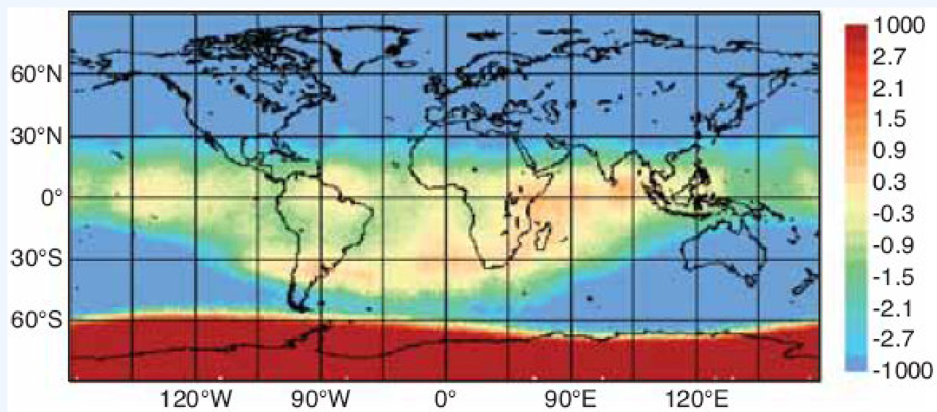


Bias depending on scan position (AMSU-A ch 7)



limb nadir limb

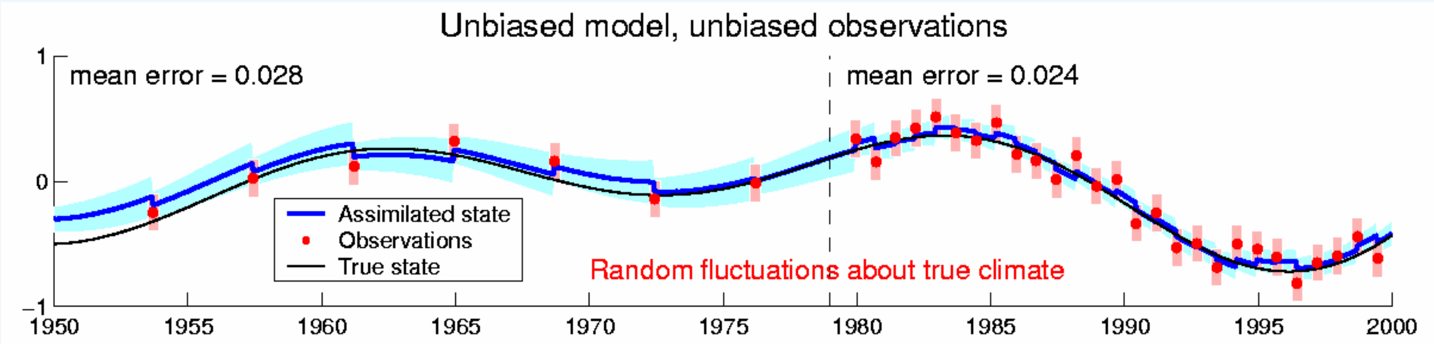
Air-mass dependent bias (AMSU-A channel 14)



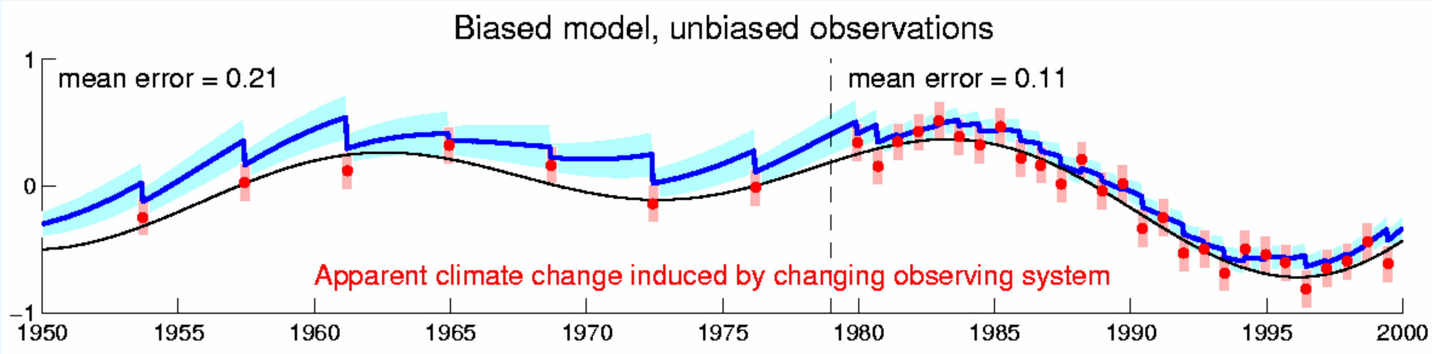
ECMWF

Implications for data assimilation:
The effect of model bias on trend estimates

Most assimilation systems assume unbiased models and unbiased data



Biases in models and/or data can induce spurious trends in the assimilatio



ECMWF

Variational bias correction:
The modified analysis problem

The original problem:

Dee 2004, 2005

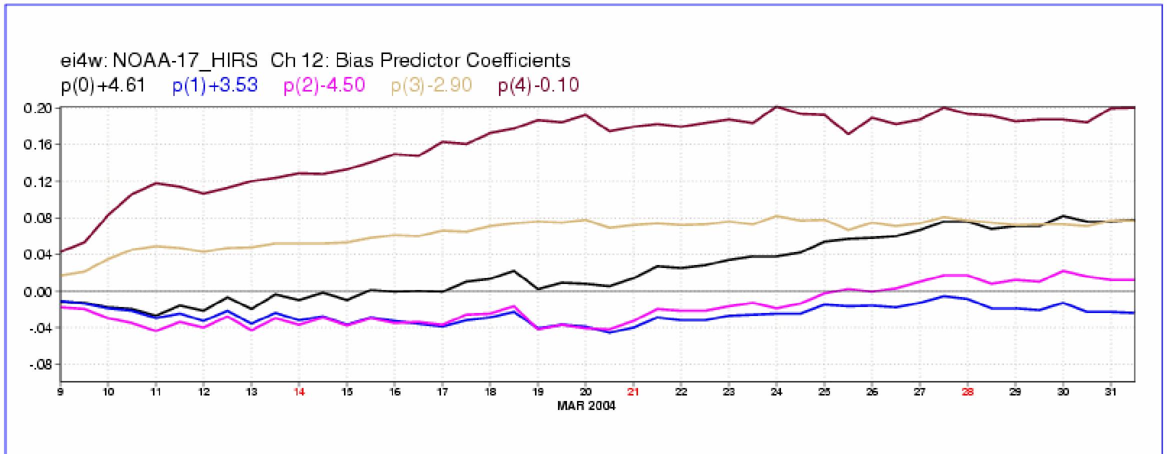
$$J(\mathbf{x}) = \overbrace{(\mathbf{x}_b - \mathbf{x})^T \mathbf{B}^{-1}(\mathbf{x}_b - \mathbf{x})}^{J_b:\ \text{background constraint}} + \underbrace{[\mathbf{y} - \mathbf{h}(\mathbf{x})]^T \mathbf{R}^{-1}[\mathbf{y} - \mathbf{h}(\mathbf{x})]}_{J_o:\ \text{observation constraint}}$$

The modified problem:

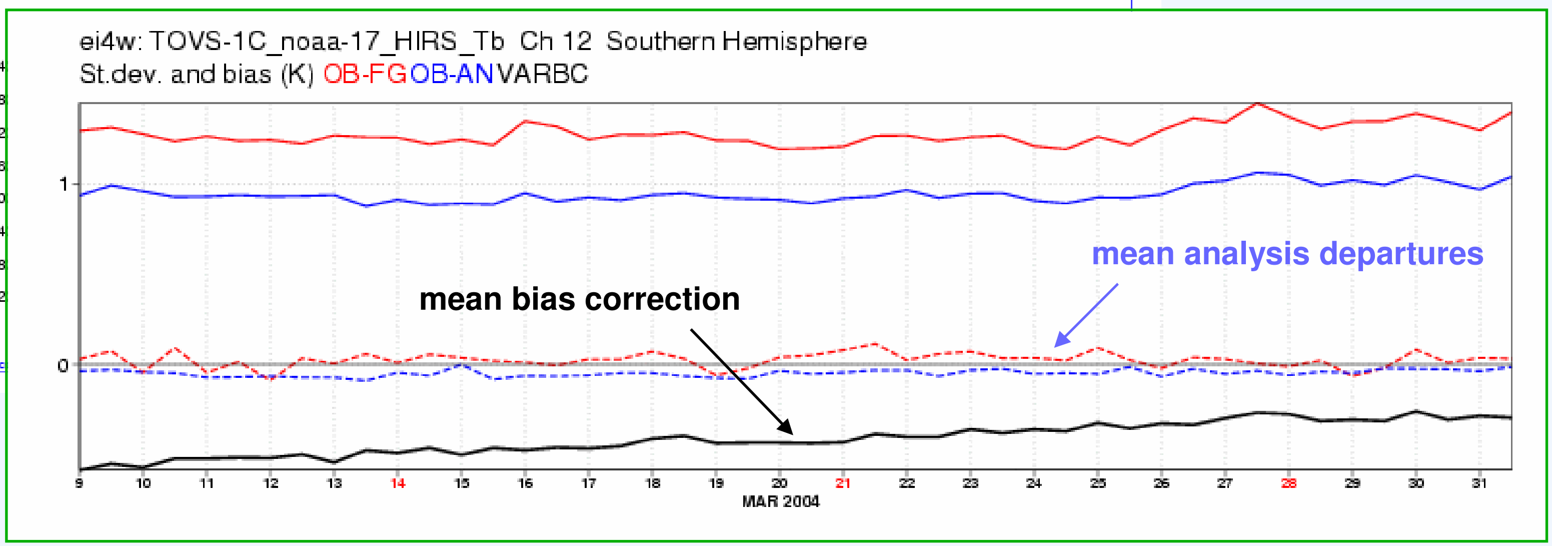
$$\mathbf{J}(\mathbf{x}, \boldsymbol{\beta}) = \overbrace{(\mathbf{x}_b - \mathbf{x})^T \mathbf{B}_x^{-1}(\mathbf{x}_b - \mathbf{x})}^{J_b:\ \text{background constraint for x}} + \overbrace{(\boldsymbol{\beta}_b - \boldsymbol{\beta})^T \mathbf{B}_\beta^{-1}(\boldsymbol{\beta}_b - \boldsymbol{\beta})}^{J_\beta:\ \text{background constraint for } \beta}$$
$$+ \underbrace{[\mathbf{y} - \mathbf{b}_o(\mathbf{x}, \boldsymbol{\beta}) - \mathbf{h}(\mathbf{x})]^T \mathbf{R}^{-1}[\mathbf{y} - \mathbf{b}_o(\mathbf{x}, \boldsymbol{\beta}) - \mathbf{h}(\mathbf{x})]}_{J_o:\ \text{bias-corrected observation constraint}}$$

Parameter estimate from previous analysis

Performance:
Adaptive bias correction of NOAA-17 HIRS Ch12



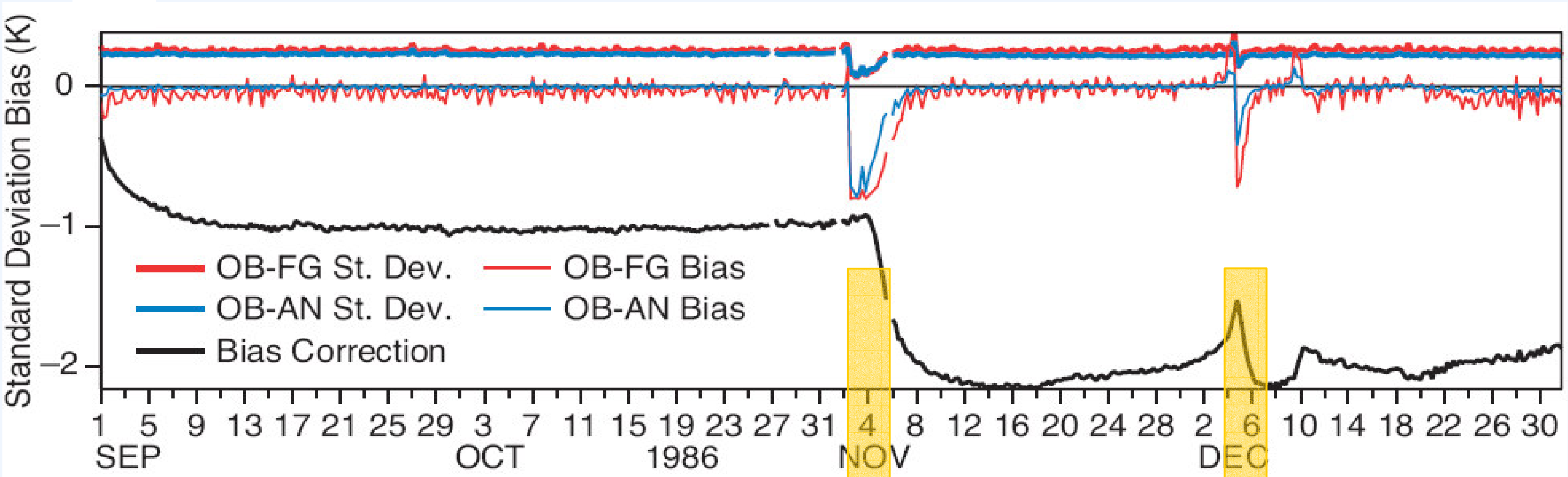
p(0): global constant
p(1): 1000-300hPa thickness
p(2): 200-50hPa thickness
p(3): surface temperature
p(4): total column water



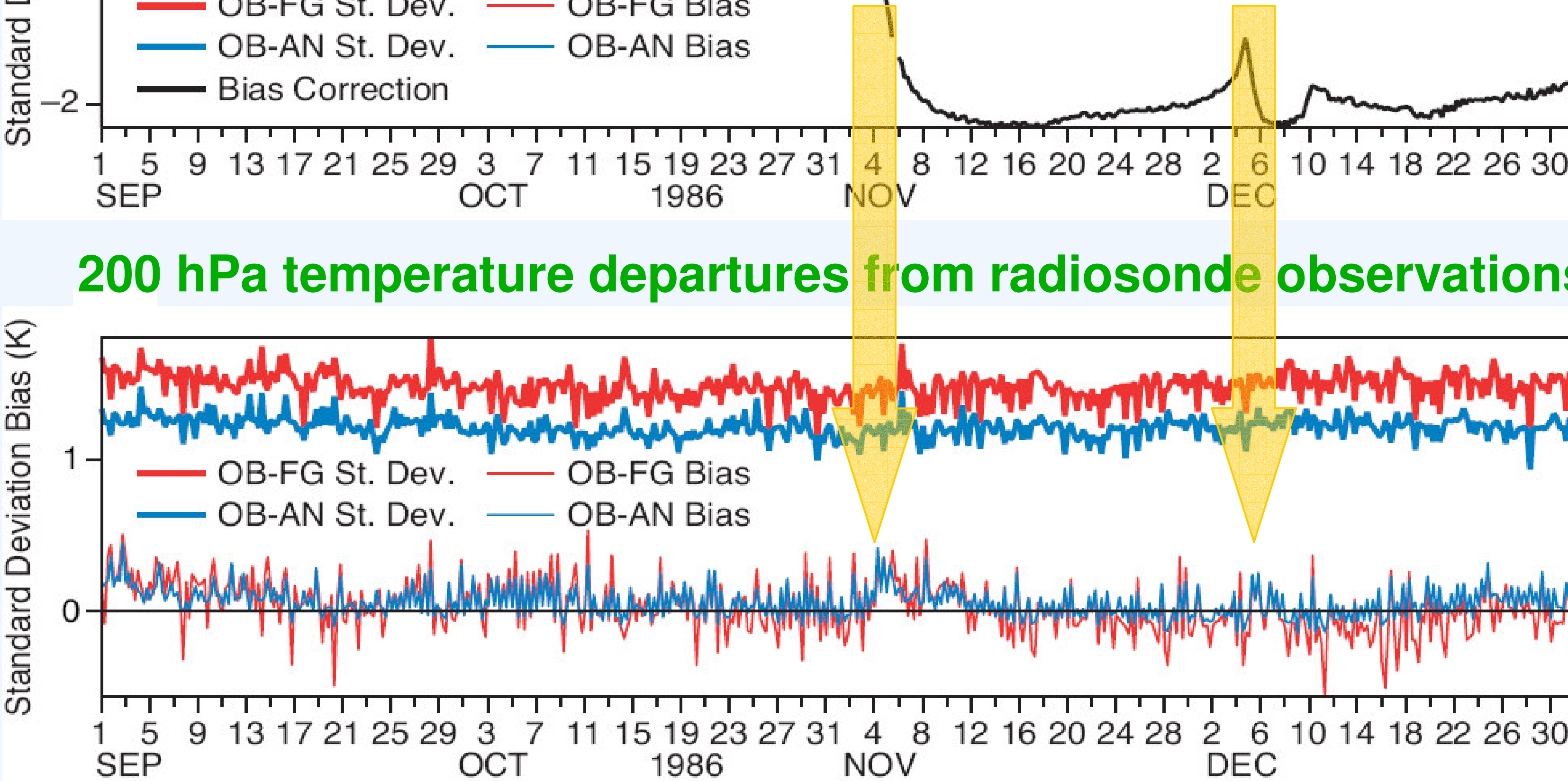
ECMWF

Performance:

NOAA-9 MSU channel 3 bias corrections (cosmic storm)



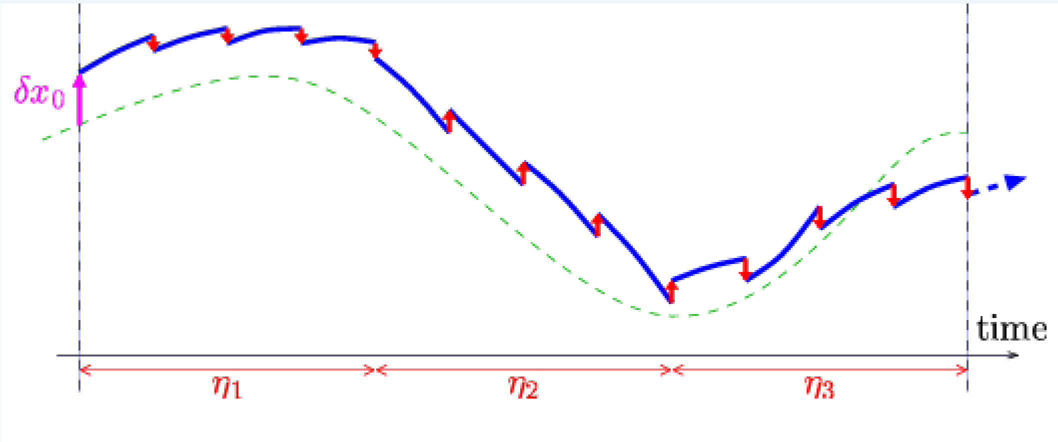
200 hPa temperature departures from radiosonde observations



Weak-constraint 4D-Var

Include model error in the control vector:

$$
\begin{aligned}
J(x_0,\eta) &= \frac{1}{2}\sum_{i=0}^{n}[\mathcal{H}(x_i)-y_i]^T R_i^{-1}[\mathcal{H}(x_i)-y_i] \\
&+ \frac{1}{2}(x_0-x_b)^T B^{-1}(x_0-x_b) + \eta^T Q^{-1}\eta \\
&\quad \text{with } x_i = \mathcal{M}_i(x_{i-1}) + \eta_i .
\end{aligned}
$$



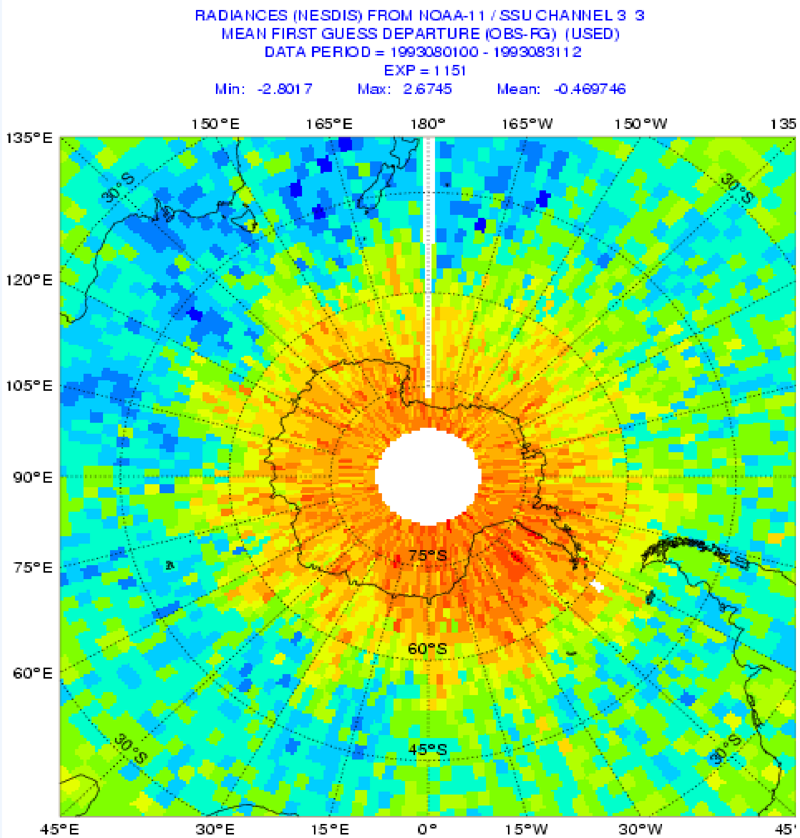
Tremolet 2007

Lindskog 2008

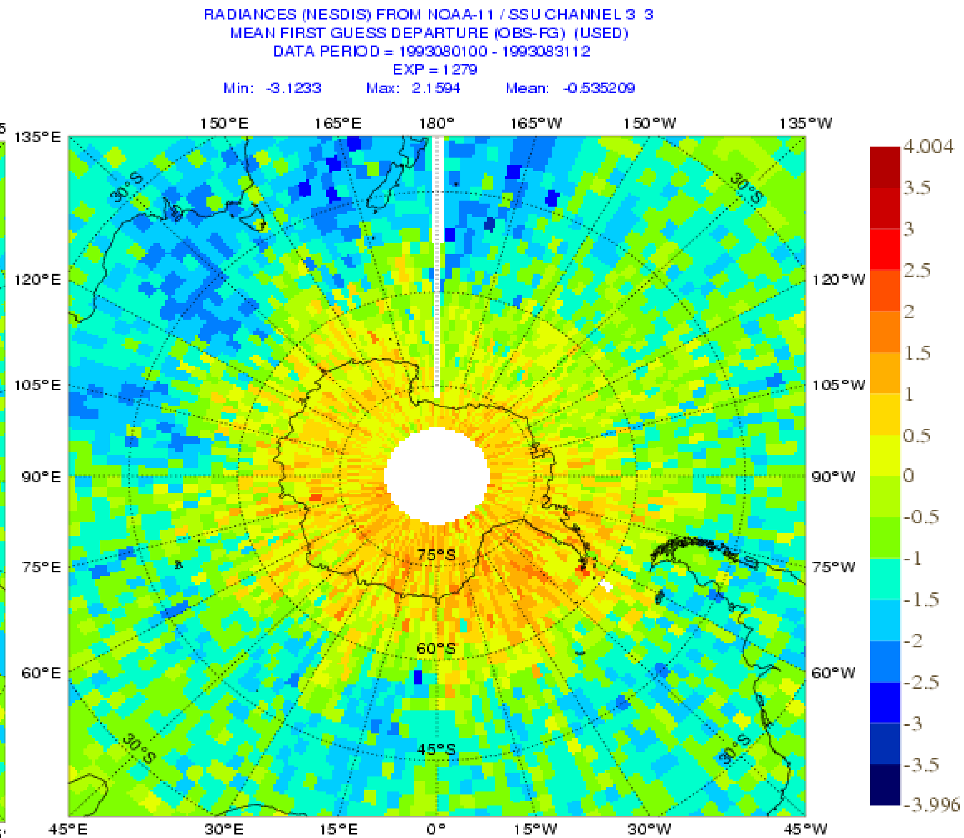
Constraint is determined by Q

SSU Ch3 mean radiance departures – Aug 1993

ERA-Interim



ERA-Interim + weak constraint



ECMWF

Fundamental challenging of ECMWF 4D-Var Assimilation System

- Incremental 4D-Var
- Linearized Physics
- Observation handling
- Assimilation of satellite data
- Model and Observation Bias
- **Modelling Background Covariance**

Importance of Background Covariances

- The formulation of the J_b term of the cost function is ***crucial*** to the performance of current analysis systems.
- To see why, suppose we have a **single observation** of the value of a **model field** at **one gridpoint**.

- For this simple case, the observation operator is:

$$H = (\, 0,\ldots,0,1,0,\ldots,0) \,.$$

- The gradient of the 3dVar cost function is:

$$\nabla J = B^{-1}(x-x_b) + H^T R^{-1}(Hx-y) = 0$$

- Multiply through by B and rearrange a bit:

$$x - x_b = B\, H^T R^{-1}(y-Hx)$$

- But, for this simple case, $R^{-1}(y-Hx)$ is a **scalar**

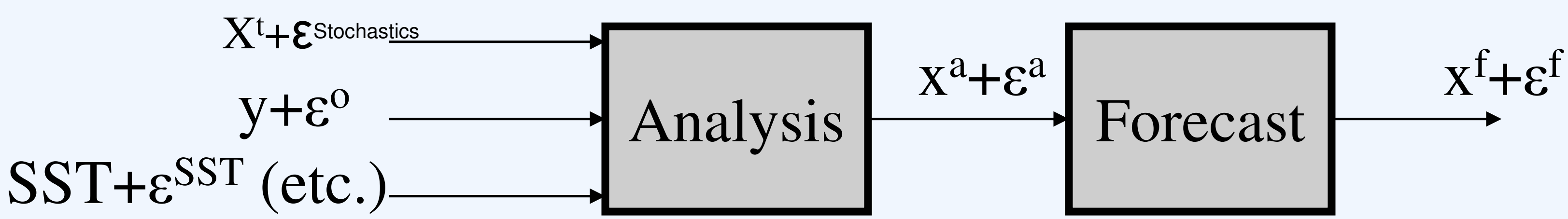
Importance of Background Covariances

- So, we have: $\mathbf{x} - \mathbf{x}_b \propto \mathbf{B}\mathbf{H}^{\mathrm{T}}$
- But, H = (0,...,0,1,0,...,0)
- => <u>The analysis increment is proportional to a column of B</u>.
- The role of B is:
  1. To spread out the information from the observations.
  2. To provide statistically consistent increments at the neighbouring gridpoints and levels of the model.
  3. To ensure that observations of one model variable (e.g. temperature) produce dynamically consistent increments in the other model variables (e.g. vorticity and divergence).

Estimating Background Error Statistics from Ensembles of Analyses

Normal Analysis

Perturbed Analysis



The ECMWF J_b Formulation – the balance operator

- The most obvious correlation in the background errors is the balance between mass errors and wind errors in the extra-tropics.
- We therefore define our change of variable as:

$$L = KB_u^{1/2}$$

- where K accounts for all the correlation ***between*** variables (e.g. between the mass and wind fields).
- The matrix B_u is a covariance matrix for variables that are uncorrelated with each other.

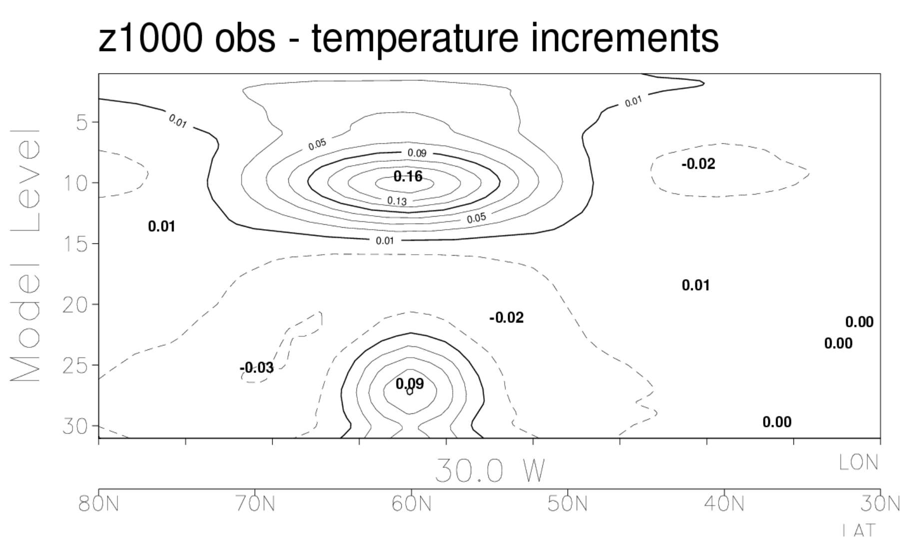
The ECMWF J_b Formulation – The balance operator

$$\begin{pmatrix} \zeta \\ \mathbf{D} \\ (\mathbf{T},\mathbf{p}_s) \\ \mathbf{q} \end{pmatrix} = \begin{pmatrix} \mathbf{I} & 0 & 0 & 0 \\ \mathbf{M} & \mathbf{I} & 0 & 0 \\ \mathbf{N} & \mathbf{P} & \mathbf{I} & 0 \\ 0 & 0 & 0 & \mathbf{I} \end{pmatrix} \begin{pmatrix} \zeta \\ \mathbf{D}_u \\ (\mathbf{T},\mathbf{p}_\mathbf{s})_u \\ \mathbf{q} \end{pmatrix}$$

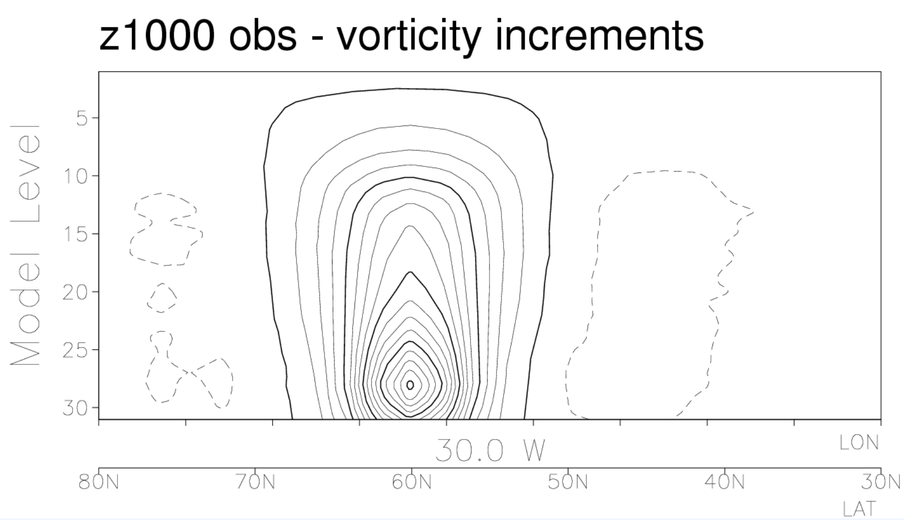
- **The most important part of the balance operator is the sub-matrix N, which calculates a balanced part of (T,p_s), determined from the vorticity.**
- **N is implemented in 2 parts:**
  1. A balanced "geopotential" is calculated from ζ.
  2. Balanced (T,p_s) are calculated using statistical regression between (T,p_s) and geopotential.

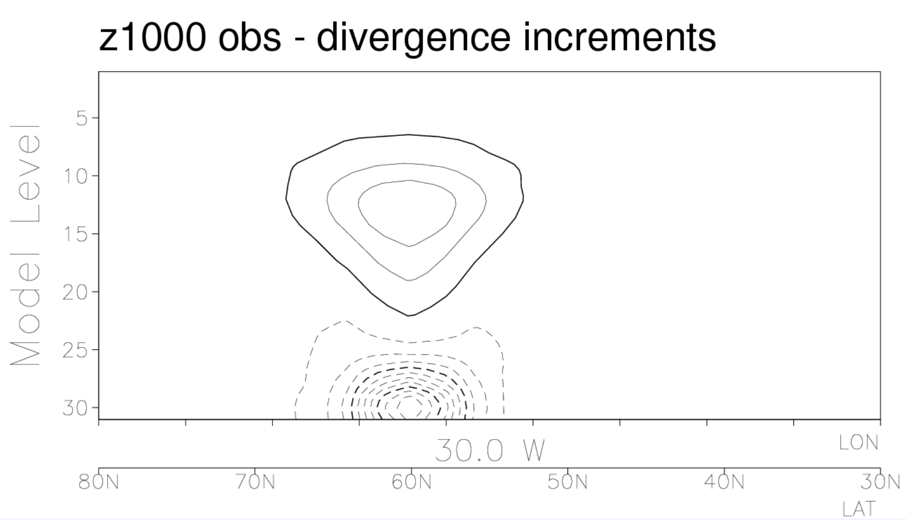
ECMWF

Increments from a single observation



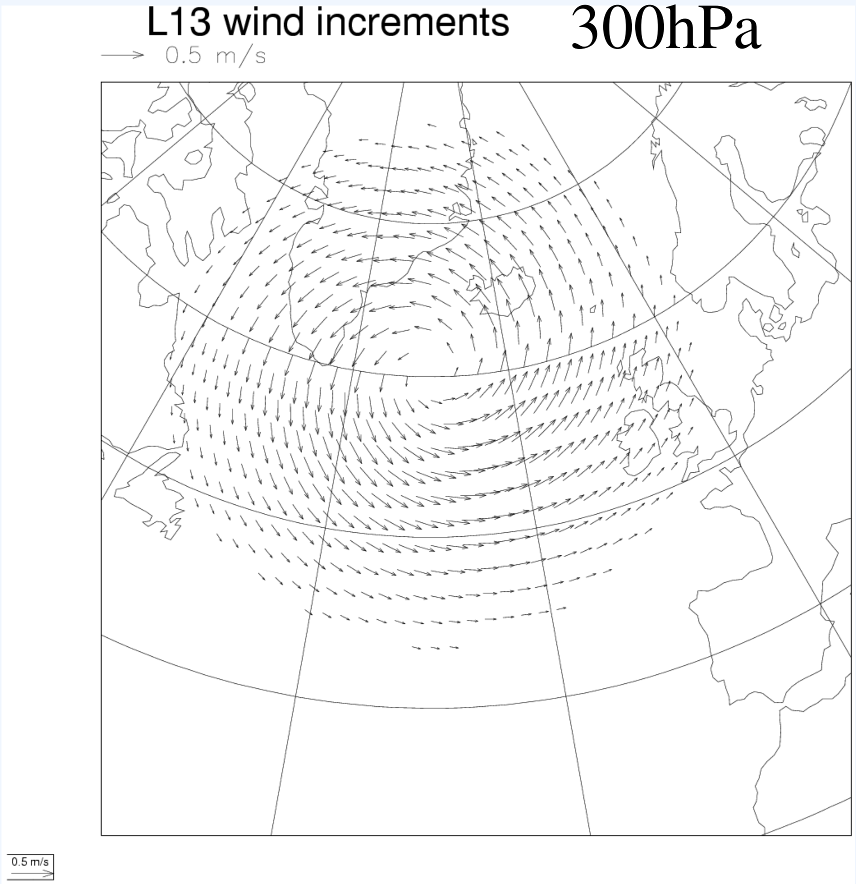
Increments due to a single observation of geopotential height at 1000 hPa 60N with value 10m below background

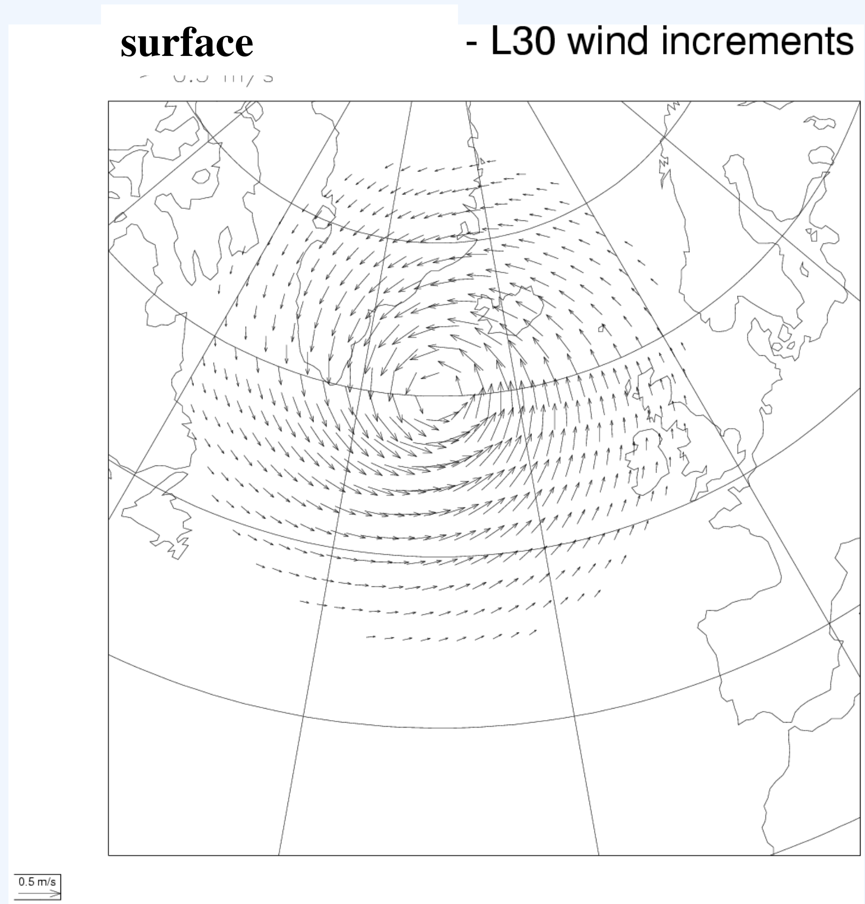




ECMWF

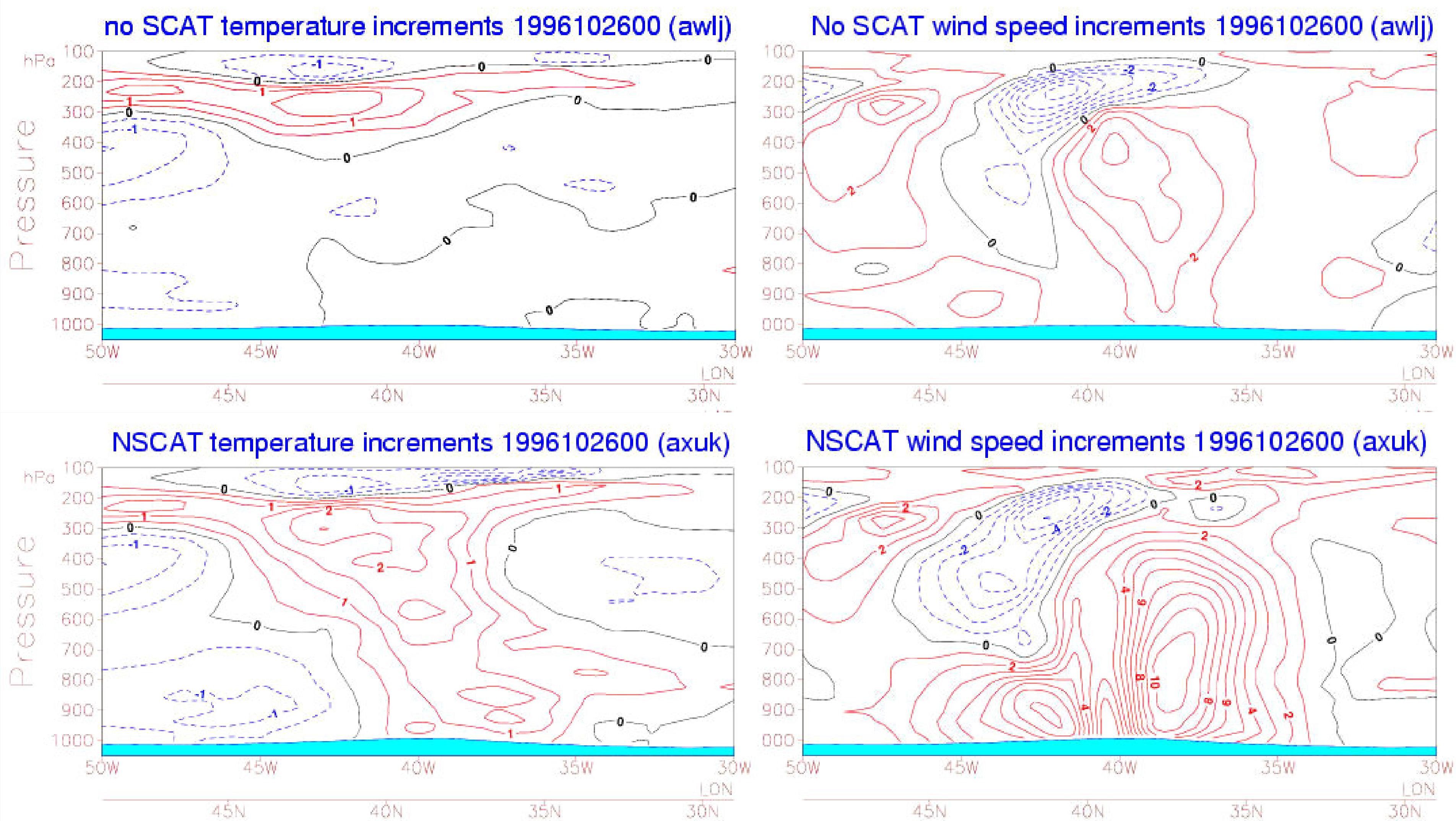
Increments for a single observation of geopotential height at 1000hPa





ECMWF

NSCAT wind information vertically propagated and impact on other variables

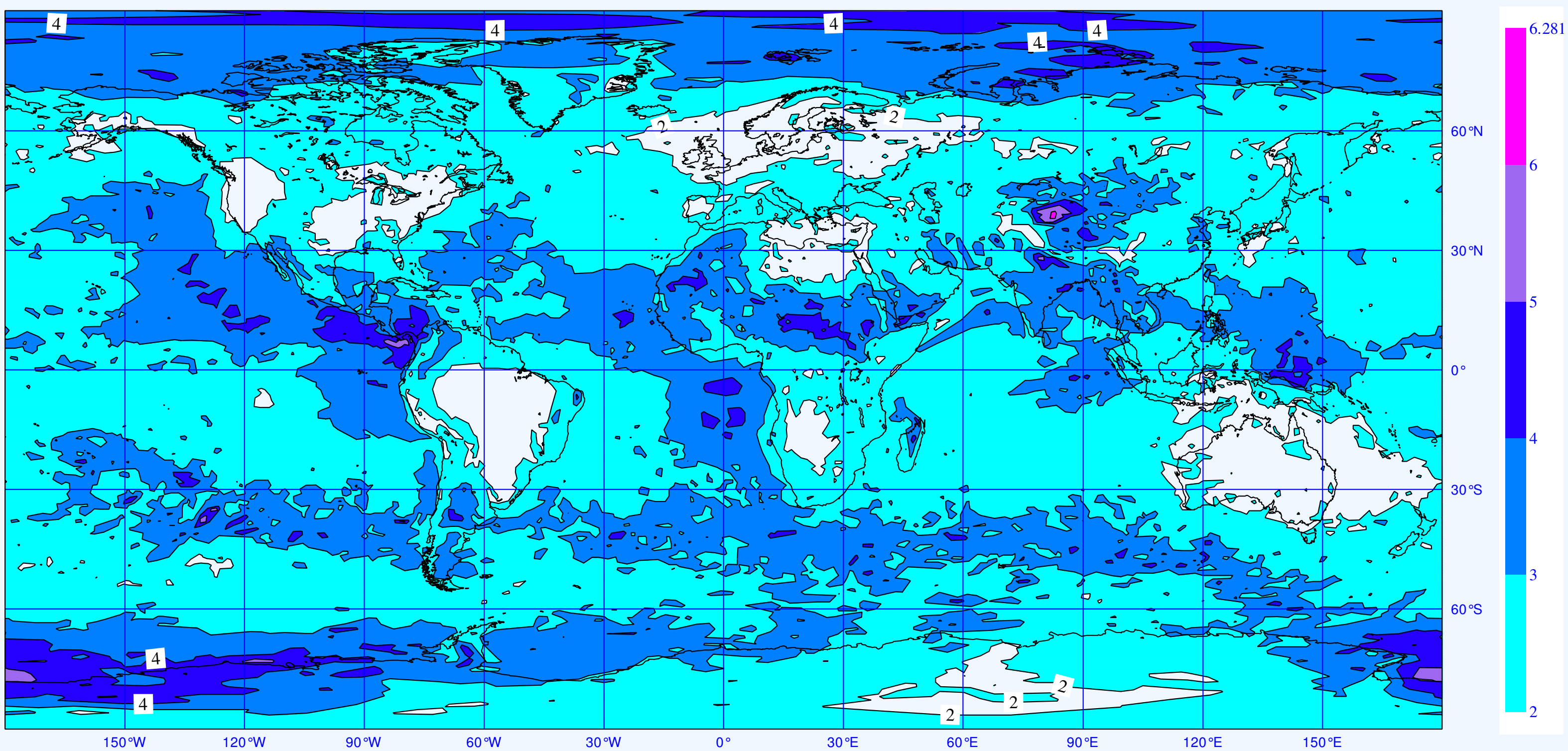


ECMWF

Ensembles of data assimilations

- Run an ensemble of analyses with randomly perturbed observations, peturbed SST field and stochastic physics perturbations.
- Compute the variance of the short-range forecast fields
- The spread will have the statistical characteristics of short-range forecast error and it will be flow dependent

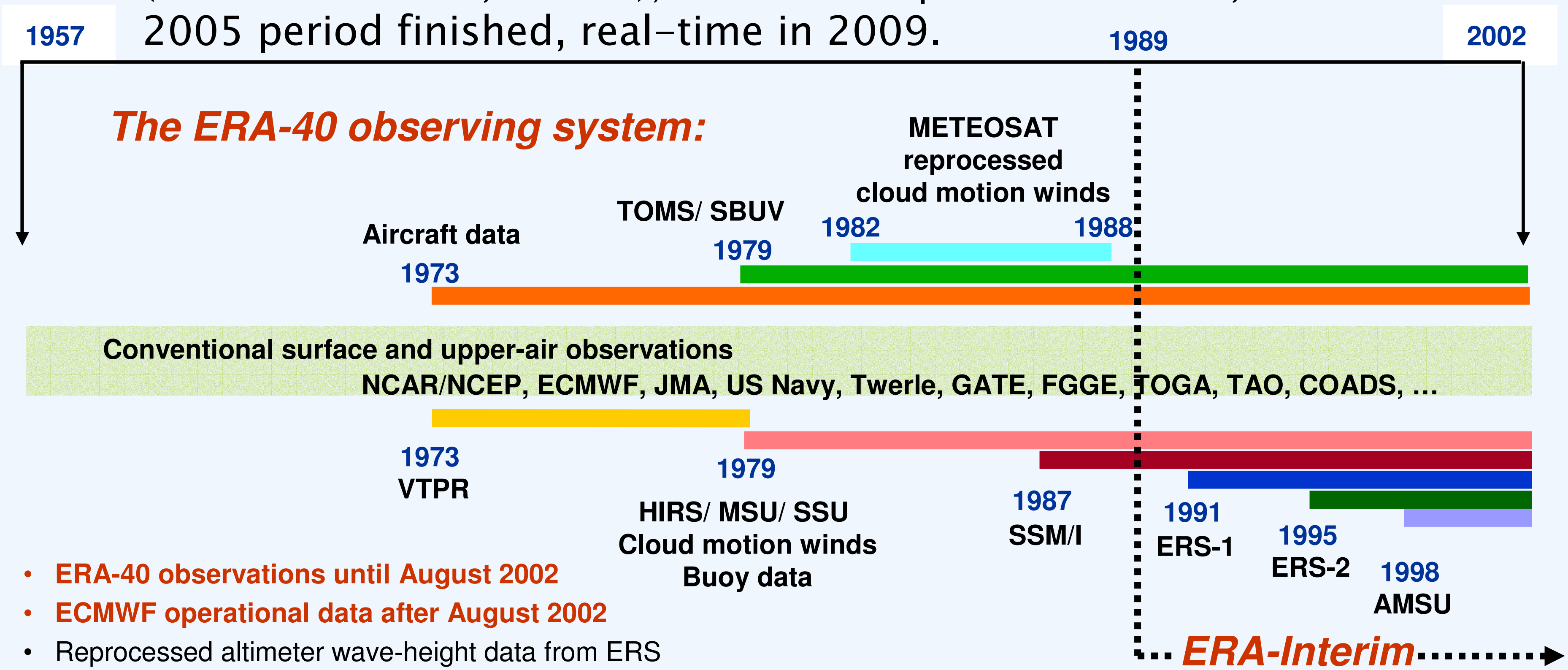
850 hPa U-Comp 1-Month EnDA Mean Spread of 3-hour forecast



ECMWF

Reanalysis

- ERA-Interim is current ECMWF reanalysis project following ERA-15 & 40.
- 2006 model cycle, 4D-Var, variational bias-correction, more data (rain assimilation, GPSRO); 1989-1998 period available, 1998-2005 period finished, real-time in 2009.



- **ERA-40 observations until August 2002**
- **ECMWF operational data after August 2002**
- Reprocessed altimeter wave-height data from ERS
- Humidity information from SSM/I rain-affected radiance data
- Reprocessed METEOSAT AMV wind data
- Reprocessed ozone profiles from GOME
- Reprocessed GPSRO data from CHAMP