Data assimilation at high latitudes

Erik Andersson

Acknowledgement: Niels Bormann, Carla Cardinali, Matthias Drusch, Mike Fisher, Lars Isaksen, Jean-Noël Thépaut, Drasko Vasiljević

- Introduction
- ECMWF's 4D-Var and surface analyses – A brief introduction
- Examples of polar features in the analyses
- The Arctic and Antarctic NWP observing systems and their impacts
- Estimates of analysis accuracy (uncertainty)
- Perspectives

Jukkasjärvi, next to ESA's space station, Kiruna, Sweden

Antarctica provides a challenging environment for data assimilation in several ways:

- **The dearth of in-situ observations**
- **Extreme topography**
- **Cloud cover issues (coastal Antarctica is one of the cloudiest places on Earth)**
- **The impact of high surface emissivity on radiances**
- **The forecast model's physical parameterizations may not have been tuned for differing (extreme) regimes**

McNally's talk

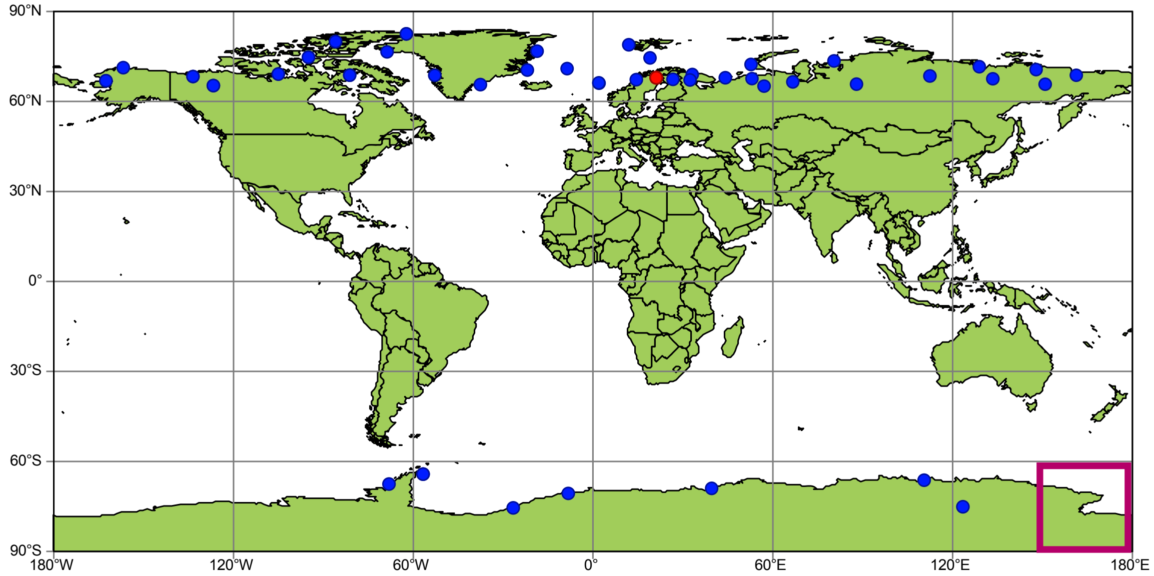
Beljaars' + Jung's talks

Barker, Lee, Rizvi and Guo (2006), NCAR,
Preparing a 3D-Var for the Antarctic Mesoscale Prediction System (AMPS)

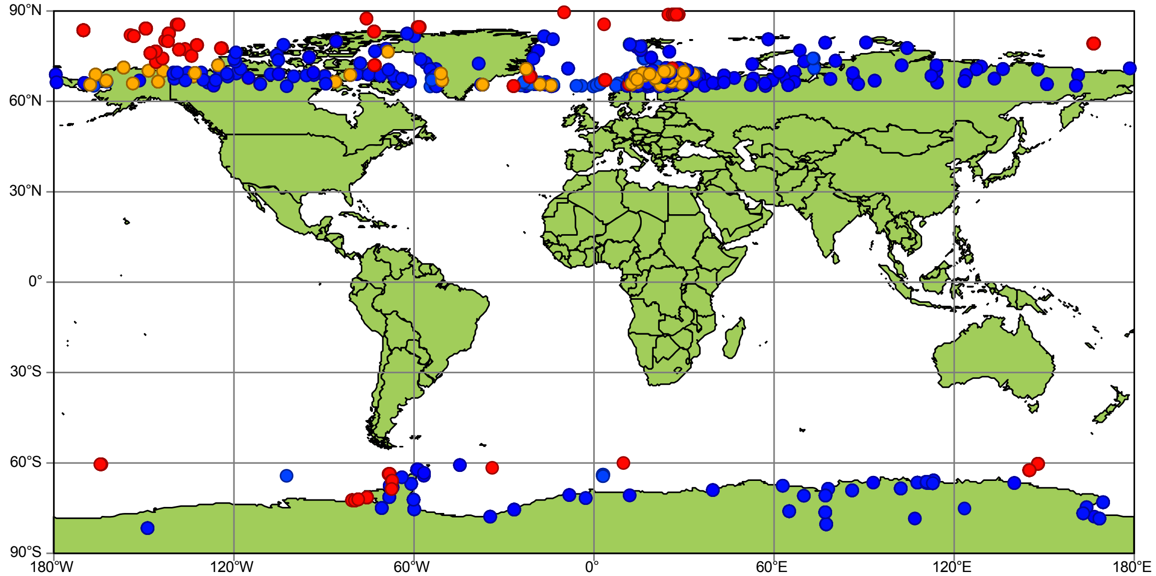
In-situ observations poleward of 65° N/S

20060701-12 UTC

64 radiosondes

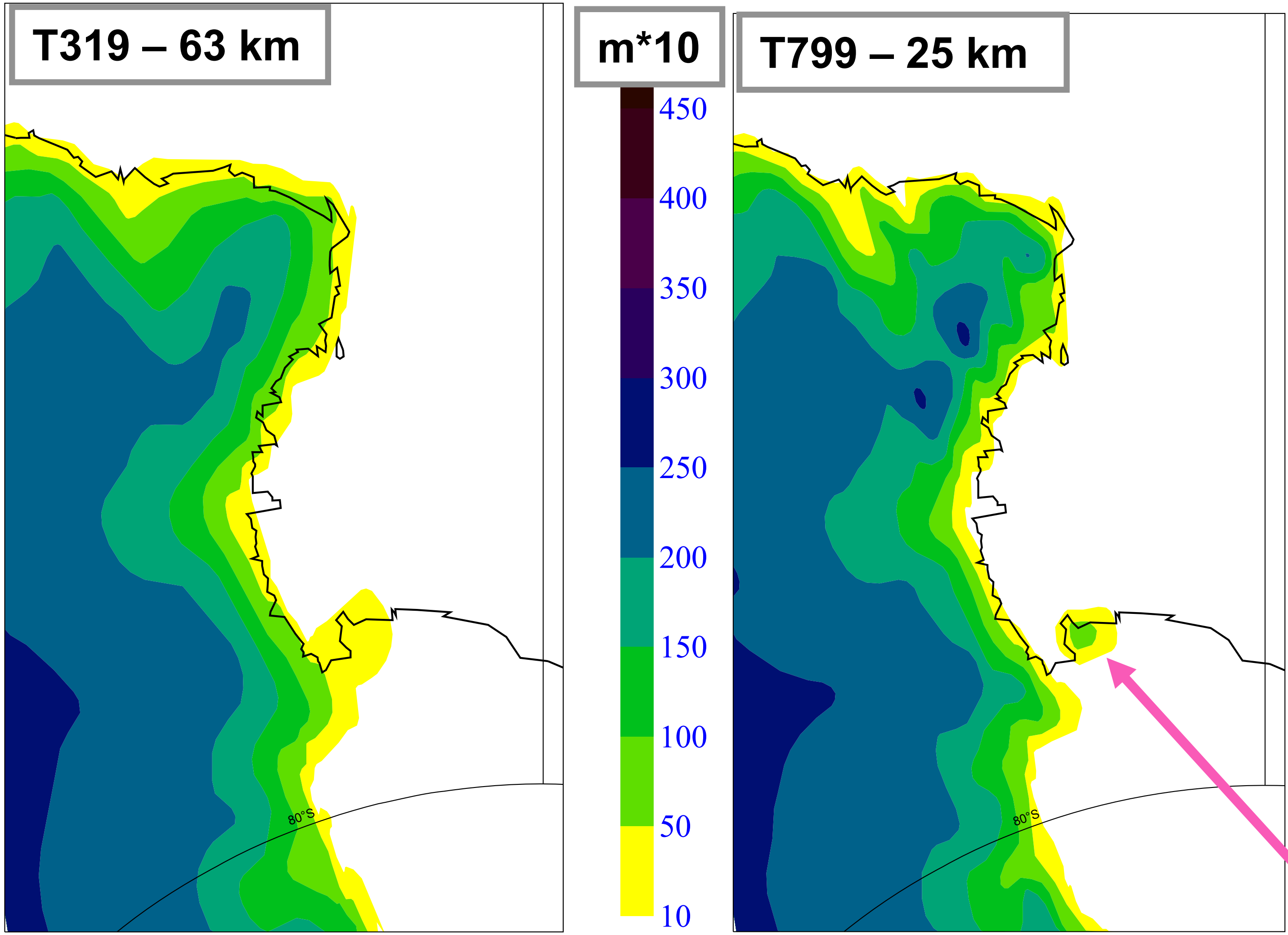


3490 surface reports in 12 hours



ECMWF

Model orography



1987: T106L19

1993: T213L31

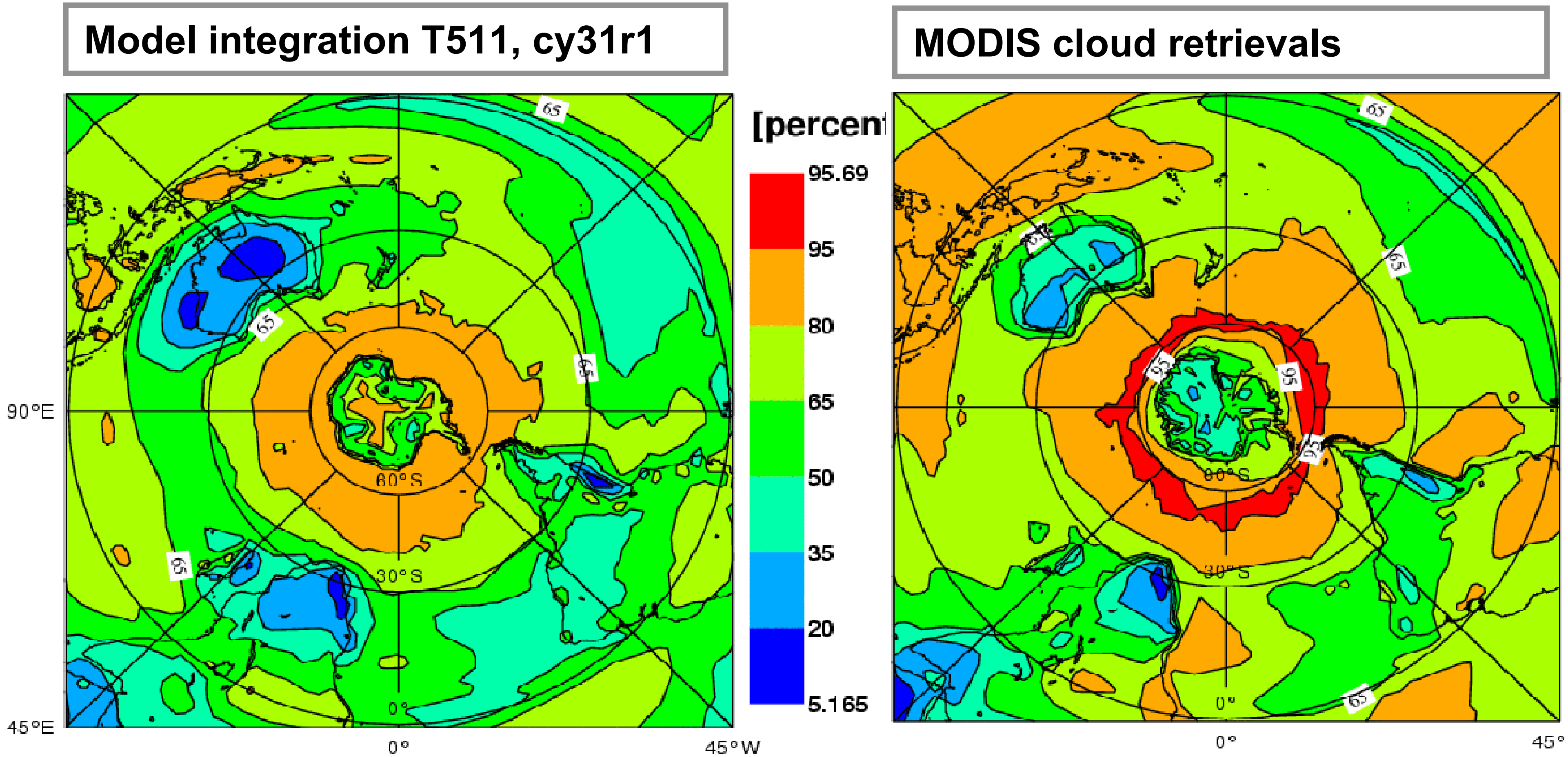
2000: TL319L60

2001: TL511L60

2006: TL799L91

Ross Island (McMurdo)

Total cloud cover (%) – 12-month average
20050601-20060531



Forecast inter-comparison, Antarctica

Comparing PMM5 (AMPS-30km), ECMWF (T511), AVN (NCEP) and GMM5 (NCAR) in terms of surface pressure, 10m-wind, 2m-temperature and 500 hPa Z, T, wind; April 2001:

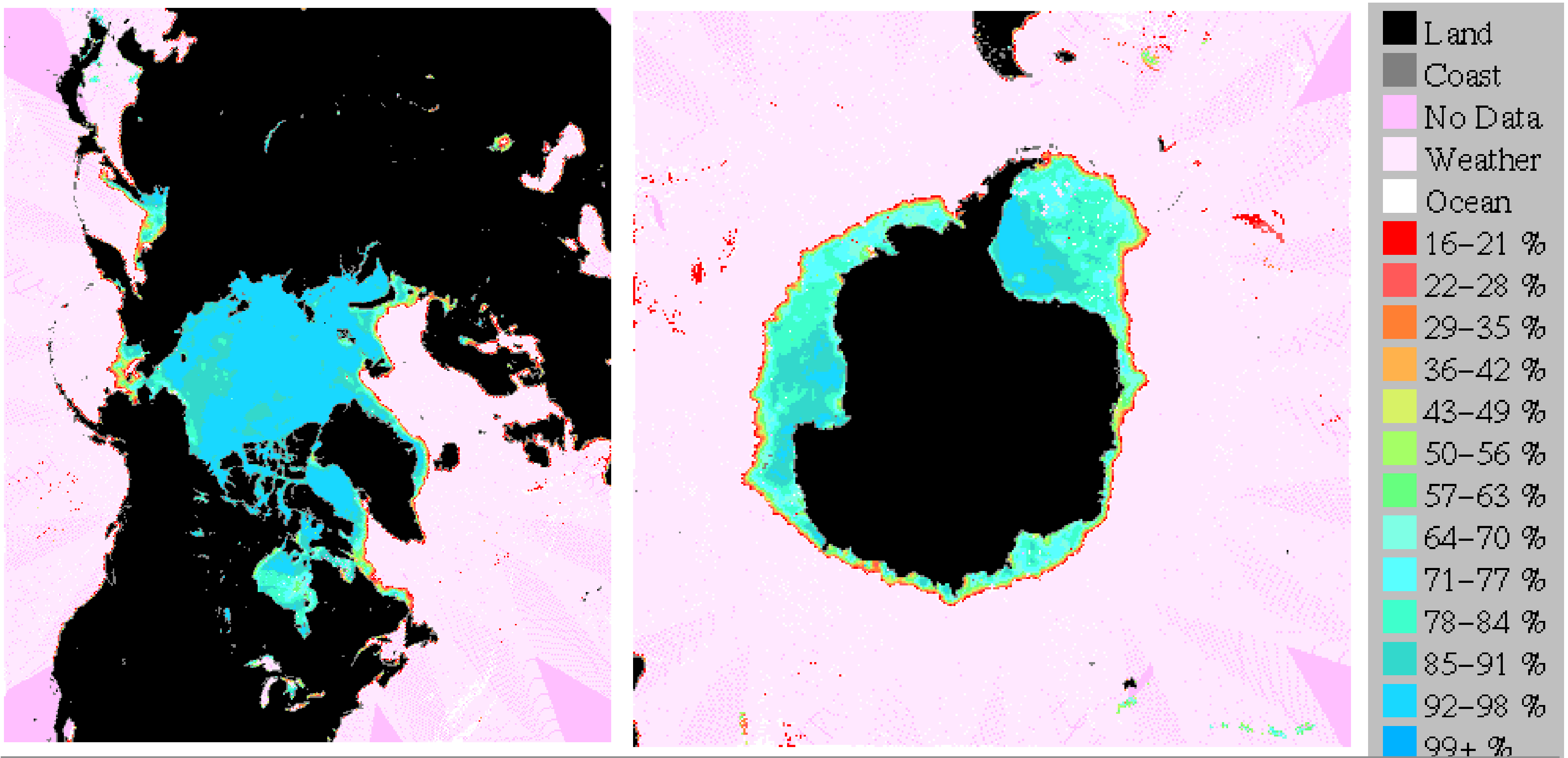
- "ECMWF performed with the highest overall skill, as defined by generally having the lowest bias and rms errors, and the highest correlation for the examined fields."
- "The ECMWF's skill in part reflected its advanced data assimilation system, including 4D-Var and use of satellite radiances from polar orbiters."

2001→2006

Powers, Monaghan, Cayette, Bromwich, Kuo and Manning (2003), NCAR,
BAMS: "Real-time mesoscale modeling over Antarctica. The Antarctic Mesoscale Prediction System (AMPS)"

ECMWF

Analysis of Sea Ice Concentration

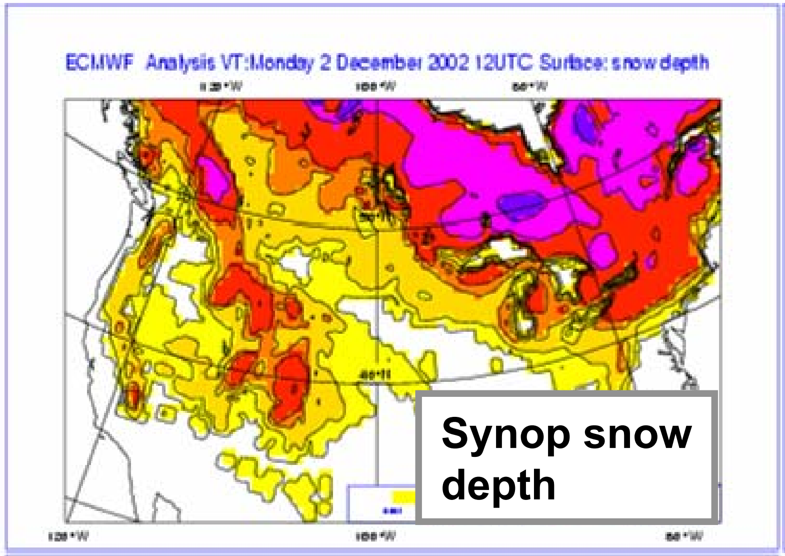


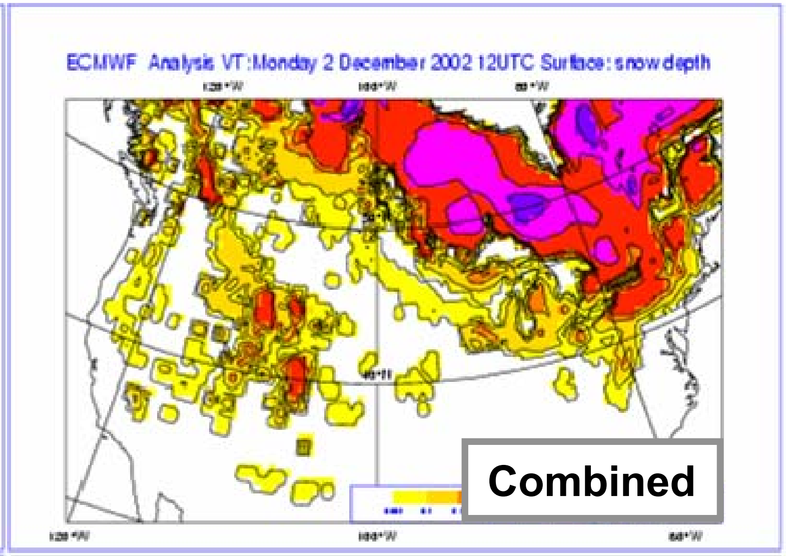
NCEP product based on SSMI microwave window channel data (Grumbine 1996) and Reynolds SST (no ICE if SST > 2 °C)

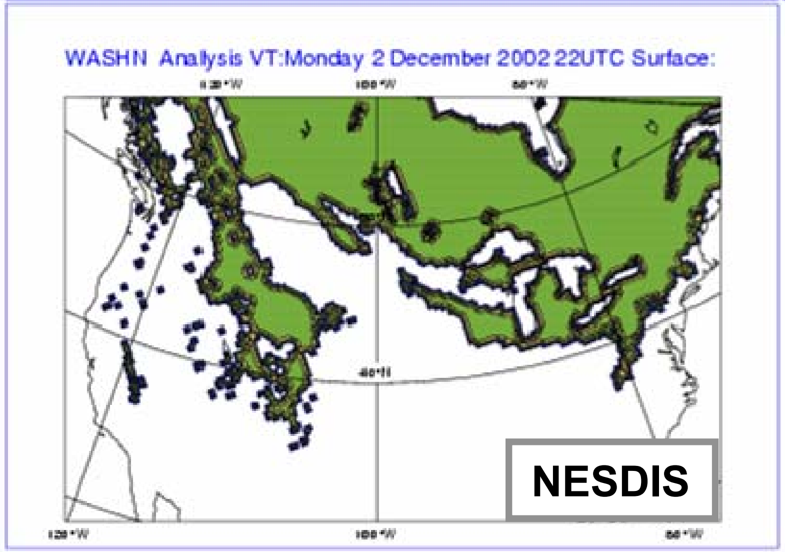
Remapped at ECMWF to model grid, using Cressman spatial interpolation
No ECMWF ice model at present

ECMWF

Analysis of Snow depth





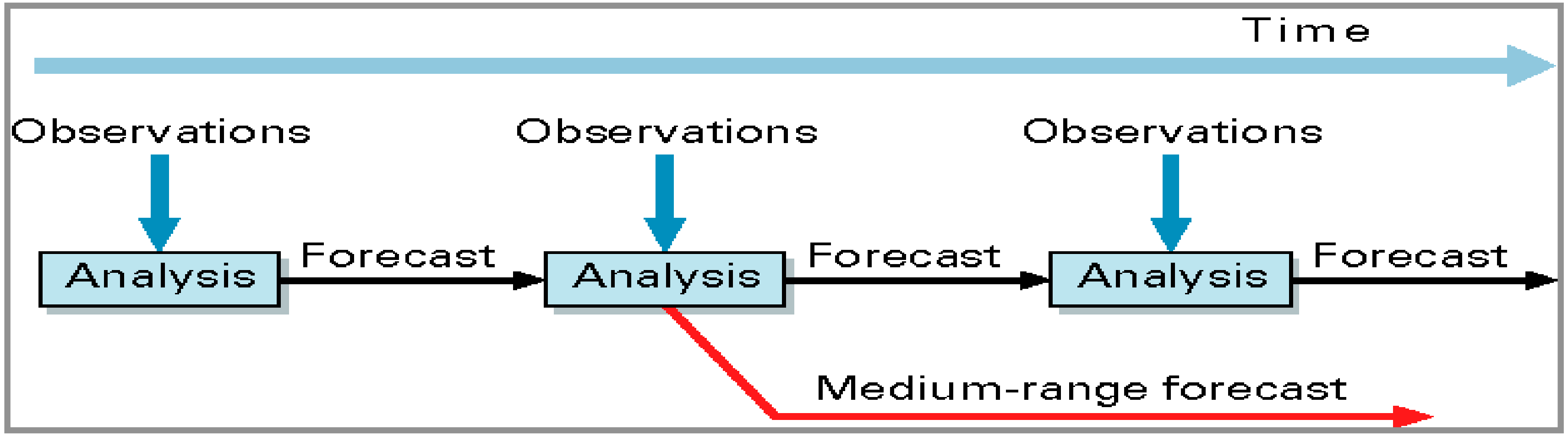


Snow depth and snow extent information are combined Drusch et al. (2004 *JAM*).

Analysed on model grid, using Cressman spatial interpolation

Interacts with forecast precipitation and model hydrology

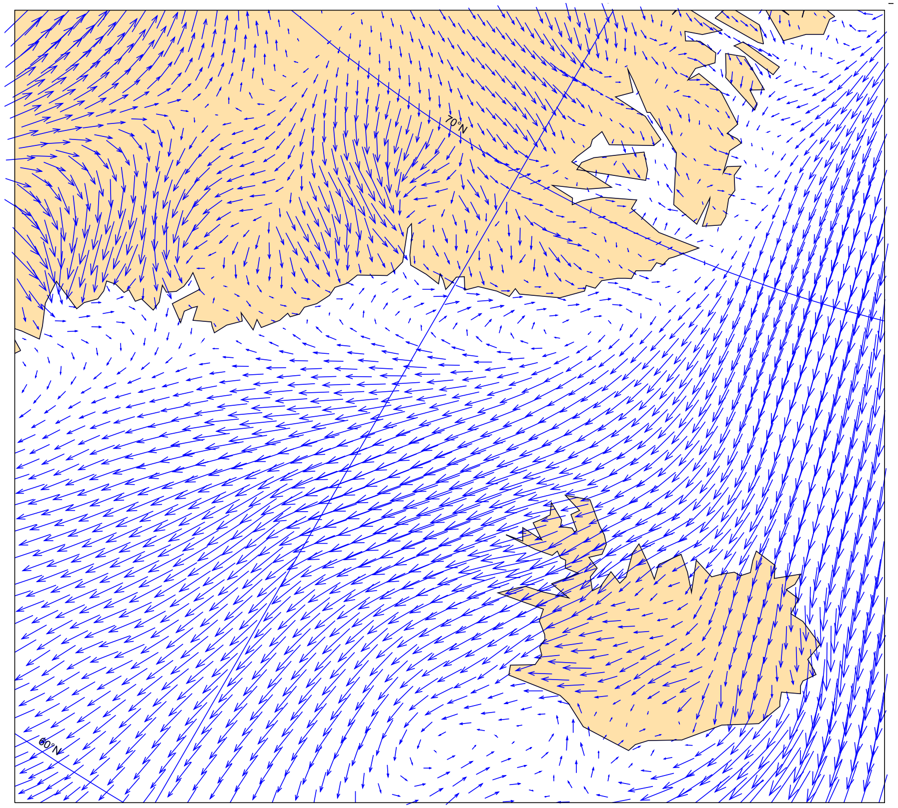
Starting Forecasts



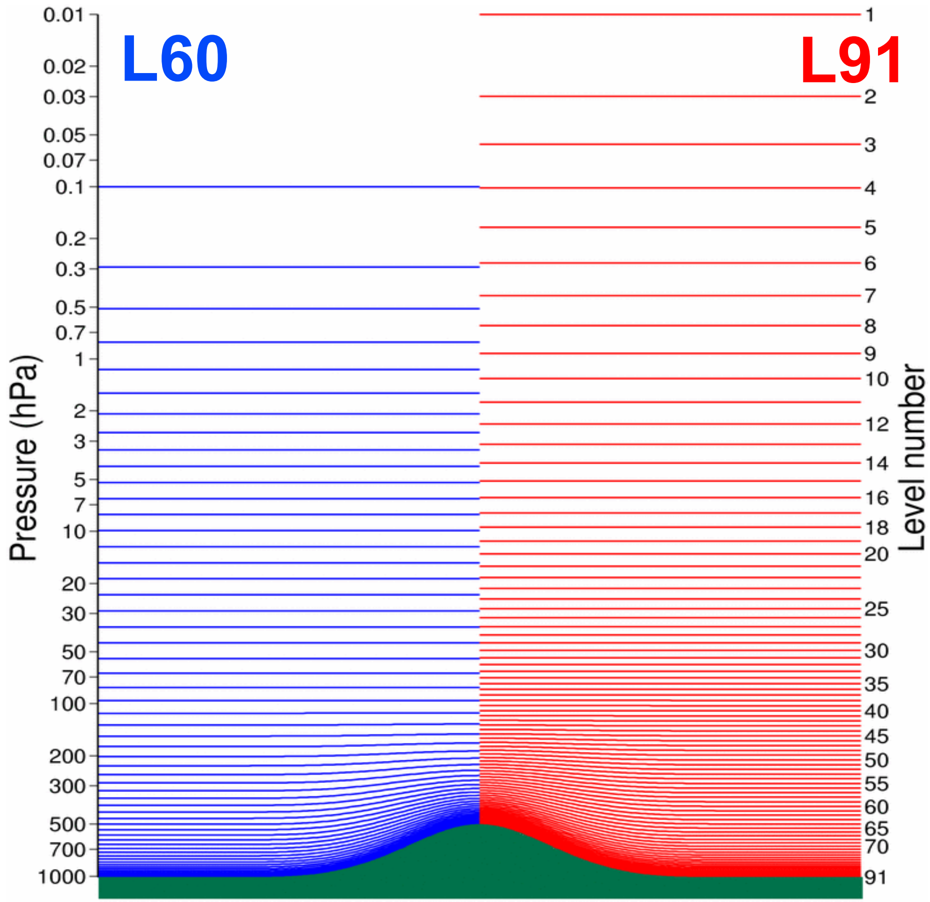
- **The observations are used to correct errors in the short forecast from the previous analysis time**
- **Every 12 hours we process 2 – 4,000,000 observations to update the 100,000,000 numbers that define the model's virtual atmosphere.**
- **This is done by a careful space-time (4D) interpolation of increments in u, v, T, q, O_3, Ps to better fit the available observations**
- **One 12-hour assimilation cycle takes about as much computer power as the 10-day forecast.**

Observations are compared against a short-range 3-15 hour forecast

Horizontal resolution
T_L799 ~ 25 km



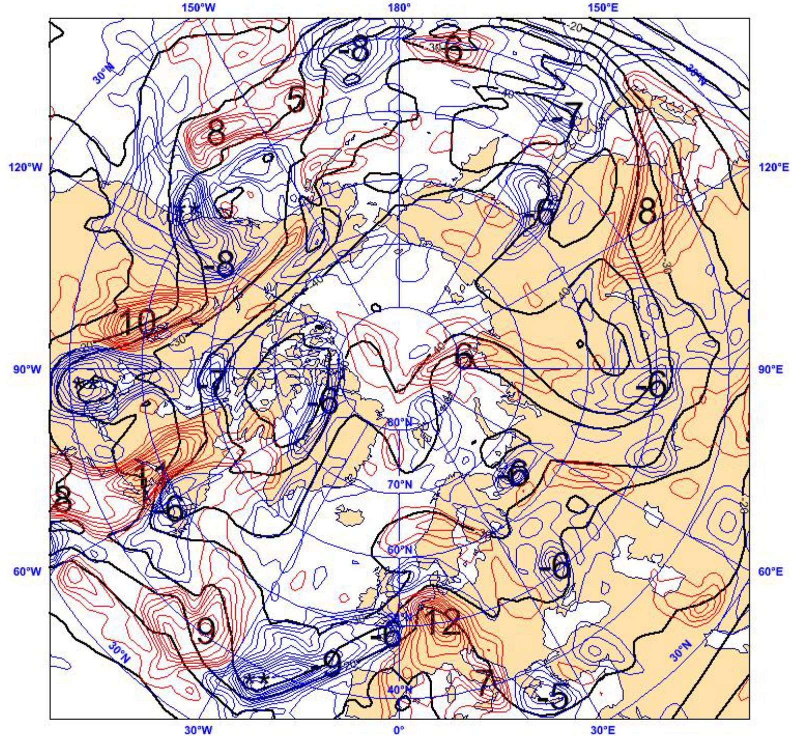
Vertical resolution
91 levels



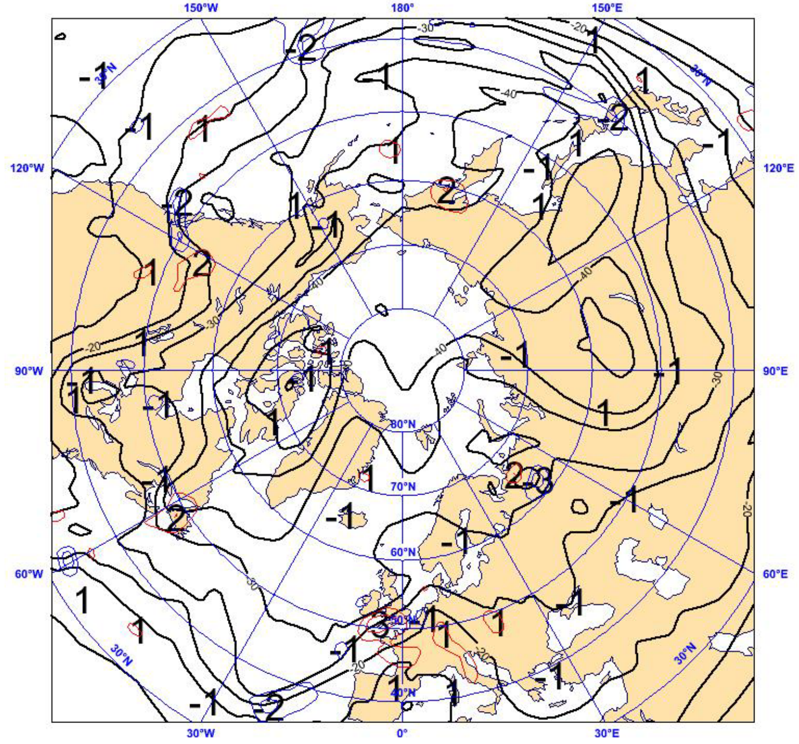
ECMWF

Forecast versus observations

12-hour forecast temperature change

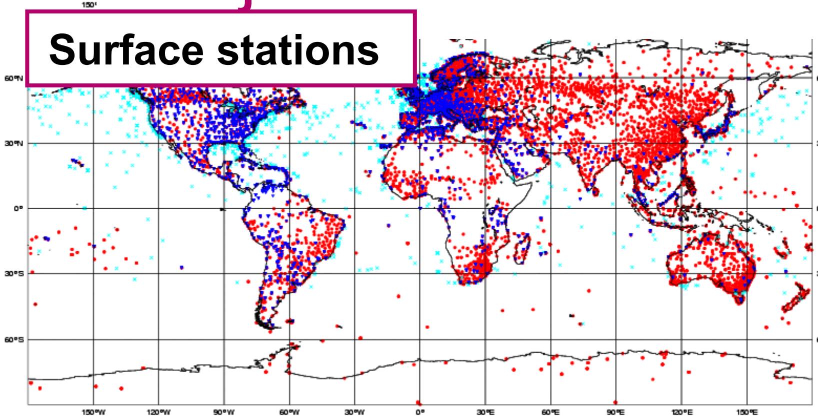


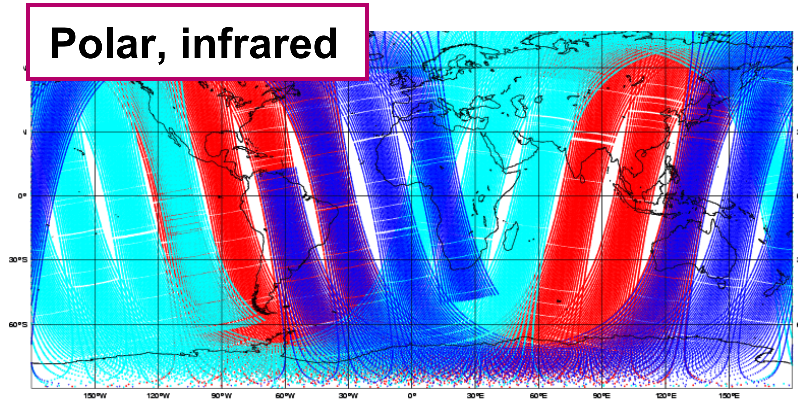
Correction as a result of data assimilation

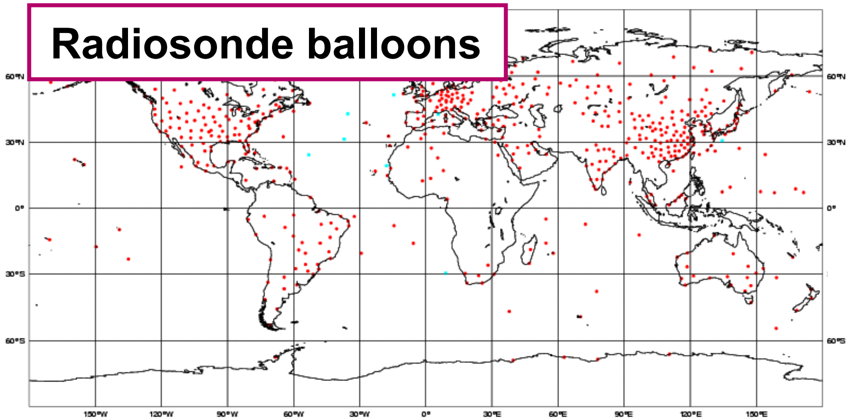


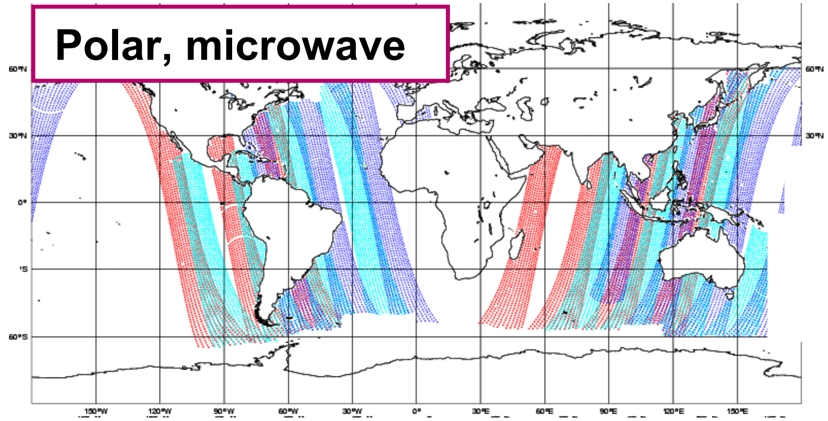
The analysis corrections are ~10 times smaller than the 12-hour forecast temperature change

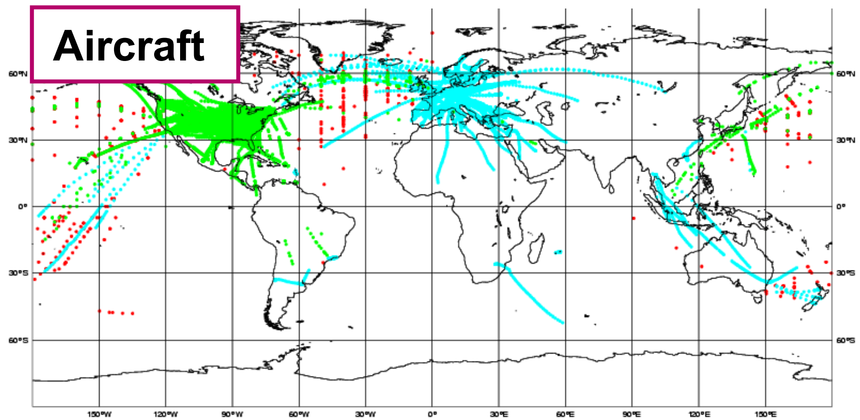
Major assimilated data sets

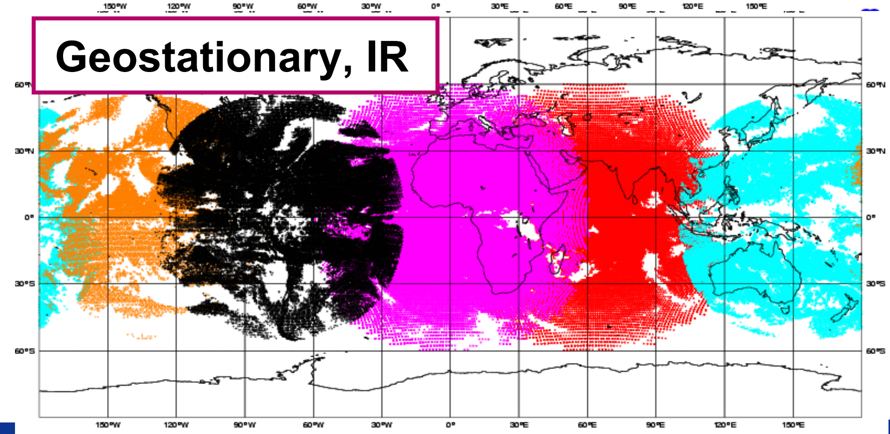




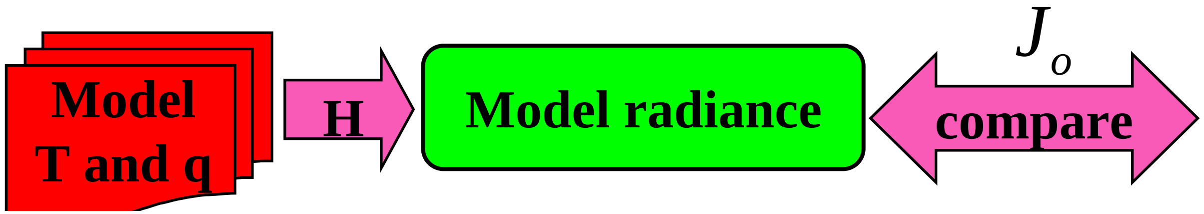


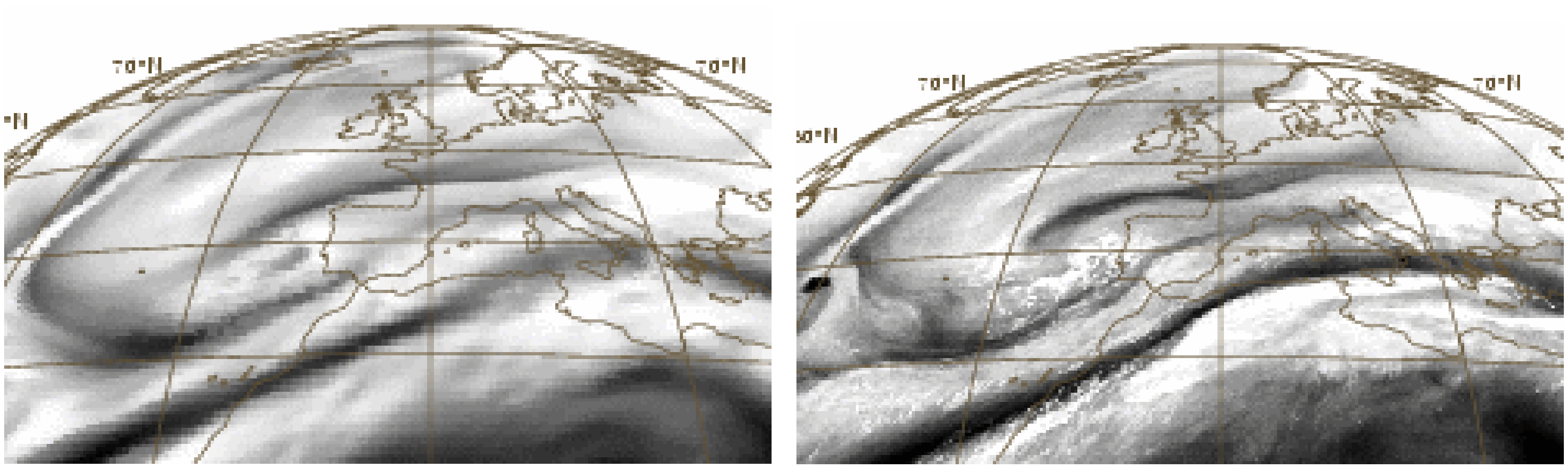






Forecast imagery versus observed





ECMWF

Formalism of variational estimation

The variational **cost function** ***J(x)*** **consists of a background term and an observation term:**

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

The relative magnitude of the two terms determine the size of the analysis increments. The **solution** **in the linear case is:**

$$(x_a - x_b) = \mathbf{K}(y - Hx_b)$$

$$\mathbf{K} = \mathbf{BH}^T(\mathbf{HBH}^T + \mathbf{R})^{-1}$$

increments

departures

y: array of observations
x: represents the model/analysis variables
H: linearized observation operators
B: background error covariance matrix
R: observation error covariance matrix

Observation-to-model analysis weights: The Kalman gain matrix

Information content

The analysis error covariance A is given by

$$\mathbf{A}^{-1} = \mathbf{B}^{-1} + \mathbf{H}^{T}\mathbf{R}^{-1}\mathbf{H}$$

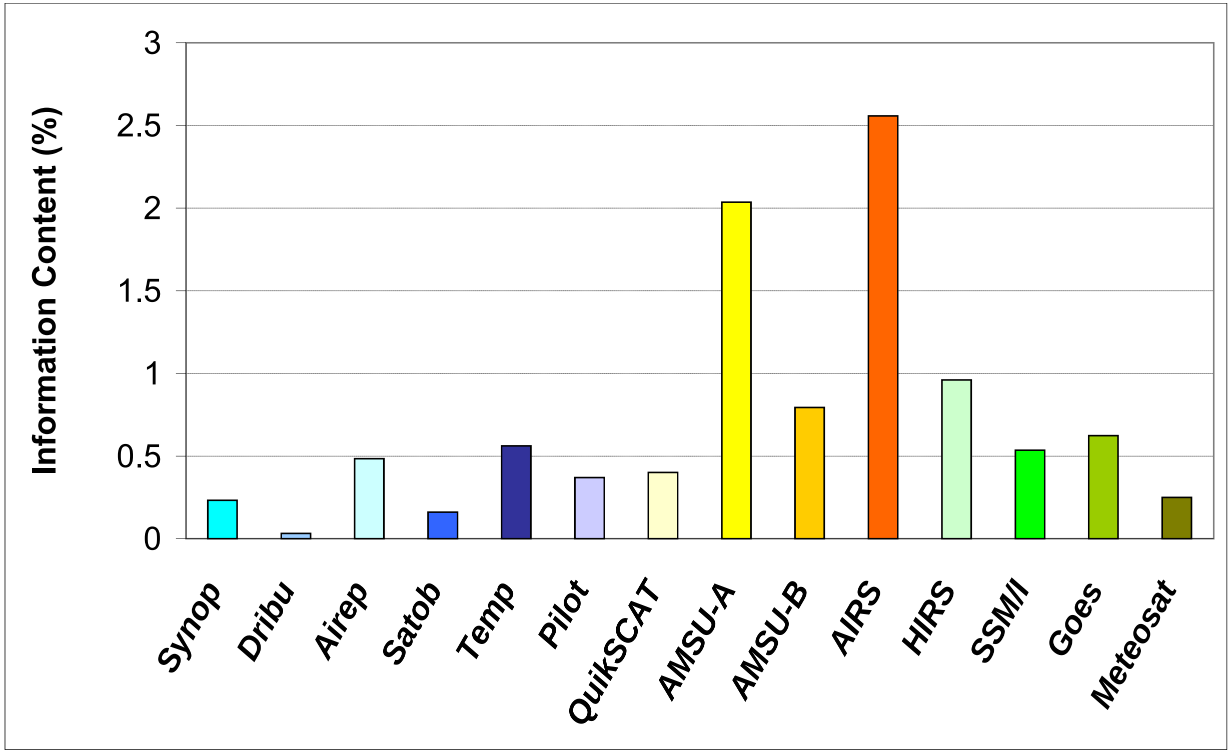
Note that A is always < both B and R.

The number of pieces of information obtained from the observations can be expressed by the 'degrees of freedom for signal' (DFS):

$$DFS = tr(\mathbf{I} - \mathbf{A}\mathbf{B}^{-1}) = tr(\mathbf{K}^{T}\mathbf{H}^{T})$$

Practical algorithms to evaluate the DFS for the global 4D-Var have recently been developed (Cardinali et al., 2004, QJ), (Fisher, 2003, TM397)

Information content (Cardinali et al. 2004)



Global observations, ECMWF 4D-Var, February 2003.

T95 (210 km): degrees of freedom = 2,802,000

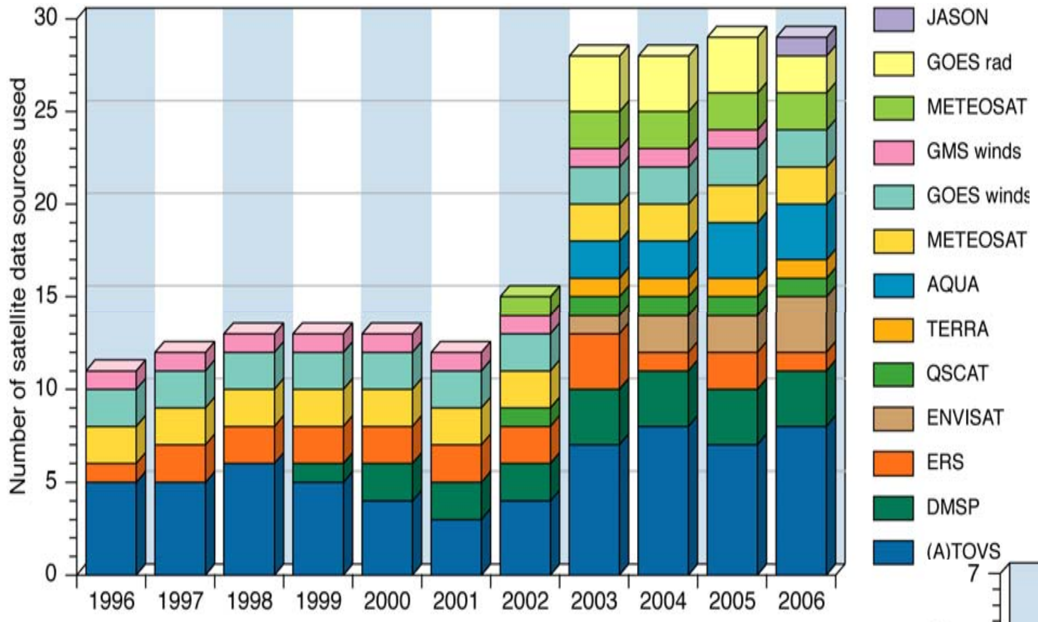
Number of observations = 1,500,000

DFS from the background = 85 %

DFS from the observations = 15 %

Feb 2006:
T255 (80 km)
15,000,000
3,500,000

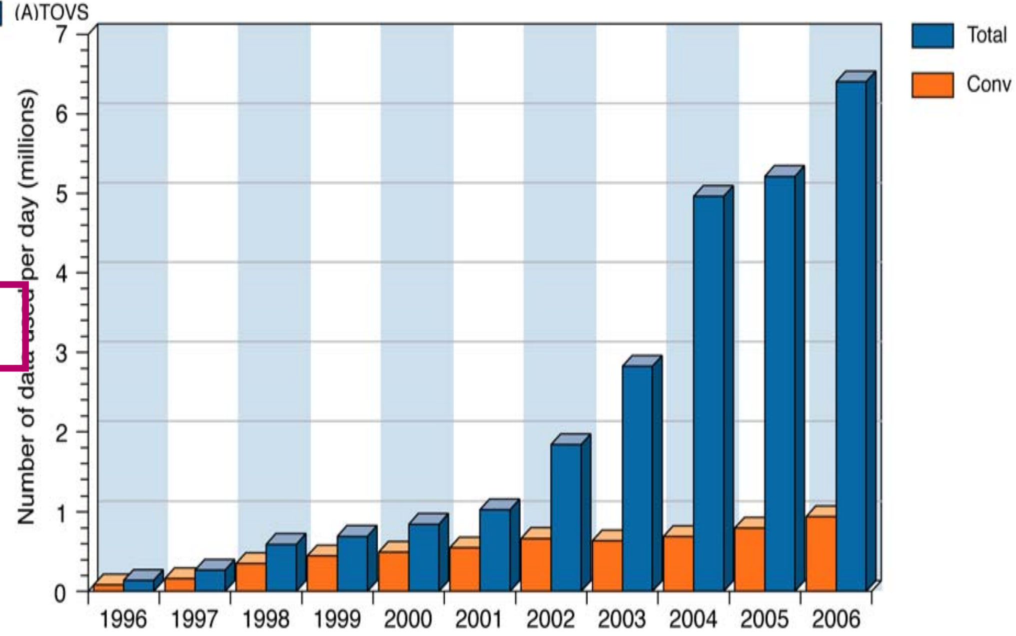
Data from 28 sources are now assimilated



July 2001

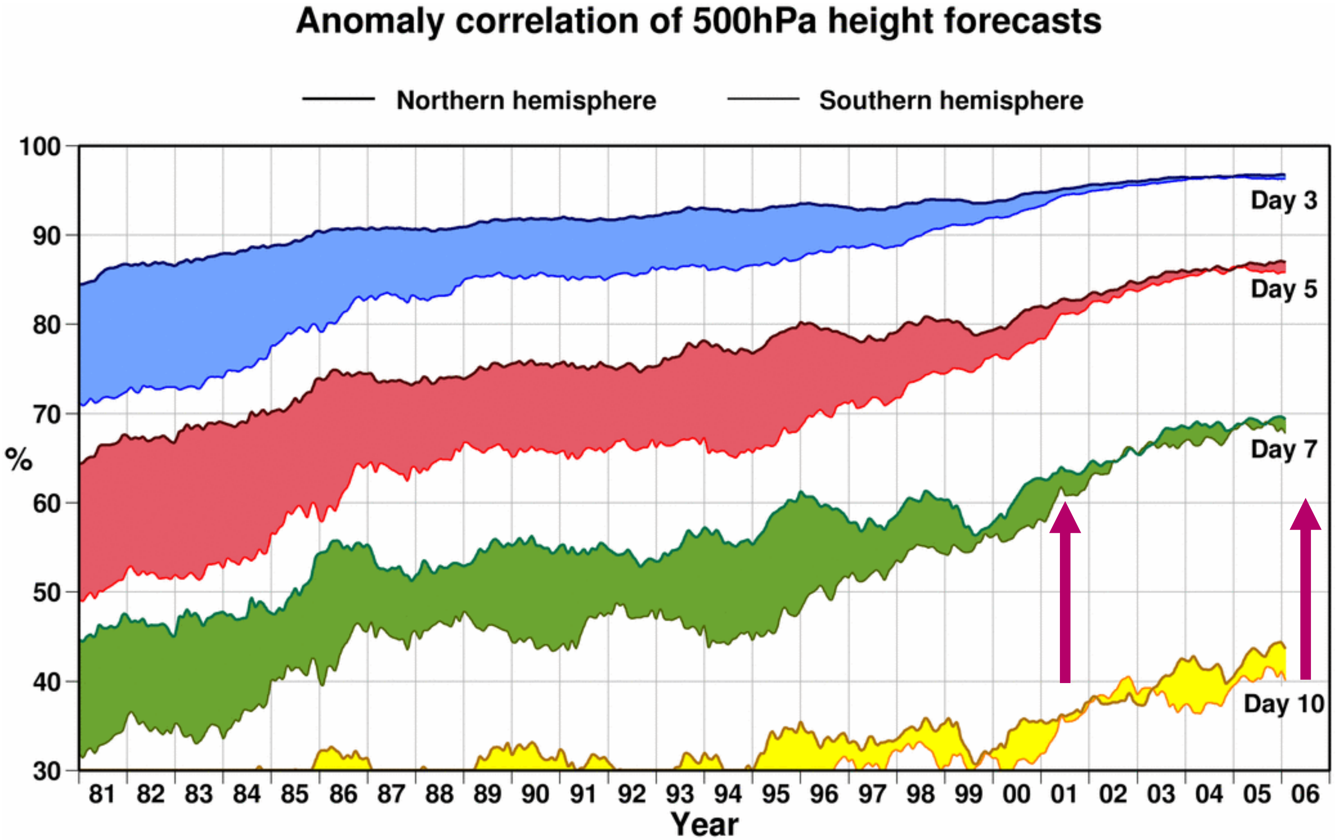
July 2006

Rapid increase in daily number of used data



General improvement of scores:

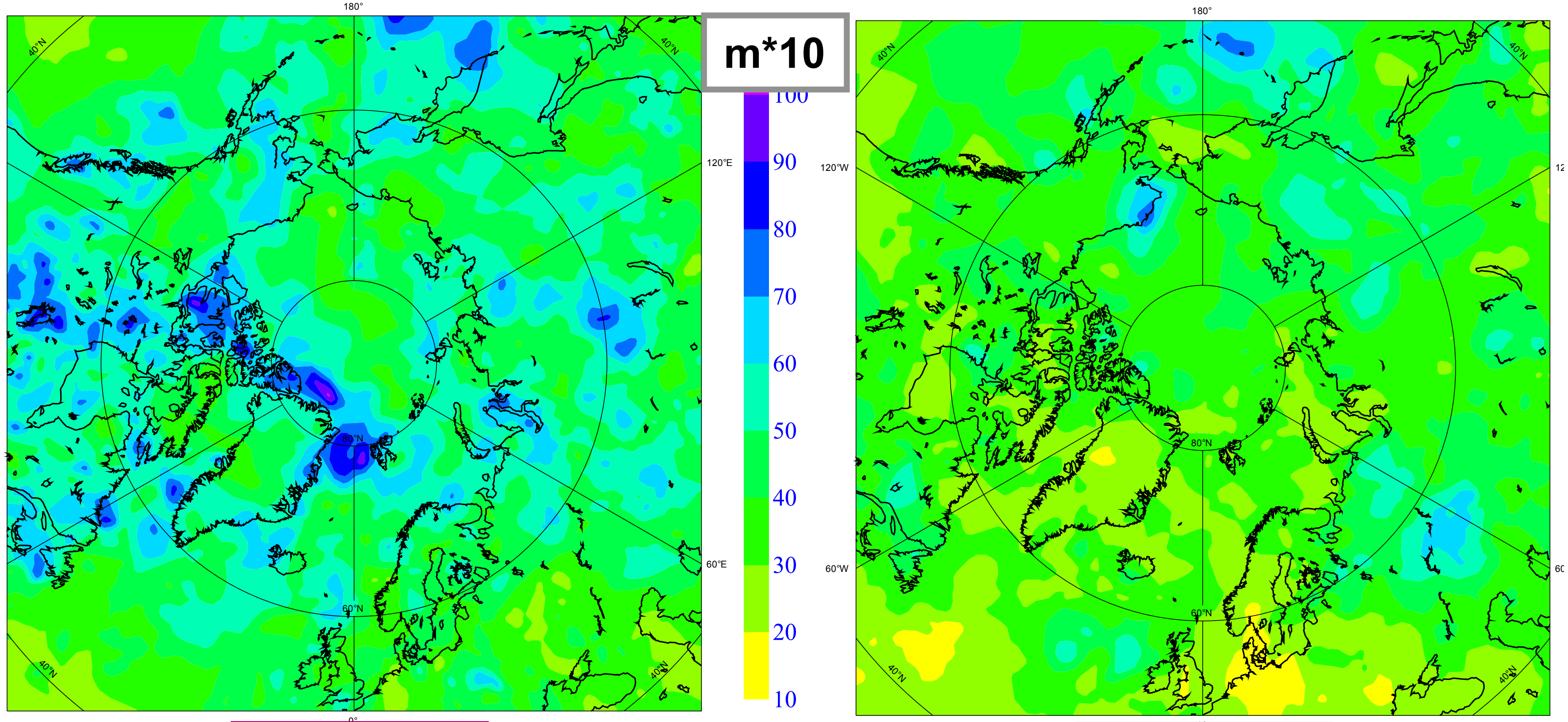
- better model
- more and better observations
- better data assimilation techniques



A. Simmons

General improvement of the assimilation system

- smaller increments (std.dev of z500)



July 2001

July 2006

ECMWF

General improvement of the assimilation system

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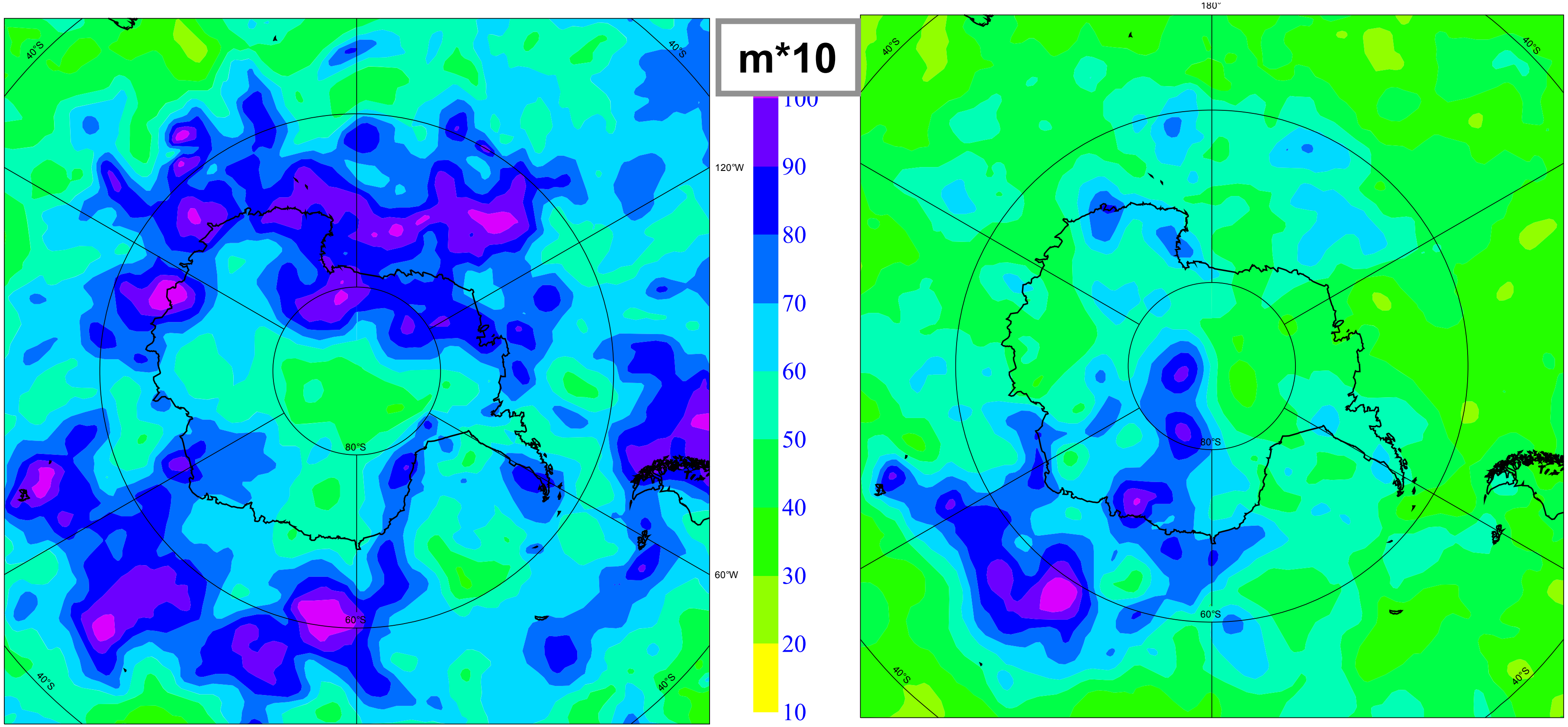
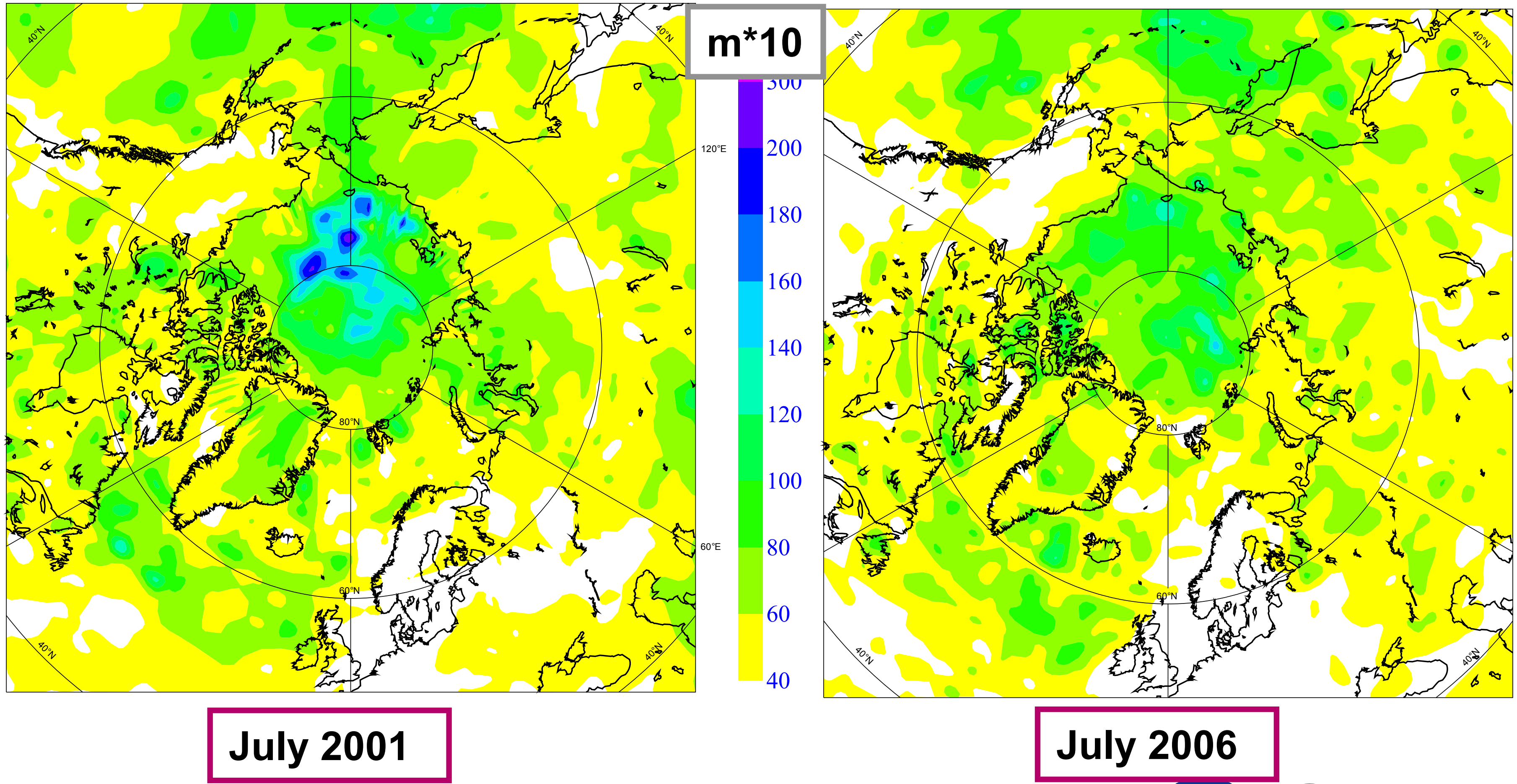


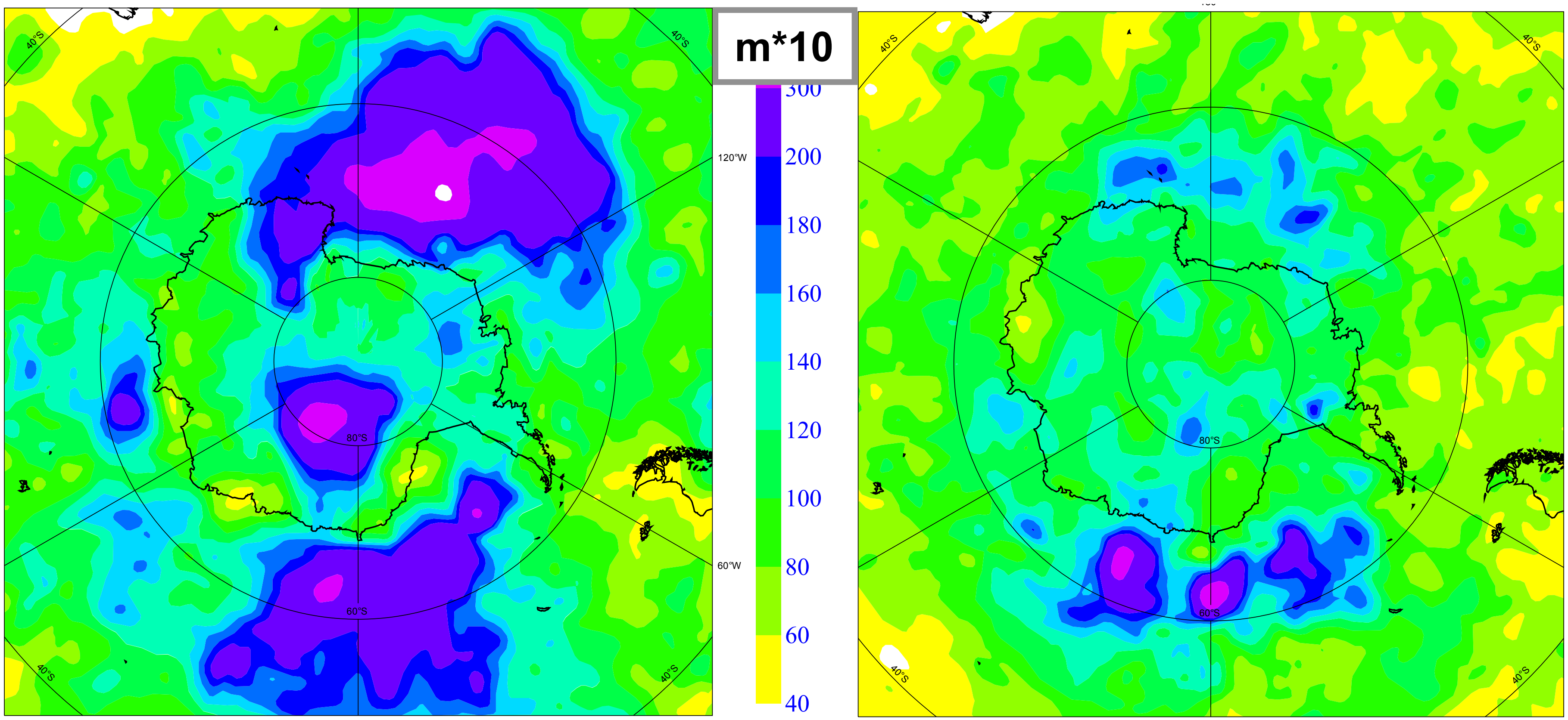
July 2001

July 2006

Comparison between ECMWF and UK MetOffice analysis
- std.dev at z500
(radiosonde obs error z500=8.4 m)



Comparison between ECMWF and UK MetOffice analysis
- std.dev at z500

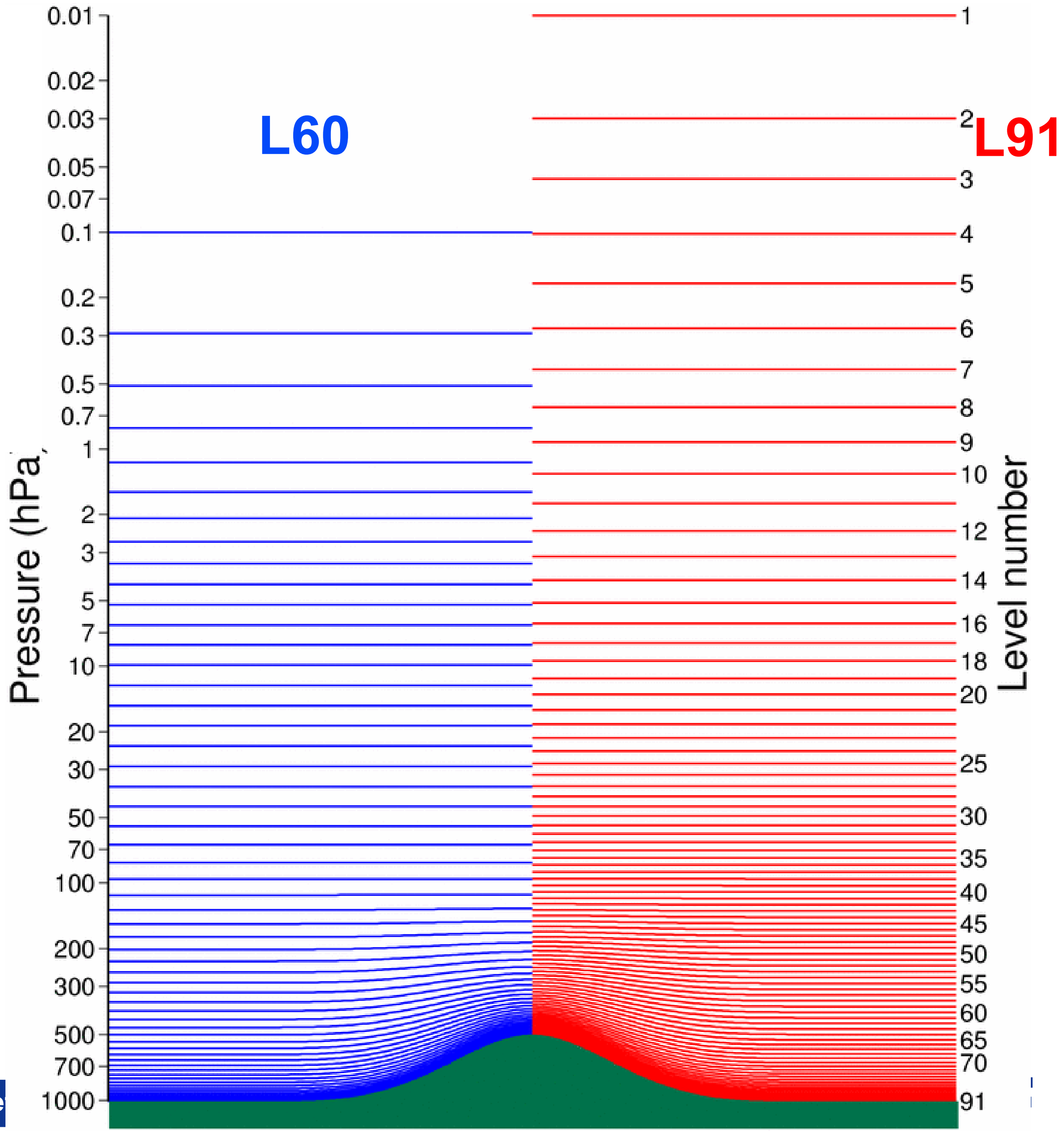


July 2001

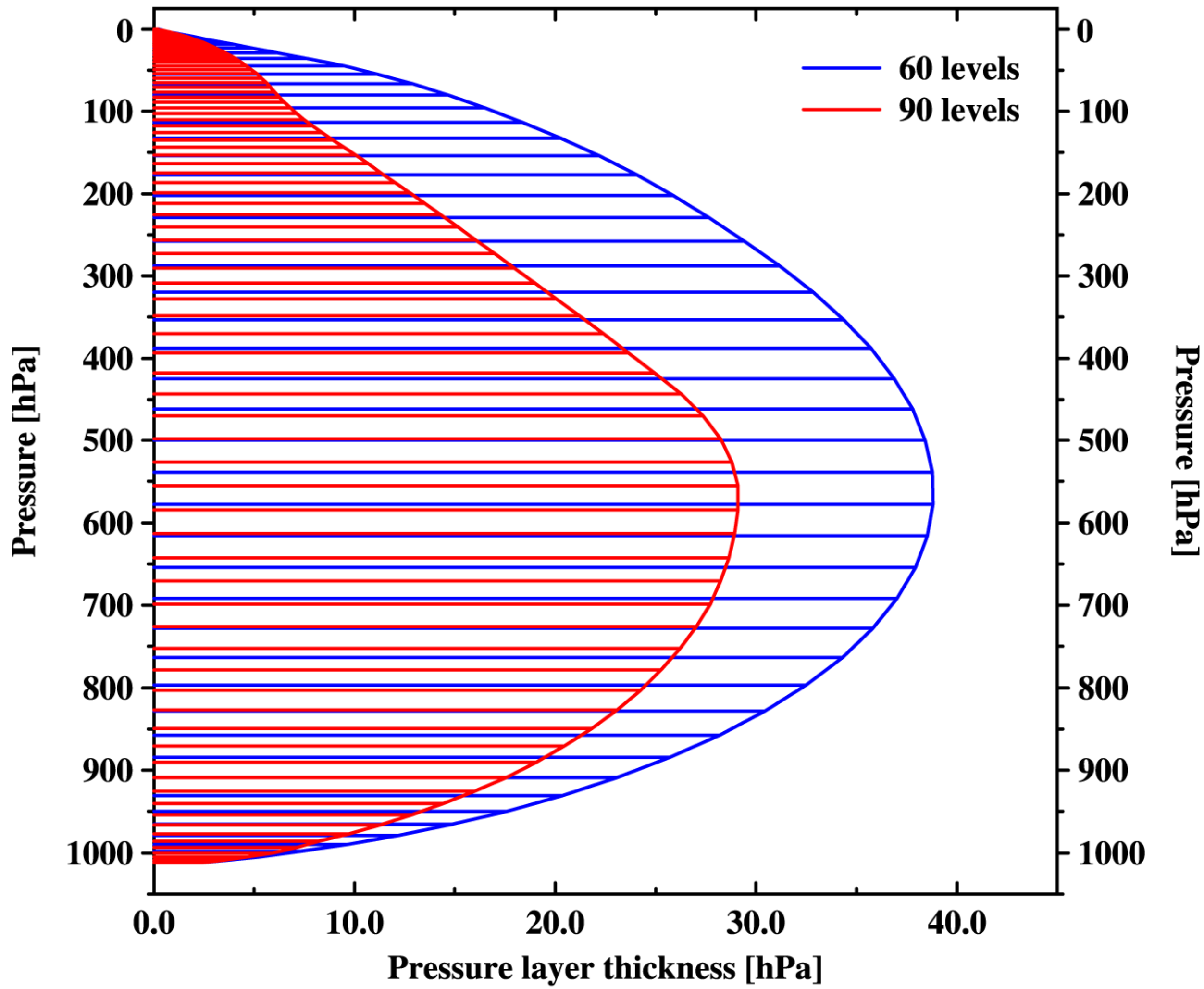
July 2006

The 91-level vertical resolution model.

Implemented 1st Feb. 2006

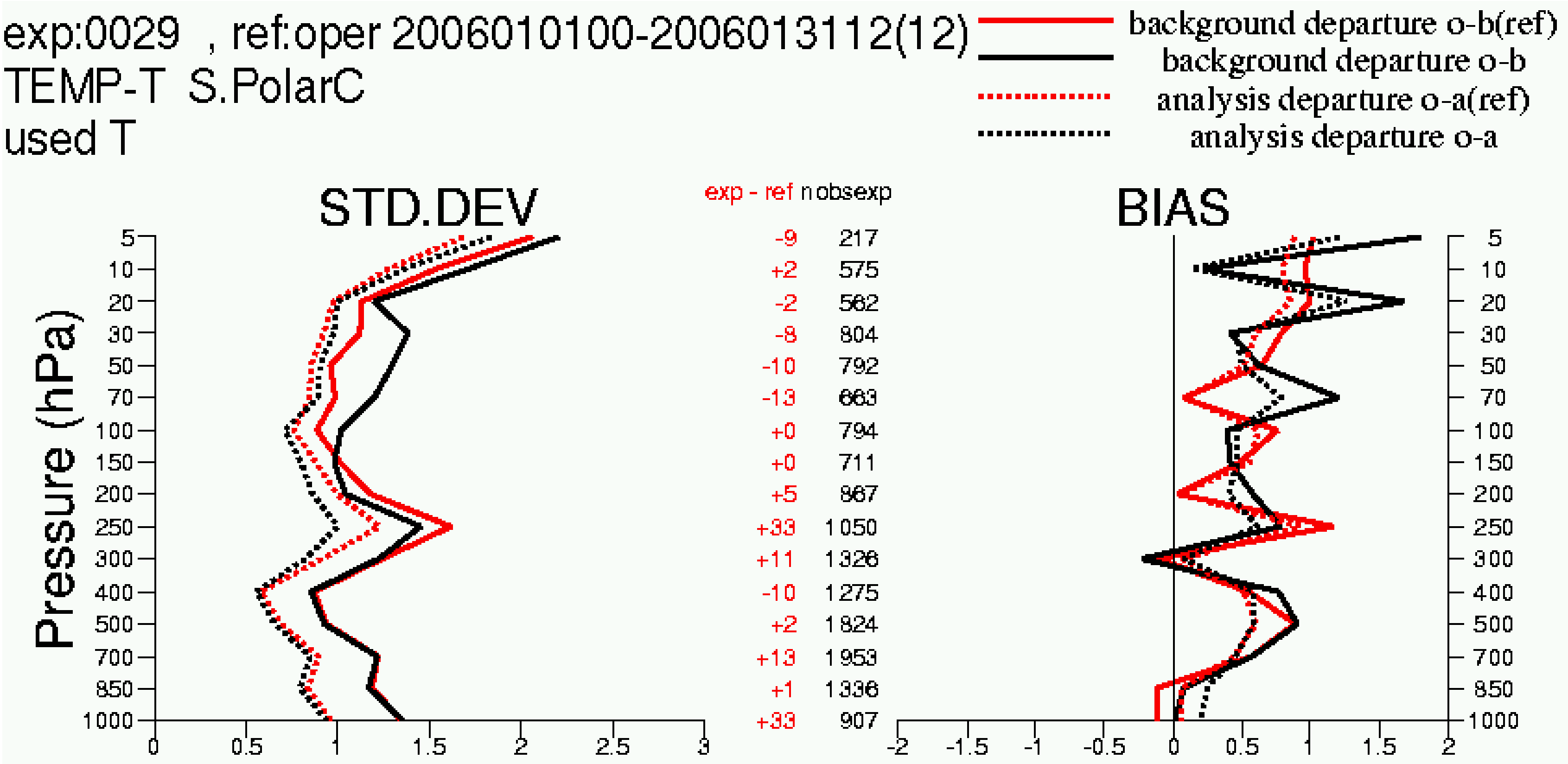


Layer thicknesses, L60 and L91



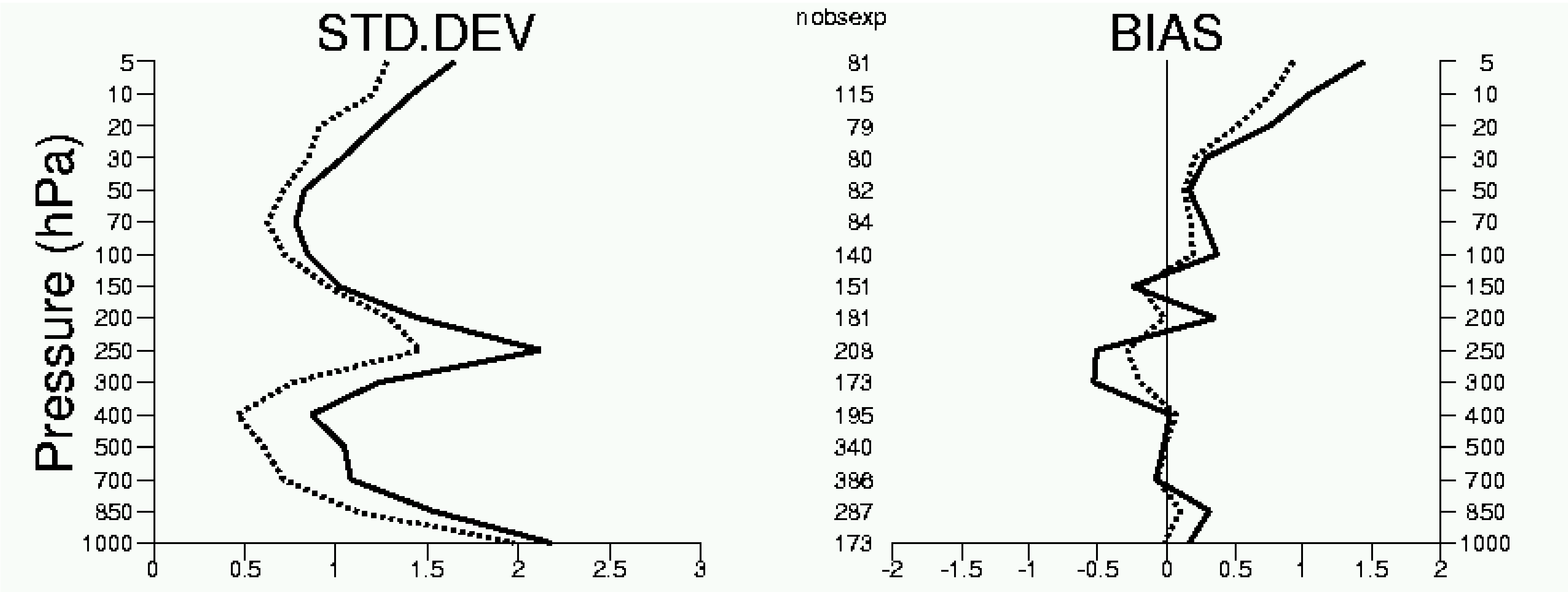
ECMWF

L60- and L91 comparison with radiosondes - Antarctica

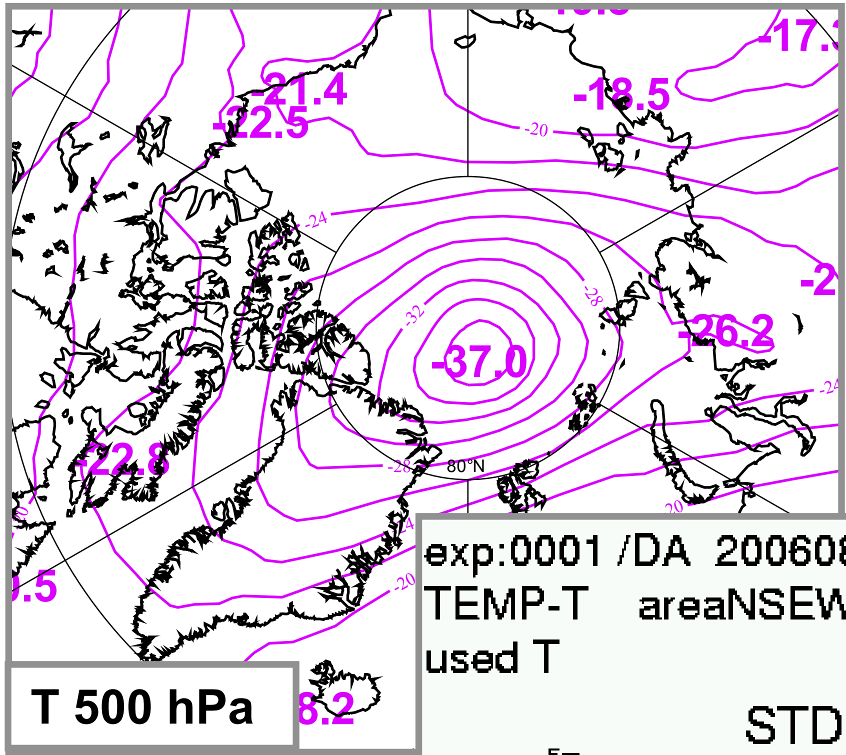


Icebreaker Oden
Arctic expedition.

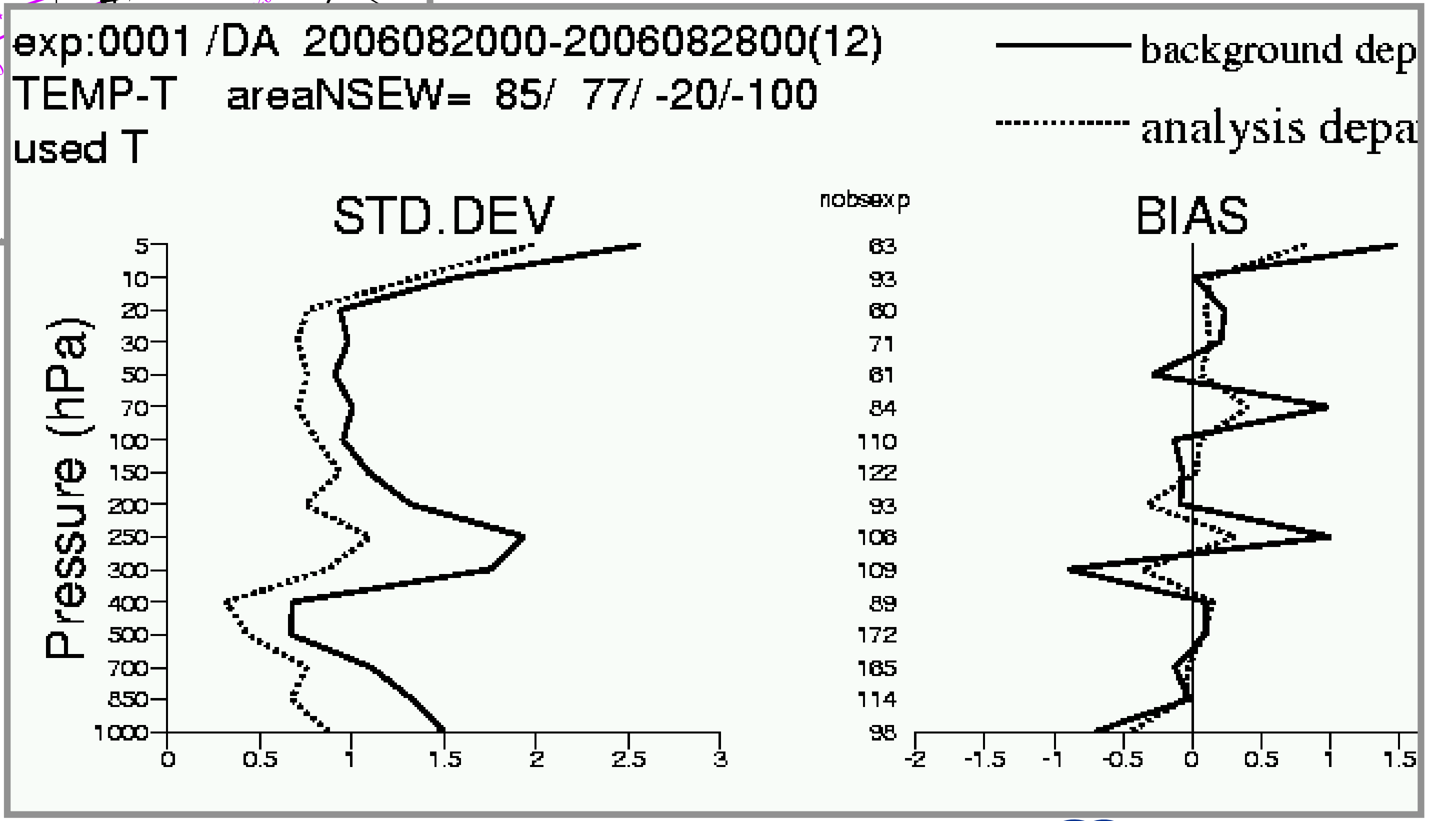
Temperature
20010801-20010822



ECMWF

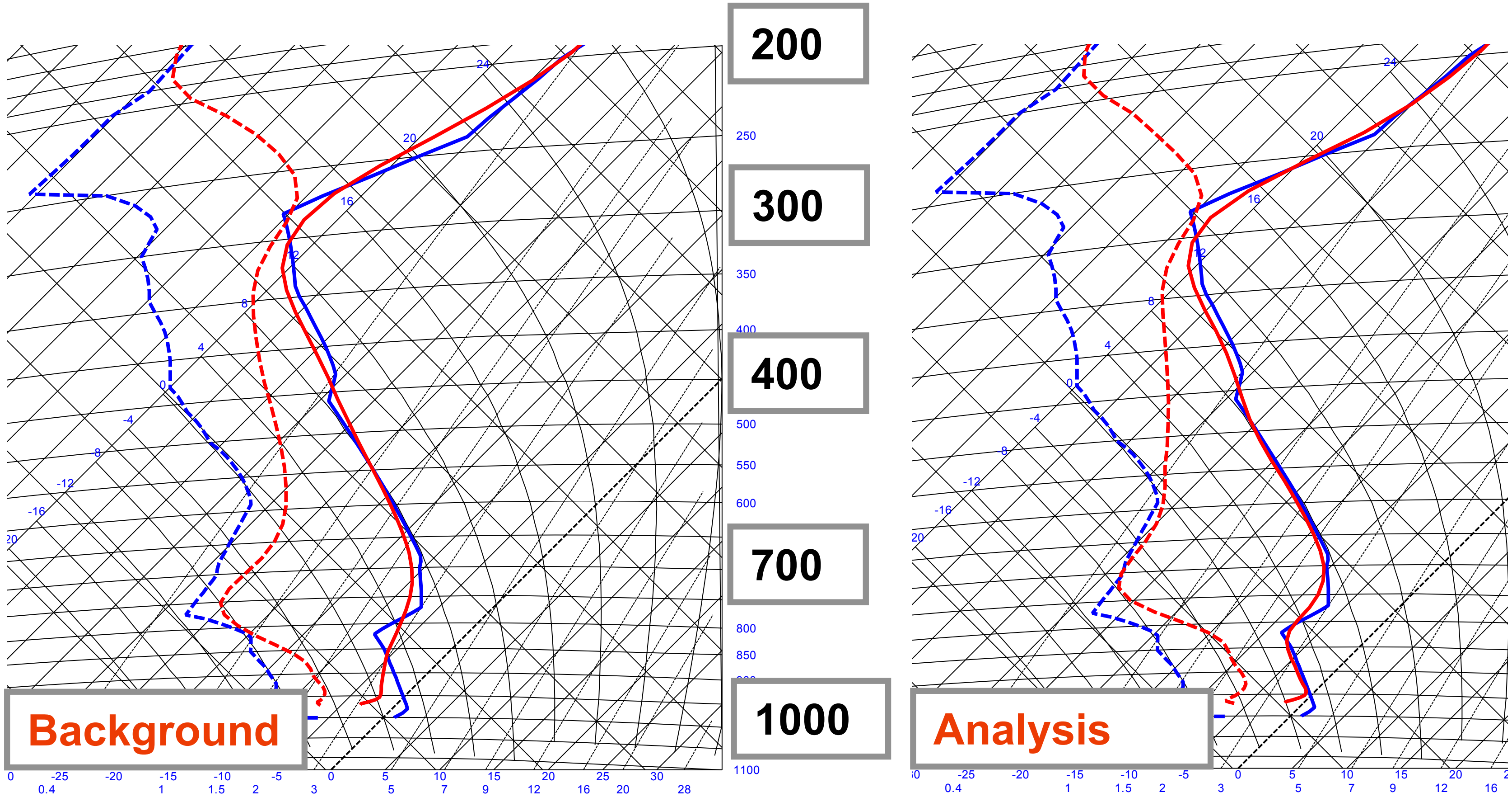


Recent cold spell, Northern Greenland



ECMWF

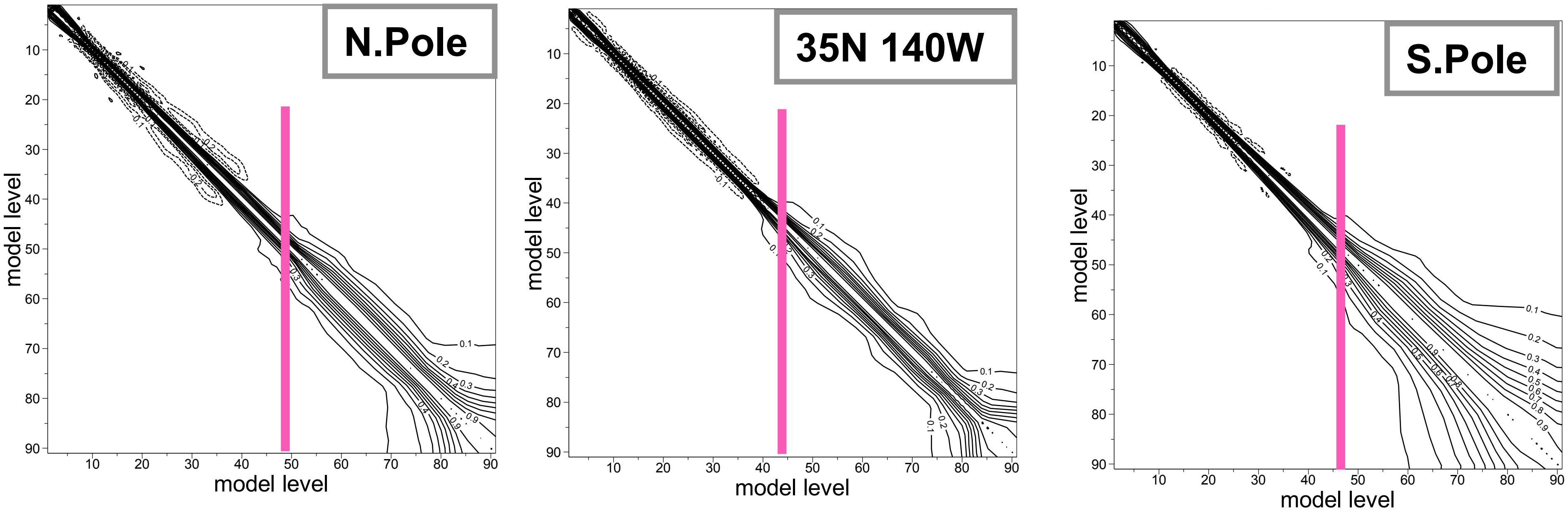
Analysis of an arctic radiosonde profile
N. Greenland, 20060826-12



- **Reporting of the full-resolution vertical radiosonde profiles is urgently required (bufr)**

Jb: Average vorticity vertical correlations

- **The current statistical model for B ('the wavelet Jb') can reproduce some of the geographical variation. Differences between regions of the globe can be due to**
  - ➔ **climate regimes,**
  - ➔ **data density,**
  - ➔ **PBL and tropopause heights…**



High-latitude features that may be difficult to analyse in a global NWP system

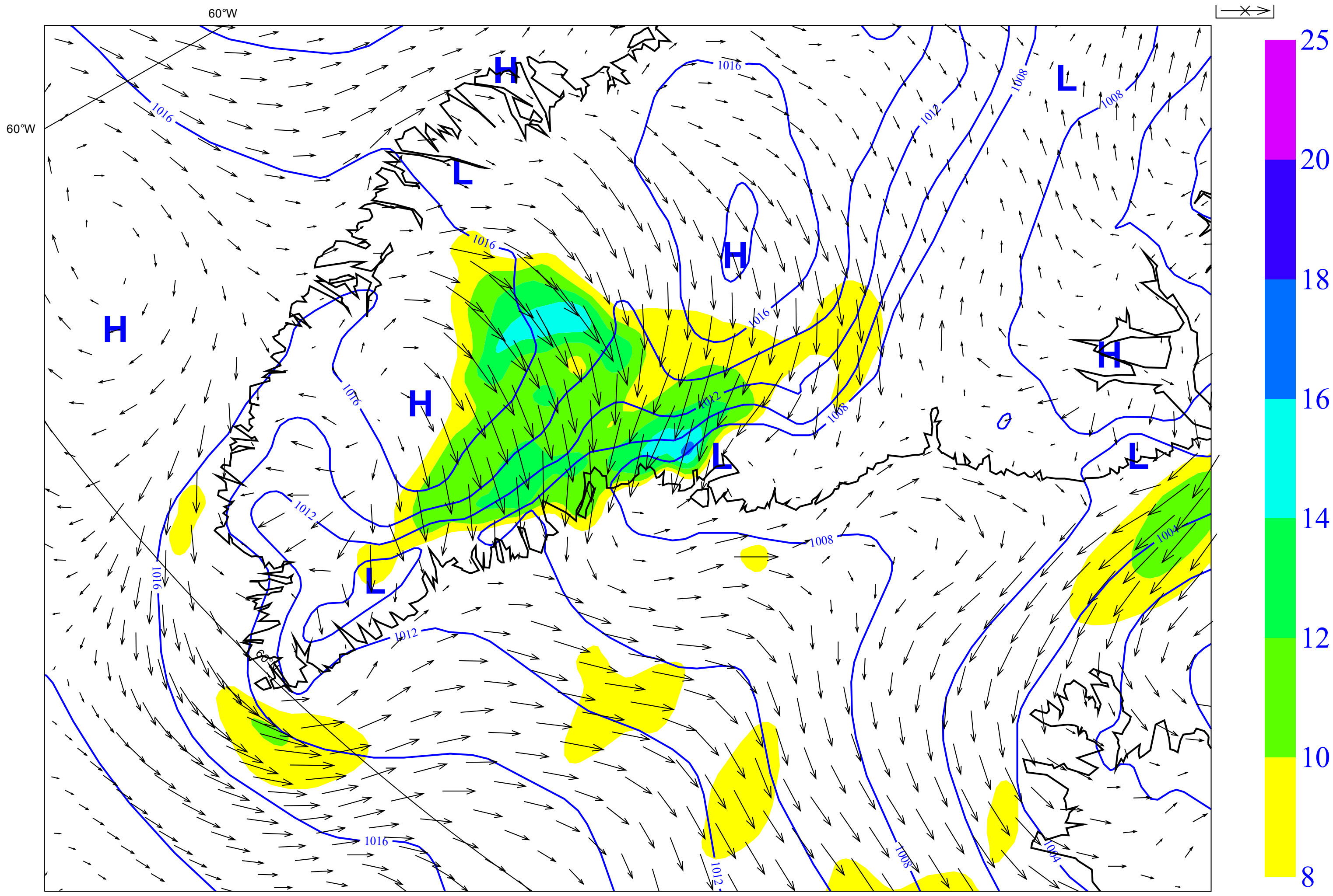
- **Strong temperature inversions**
  - ➔ **Surface inversion makes surface data less representative,**
  - ➔ **Tropopause requires accurate profiling observations and good model**
- **Katabatic winds**
  - ➔ **Influences surface pressure (mesoscale lows) but is non-geostrophic**
- **Polar lows**
  - ➔ **Small-scale and intense. Detectable by scatterometers**

These issues may be better addressed in meso-scale, limited area applications such as

HIRLAM 3D/4D-Var (Nils Gustafsson's talk tomorrow), and

AMPS 3D-Var, Barker et al. (2006) = the Antarctic Meso-scale Predictions System

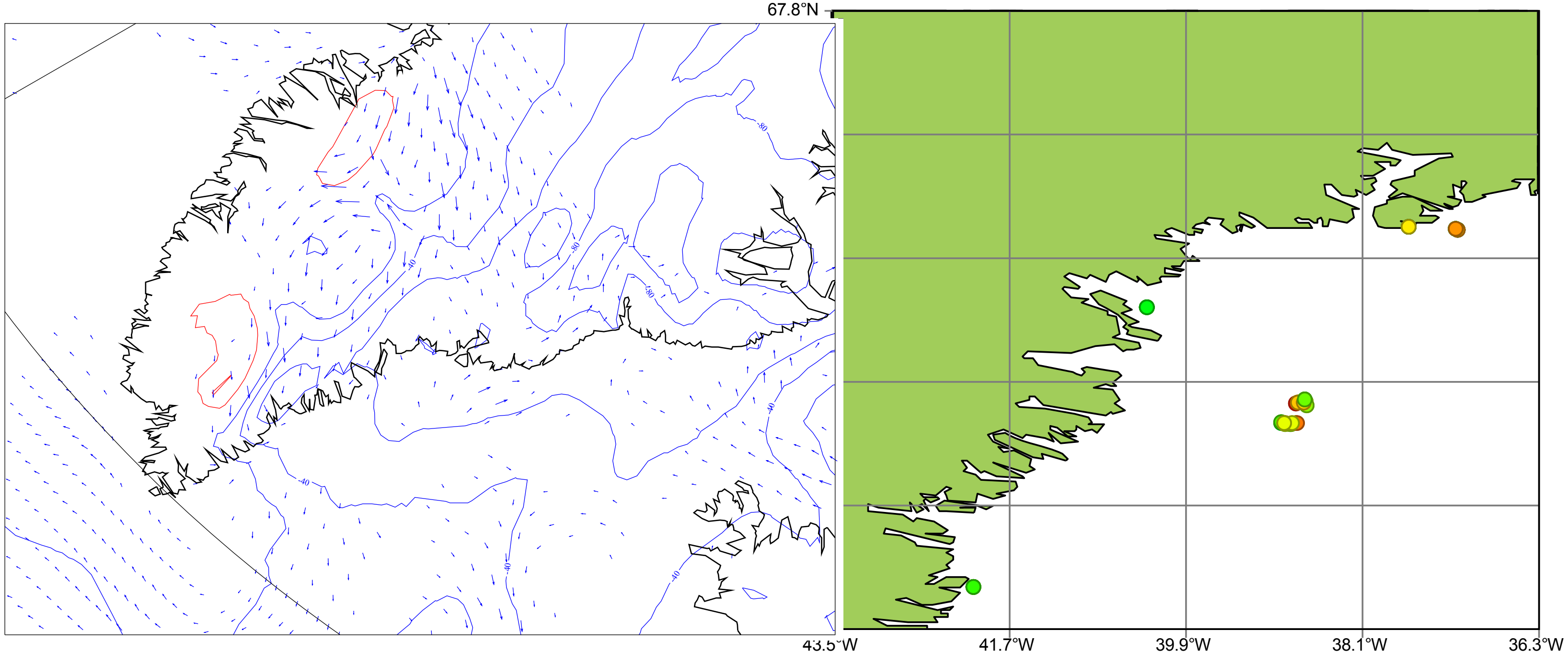
Katabatic winds, ECMWF analysis



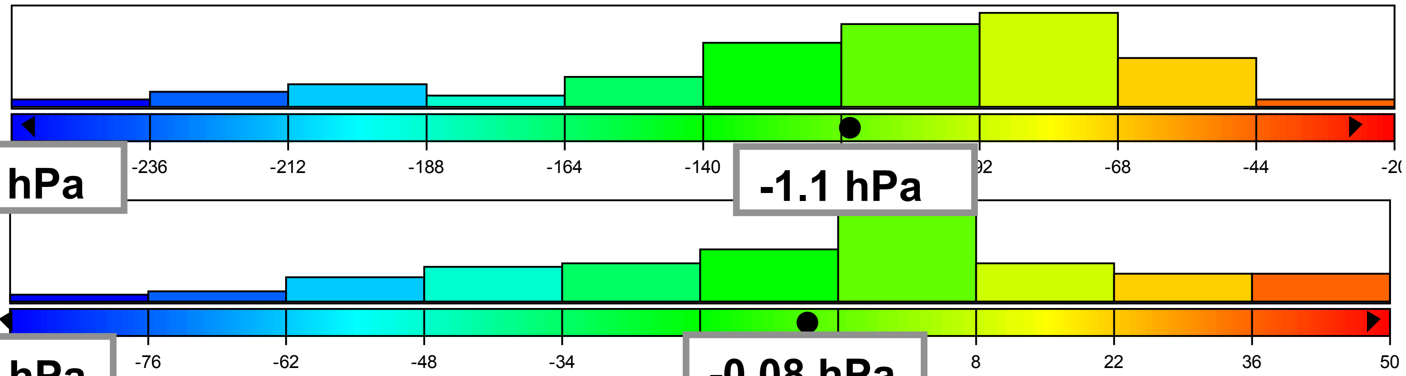
20060701-12 UTC, 10m-wind, surface pressure

ECMWF

Katabatic wind, analysis increments
102 surface pressure observations

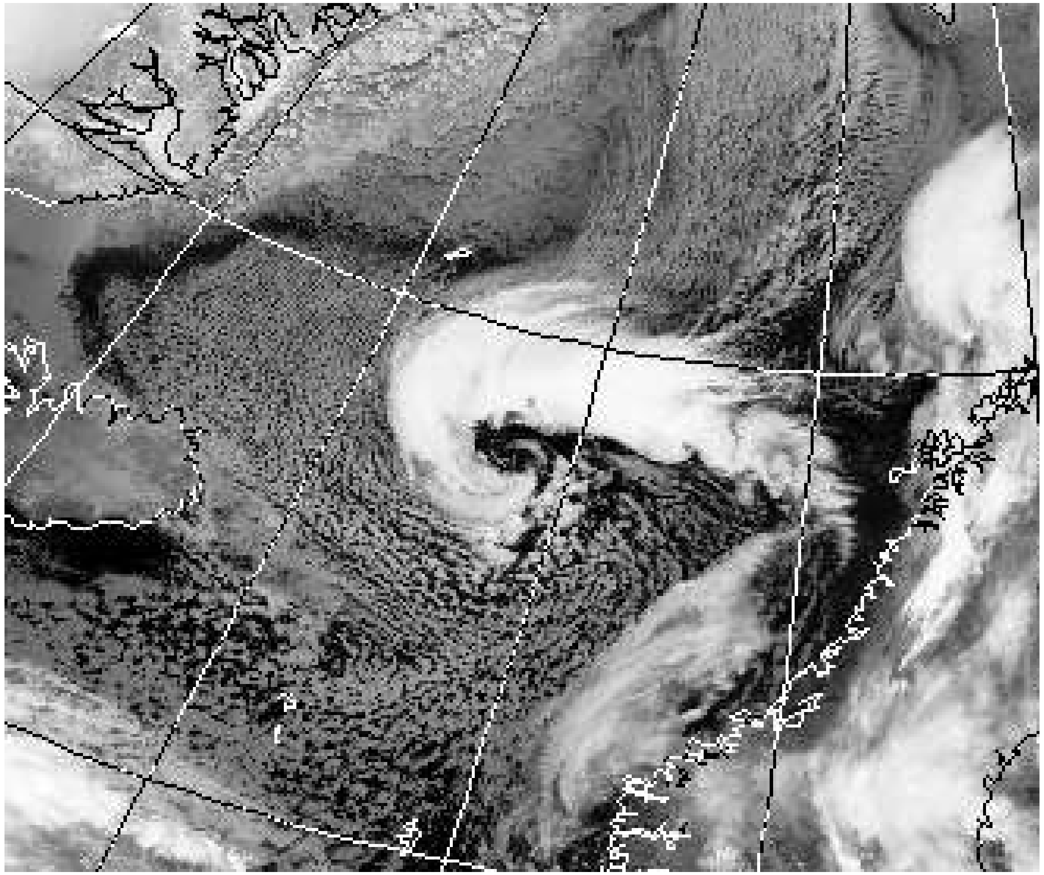


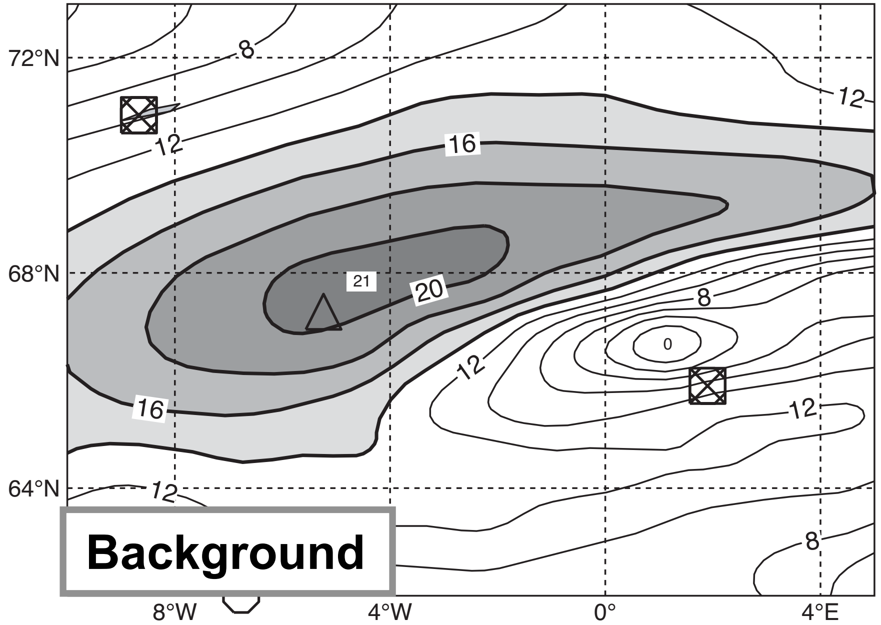
obs-bg:

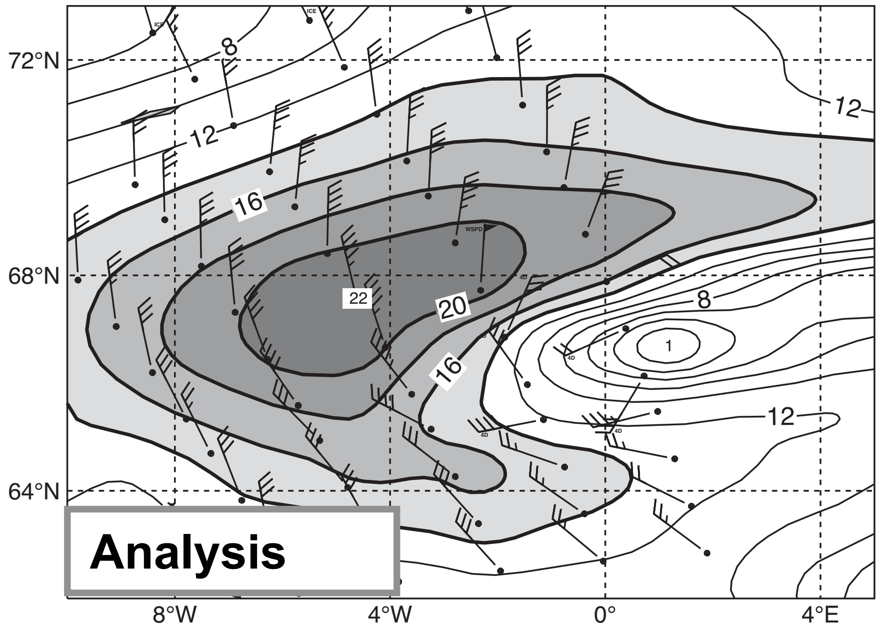


obs-an:

Polar Low case, 19980117







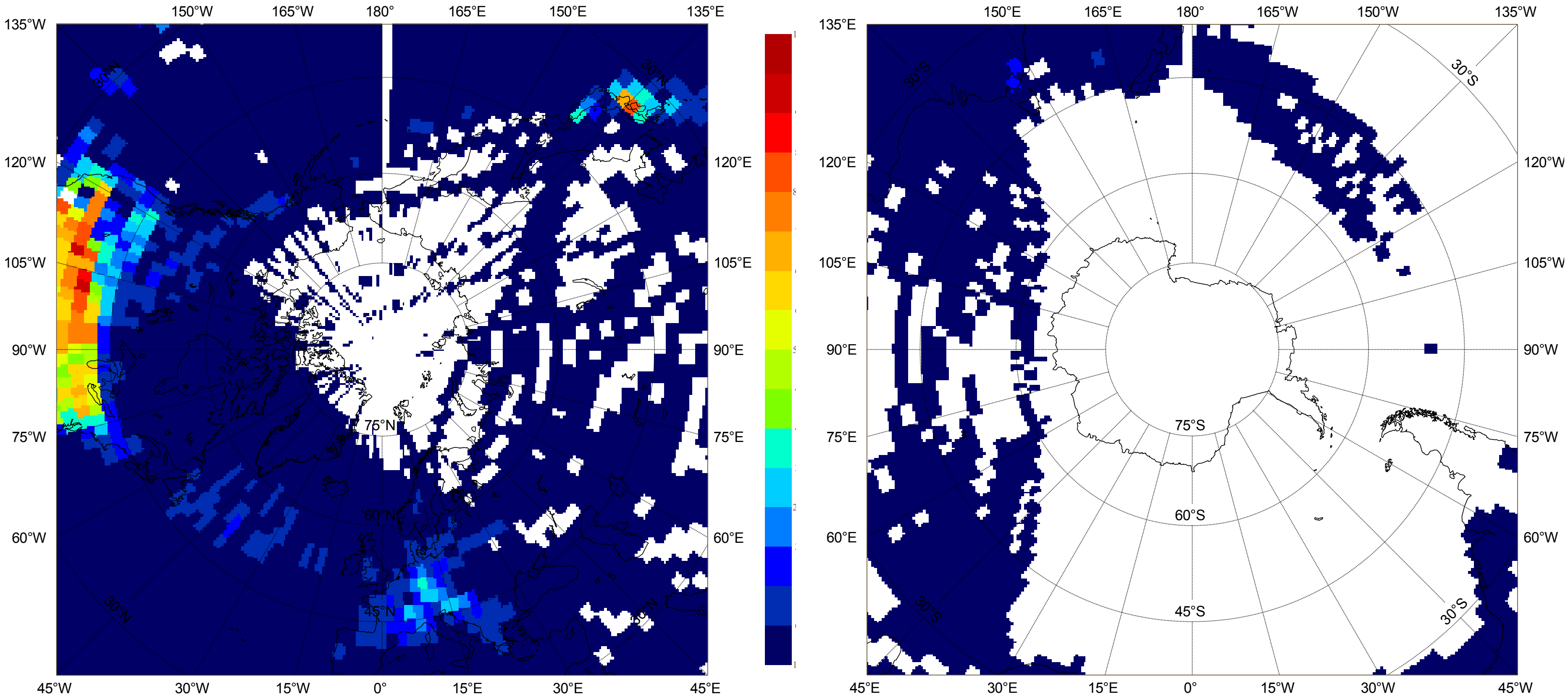
ERS 10m-wind observations

Isaksen and Janssen (QJ 2004)

ECMWF

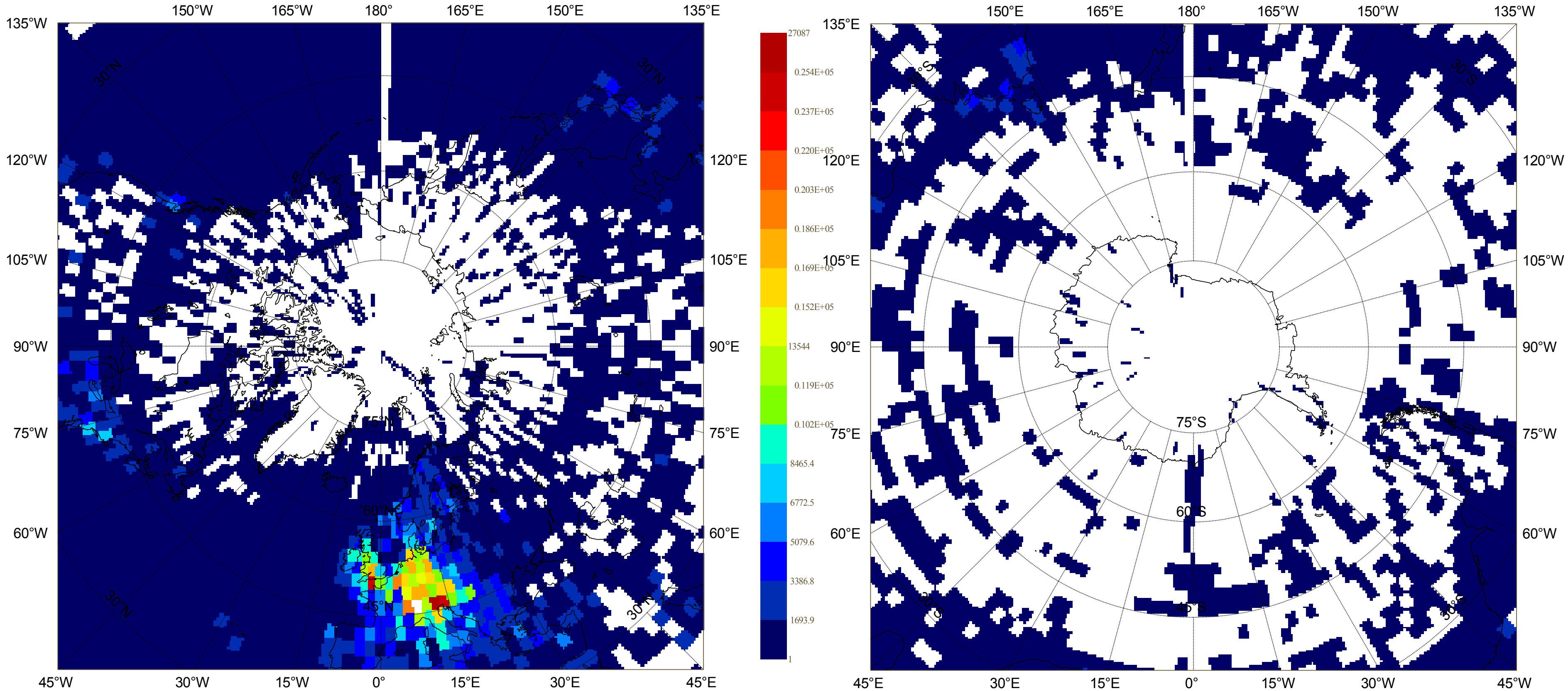
Polar observing systems and their impacts on analyses and short-range forecast

Data coverage - aircraft



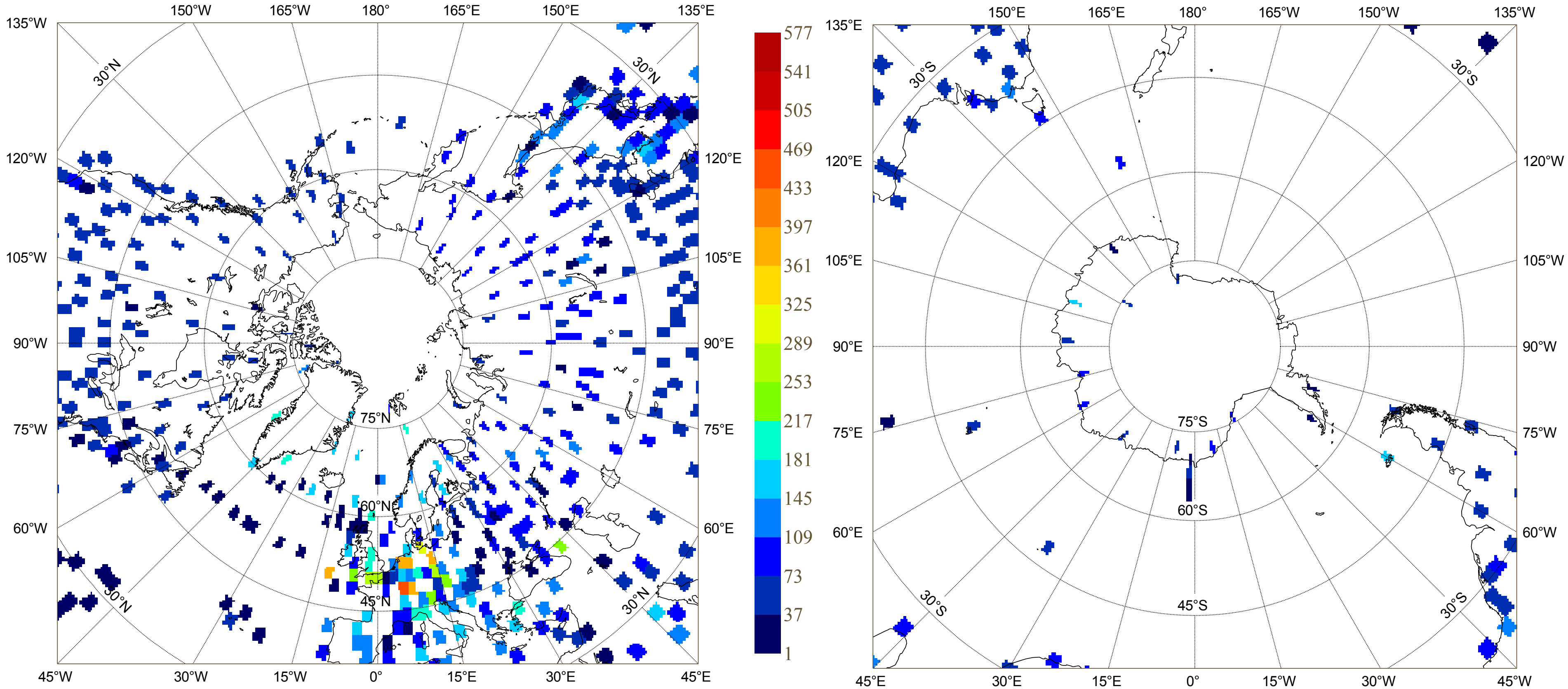
July 2006, 150-300 hPa

Data coverage – synop, ship and buoy



July 2006, surface pressure

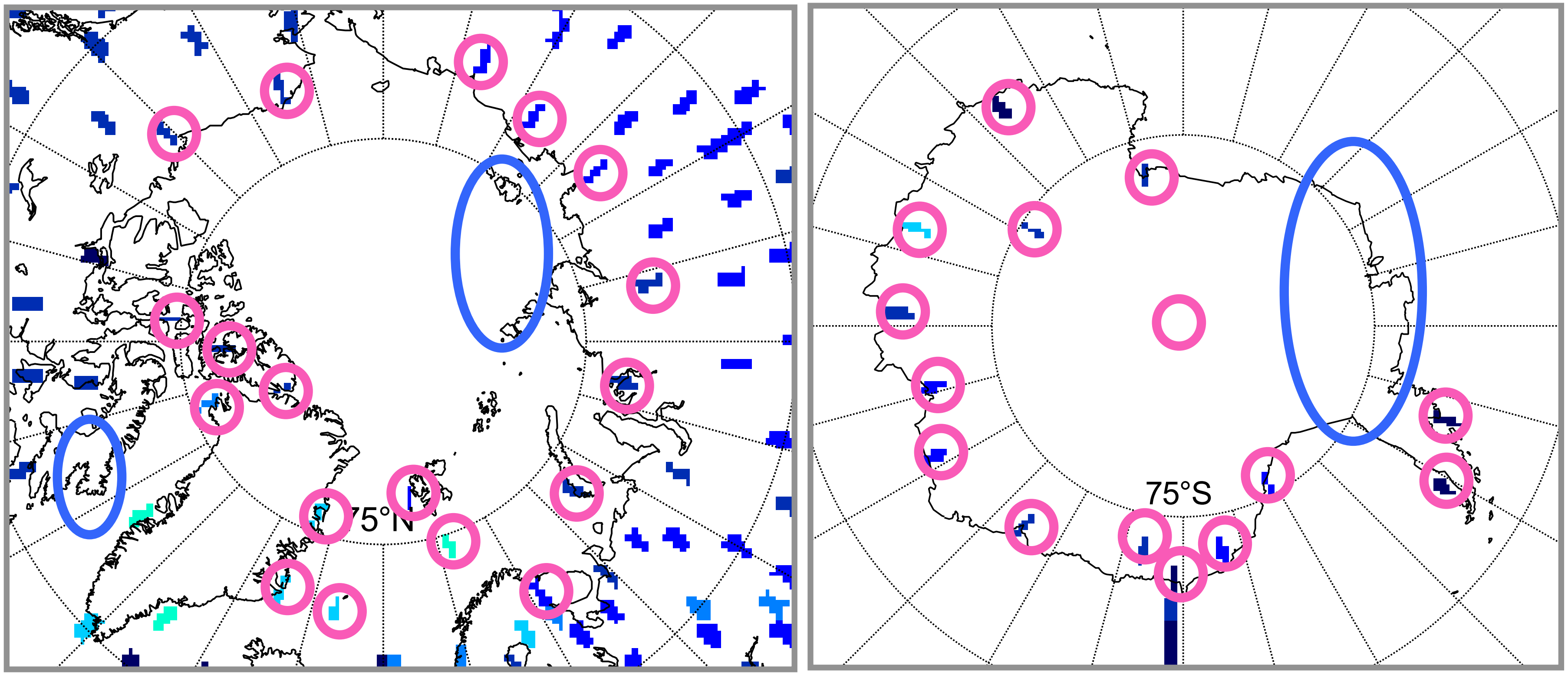
Data coverage - radiosondes



July 2006, 150-300 hPa

ECMWF

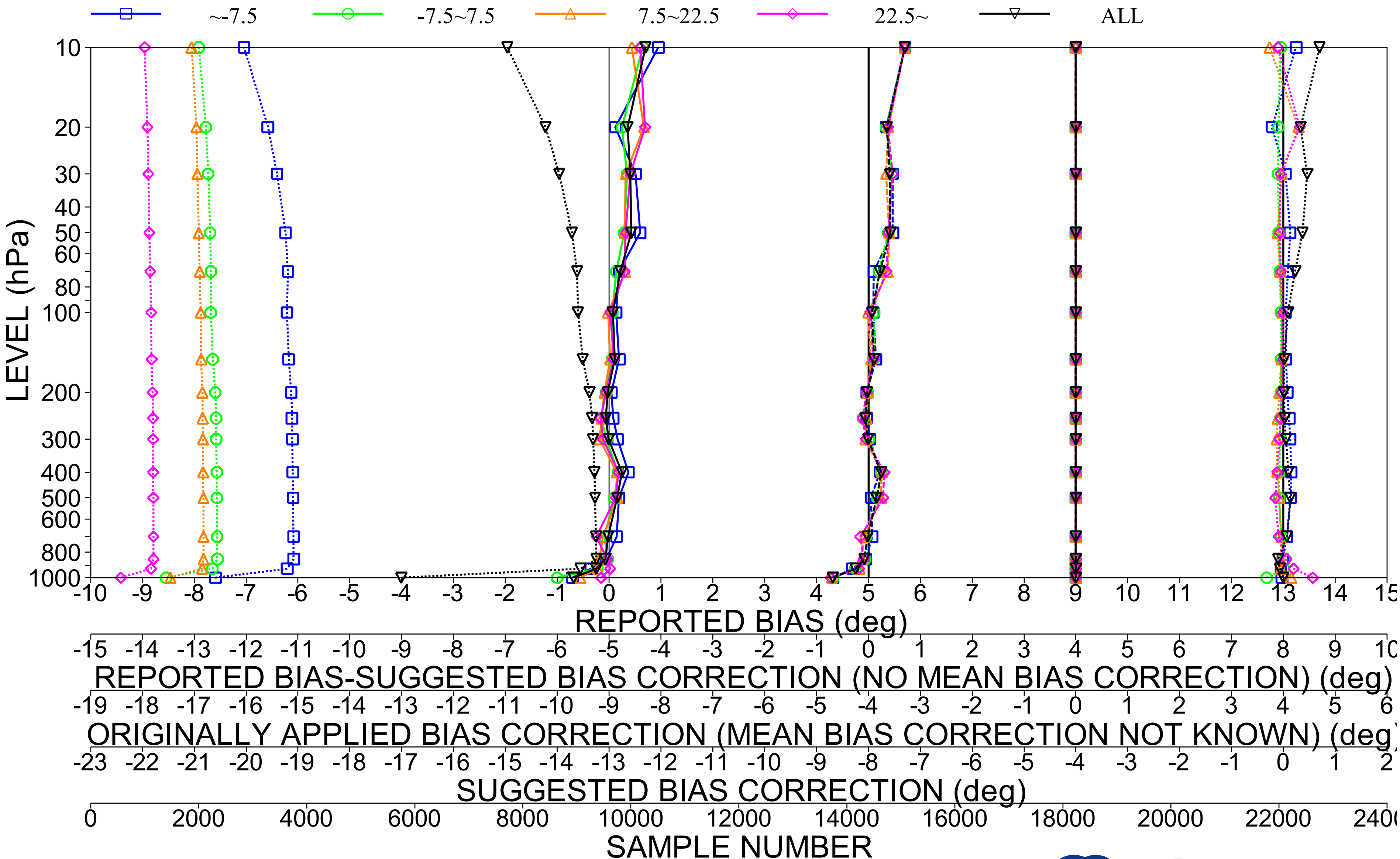
Data coverage – radiosondes (zoomed)



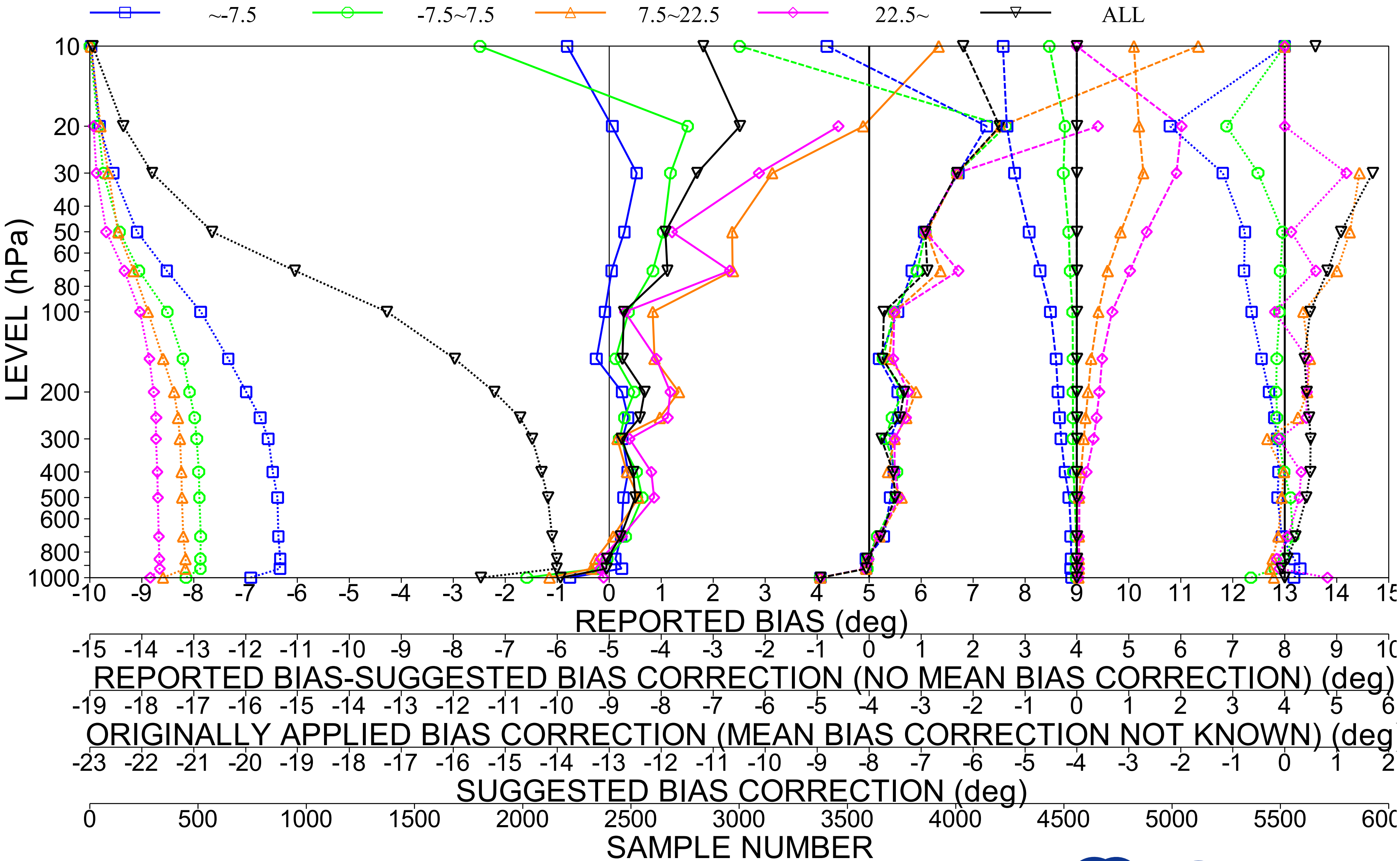
July 2006, 150-300 hPa

ECMWF

Radiosonde temperature bias, Canada North
20050930-20060731

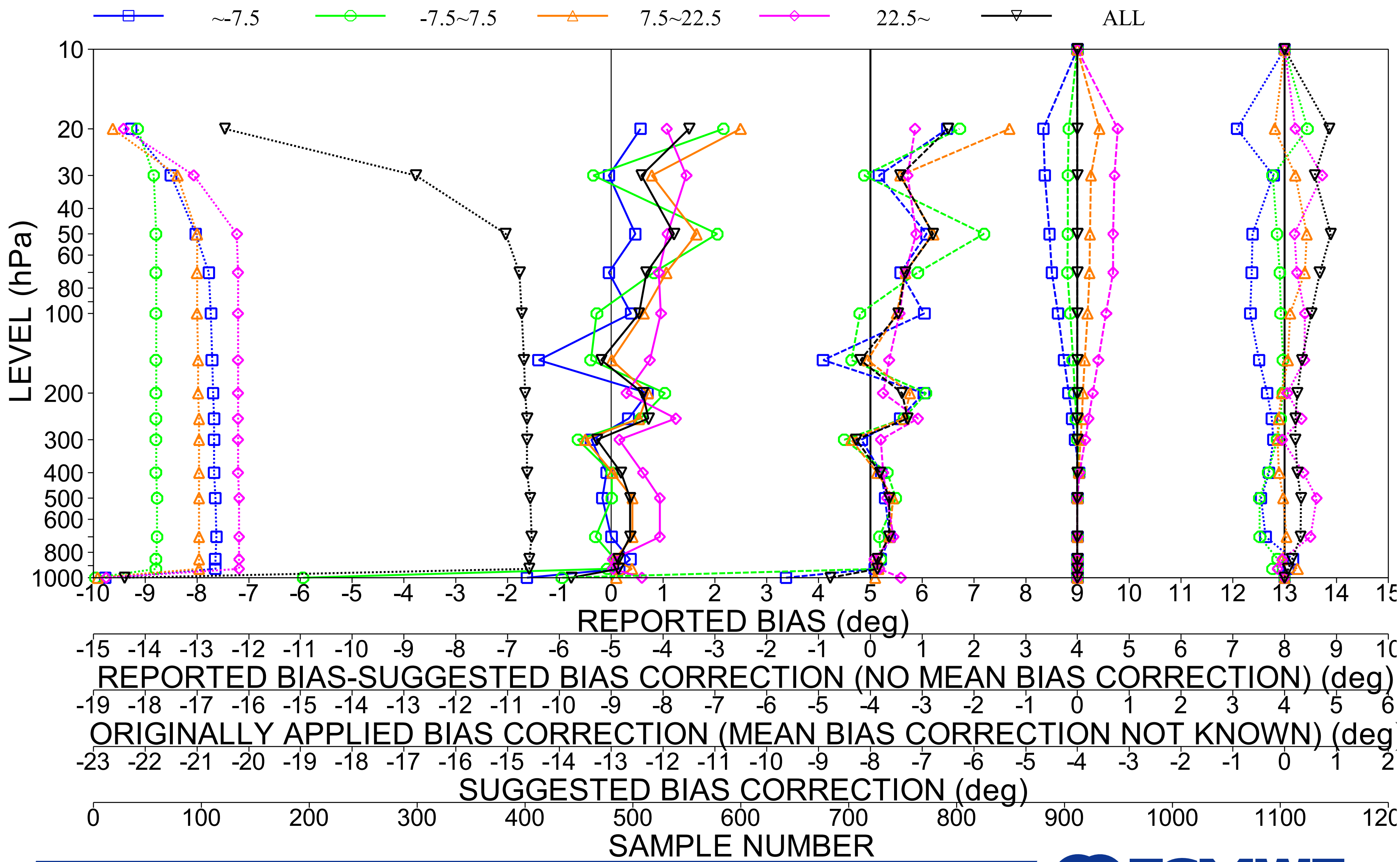


Radiosonde temperature bias, Russia North
20050930-20060731

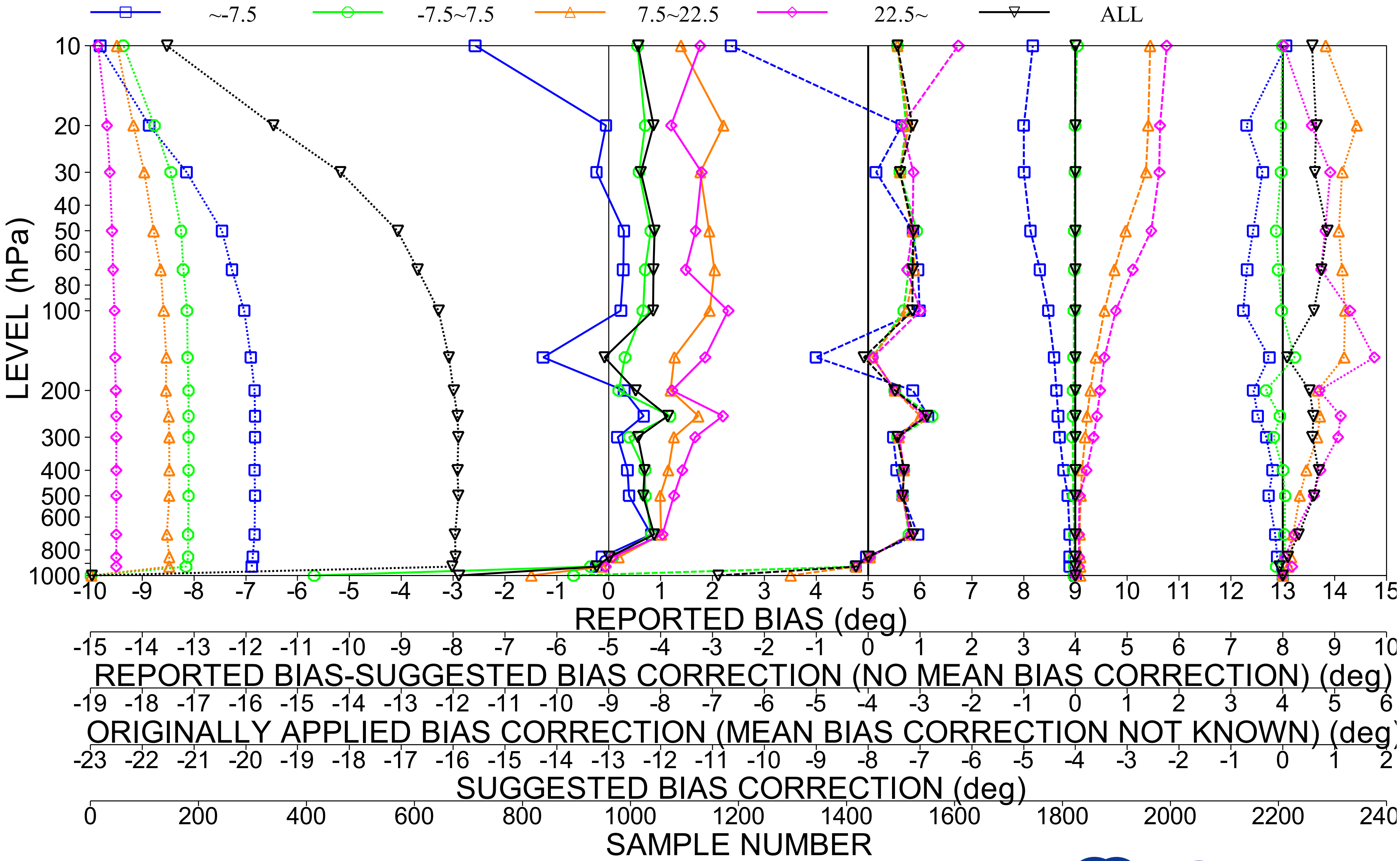


ECMWF

Radiosonde temperature bias, Antarctic_UK
20050930-20060731



Radiosonde temperature bias, Antarctic_RUSSIA
20050930-20060731

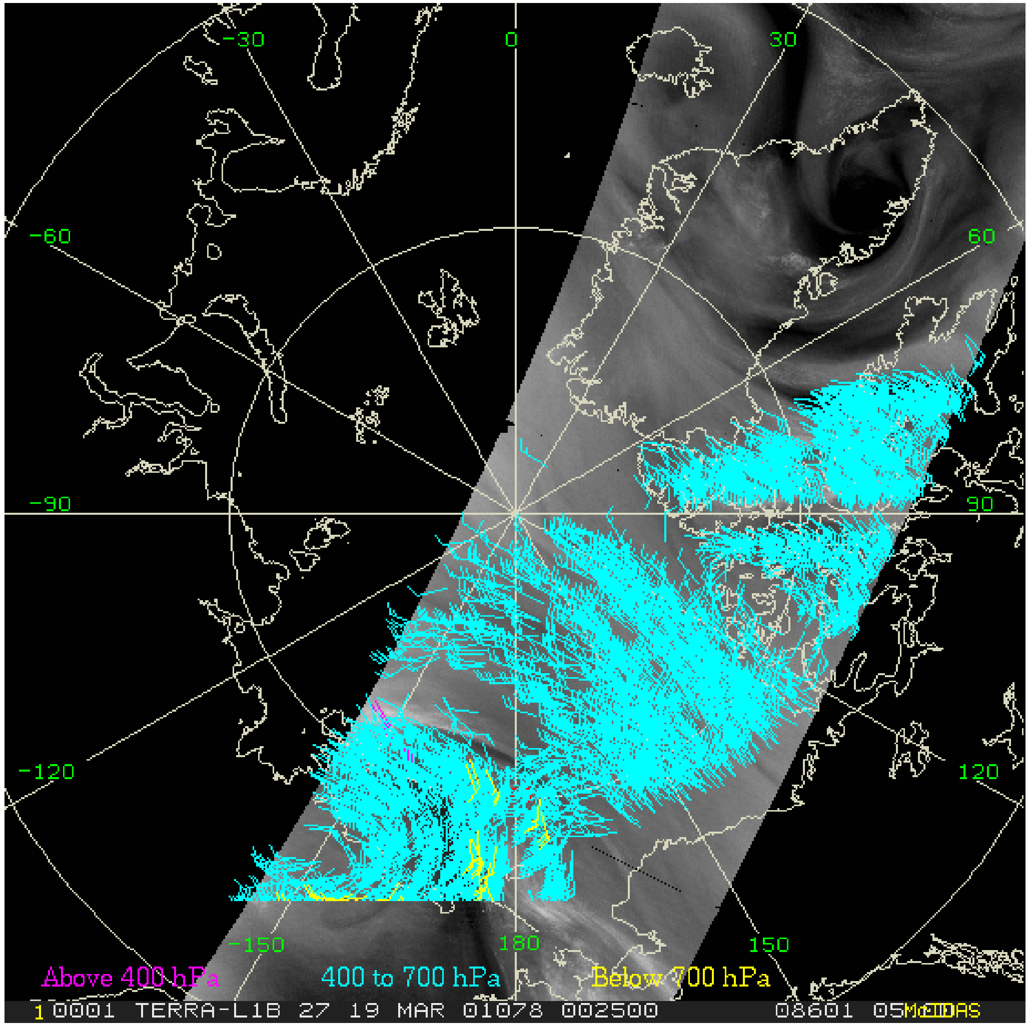


ECMWF

Polar WV winds from MODIS

Moderate resolution Infrared Spectroradiometer

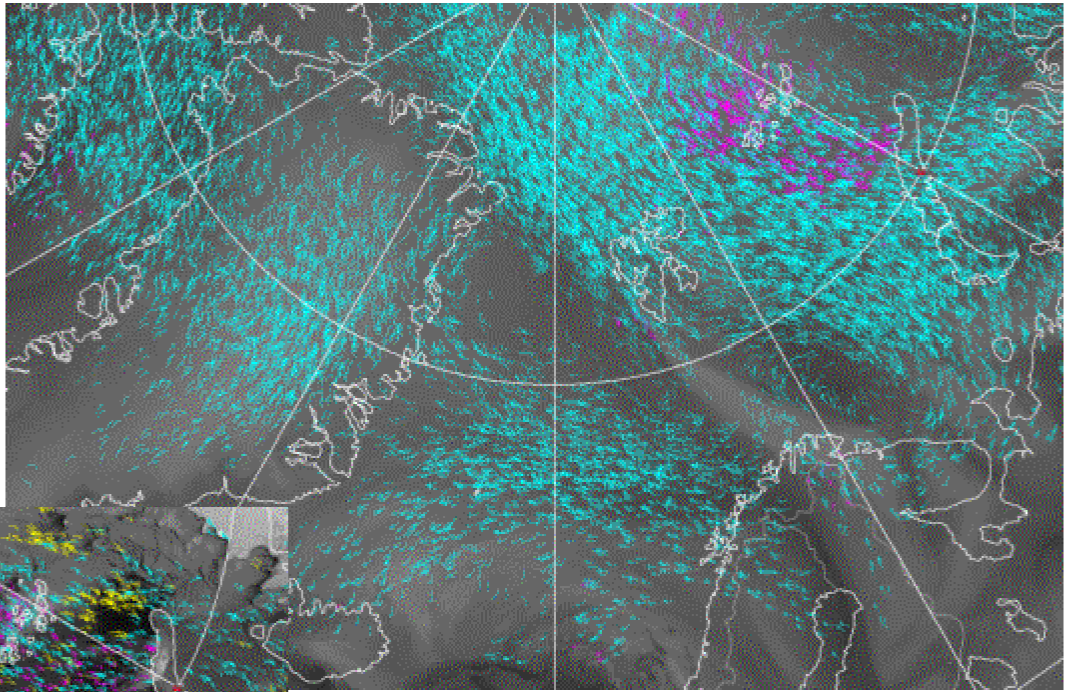
- **Winds derived at <u>CIMSS</u> (Cooperative Institute for Meteorological Satellite Studies) at Uni. of Wisconsin.**
- **Tracking of features in subsequent MODIS swaths (similar to "cloud track winds" from geostationary satellites)**
- **Height assigned to cloud top**



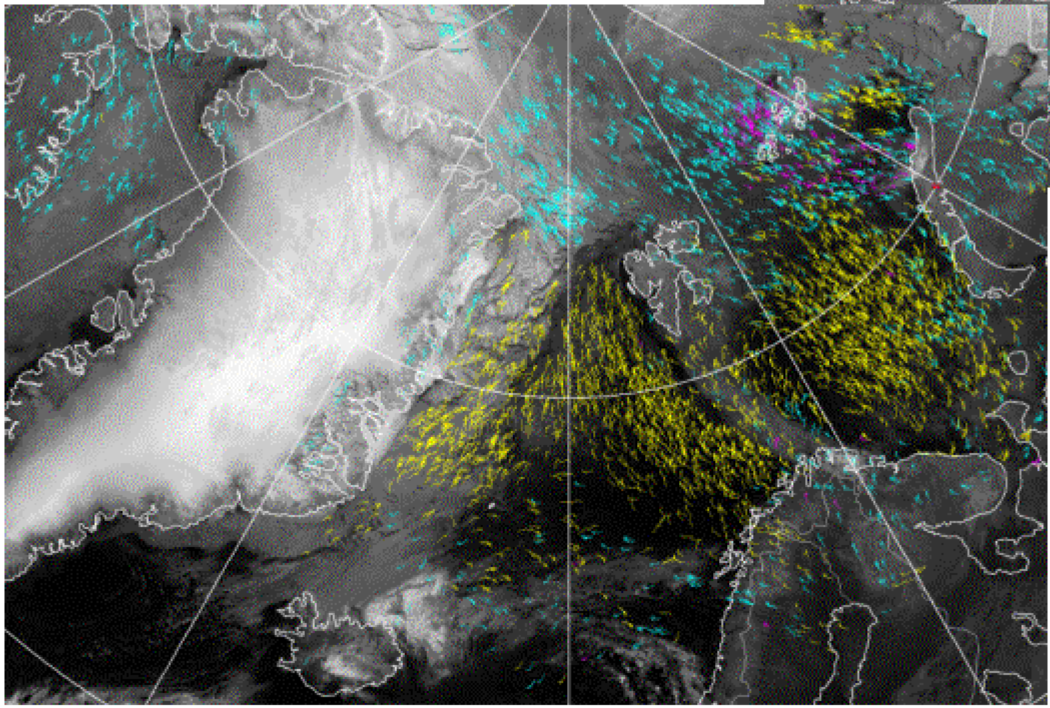
Source: P. Menzel, 2003

Polar winds from MODIS

WV

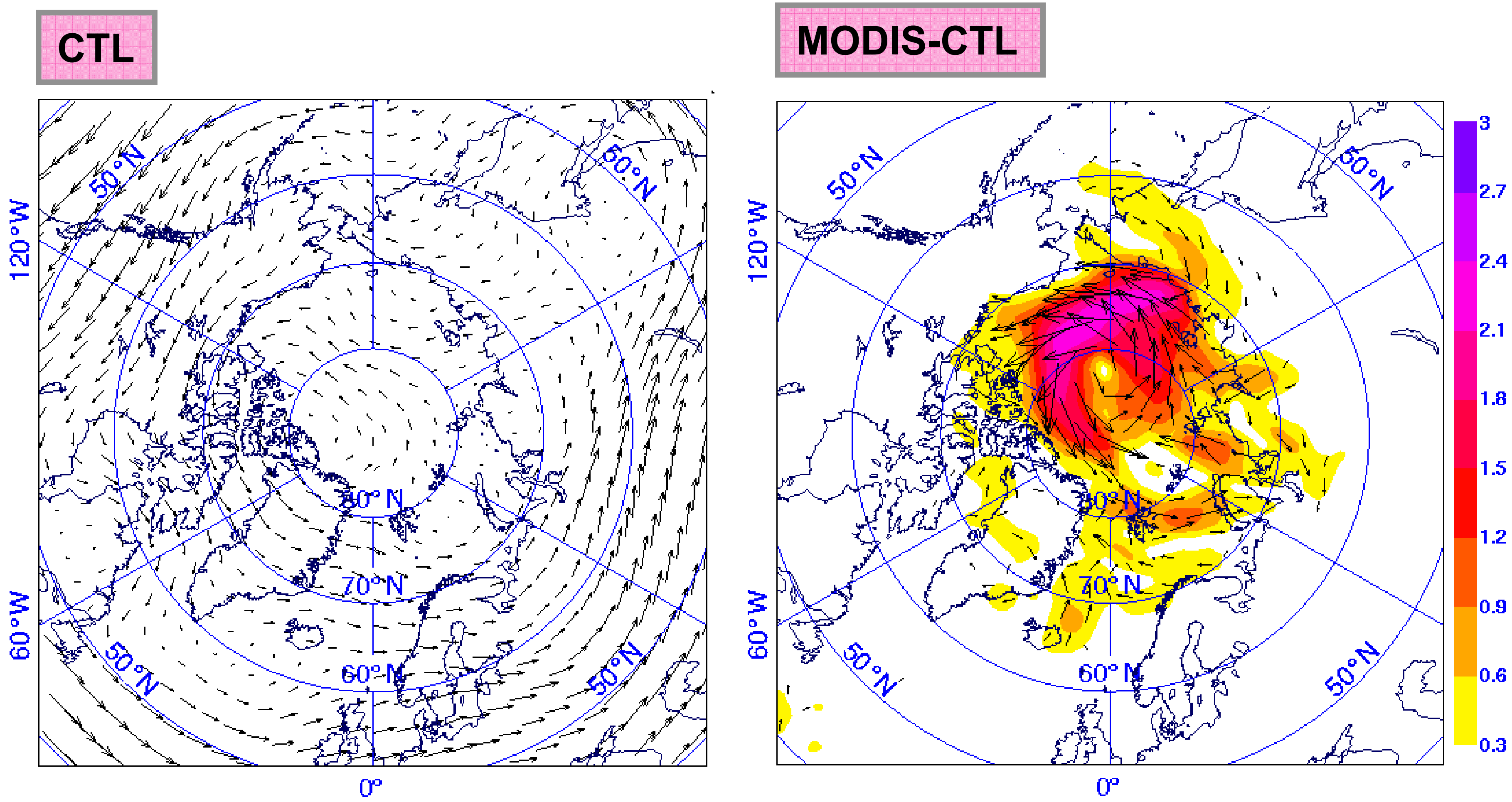


IR



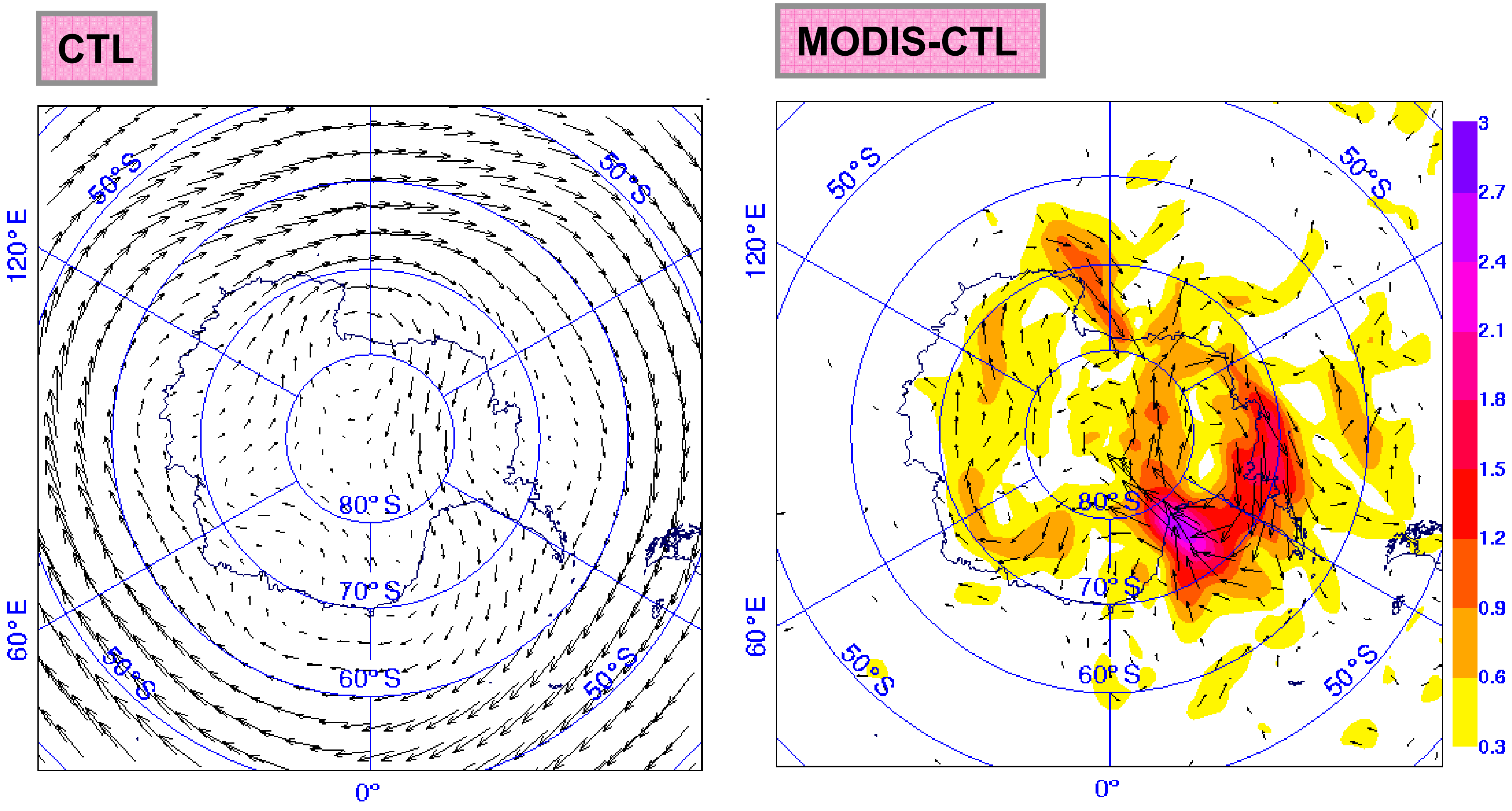
- Unprecedented coverage of wind observations over the polar regions
- Approx. 12 wind-sets daily per pole (N of 65N and S of 65S)

MODIS analysis impact - mean 400 hPa wind
20010305-20010403, T159 3D-Var

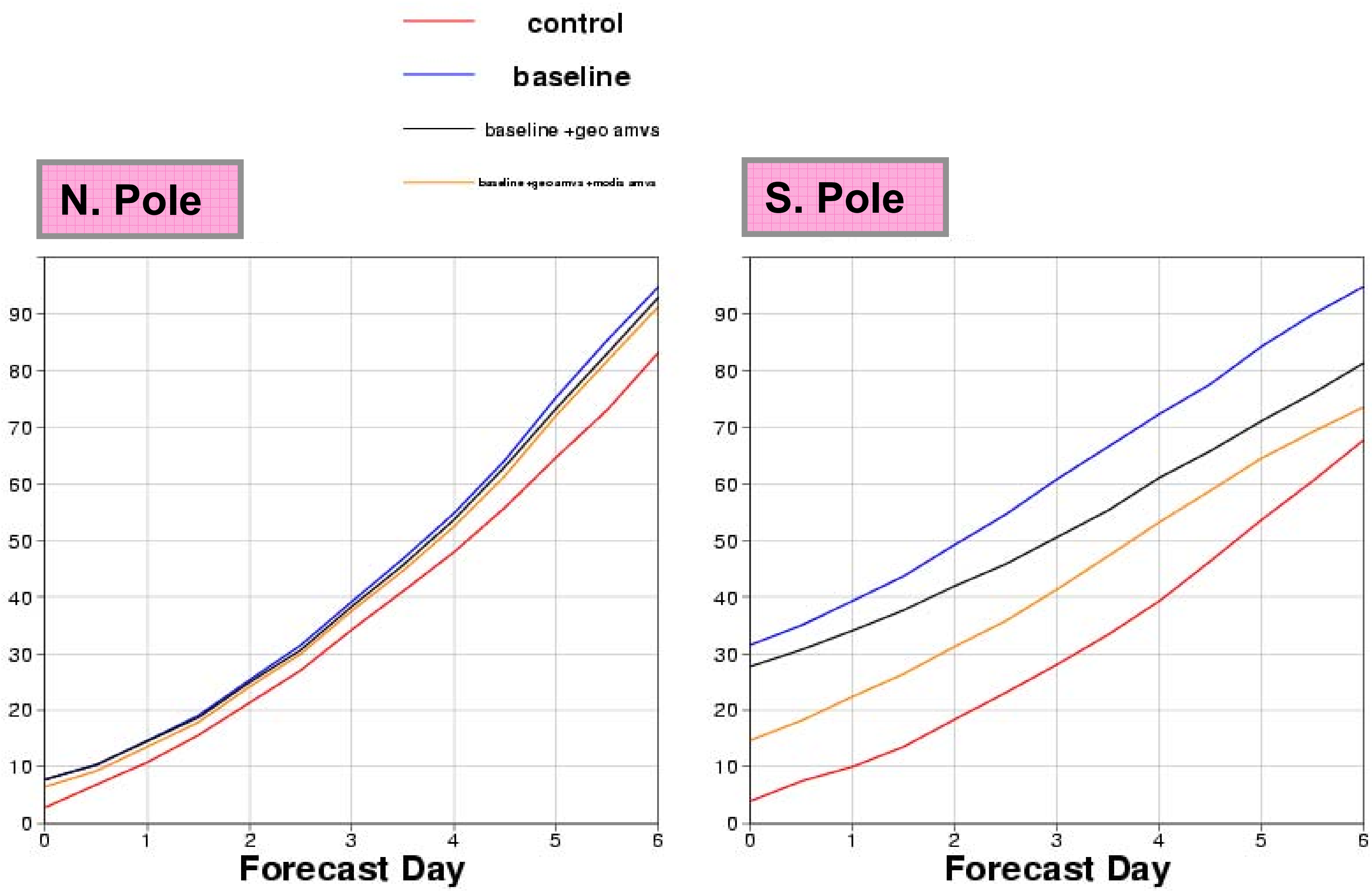


MODIS analysis impact - mean 400 hPa wind

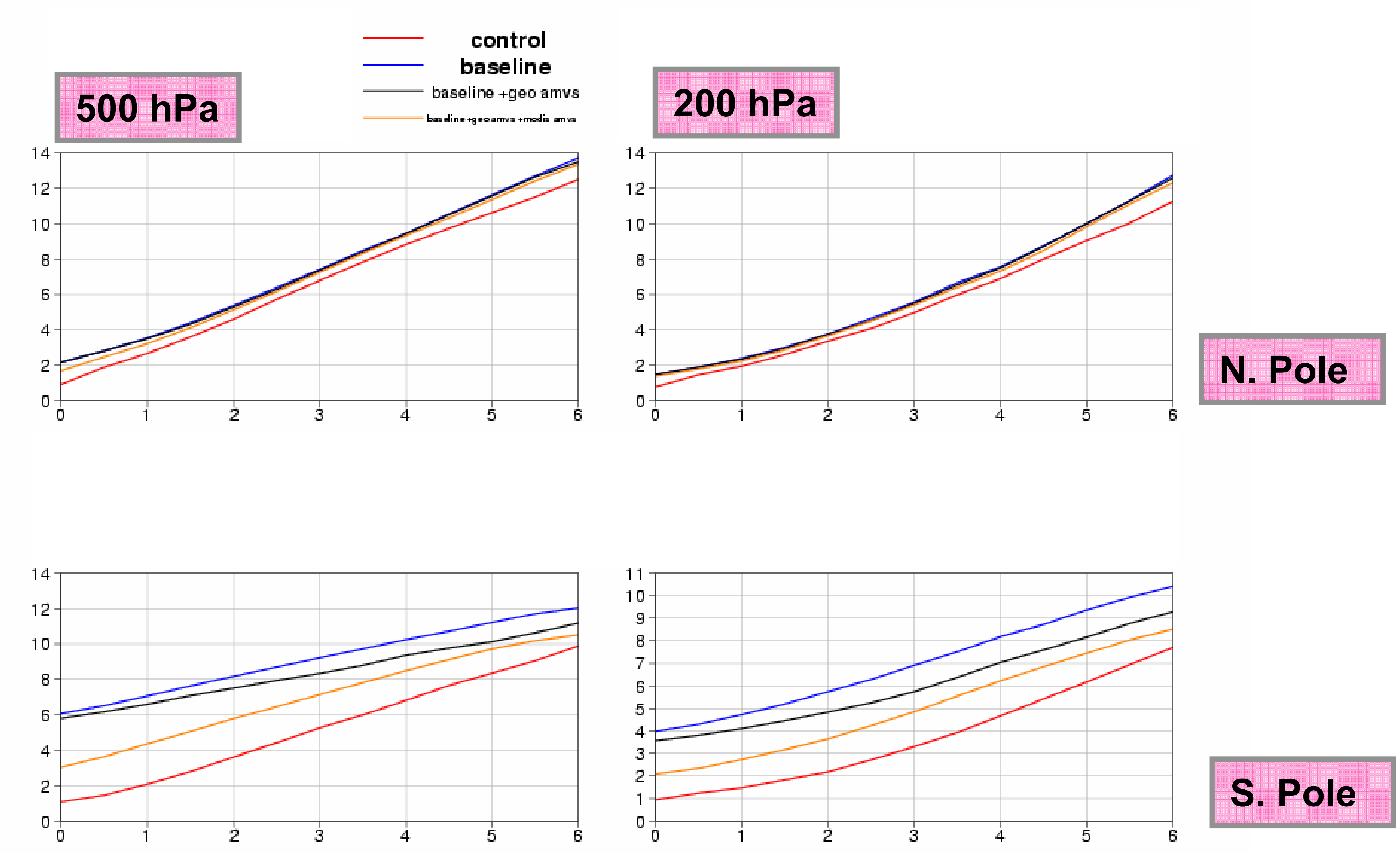
20010305-20010403, T159 3D-Var



Impact of polar AMVs
500 hPa geopotential



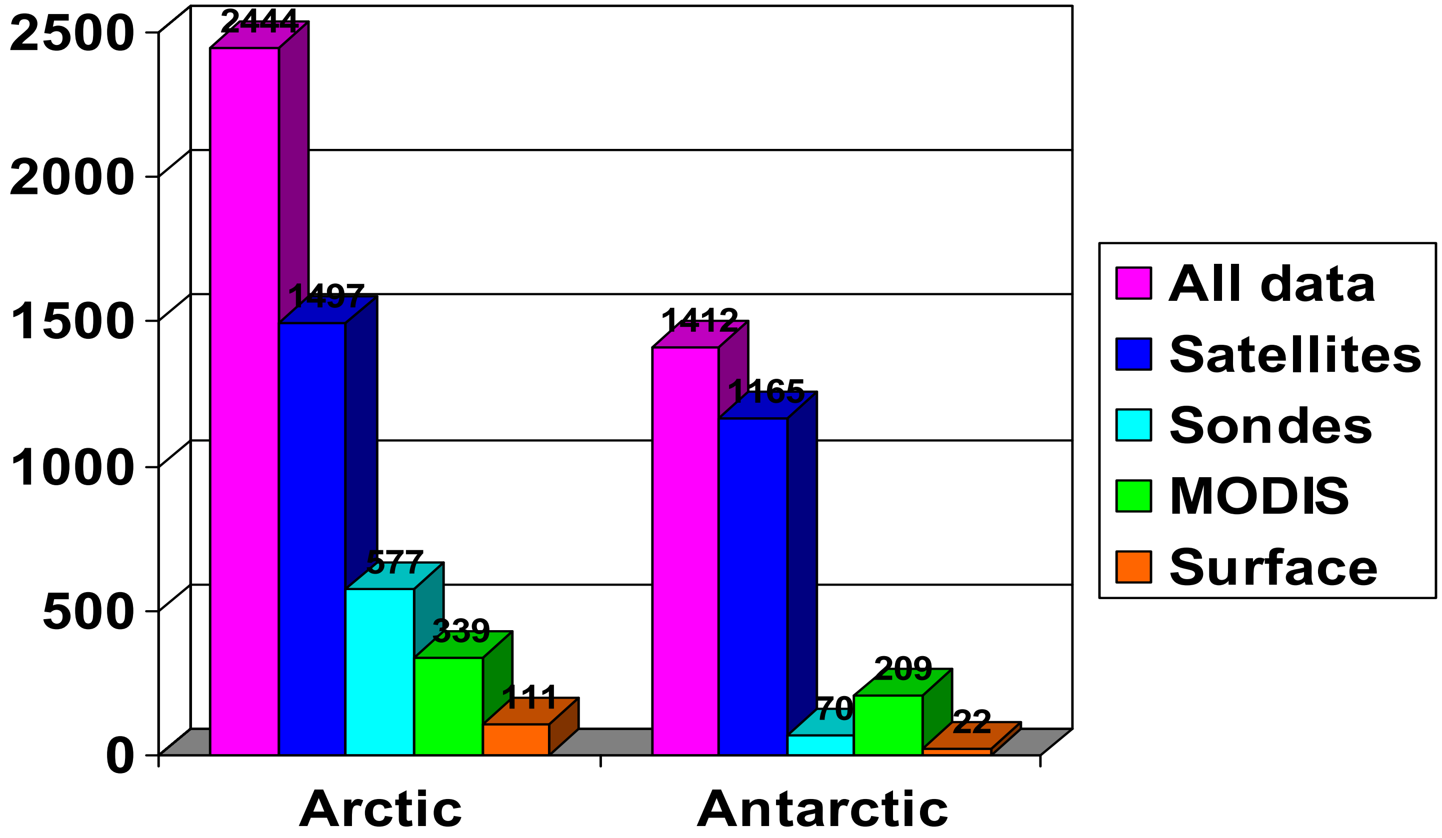
Impact of polar AMVs
Vector Wind



ECMWF

Information content
Poleward of 65° N/S, 20060801-12:

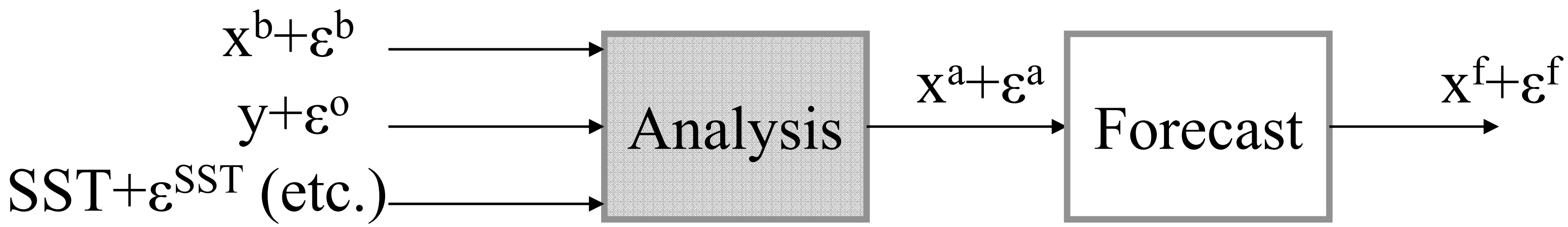
The number of pieces of information provided to the analysis by the observations can be measured by DFS=Degrees of freedom for signal.



ECMWF

The DA-ensemble method (Fisher 2003)

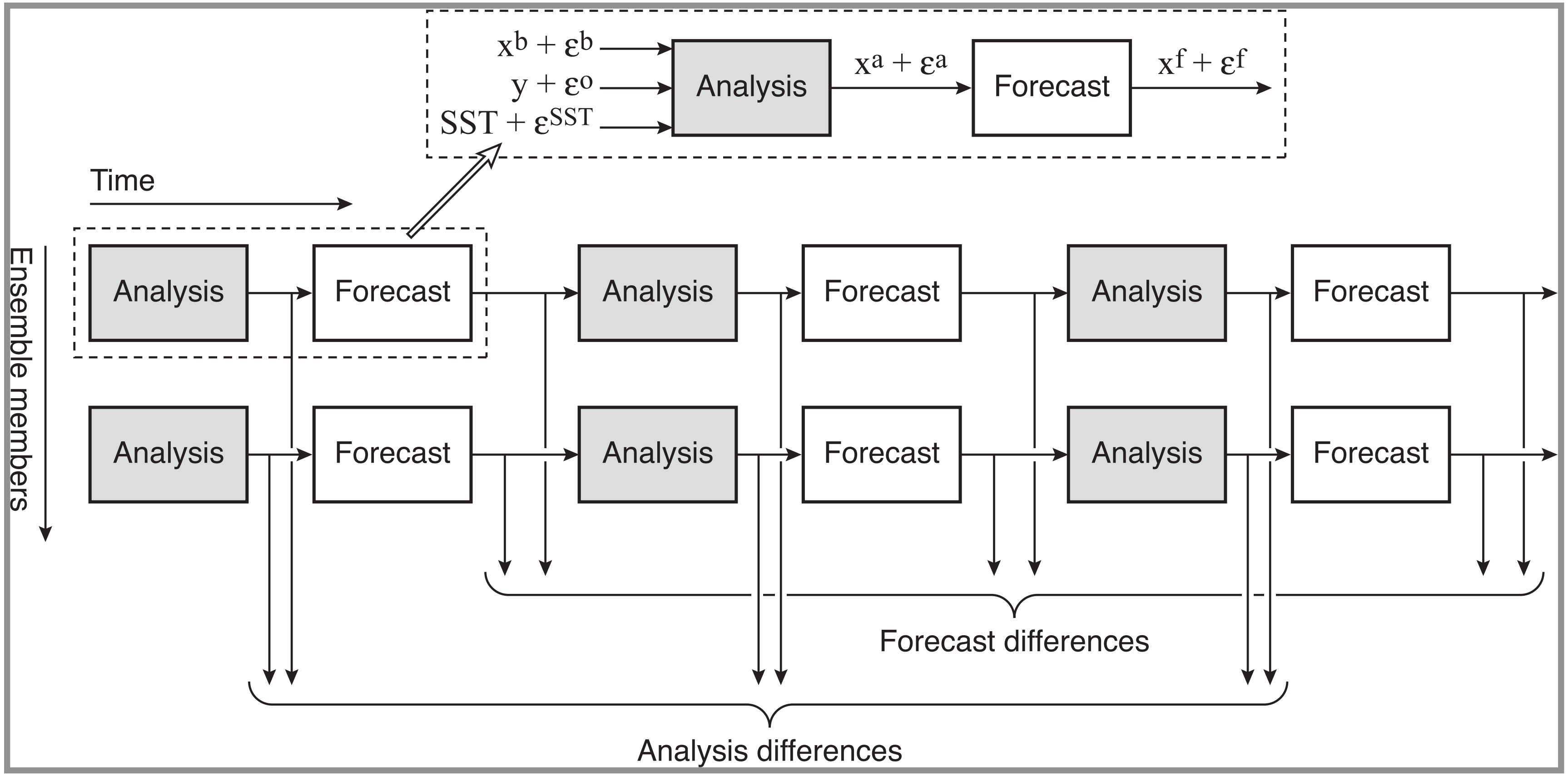
Suppose we perturb all the inputs to the AN/FC system with random perturbations, drawn from the relevant distributions:



- **The result will be a perturbed AN and FC, with perturbations characteristic of AN and FC error.**
- **The perturbed FC may be used as the Bg for the next (perturbed) cycle.**
- **After a few cycles, the system will have forgotten the original initial Bg perturbations.**

The DA-ensemble method, continued

- **Run the analysis system several times with different perturbations**
- **Form differences between pairs of background fields: The differences have the statistical characteristics of Bg error (but twice the variance).**

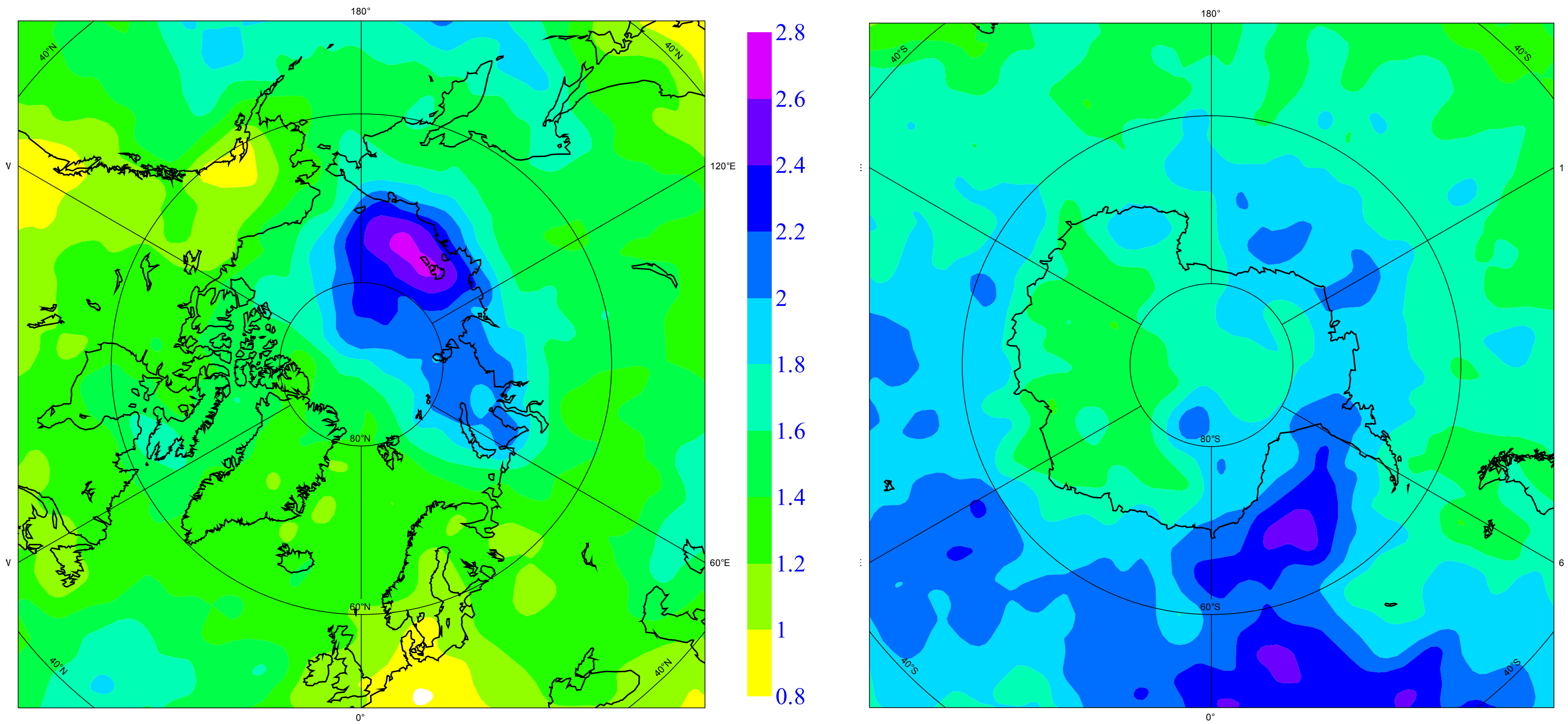


ECMWF

Analysis uncertainty, 500 hPa geopotential

Ensemble of ten cycling 4D-Var assimilations, 20030906-20031007

- **Lack of data from Siberian coast to N.Pole**
- **In S.Hem, the largest uncertainty is in the Atlantic sector**

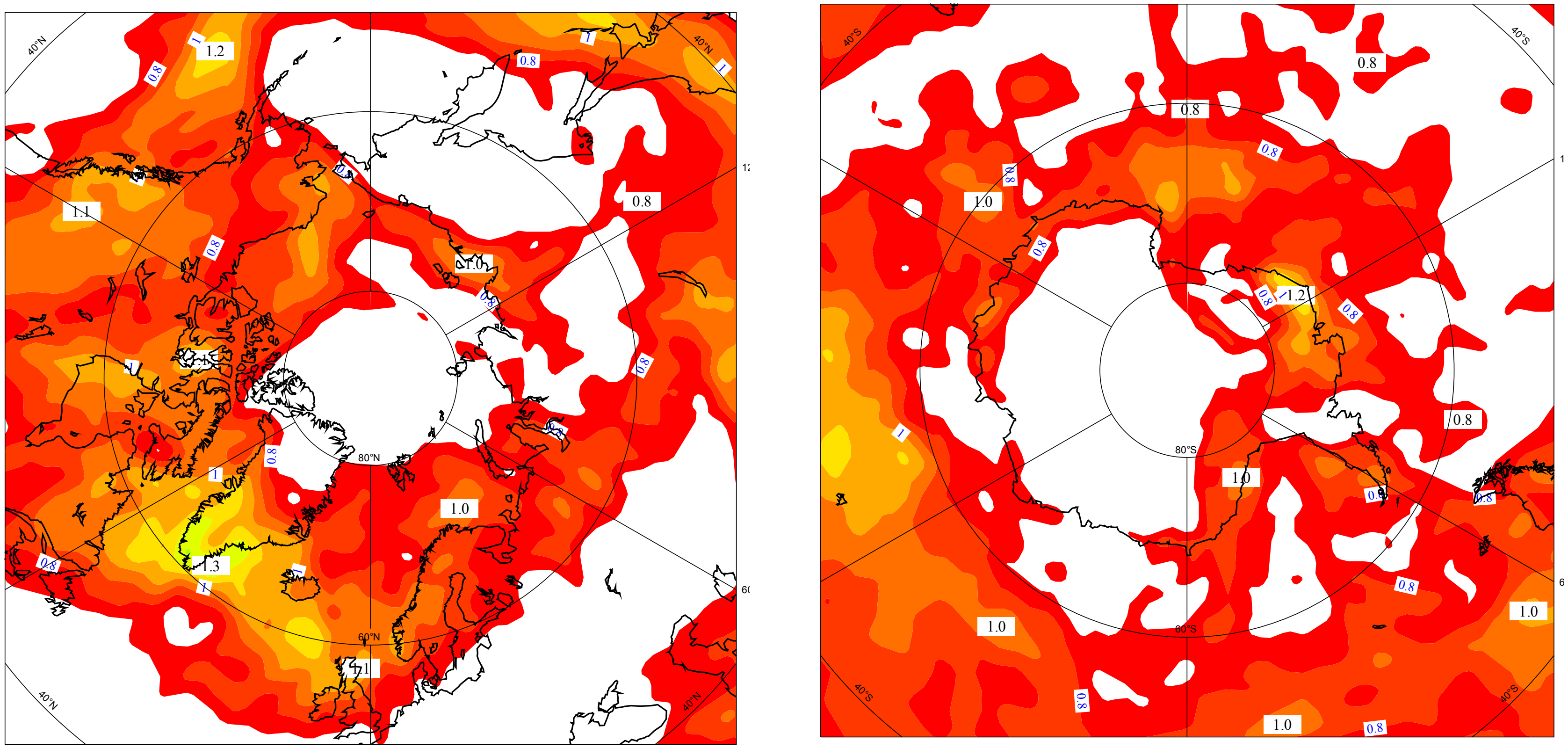


ECMWF

Eady index - baroclinicity

Ensemble of ten cycling 4D-Var assimilations, 20030906-20031007

- **Very little error growth over Antarctica (on this period)**
- **Some in the Arctic: N. of Alaska, around S. Greenland**

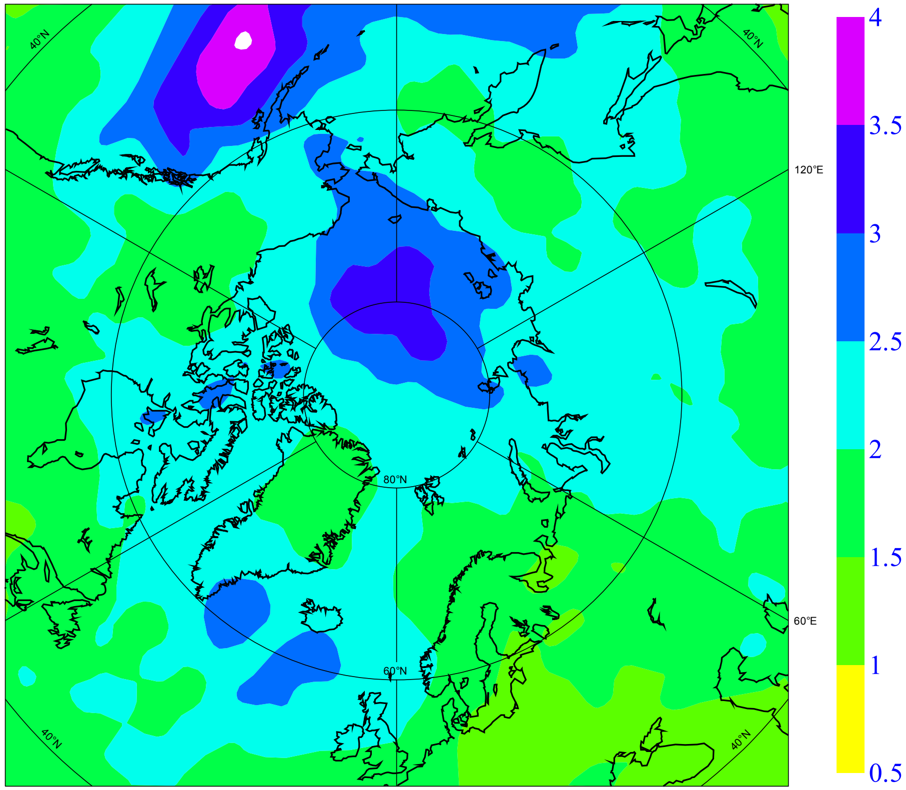


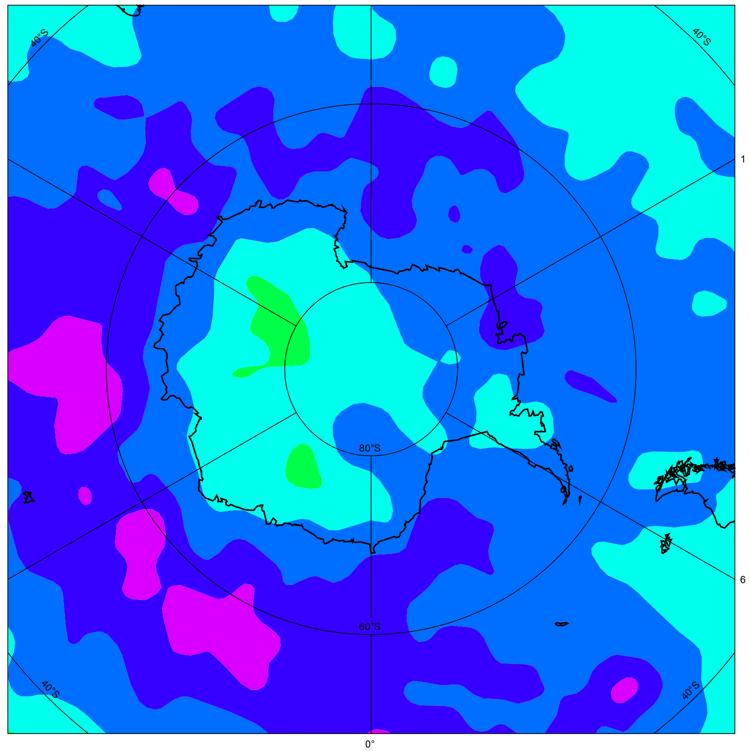
ECMWF

24-hour forecast uncertainty, 500 hPa Z

Ensemble of ten cycling 4D-Var assimilations, 20030906-20031007

- **Error growth occurs where Polar errors can interact with mid-latitude baroclinic zones**

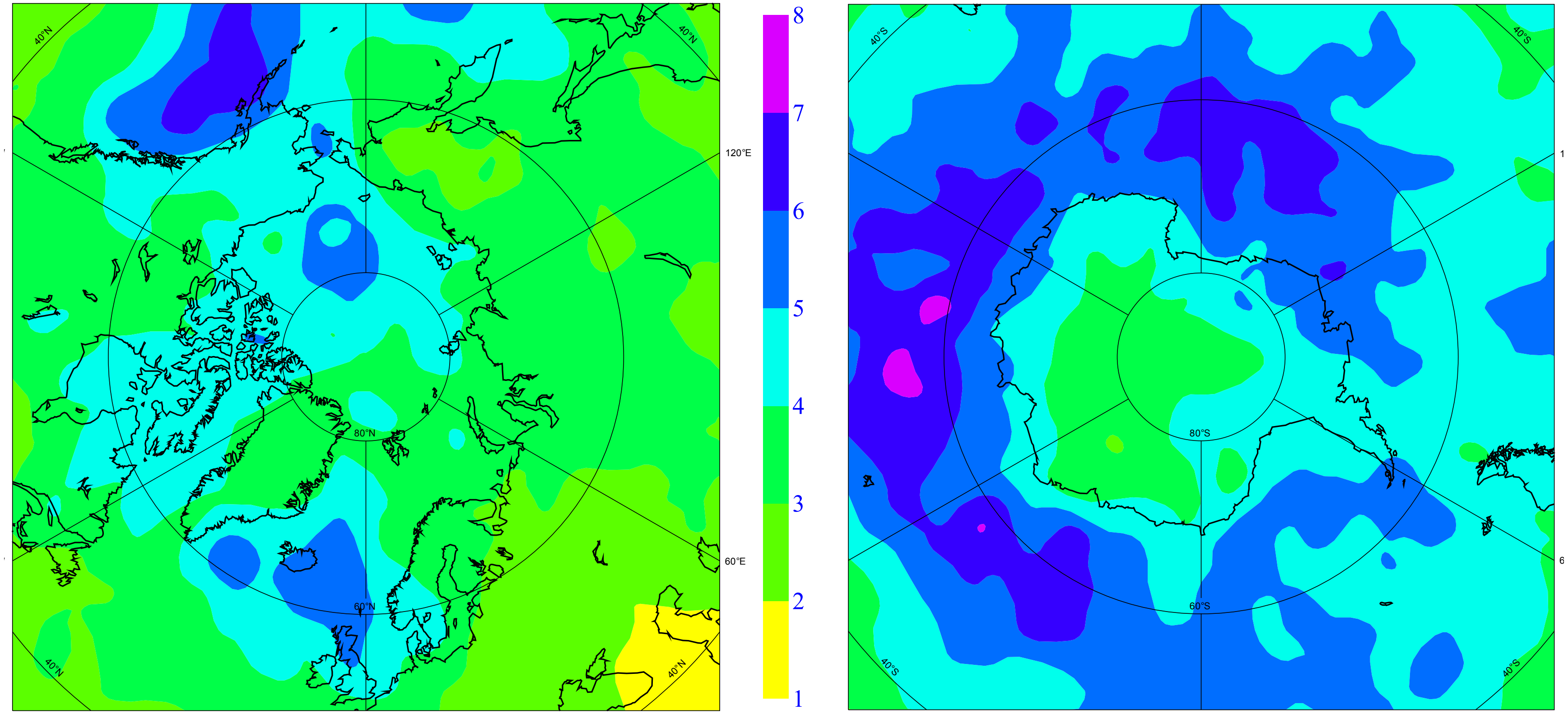




48-hour forecast uncertainty, 500 hPa Z

Ensemble of ten cycling 4D-Var assimilations, 20030906-20031007

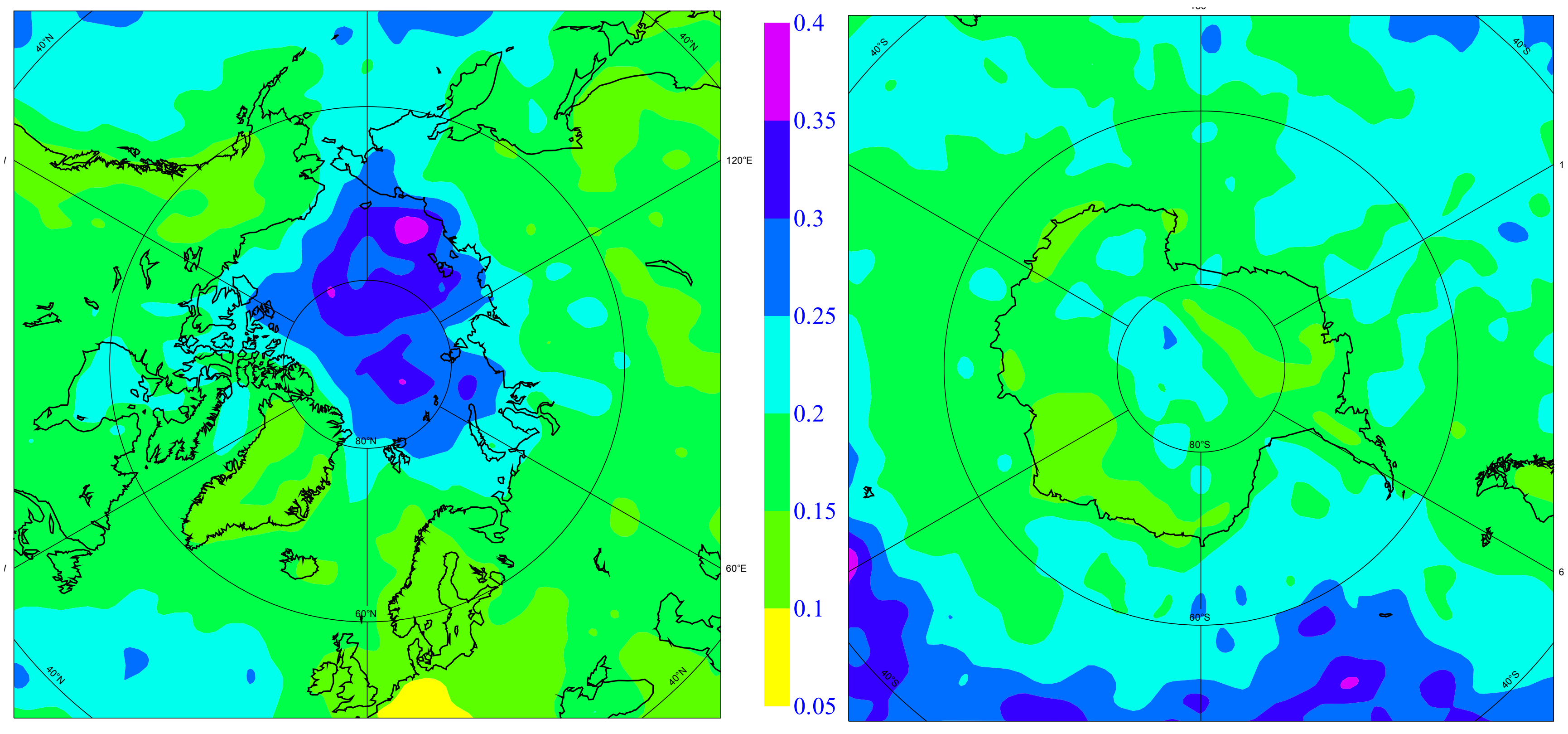
- **The oceanic storm track regions dominate**



Analysis uncertainty, 850 hPa temperature

Ensemble of ten cycling 4D-Var assimilations, 20030906-20031007

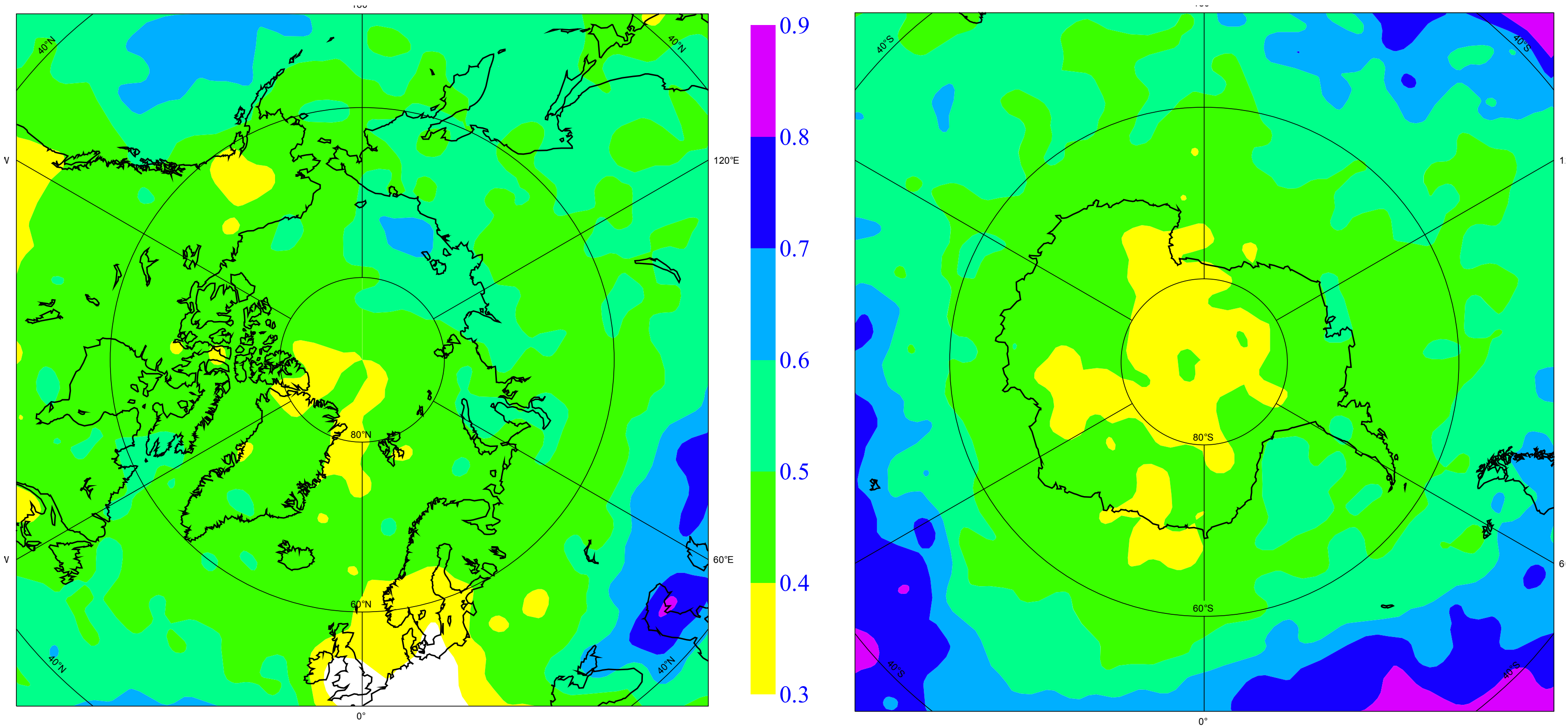
- **In the Arctic, there is large uncertainty in lower-tropospheric analysed temperature**



Analysis uncertainty, 300 hPa wind

Ensemble of ten cycling 4D-Var assimilations, 20030906-20031007

- **Small wind uncertainty over both poles**
- **This is due to assimilation of MODIS winds**

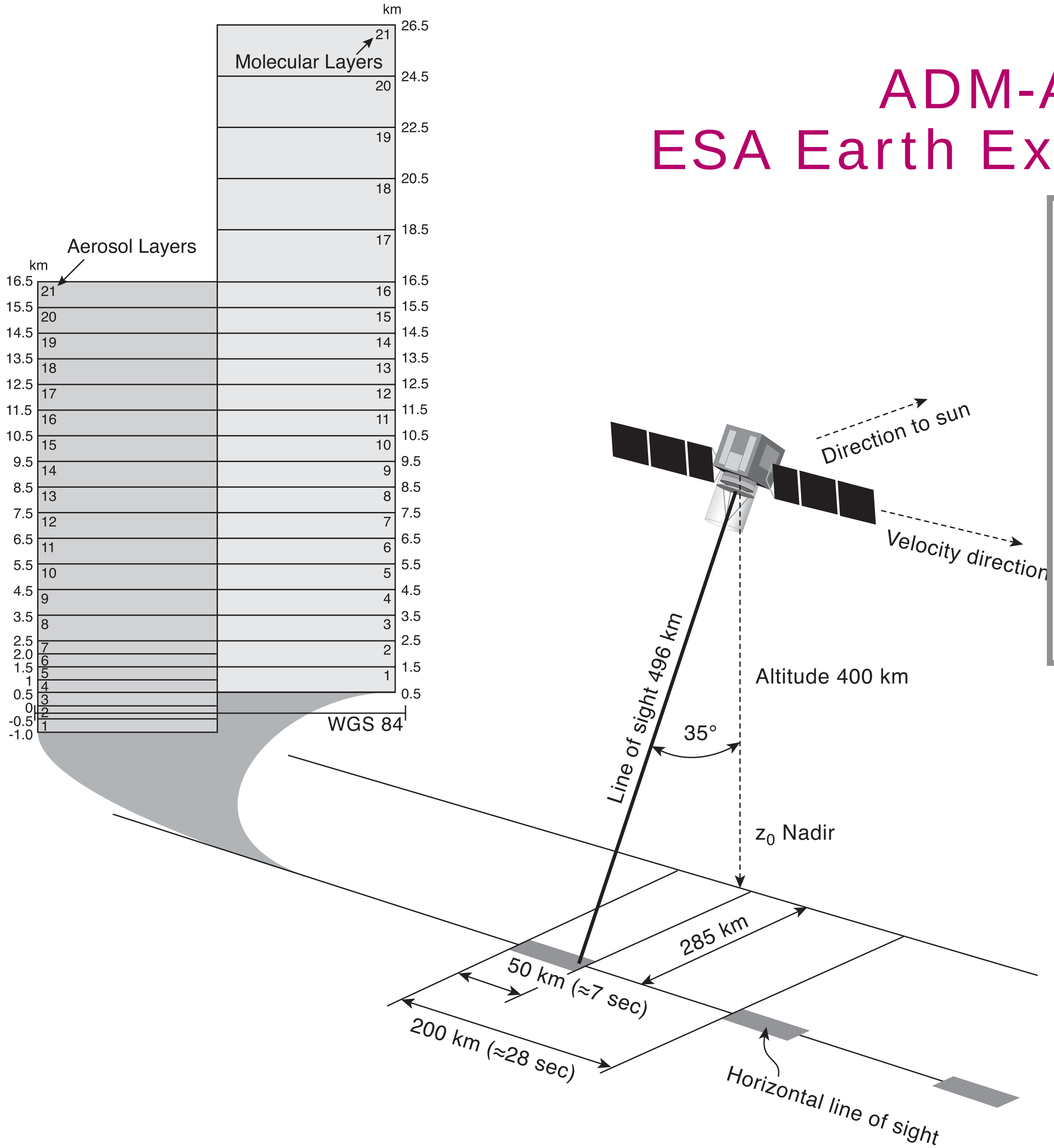


ECMWF

Summary of polar data impact

- There has been a very significant improvement in analysis quality in both polar regions, in particular for the Antarctic. (2001 vs. 2006)
- Main improvements are due to more extensive assimilation of radiances, and addition of MODIS winds
- In order of importance,
  - ➔N.Pole: Rad, RS, MODIS, Ps
  - ➔S. Pole: Rad, MODIS, RS, Ps
- Largest uncertainties: Temperature tropopause, and surface inversion
- Calibration of MODIS winds (with ADM-Aeolus…)

ADM-Aeolus, ESA Earth Explorer Mission

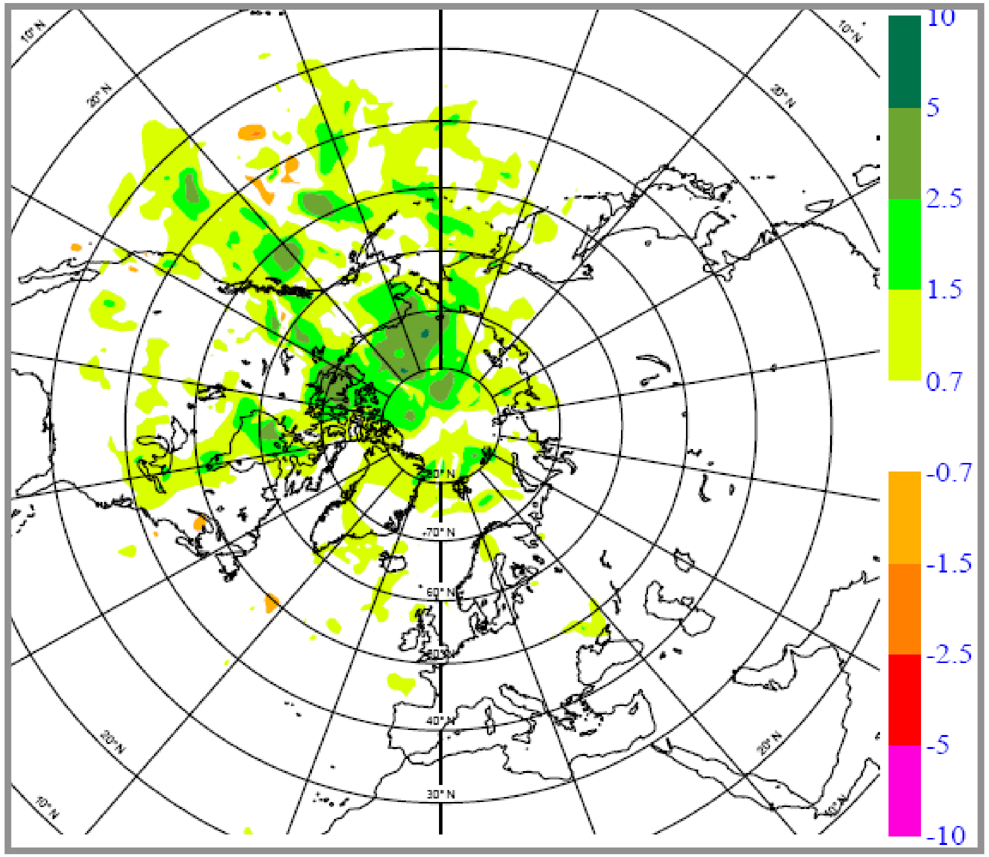


Doppler Wind Lidar

Single-component wind, in 21 layers, from surface to 20 km

Stoffelen et al. (2005, BAMS)

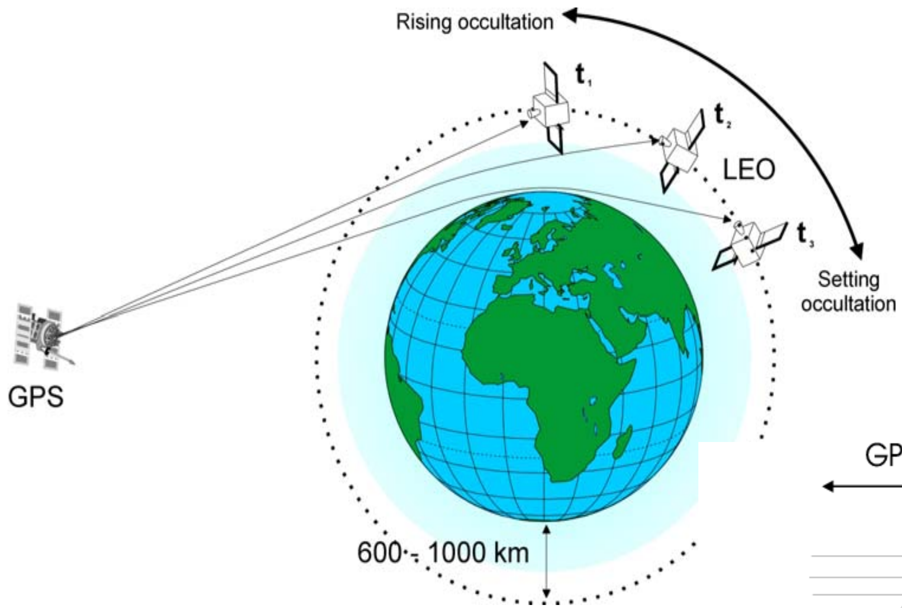
ADM-Aeolus simulated forecast impact 500 hPa wind



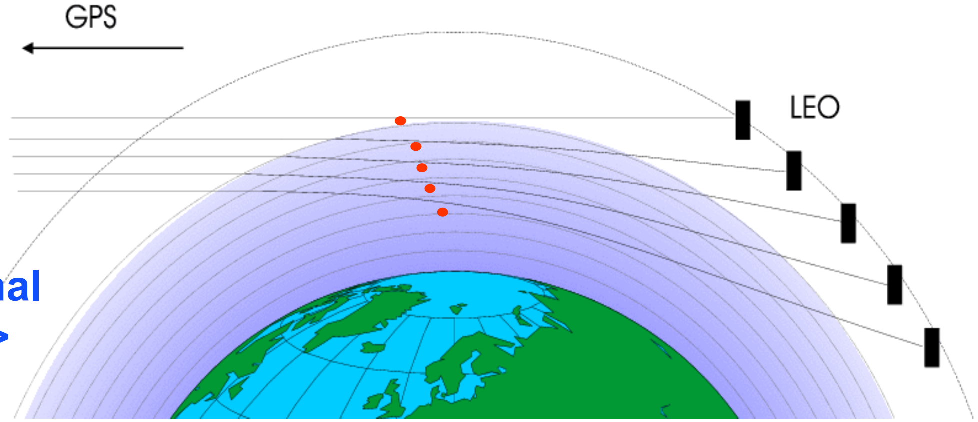
- **Best impact over North-America, Pole, and Pacific**

(Stoffelen and Marseille, KNMI, 2006, unpublished)

GPS radio occultation technologies

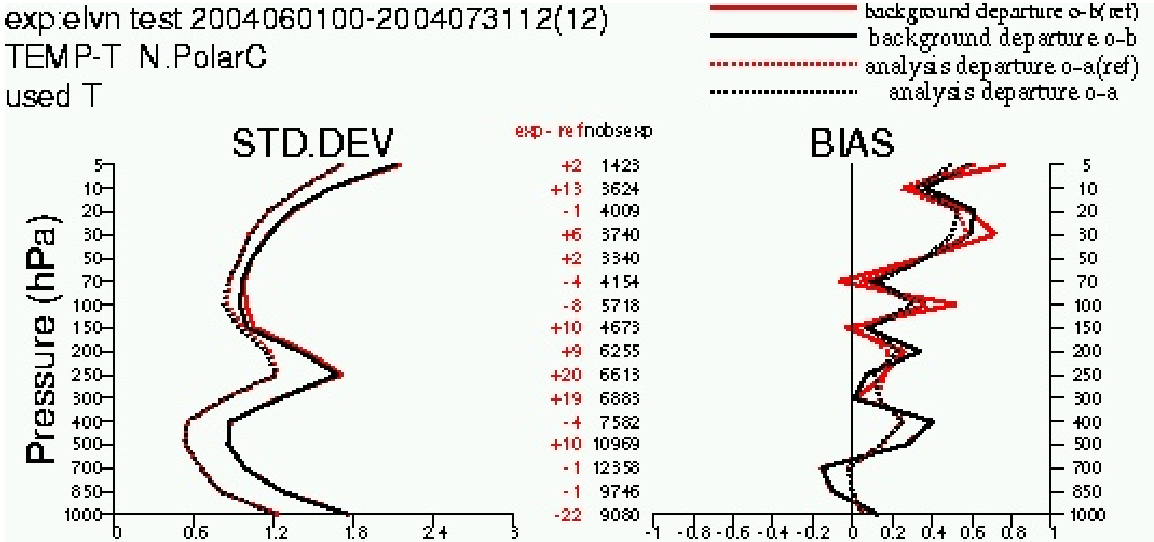


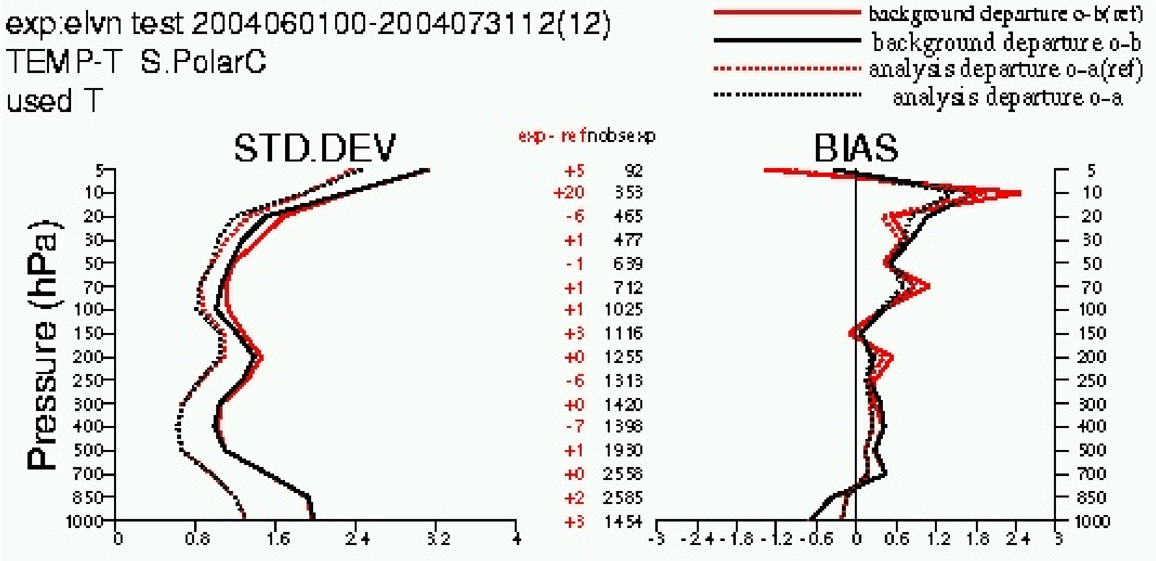
= the path of the ray perigee through the atmosphere



- **GPS-MET, CHAMP**
- **The impact of the atmosphere on the signal propagation depends on the refractivity => the vertical profile of the refractivity (and further down temperature, humidity and pressure) at the location of the ray perigee can be inverted from the observation**

GPS RO (CHAMP) assimilation trials June/July 2004, Sean Healy ECMWF





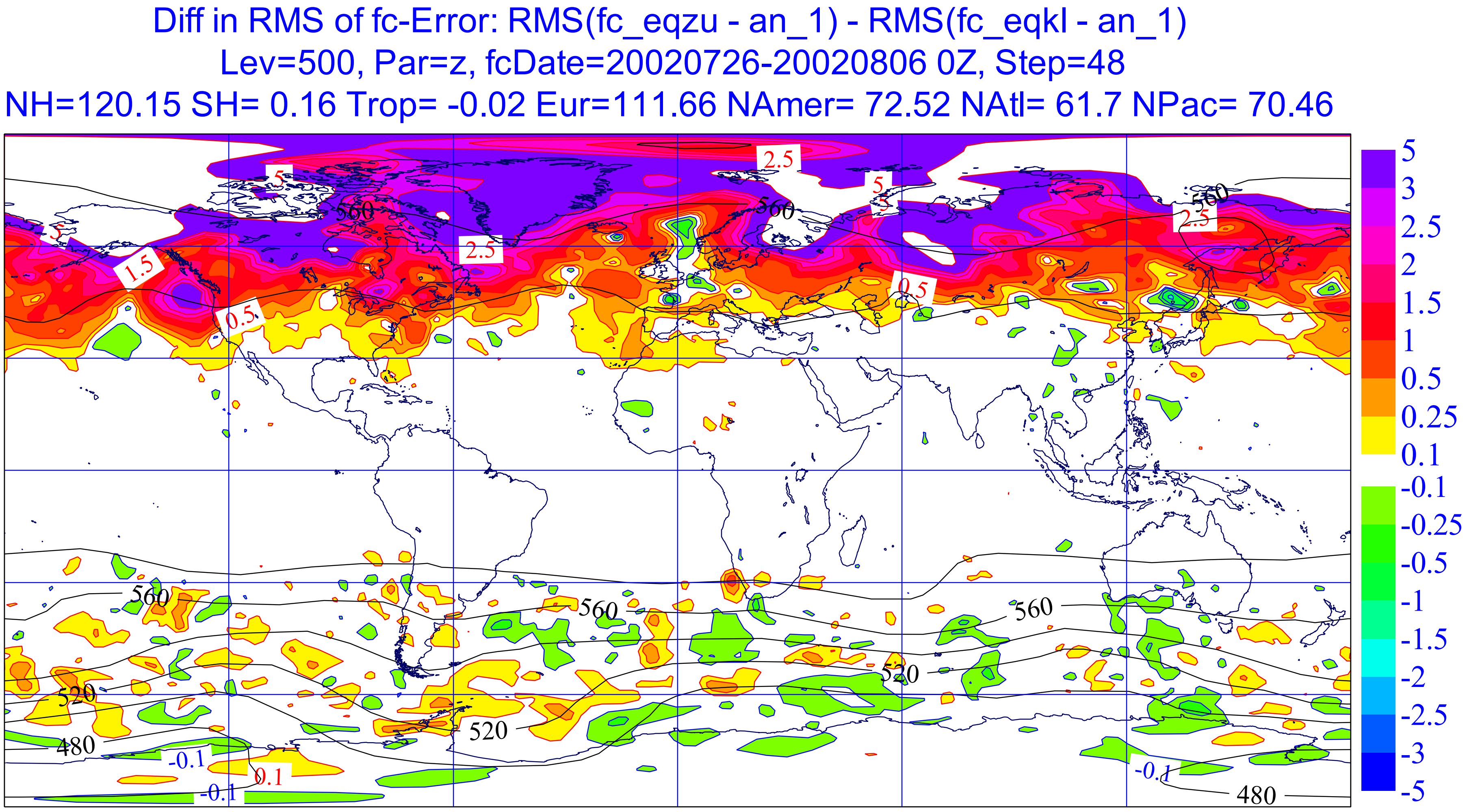
Polar stratospheric bias and oscillations are largely improved by GPS data

Operational assimilation of CHAMP data will start as soon as data are received in real-time, then COSMIC and GRAS

Perspectives

- ADM-Aeolus will provide good quality winds for assimilation and also for calibration and improvement of MODIS winds
  - ➔ From 2009
- GPS radio occultation data will provide high vertical resolution temperature data (stratosphere and tropopause) for assimilation and for calibration of radiance data
  - ➔ From 2006
- Radiosonde improvements
  - ➔ BUFR reporting
  - ➔ More homogeneous network w.r.t. instrumentation and location
- Exchange of hourly surface data (automatic stations)
- Higher resolution models and analyses
- Use of DA ensembles, in real-time, to help specify flow-dependent B (under development)

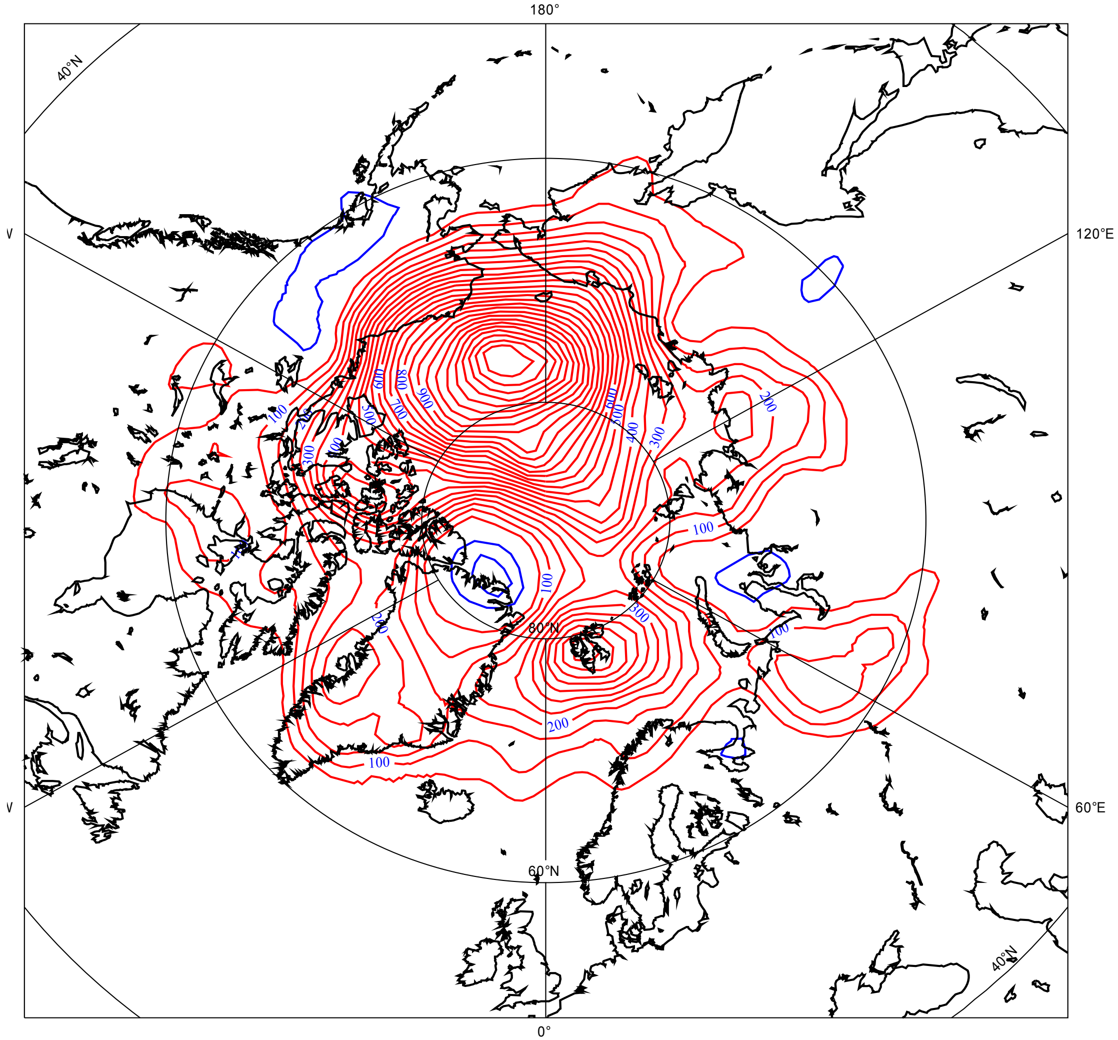
Data denial trial – no data assimilated North of 60 North



ECMWF

Data denial trial – no data assimilated North of 60 North

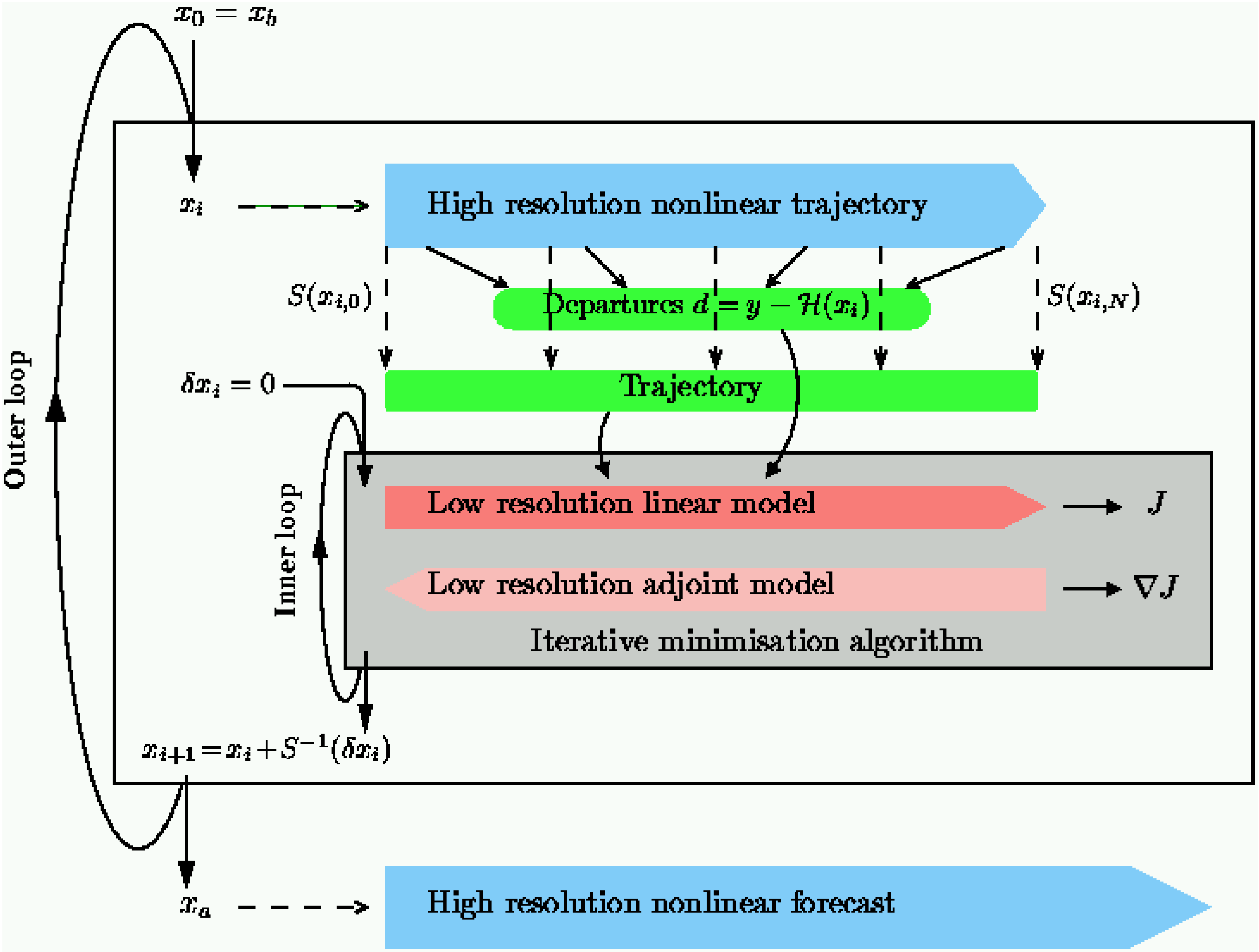
ECMWF Analysis VT:Saturday 27 July 2002 12UTC 500hPa **geopotential height



Incremental 4D-Var schematic

Showing:

- **Inner and outer loops,**
- **High and low resolution 'trajectories',**
- **Truncation operator S, and its pseudo-inverse,**
- **Observation minus model 'departures',**
- **NL and TL model integrations, *M* and M**



The High Resolution Forecasting System implemented at ECMWF 1st February 2006

Operational before 1. Feb	Operational since 1. Feb
▪ Deterministic 10d-forecast: T_L511 L60 (Δt=15min)	▪ Deterministic 10d-forecast: TL799 L91 (Δt=12min)
▪ 4D-Var Analysis:	▪ 4D-Var Analysis:
1st minimization: T_L95 L60 Δt=1h	1st minimization: TL95 L91 Δt=1h
2nd minimization: T_L159L60 Δt=1/2h	2nd minimization: TL255L91 Δt=1/2h
▪ Wave Model: 0.50°	▪ Wave Model: 0.36°

ECMWF

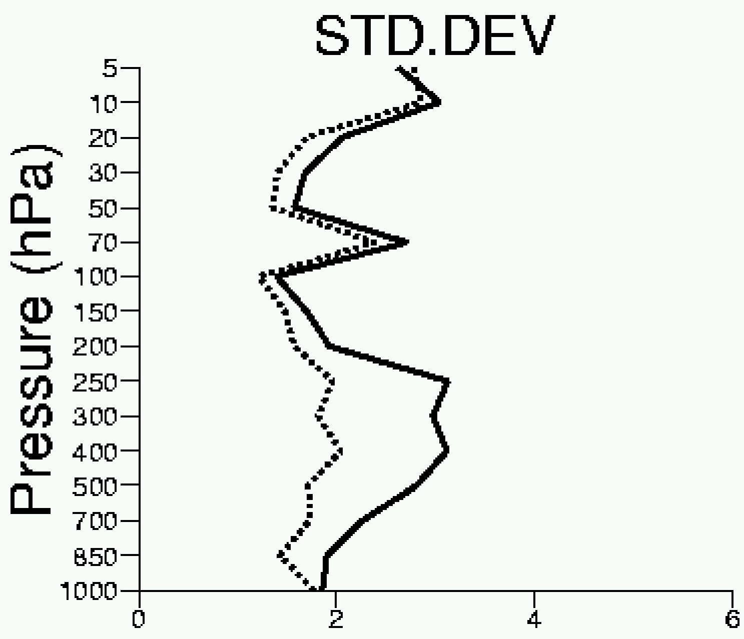
Icebreaker Oden Arctic expedition.

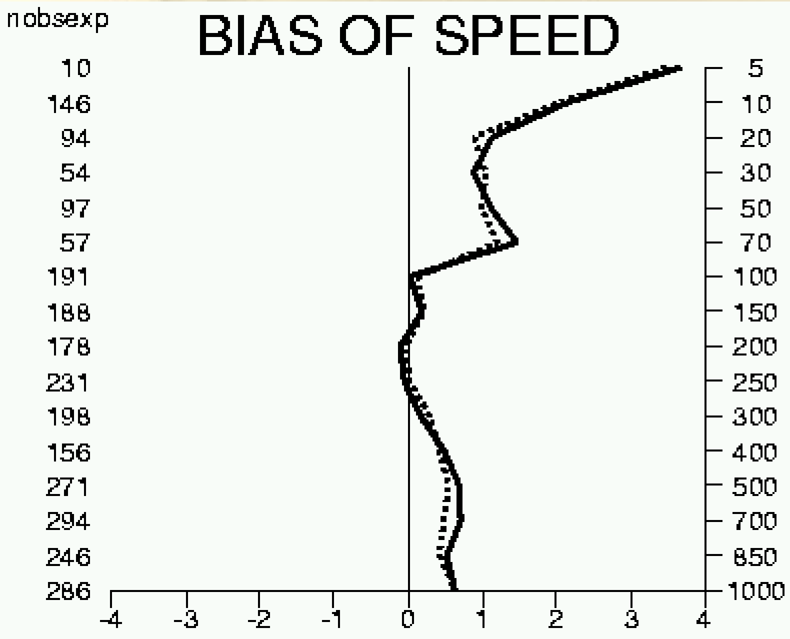
80 R/S launches at N.Pole

(Tjernström and Erixon Vaisala News, 2002)

Wind speed

20010801-20010822

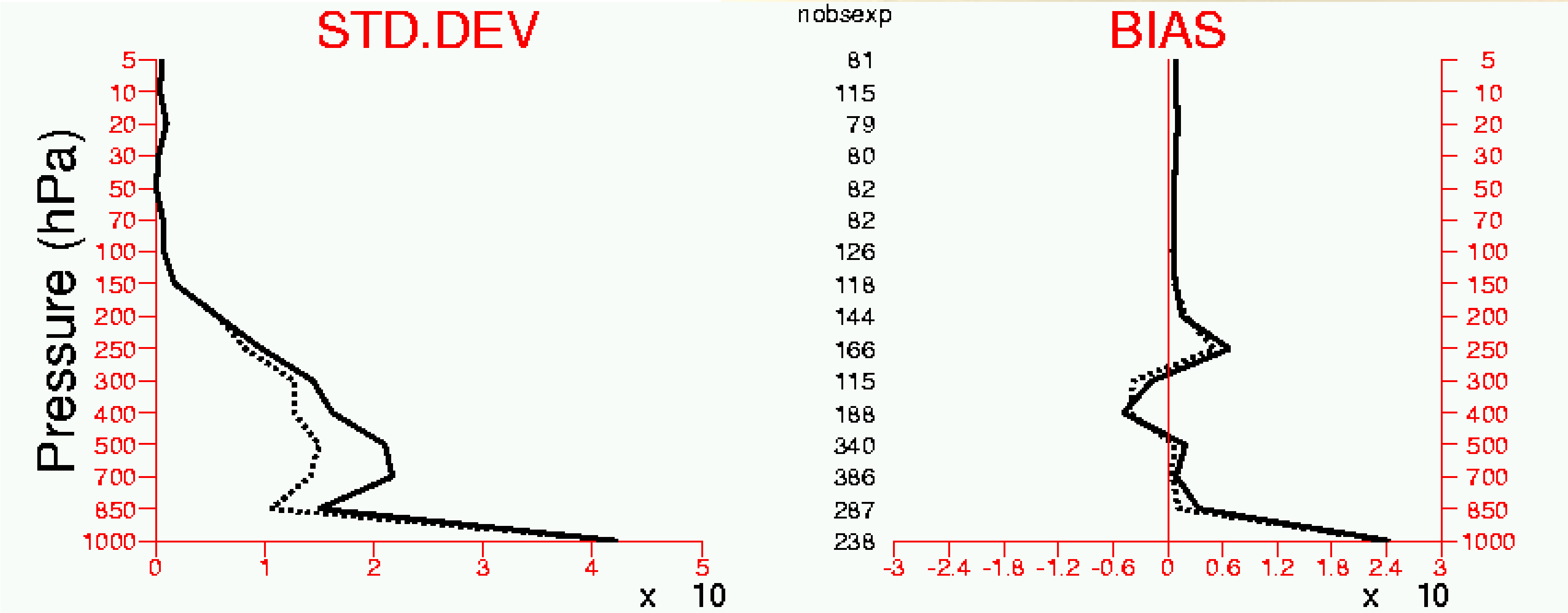




ECMWF

Icebreaker Oden
Arctic expedition.

Relative humidity
20010801-20010822



ECMWF