Use of satellite data in Polar regions

Tony McNally
ECMWF

Acknowledgements
Antje Dethof, Adrian Simmons, Hans Hersbach, Sean Healy, Fuzong Weng

ECMWF

or

(from Mark Drinkwater's talk)

European Centre for Medium-range "*Geophysical Noise*" Forecasts

Overview

…what atmospheric information (for NWP, reanalysis, climate) can we estimate from satellite observations in polar regions ? …

- types of satellite observation available
- the data assimilation system
- radiative transfer (forward) modelling
- quality control and data selection
- surface ambiguity
- handling of systematic errors
- some successes
- summary

Satellite observations available / used

NOAA satellites (N15/N16/N17/N18)
(**AMSUA**, **AMSUB**, **HIRS**, **SBUV**)

NASA AQUA/TERRA
(**AIRS**, **AMSUA**, **MODIS-AMV**)

NASA QuikSCAT
(SeaWinds)

DMSP satellites (F13,F14,F15,F16)
(**SSM/I**, **SSM/IS**)

GPS satellites
(***CHAMP*, *COSMIC***)

ESA ENVISAT
(***MIPAS,GOMOS,SCIAMACHY***)

red = radiance observations

green = retrieved products

Note that we make no great distinction between "operational" and "research" missions

What do these instruments measure ?

They **DO NOT** measure TEMPERATURE
They **DO NOT** measure HUMIDITY or OZONE
They **DO NOT** measure WIND
They **DO NOT** measure SNOW/ICE properties

Satellite instruments (active and passive) can only measure the **radiance** *L* that reaches the top of the atmosphere at given frequency *v*
The measured radiance is **related to geophysical atmospheric variables** by the **radiative transfer equation**

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz}\right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \dots$$

atmospheric term

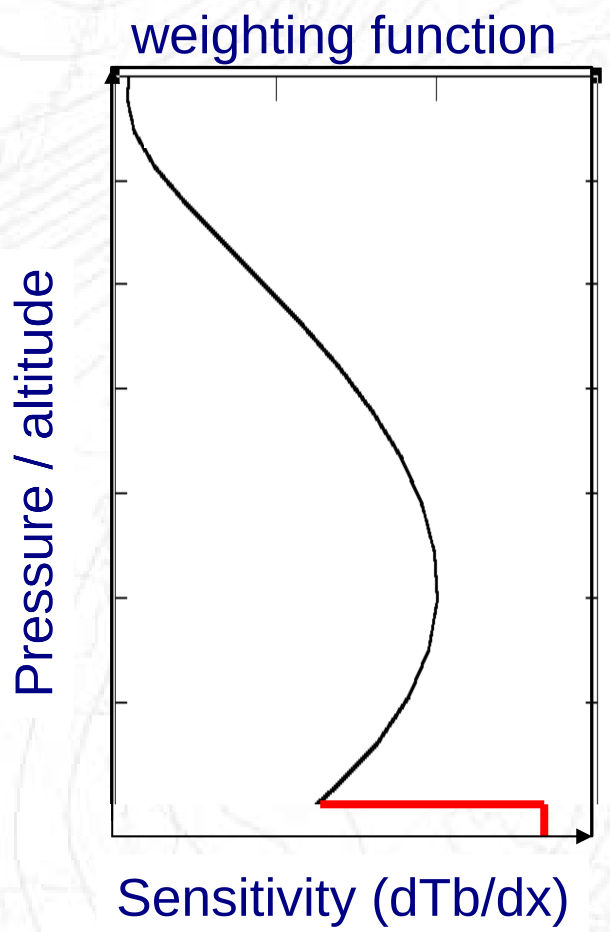
surface terms

Radiance Observations

Sensitivity and Weighting Functions

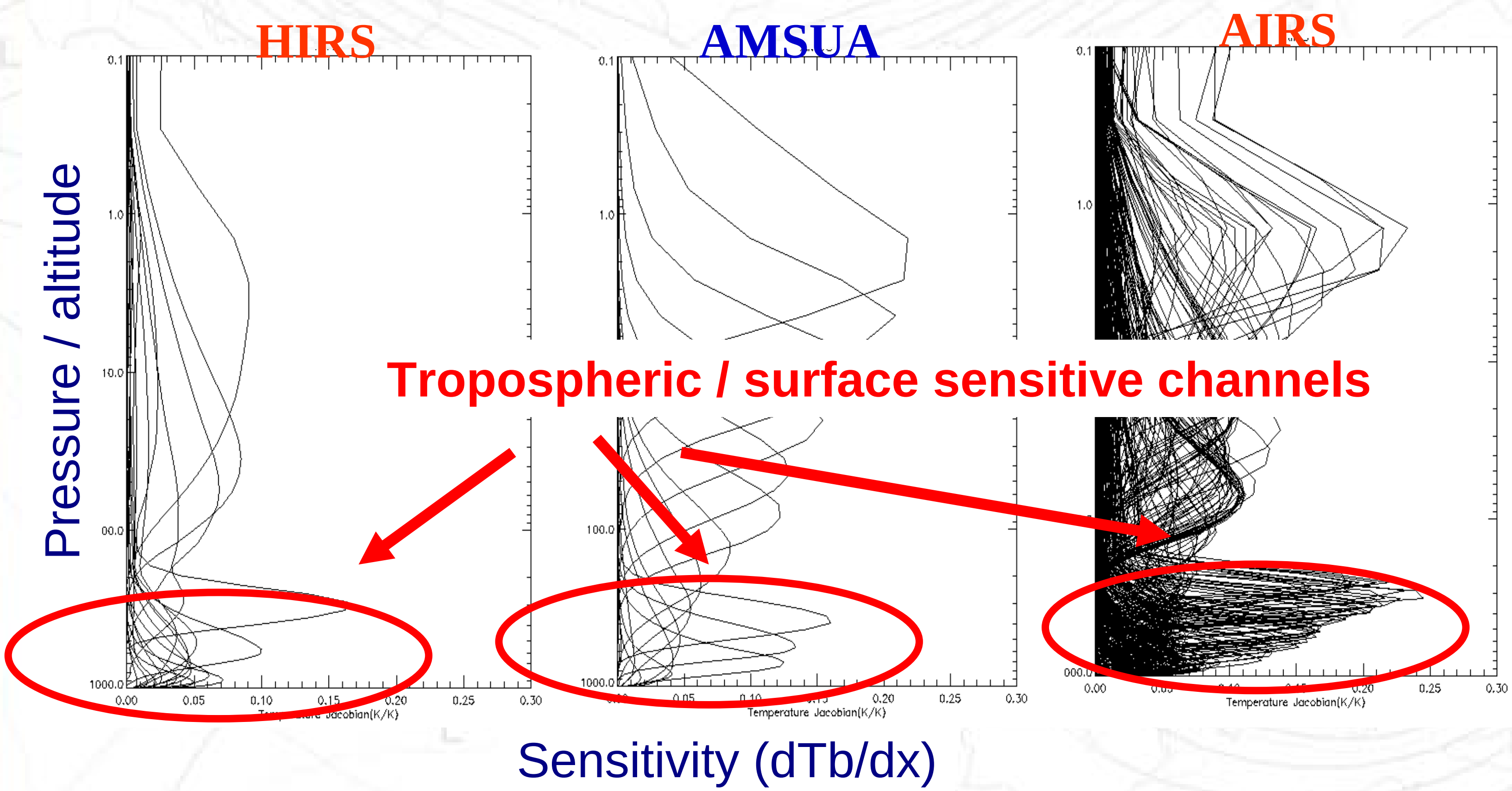
The sensitivity of a particular radiance observation to temperature (or indeed other geophysical parameters) at different altitudes is described by its ***weighting function*** (closely related to the jacobian of the radiative transfer model).

In general these have a **broad vertical extent** and e.g. data sensitive to the lower troposphere are also **sensitive to the surface**.



Tropospheric / surface sensing channels

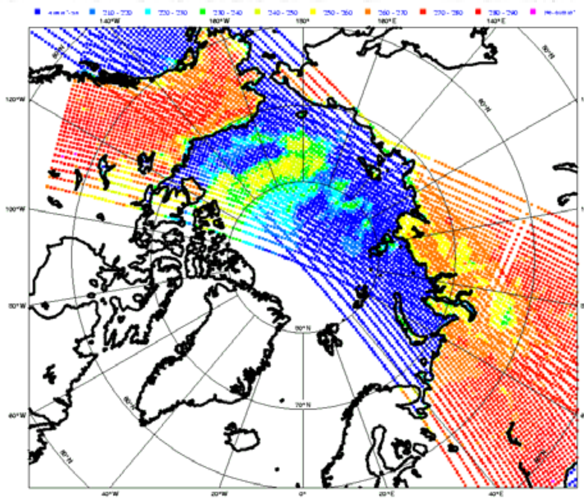
Radiance observations made in channels (=frequencies) where the atmospheric absorption is relatively weak are sensitive to the lower troposphere and surface.

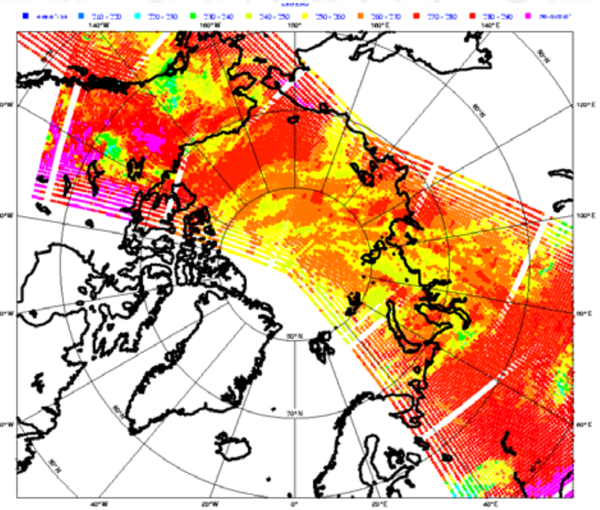


Tropospheric / surface sensing channels

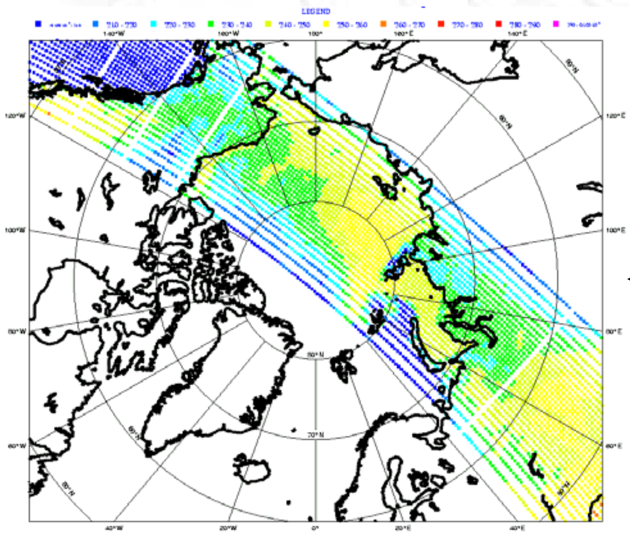
Microwave AMSU-A | **Infrared HIRS / AIRS**

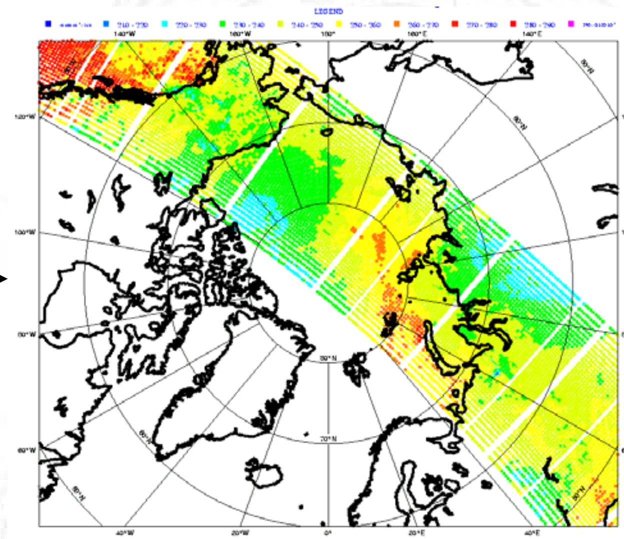
summer





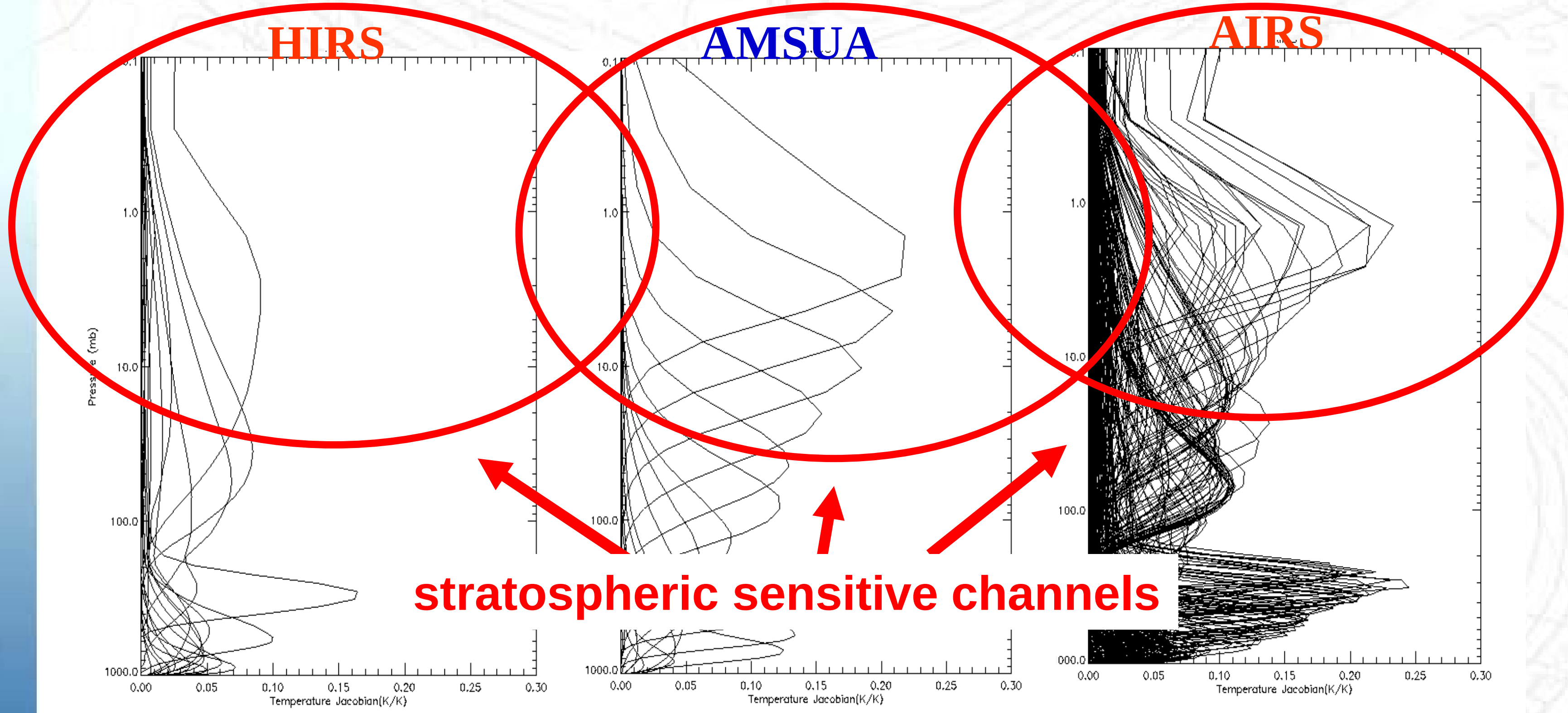
winter





Stratospheric sensing channels

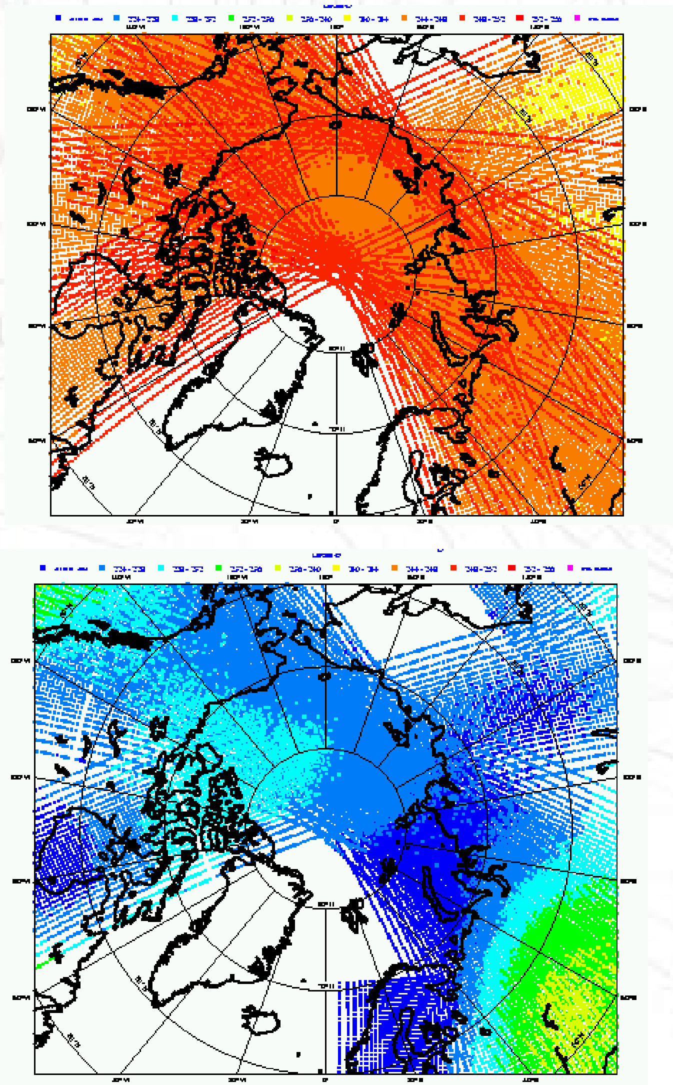
Radiance observations made in channels (=frequencies) where the atmospheric absorption is strong are sensitive to the upper troposphere and stratosphere.



Stratospheric sensing channels

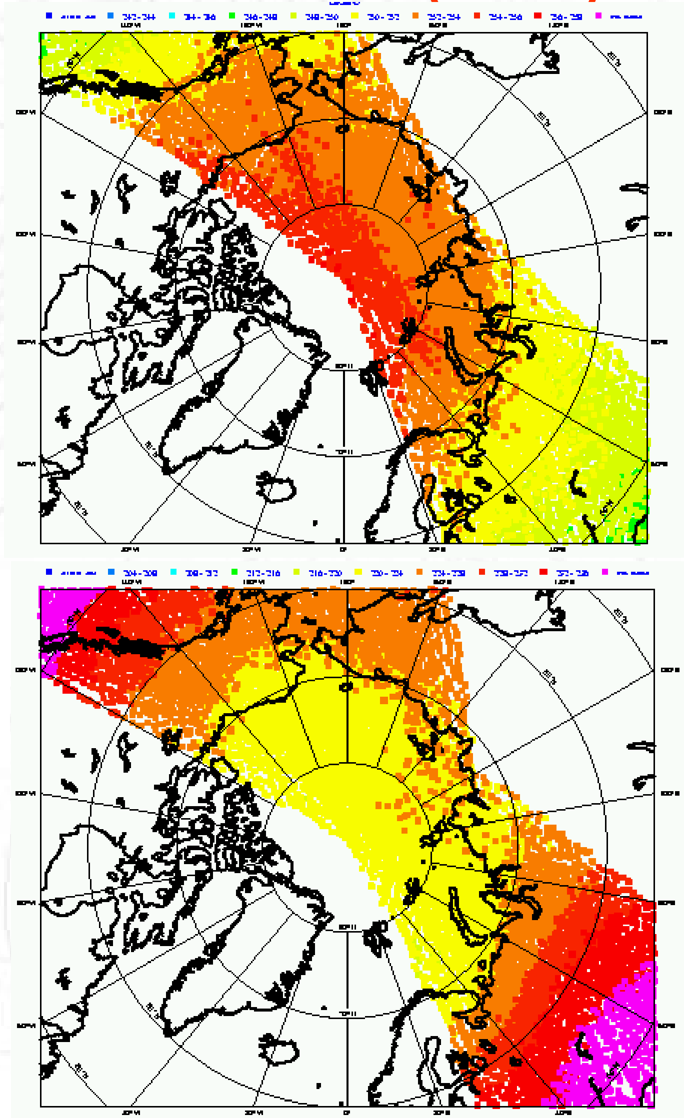
Microwave AMSU-A (~5hPa)

Infrared AIRS (~1hPa)



summer

winter



Retrieved Products

Retrieved Products

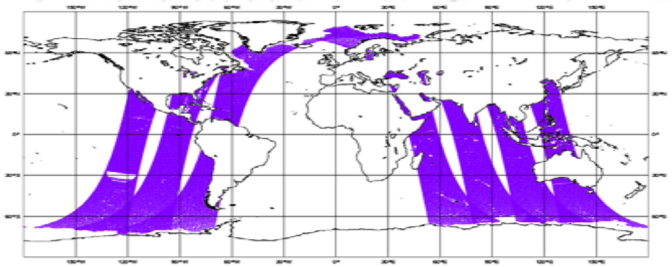
Observed radiance observations are ***pre-converted*** to geophysical products (externally) before being provided to the NWP data assimilation system.

In most cases these have been phased out and replaced with the **preferred direct assimilation** of the original radiance observations.

However some have been retained and are still assimilated.

Satellite retrieved products

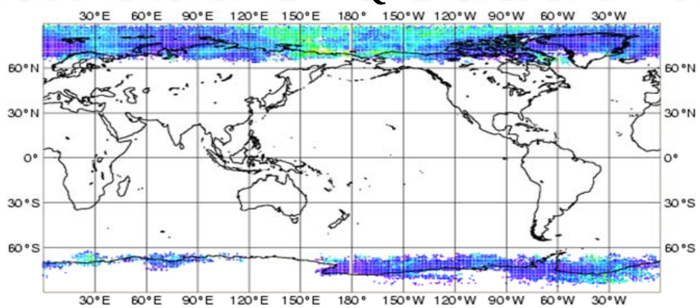
NASA QuickScat



Sea surface wind vectors

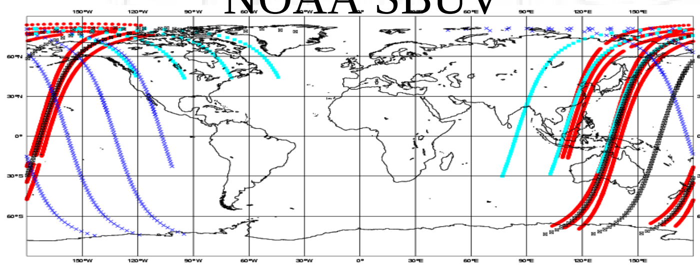
Plus composite products of SSM/I, AVHRR feeding Into sea ice / SST fields

TERRA / AQUA MODIS



atmospheric wind vectors

NOAA SBUV



ozone concentrations

Satellite radiance assimilation

The data assimilation system

Radiances are assimilated **directly in to the 4D-Var** analysis system, which finds the trajectory of atmospheric states that best minimizes a cost or penalty function

$$J(x) = (x - x_b)^T \mathbf{B}^{-1}(x - x_b)$$ ← Fit to the background

$$+ \sum_i (y_i - \mathrm{H}[x_i])^T \mathbf{R}^{-1}(y_i - \mathrm{H}[x_i])$$ ← Fit to the observations

Other constraints → $$+ J_c$$

Subject to the additional implicit *hard constraint* that the atmospheric states follow the model equations

$$\forall i, x_i = \mathbf{M}_{0 \to i}(x)$$

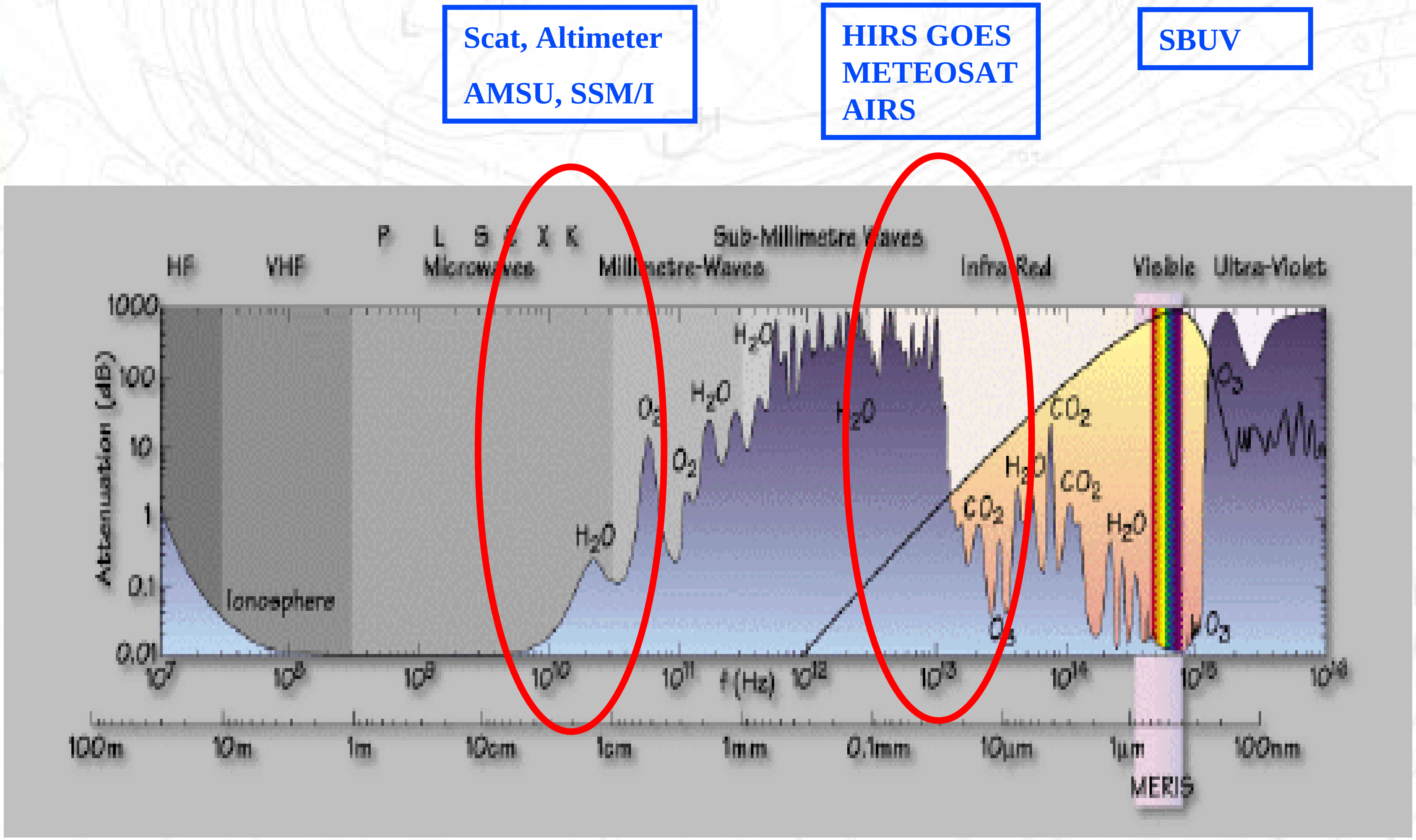
The key elements of satellite radiance assimilation

- Radiative Transfer (or forward) Model ←
- Quality Control (data screening) ←
- Handling of surface ambiguity ←
- Observation errors (inc errors in RTM)
- Handling of systematic errors (biases) ←
- Background errors

Radiative Transfer

Radiative Transfer (1)

Atmospheric Radiation Spectrum



Radiative Transfer (2)

The RTM is used to simulate radiance from the NWP model fields for comparison to the satellite observed radiances. The main issues in **polar areas** are:

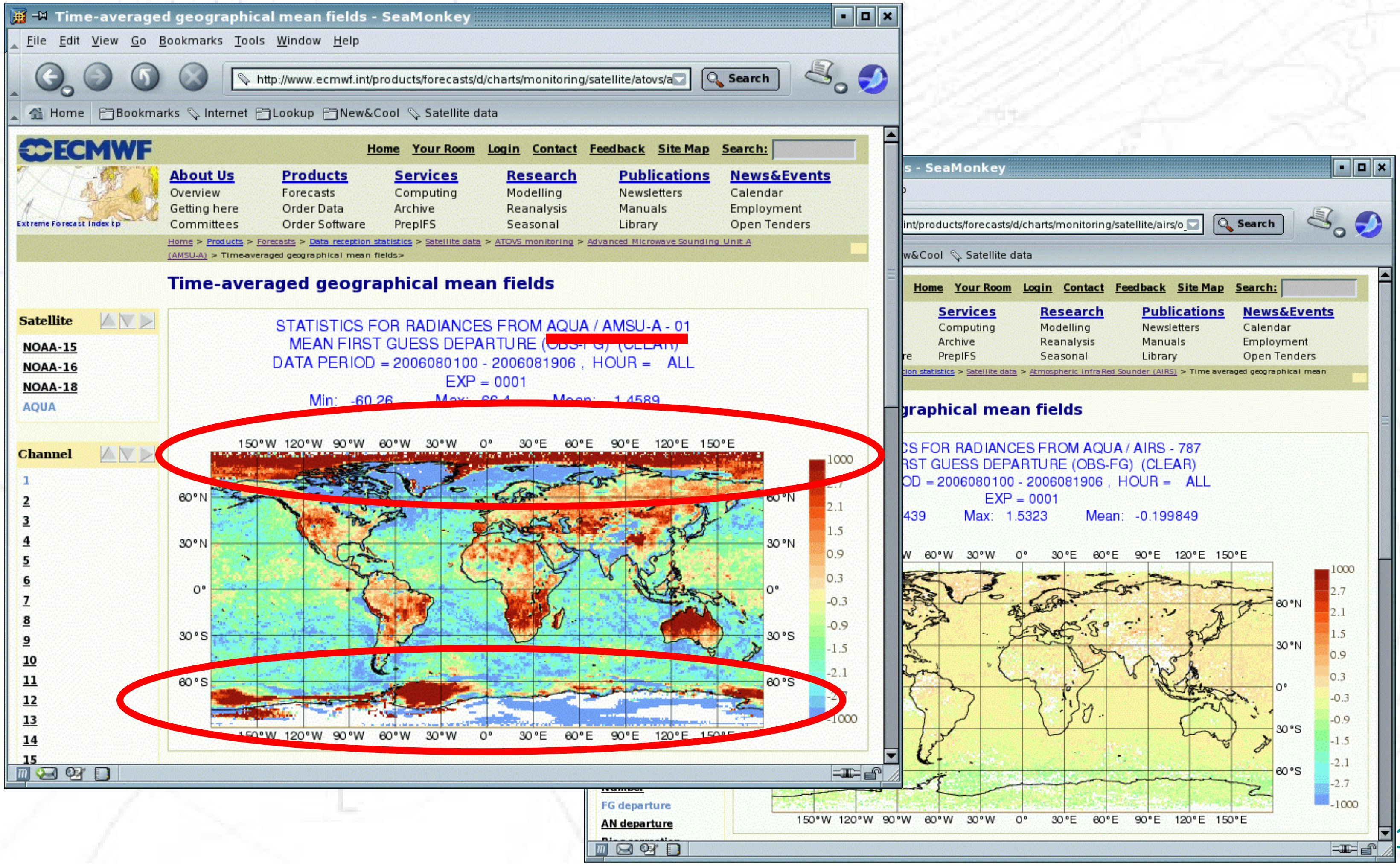
- We must ensure that if fast RTM is based on regression against LBL, that the atmospheric profiles used in training are representative of possibly **extreme polar situations**.

- Assumptions about **trace gas concentrations** may not be appropriate to extreme polar atmospheres (e.g. polar night)

- Great care must be taken with the modelling of **surface emissivity**

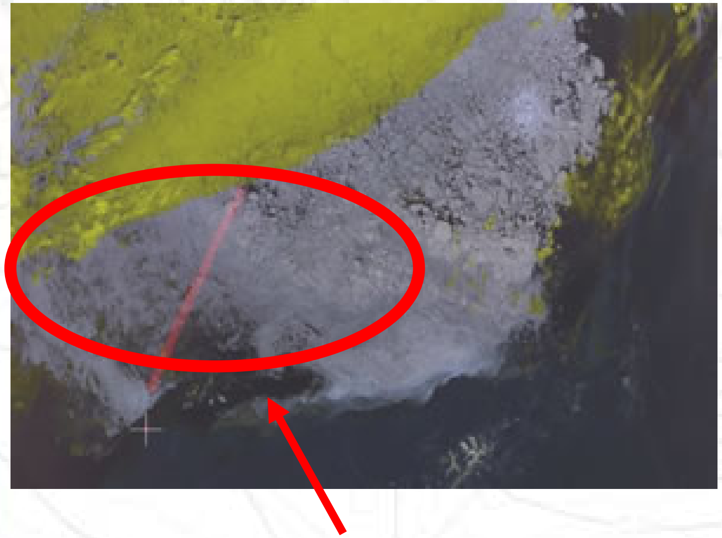
Radiative Transfer (3)

Modelling the surface emission contribution is particularly problematic for microwave channels (especially cross-track scanning as opposed to conical scanning instruments, single v many angles mixed polarized)



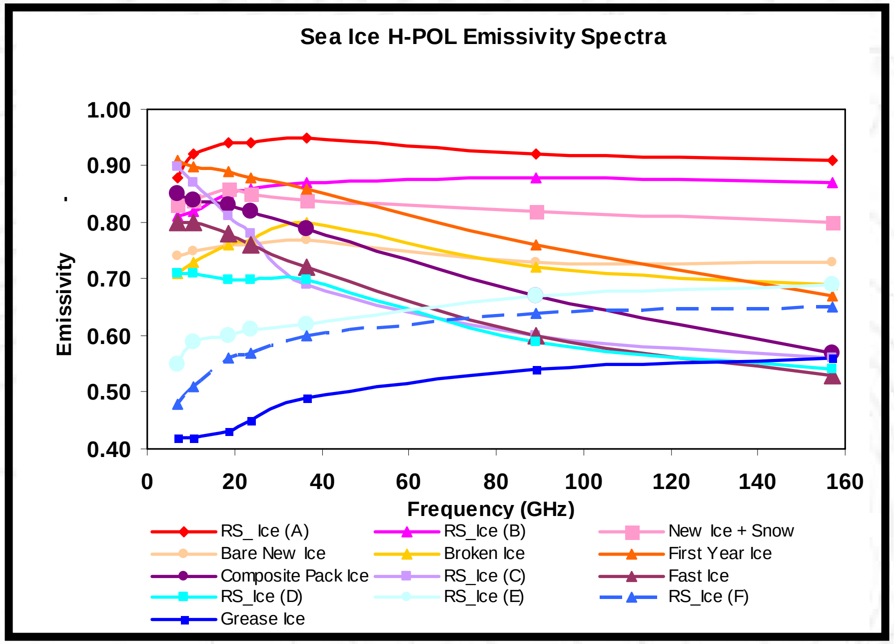
Radiative Transfer (4)

Microwave surface emissivity over sea ice and snow is highly variable and poorly known



Large meltponds can further complicate the sub satellite surface emissivity

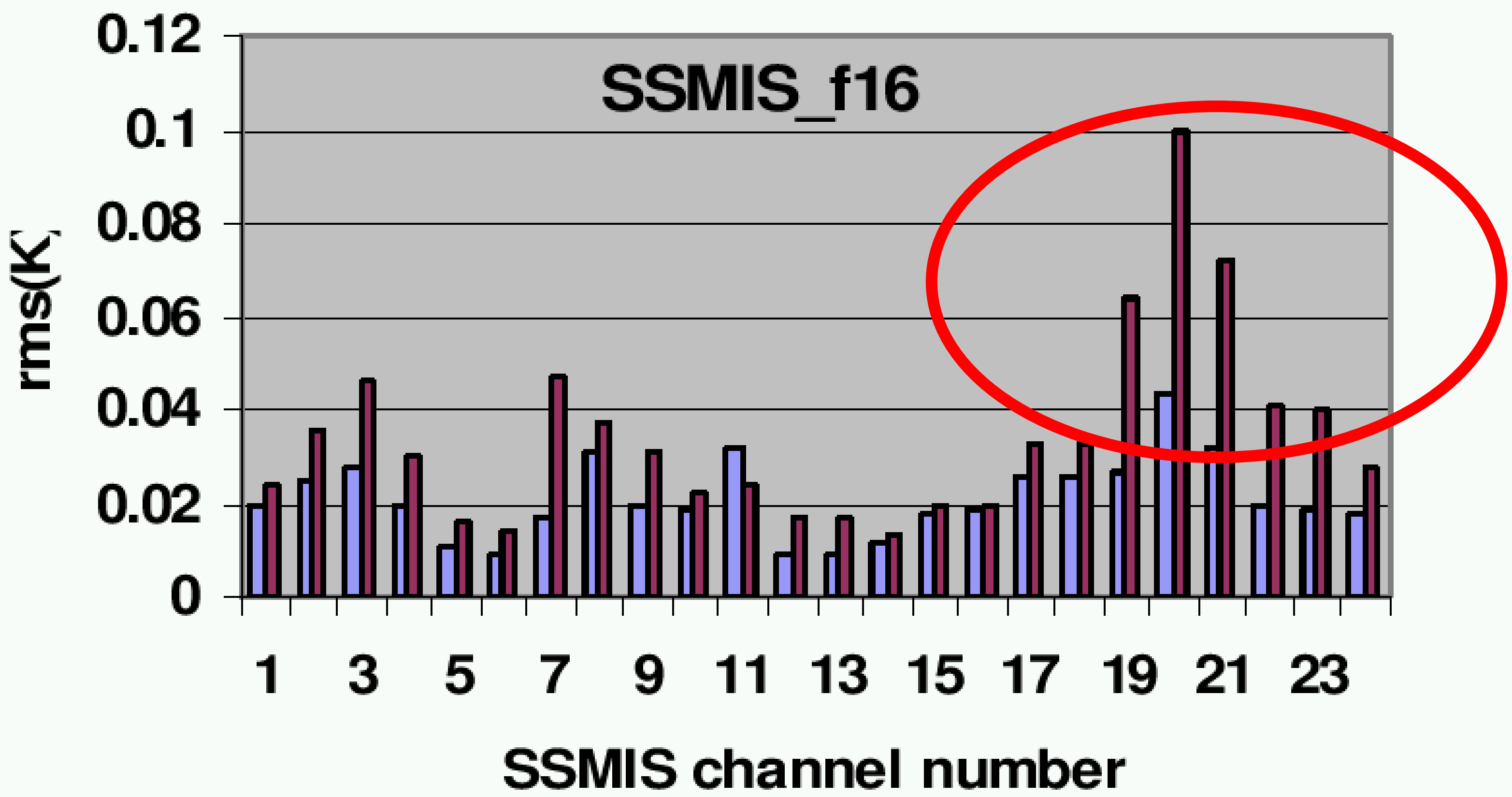
emissivity for different types of ice
At different microwave frequencies



NB. Incorrectly specifying the emissivity introduces errors of 10s of kelvin !

Radiative Transfer (5)

Zeeman splitting of microwave absorption lines combined with strong mesospheric lapse rates can result in significant errors if the effect is not parameterized.



Quality Control

Quality Control (1)

With modern day instruments QC is more concerned with identifying situations where our assumptions (both discrete and statistical) are invalid, rather than identifying **bad** observations….e.g. …

- Cloud contamination (IR and MW)
- Rain (precipitation) contamination (MW)
- Poor surface characterization (or heterogeneous scenes)

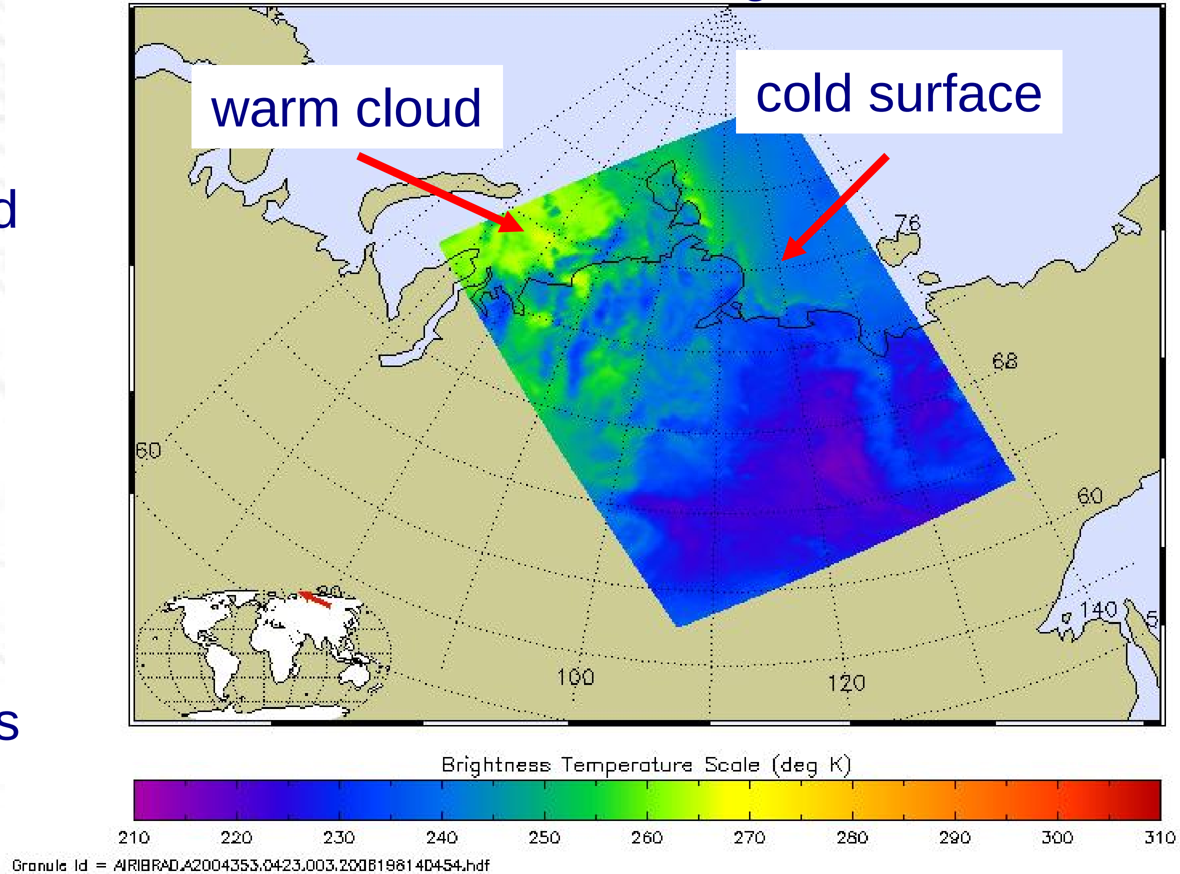
Quality Control (2)

Cloud detection in polar areas:

Clouds over very cold surfaces can often appear **warmer** in infrared data compared to the underlying surface.

This is the **opposite** signal many cloud detection schemes are looking for.

11 micron infrared image from MODIS

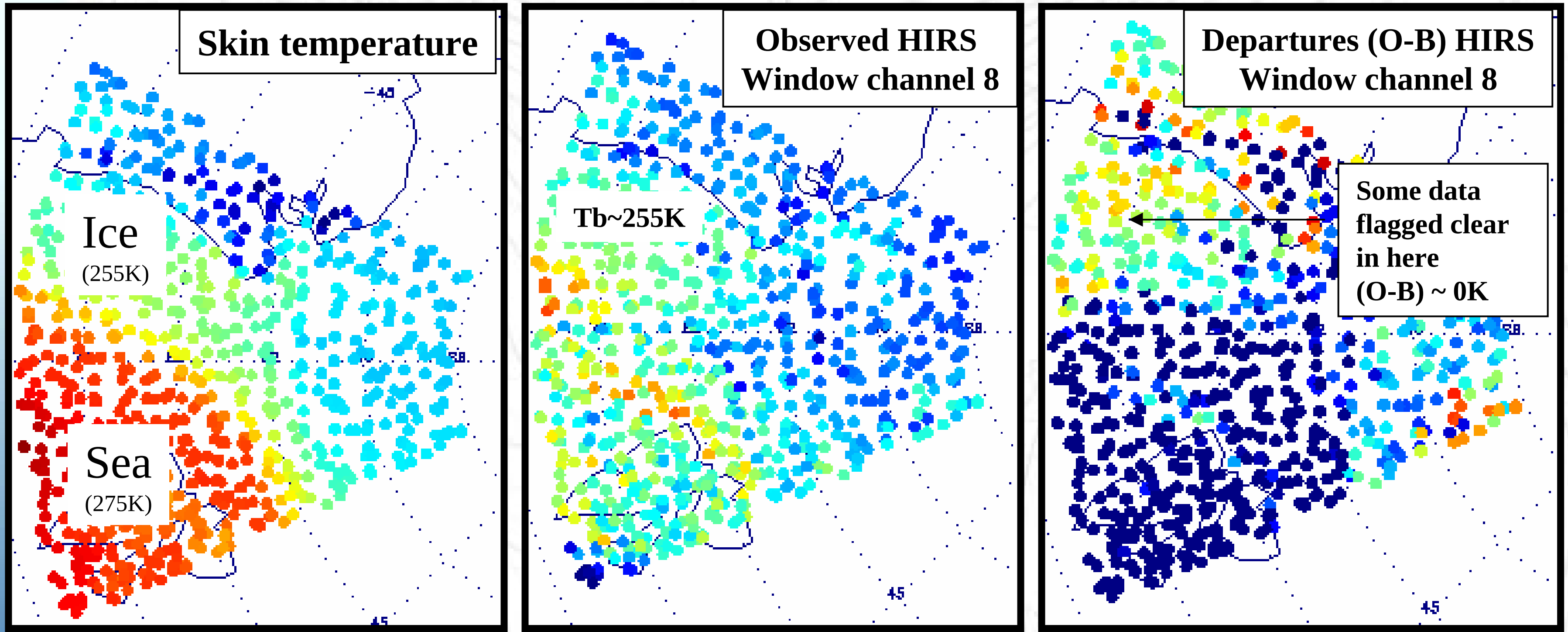


Quality Control (3)

- Cloud detection algorithms generally rely on an accurate **a priori knowledge** of the underlying surface emission.
- Errors in the modelling the underlying surface emission (T* or E) can compromise our ability to **safely detect clouds**
- Single channel cloud detection (i.e. window channel checks) can be **dangerous** (cloud compensates in window channel, but not channels above)
- If these problems are severe, we may have to **blacklist** (i.e. a priori reject) the radiance observations

Quality Control (4)

Single window channel cloud detection checks must be tuned to allow for warm departures over cold surfaces, but even then can be problematic if the cloud is at the same temperature as the surface.

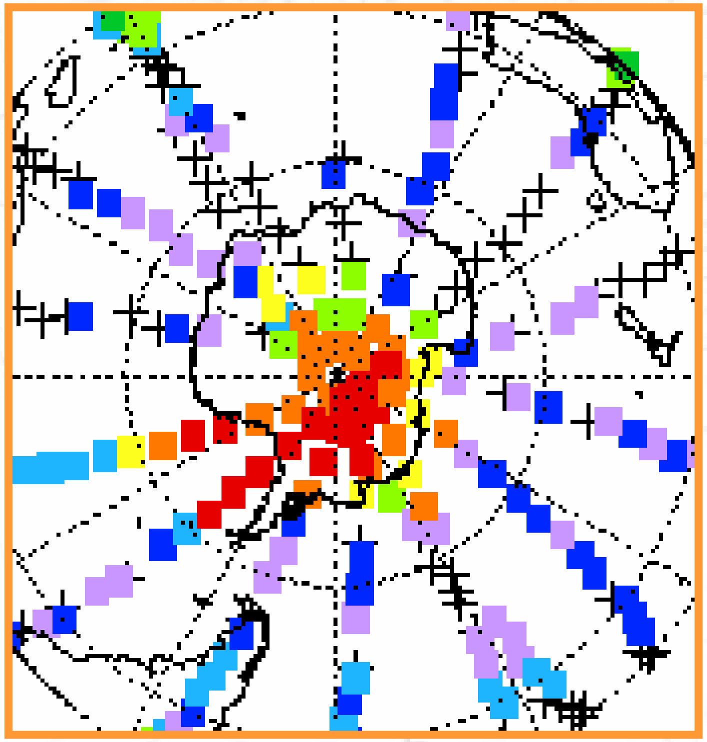


(* without more information we cannot eliminate the possibility that a cloud at the same temperature as the ice actually stops at exactly the ice edge … although unlikely ?)

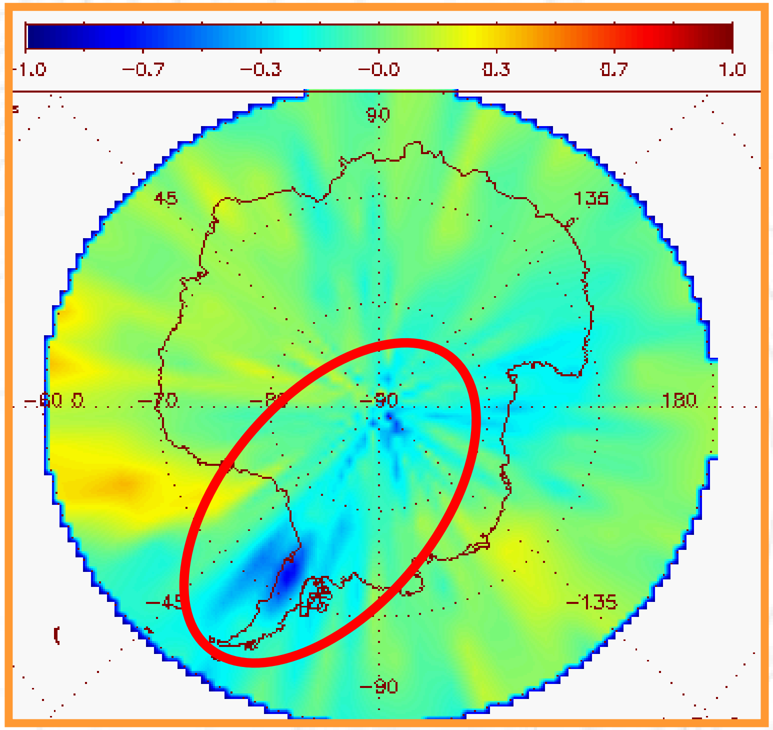
Quality Control (5)

Cloud detection schemes **must be also extended into the polar stratosphere** as undetected **PSCs** can alias into erroneous temperature and ozone increments

Cloud level from MIPAS



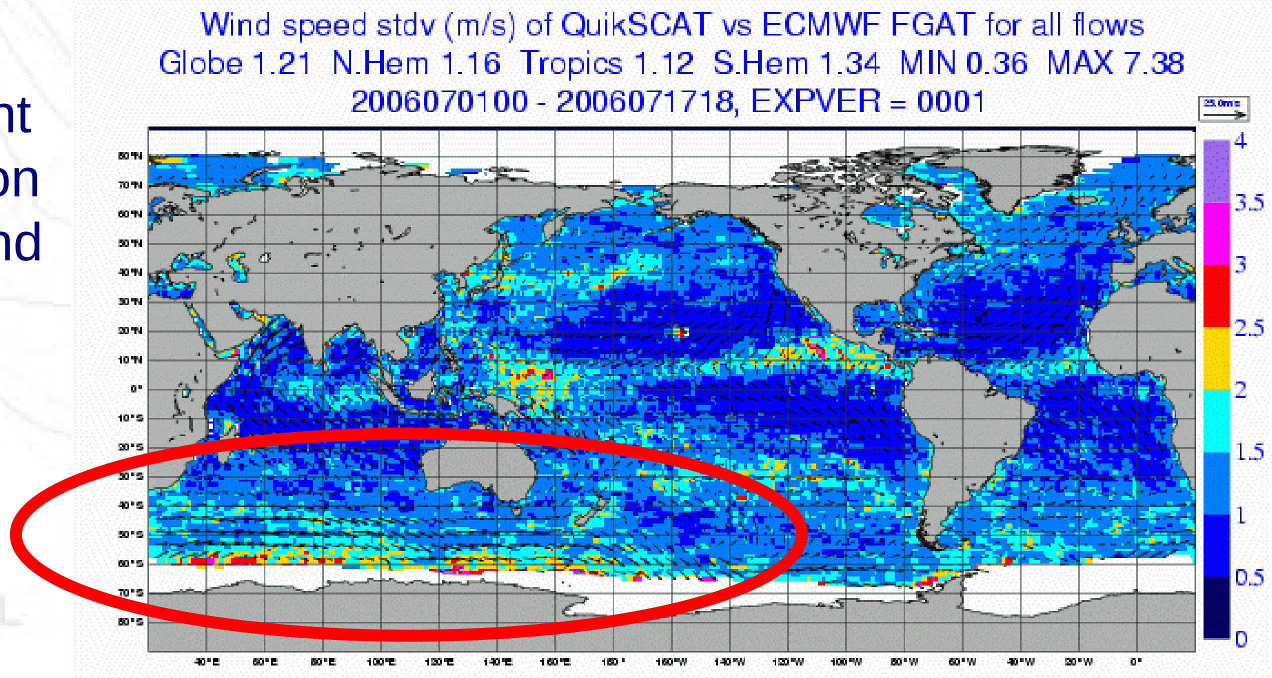
AIRS channel 64 Departure (K)



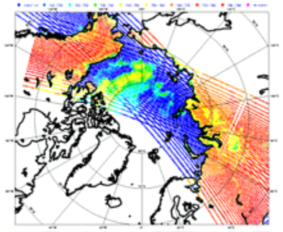
Quality Control (6)

Due to the large variation in microwave surface radiative properties even a **slightly heterogeneous surface** (compared to the satellite field of view) can **alias large errors into the analysis if undetected**

e.g. a small amount of ice contamination produces large wind departures in scatterometer sea surface wind retrievals



Handling Surface Ambiguity (1)



The **variability of the polar surface** (particularly in terms of microwave surface emissivity) is significant. Channels designed to provide temperature information in the **mid-troposphere** still have ~ **10% sensitivity to the surface**.

In channels such as **AMSU-5 and MSU-2** (very important for NWP and reanalysis) the surface variability (e.g. going from sea to ice) is **~ 2K** whereas the atmospheric variability (i.e. due to temperature variations) is typically less than **0.5K**.

Thus errors in modelling the surface emission in these channels can completely **dominate the useful atmospheric signal!**

Handling Surface Ambiguity (2)

Options for handling the surface contribution:

1. Model the surface emissivity explicitly from our knowledge of the surface conditions (e.g. ice type, snow cover …) and then use a fixed value in the RTM

2. Use indicators from the radiance observations to estimate or classify the surface and then fix in the RTM

3. Add emissivity to the analysis variables and estimate it simultaneously with other geophysical variables within the assimilation

4. Use radiances from sensors better suited to handling surface effects (e.g. conical scanning SSM/IS rather than cross-track scanning AMSUA)

Systematic Errors (biases)

Systematic Errors (1)

- Biases in satellite observations and / or RTM are a serious problem as they can quickly propagate into **large scale biases in the analysis**.

- Traditionally satellite bias corrections are estimated from **monitoring data against the NWP system** (in the absence of any other globally available ground truth)

Systematic Errors (2)

- **Satellite instrument**
  (calibration / charaterization / environmental effects)

- **Radiative transfer (RT) model**
  (physics / specroscopy / emissivity)

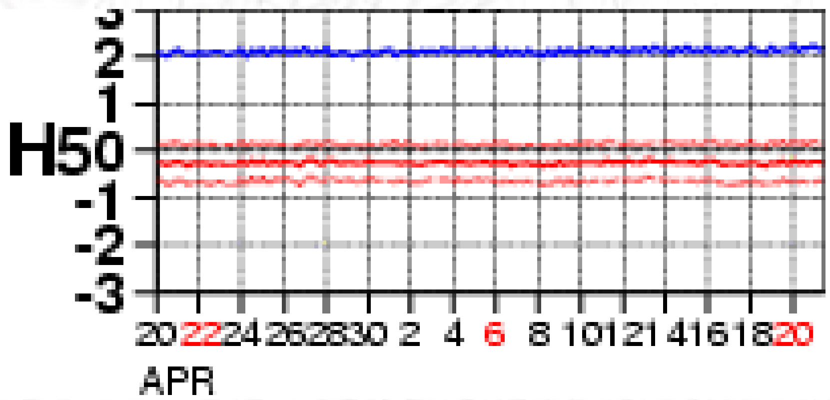
- **Pre-processing of observations**
  (cloud-precipitation detection / level-2 processing)

- **NWP model ***
  (systematic errors in the background state)

most acute over the poles

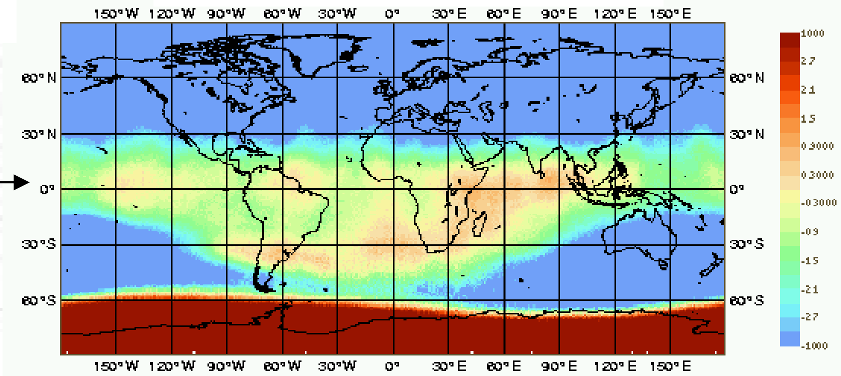
Systematic Errors (3)

HIRS channel 5



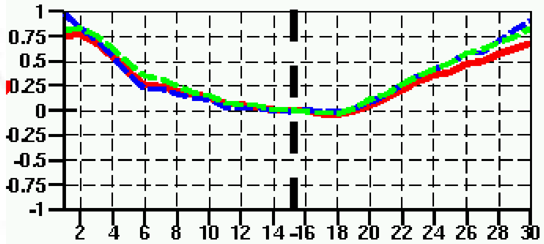
simple flat offset biases that are constant in time

AMSU-A channel 14



biases that vary depending on location or air-mass

AMSU-A channel 7



biases that vary depending on the Scan position of the satellite instrument

limb **nadir** **limb**

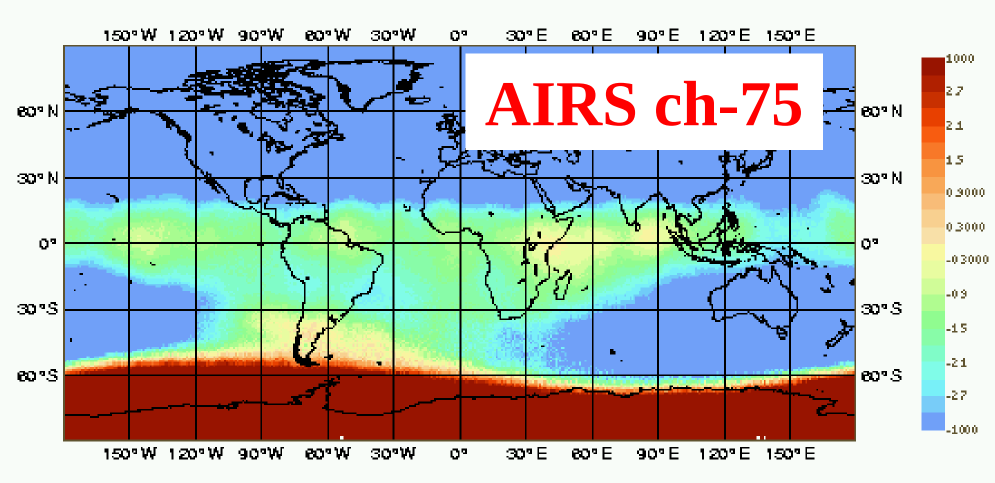
Systematic Errors (4)

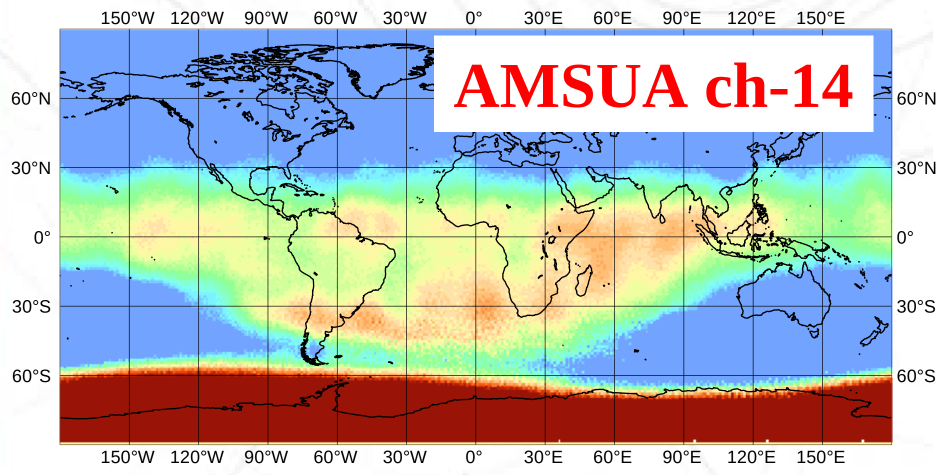
- Over the **polar regions** (particularly in the stratosphere) we can have **large systematic errors in the NWP model** (suggesting *apparent* air-mass and scan dependent biases in the satellite observations)

- It is important that we do not derive observation bias corrections that **actually compensate for systematic errors in the NWP model** as this will perpetuate or even reinforce the system bias

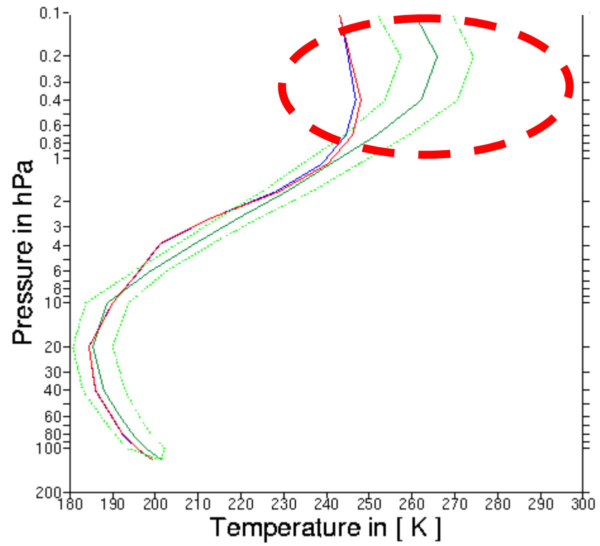
Systematic Errors (5)

A number of **independent sensors** confirm the existence of a **significant cold temperature bias in the NWP model** for the polar night stratosphere





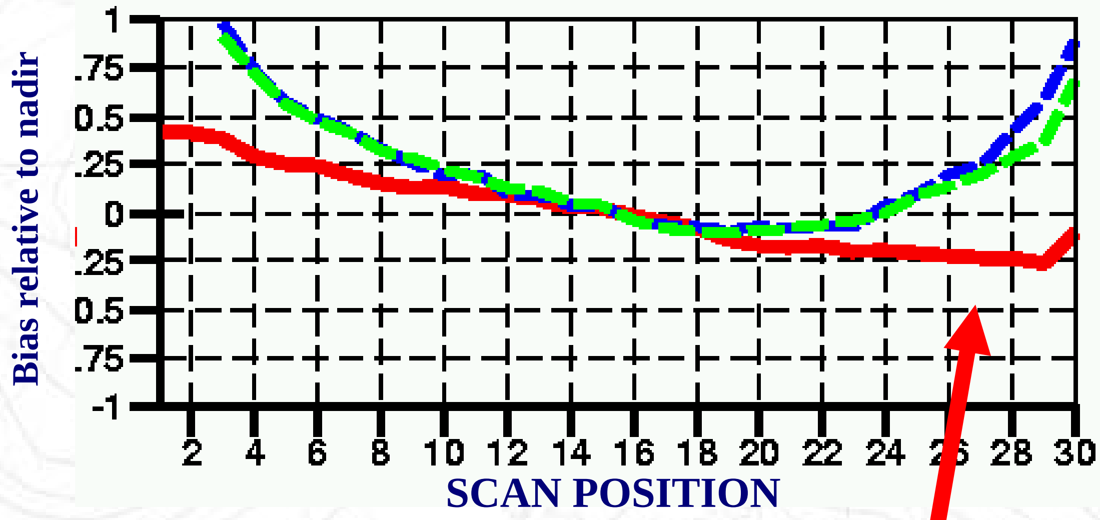
MIPAS retrievals

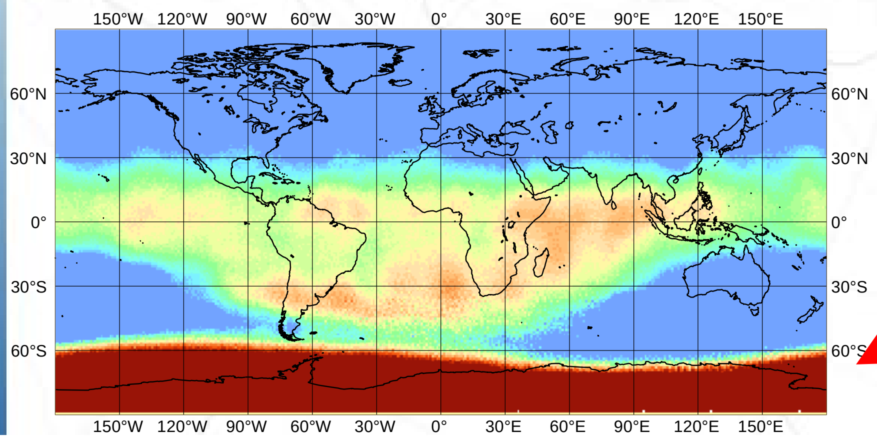


Systematic Errors (6)

In addition, systematic errors in the NWP model lapse rate for the polar night stratosphere will also compute the **wrong limb effect**. This will give an apparent satellite **scan bias** between the NWP model and observations

AMSUA channel 14 (1hPa)





Asymmetric scan dependent bias associated with large systematic lapse rate error in the polar night

Systematic Errors (7)

So what can we do if the NWP model has a significant bias ?

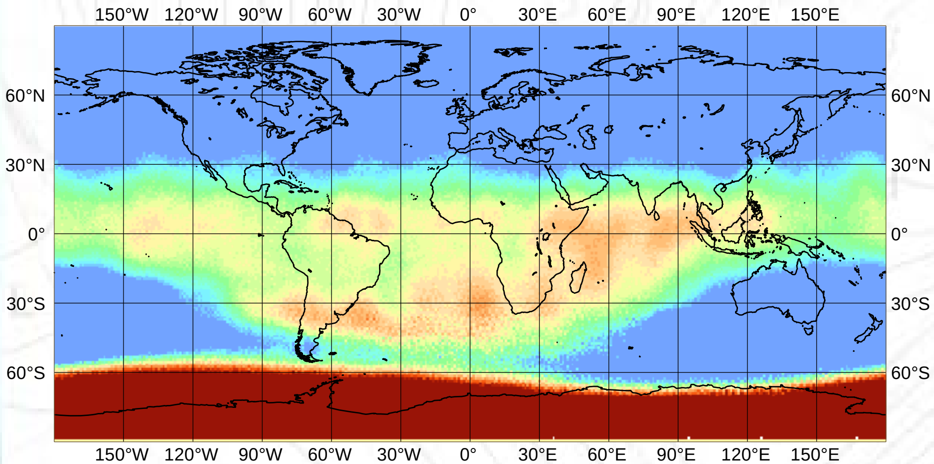
- **Force** the (**uncorrected**) satellite observations into the data assimilation system to correct the NWP model bias (can be problematic).

or

- **Pragmatically** apply a bias correction to the observations to **compensate** for the model error (produces a biased analysis).

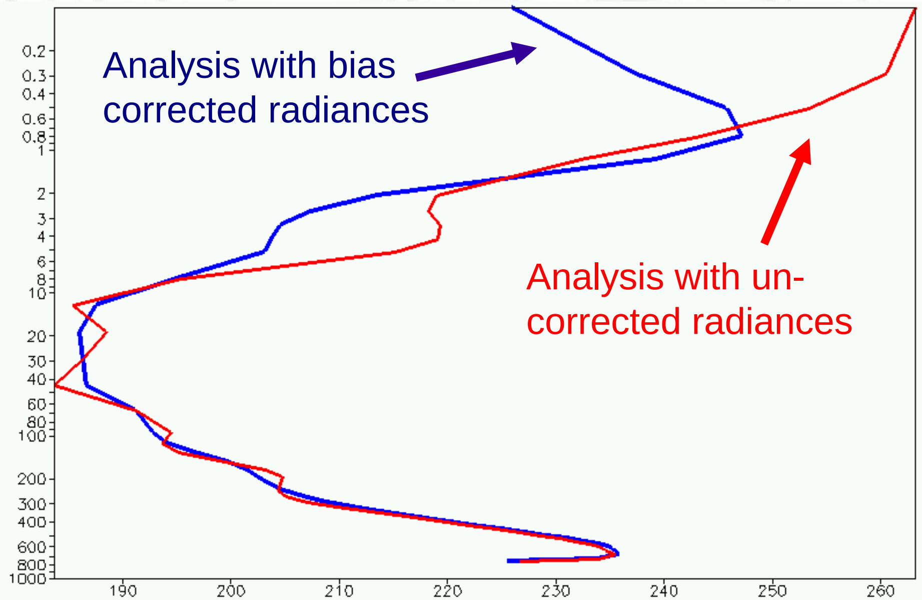
Systematic Errors (8)

AMSUA ch-14 mean departures



Forcing these data uncorrected into the assimilation improves the NWP model top, but causes significant spurious oscillations in the temperature profile below

The temperature changes at the model top (> 30K) verify well with other independent data, but the spurious oscillations are in the null-space of the radiances and are essentially an artefact of the assimilation system



Miscellaneous issues in polar areas

- Observation weights (errors and spatial correlations) and thinning to account for high density of radiance observations over the poles

- Constituent estimation (humidity, CO2 and ozone) from passive sensors is very difficult in some isothermal polar atmospheres.

- Assimilation of rain / snow affected microwave radiances very difficult over bright frozen surfaces

- A general lack of verification / validation information

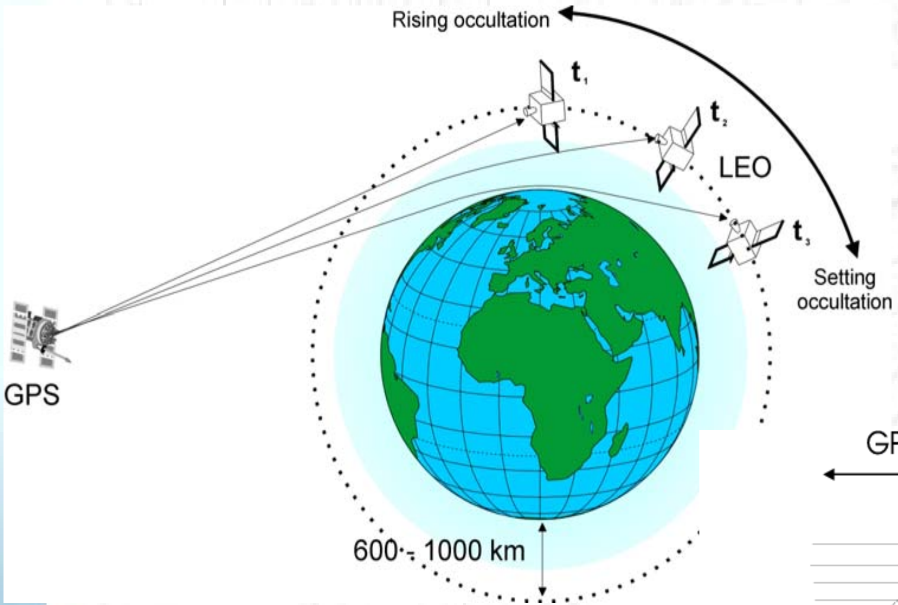
… but on the brighter side …

Examples of the successful exploitation of satellite data in polar regions

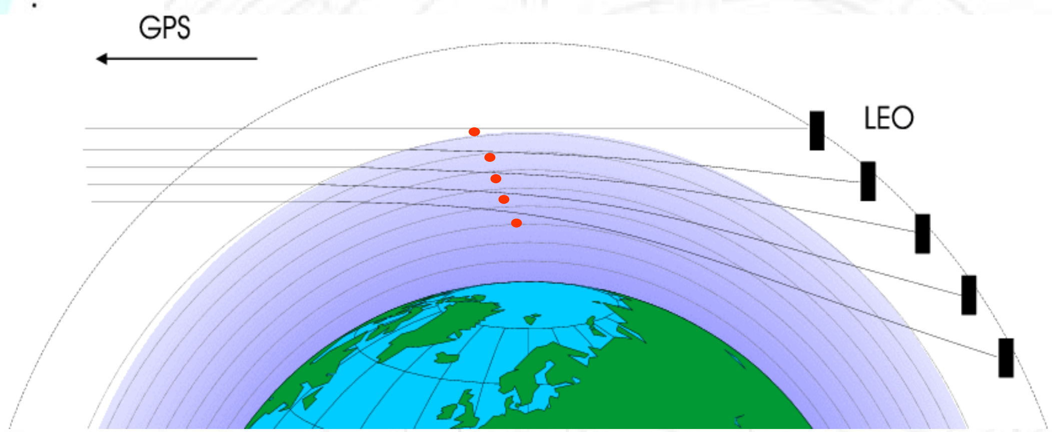
Polar successes with satellite data

- Validation of ERA-40 and operational analyses suggest that satellite radiance observations are used well in polar areas and are a vital component of the observing system
- Surface mapping products now taken for granted and are a main-stay of polar studies
- Monitoring / forecasting sudden warming of the polar stratosphere
- Polar ozone analysis
- MODIS winds products have a good impact on forecasts
- Constraining the polar wind field with temperature sounder data
- Synergy between nadir and limb sounding data
- Tuning physical parameterizations with satellite observations

Synergy between nadir and limb (GPS) sounding



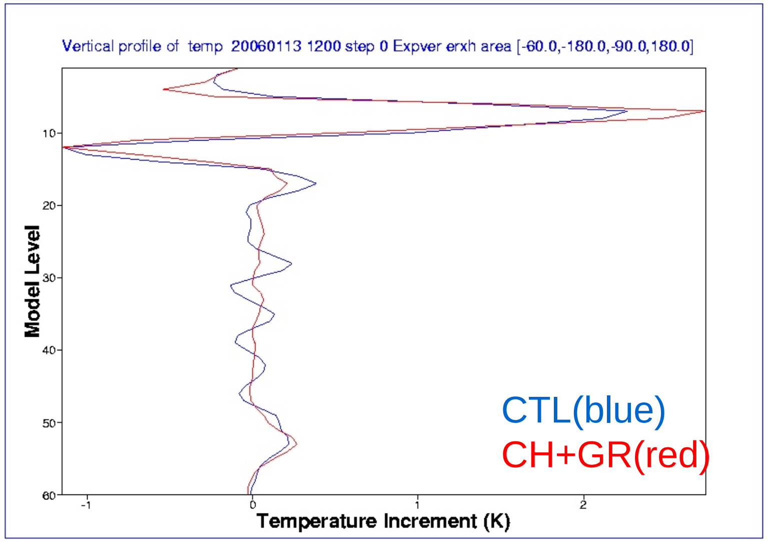
- = the path of the ray perigee through the atmosphere

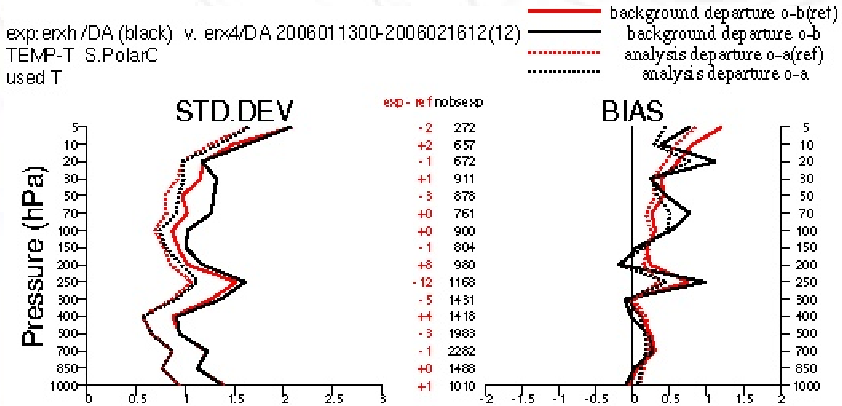


GPS controlling Polar oscillations

Nadir radiance data (AIRS,AMSUA) can be forced into the assimilation system with little or no bias correction if GPS data (with very high vertical resolution) are used to control oscillations in the stratosphere

Mean increments





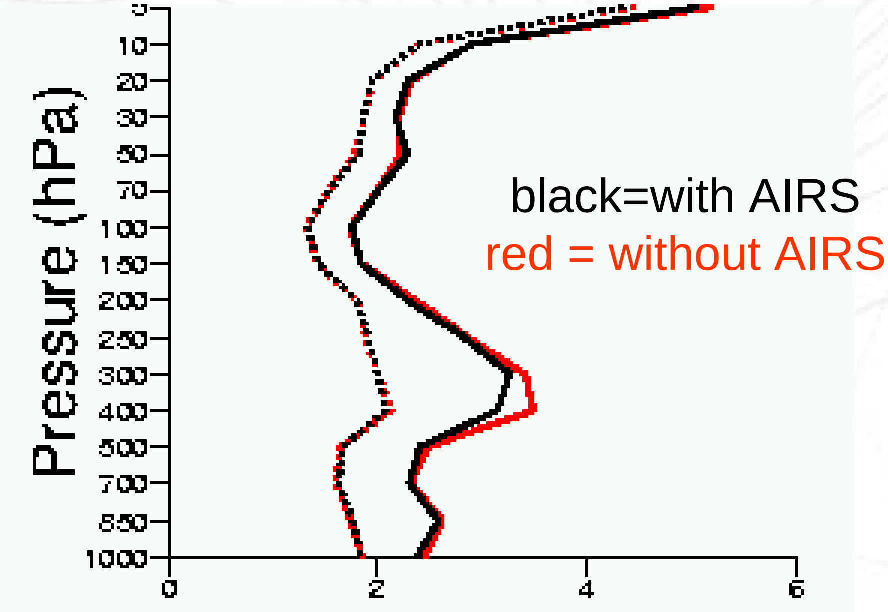
CTL(black): CH+GR(red)

radiosonde observations confirm that the GPS data are very effective at controlling the spurious oscillations

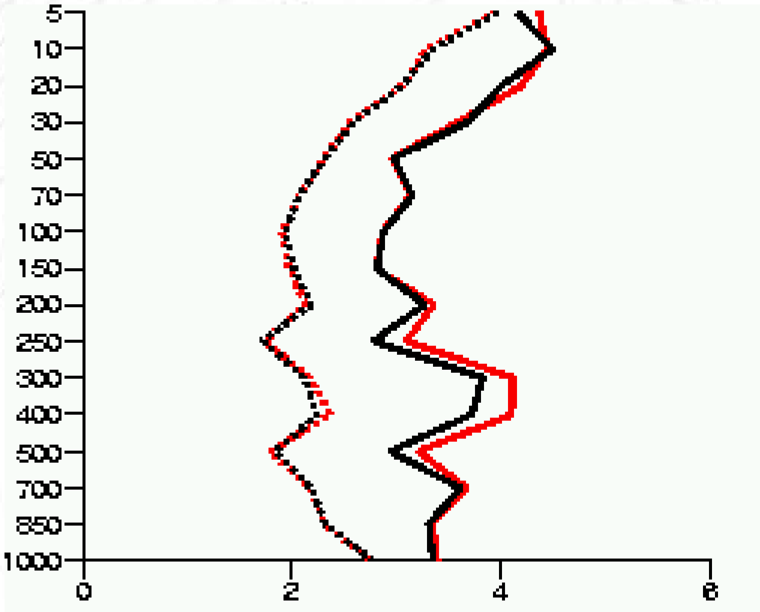
Temperature sounding radiances controlling the polar wind field

The assimilation of temperature sensitive radiance data (particularly AIRS) constrains the wind field and results in a better fit to radiosonde wind observations in Polar regions

analysis and background fit to radiosonde **wind data** (u-comp) averaged over the **N Pole**



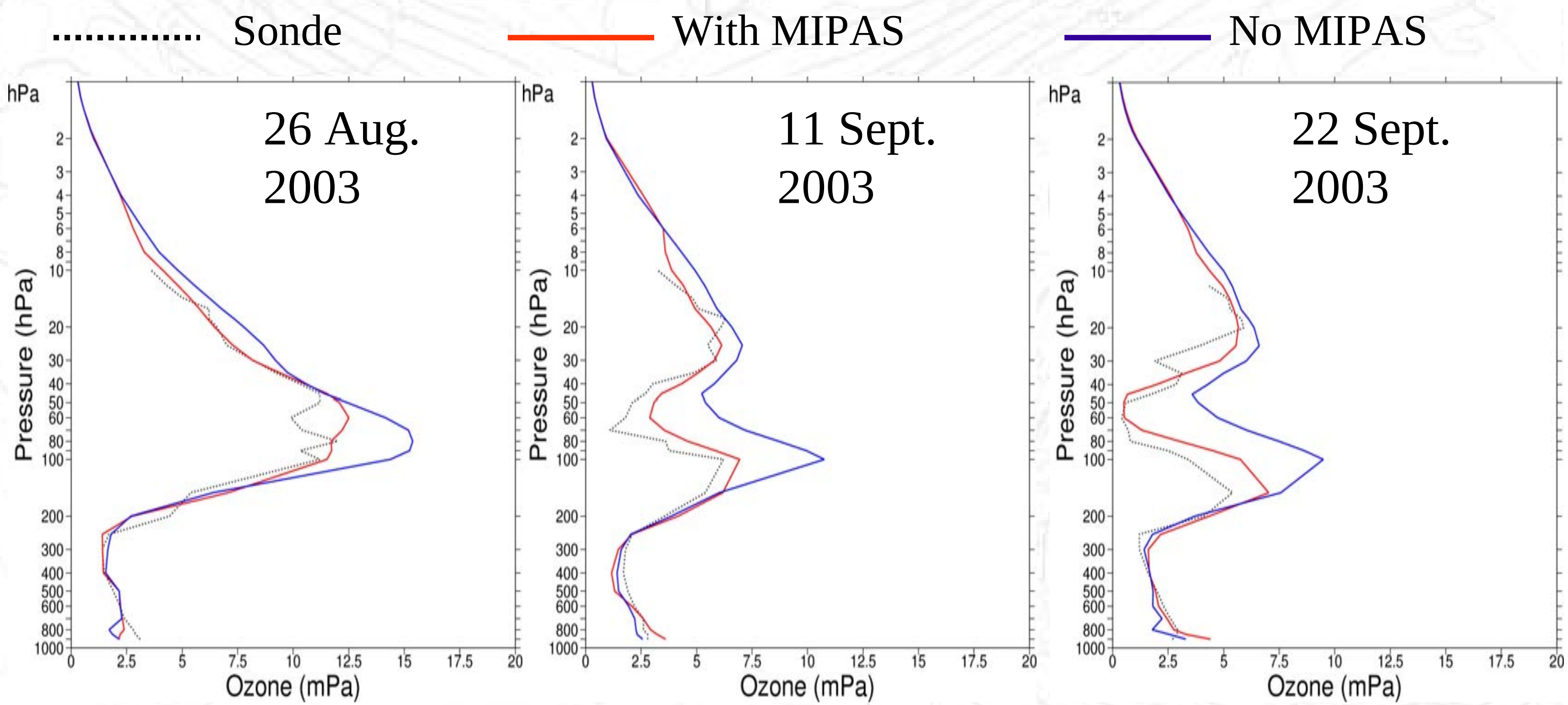
analysis and background fit to radiosonde **wind data** (u-comp) averaged over the **S Pole**



(2 week average in June 06)

The Assimilation of MIPAS Ozone Retrievals

High vertical resolution MIPAS ozone retrievals are very effective in constraining the vertical distribution of ozone in the assimilation system (nadir data cannot)

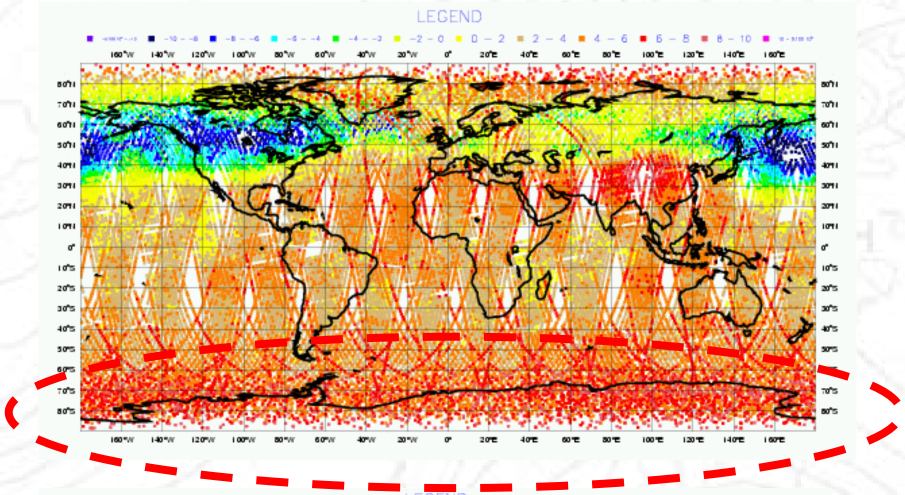


Ozone profiles at Neumayer (71 S, 8 W)

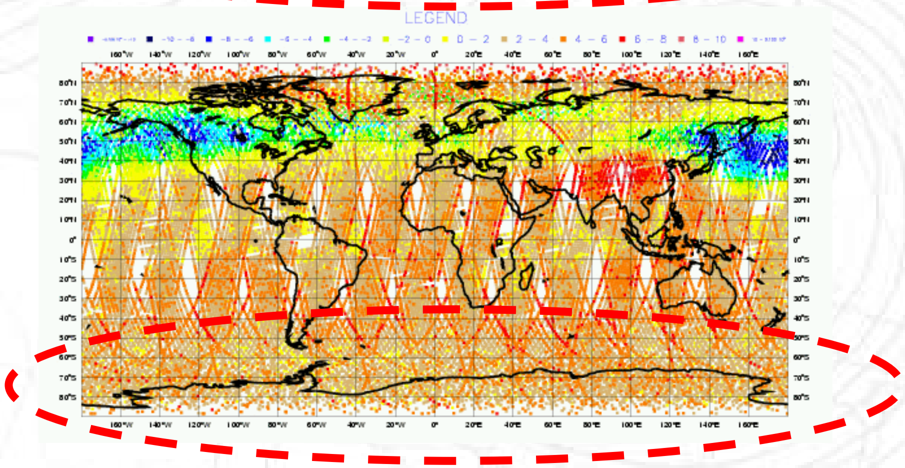
Tuning NWP model parameters to observations

Some of the temperature biases in the stratosphere have been reduced by tuning parameters such as Rayleigh friction

Mean AMSUA ch-14 radiance departures with OLD Rayleigh friction

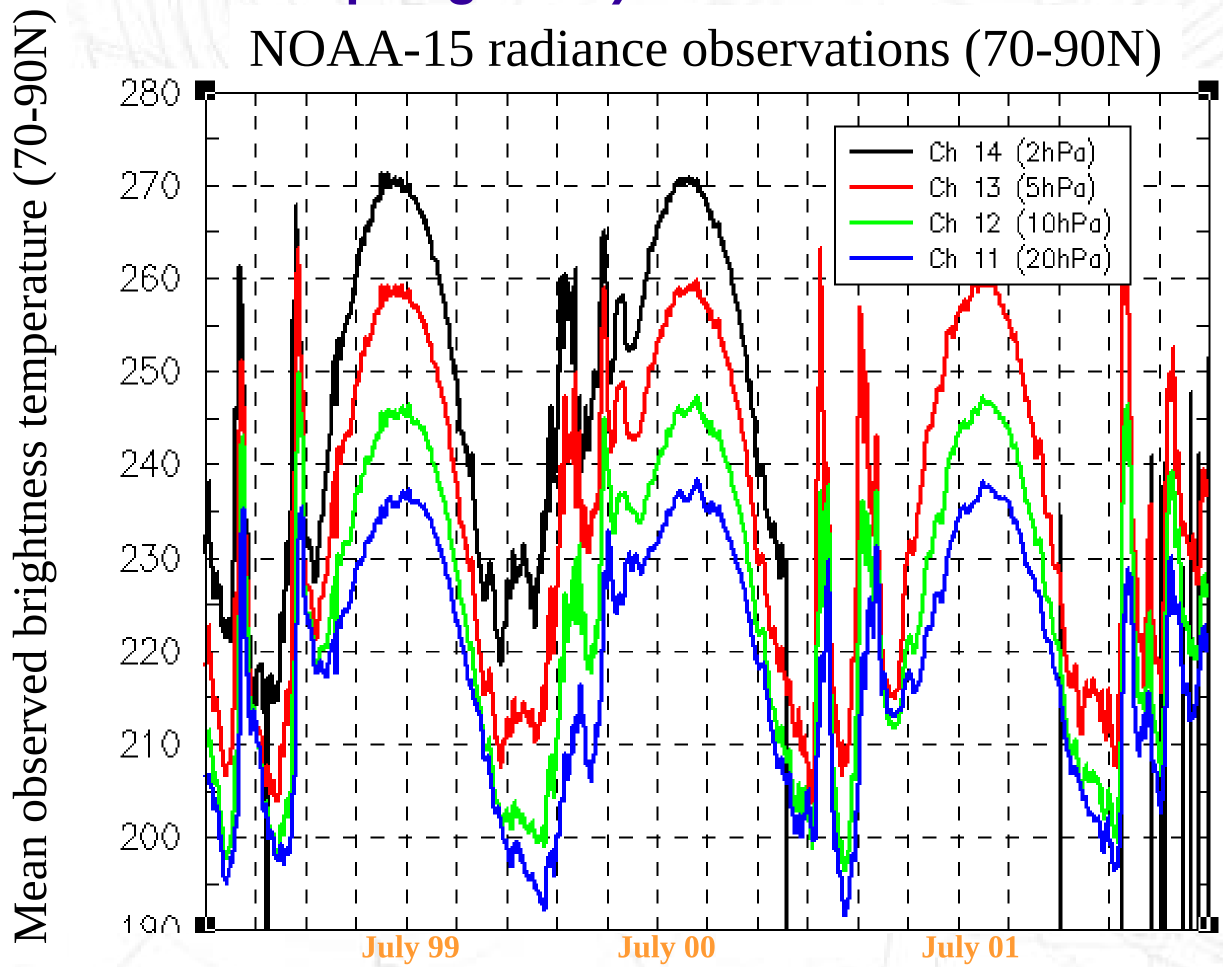


Mean AMSUA ch-14 radiance departures with NEW Rayleigh friction



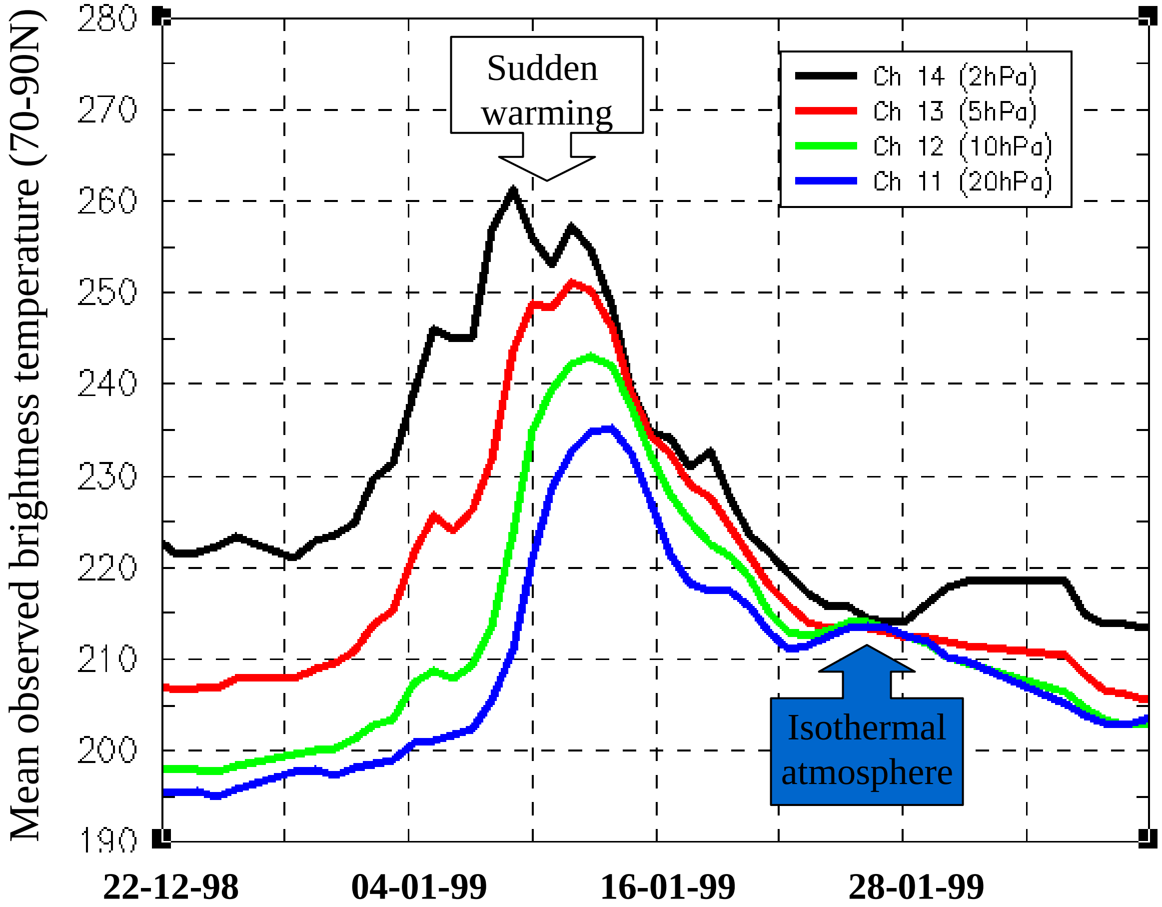
Occurrence of sudden warmings

NOAA-15 AMSU-A
(Autumn 98 – Spring 2002)



Vertical structure of sudden warmings (from AMSUA and AIRS)

NOAA-15 radiance observations (70-90N)

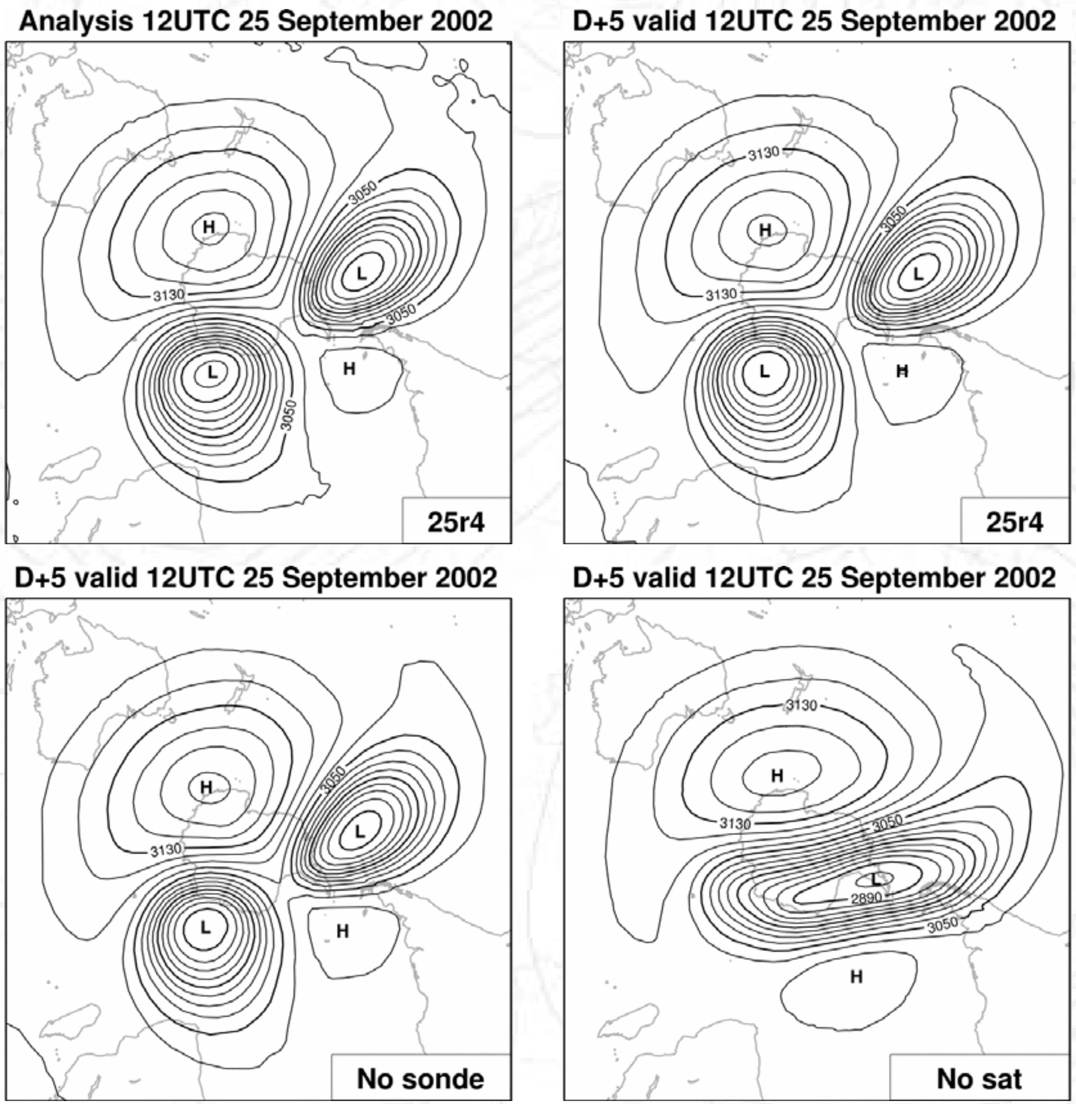


Winter 1998 / 1999

Forecasts of Southern Polar Vortex Split

Verifying analyses

Day-5 forecats



Summary

•There is a vast amount of satellite data available at the poles, however the polar regions present some particular assimilation challenges:

•The variability of the polar surface (and our poor knowledge of it) makes mid-lower tropospheric radiance data difficult to use safely (both from a RT perspective and the detection of clouds when the surface variability far exceeds the atmospheric signal).

•However, microwave and infrared radiance data sensitive to the upper troposphere and stratosphere are used extensively and have a significant measurable impact on Polar NWP / reanalysis.

•Systematic errors in the NWP model can be large in the polar stratosphere and care must be taken how the radiance data are bias corrected and introduced into the assimilation system.

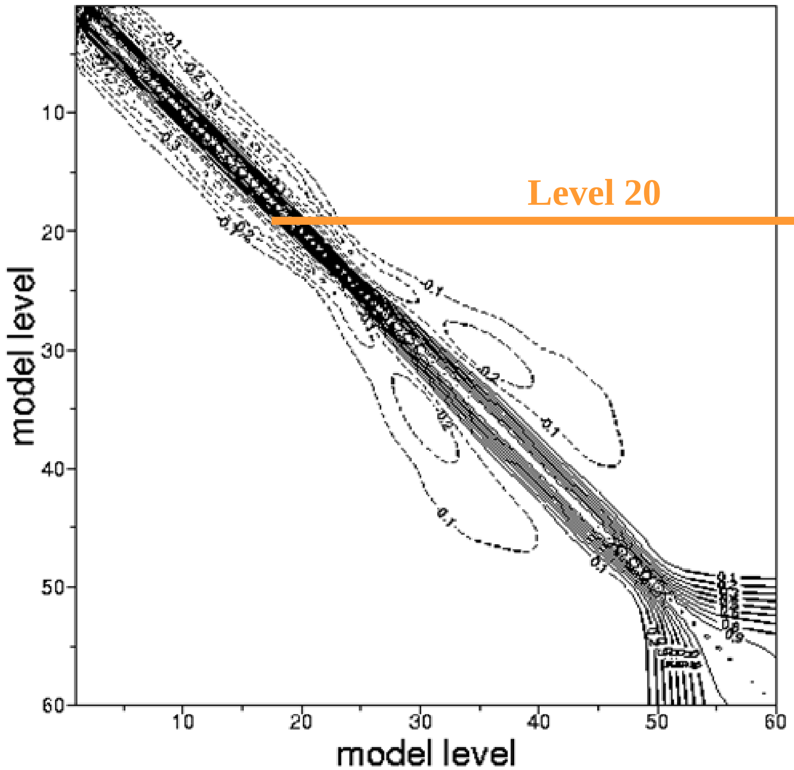
End

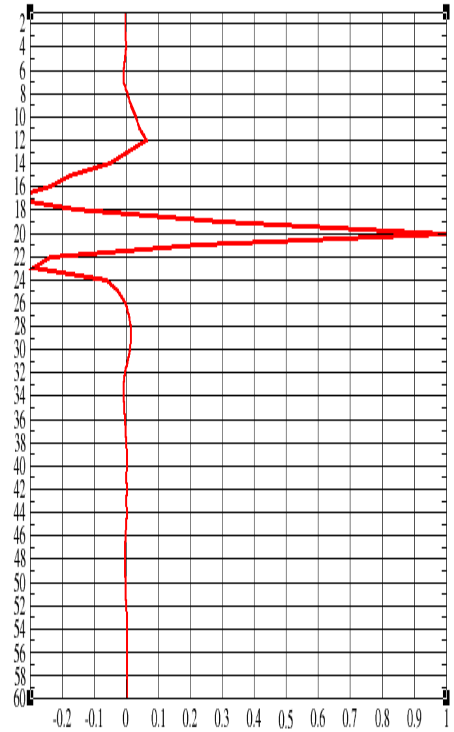
Systematic Errors (9)

Vertical correlation of background temperature errors

These are generally very sharp (describing random background errors) and as such do not prevent oscillating increments in between broad overlapping channels

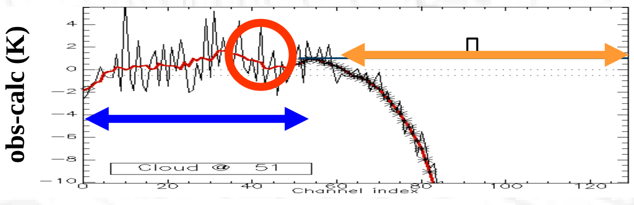
Globally averaged correlation of temperature errors in 4DVAR





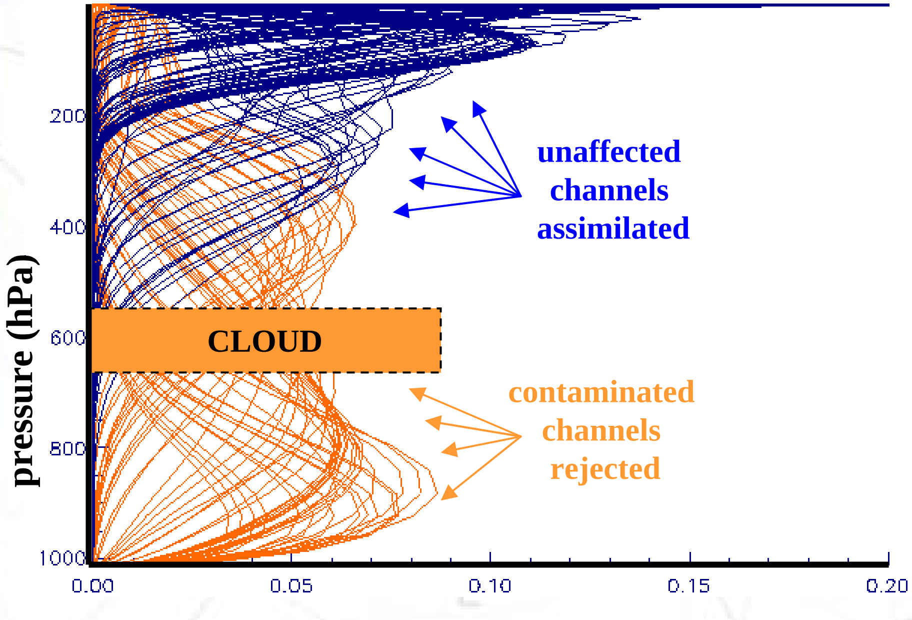
Multispectral Cloud detection scheme for AIRS

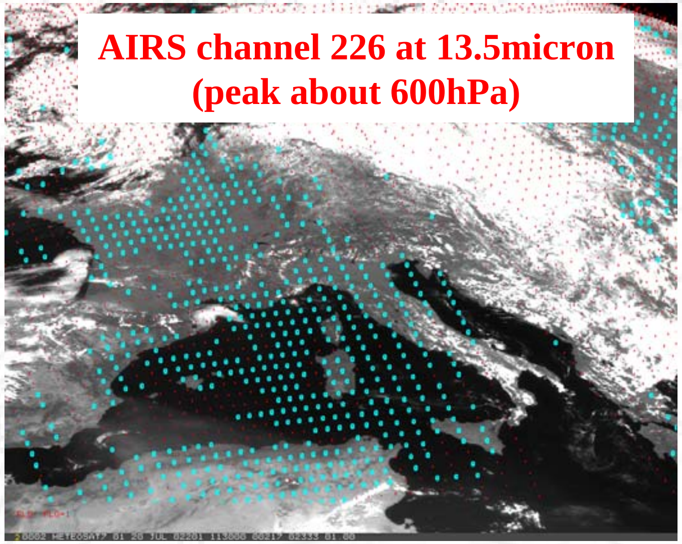
A non-linear pattern recognition algorithm is applied to departures of the observed radiance spectra from a computed clear-sky background spectra.

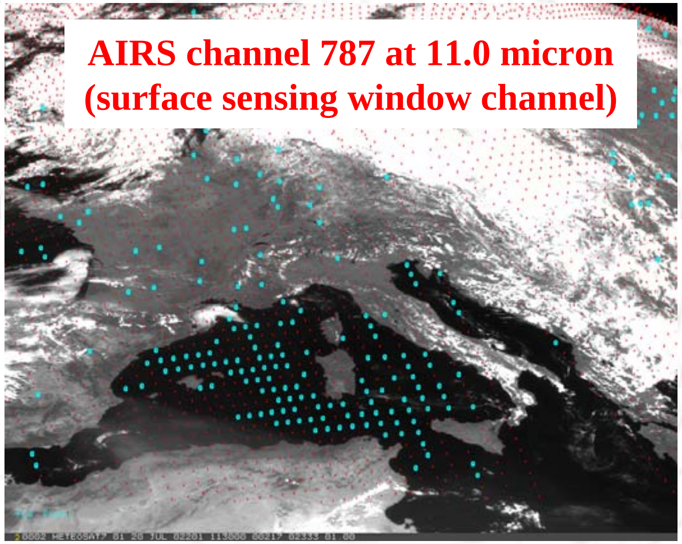


Vertically ranked channel index

This identifies the characteristic signal of cloud in the data and allows contaminated channels to be rejected



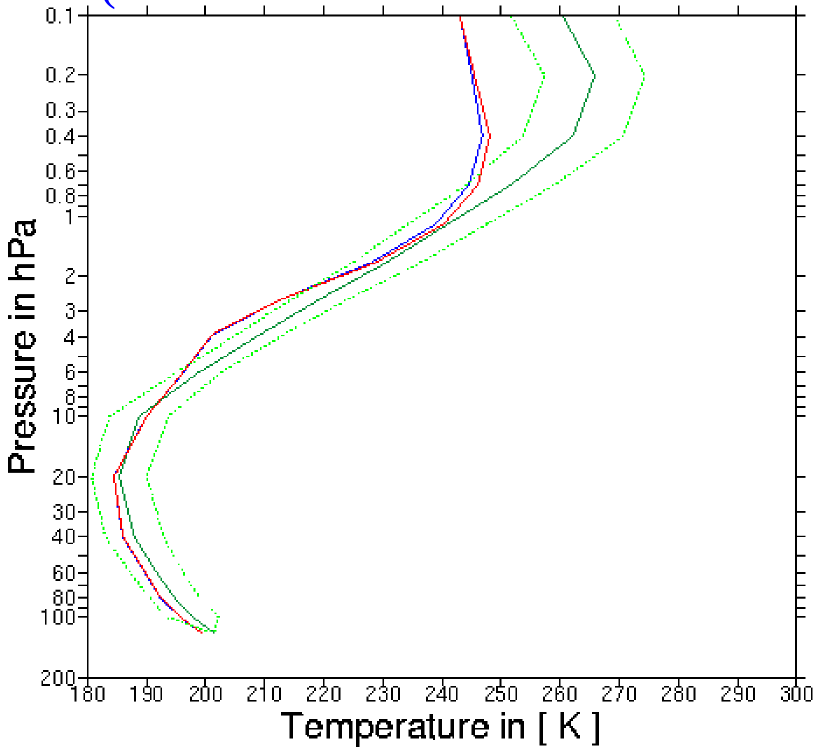




Systematic Errors (8)

Analysis fit to MIPAS temperature data (with and without AIRS radiances)

26R3 – **WITHOUT AIRS** radiances
(65S – 90S for 20 – 30 June 2003



26R3 – **WITH AIRS** radiances
(65S – 90S for 20 – 30 June 2003