The Assimilation of Satellite Data for Numerical Weather Prediction

lecture 2

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1. REVIEW OF KEY CONCEPTS

Radiance information content

2. BACKGROUND ERROR STRUCTURES

Why are they important ?

How do we estimate them ?

3. AMBIGUITY BETWEEN VARIABLES

Temperature and humidity

Surface and the atmosphere

Clouds / precipitation and the atmosphere

4. SYSTEMATIC ERRORS

Why are they important ?

How do we estimate them ?

5. WIND ADJUSTMENTS FROM RADIANCES

Direct and indirect wind adjustments

1. The radiances measured by a satellite are related to the atmospheric variables (T,Q ..) by the **radiative transfer equation**.

2. Channels (frequencies) are **selected** to simplify the relationship and obtain information on **particular aspects of the atmosphere** (e.g. T)

3. The physics of the emission / absorption processes mean **radiances are broad vertical averages** of the atmospheric temperature (defined by weighting functions) -> **limited vertical resolution**

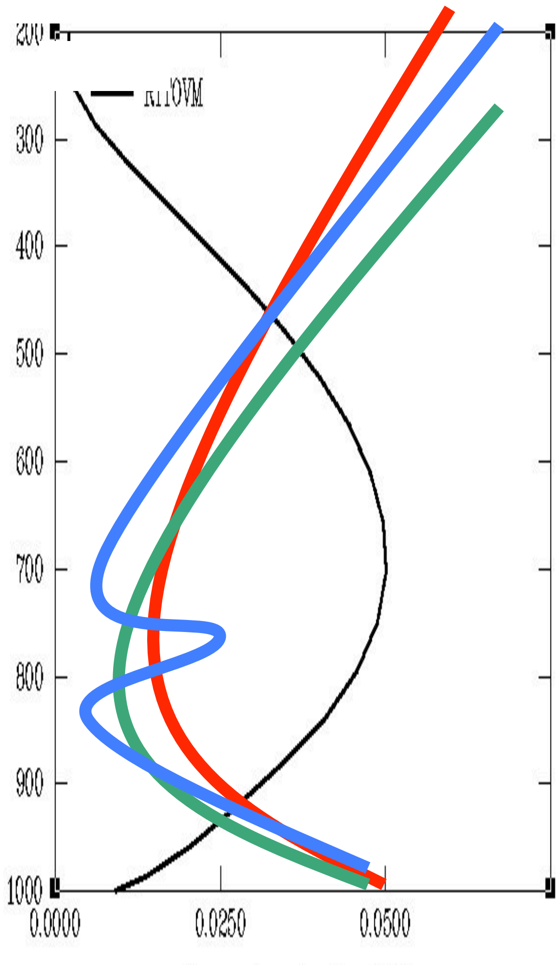
4. The conversion from radiance to temperature is **ill posed** and conversion (retrieval / analysis) schemes use **prior or background information**

5. The **direct assimilation** of radiances is arguably the **cleanest /simplest approach** to this process and is widely used in operational NWP.

Vertical resolution, background errors and radiance assimilation

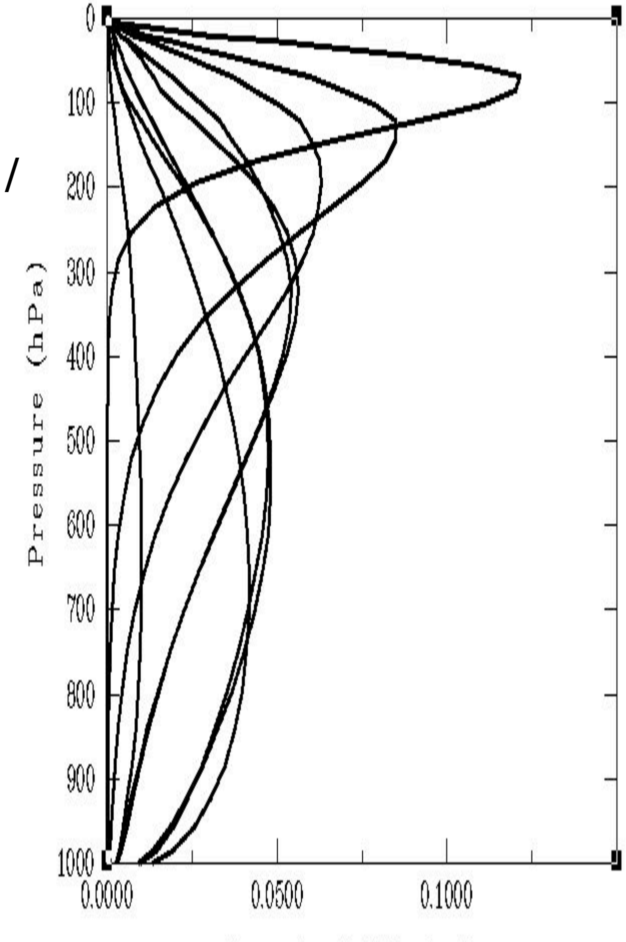
Lecture 1: > Satellite radiances have limited vertical resolution

single channel

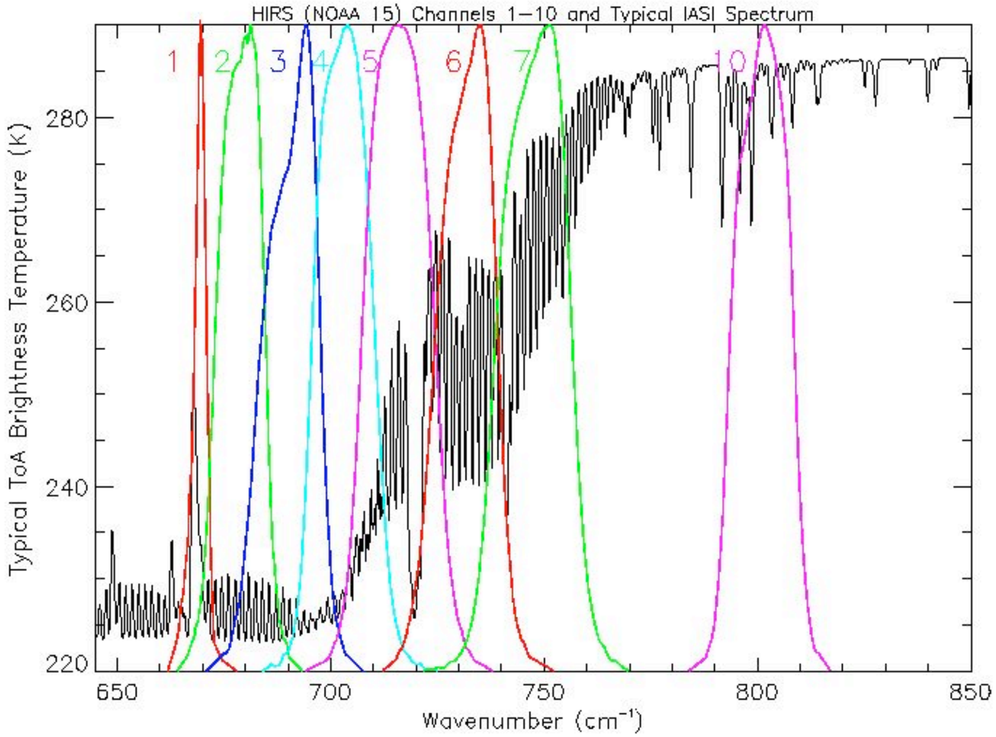


Selecting radiation in a number of frequencies / channels improves vertical sampling and resolution

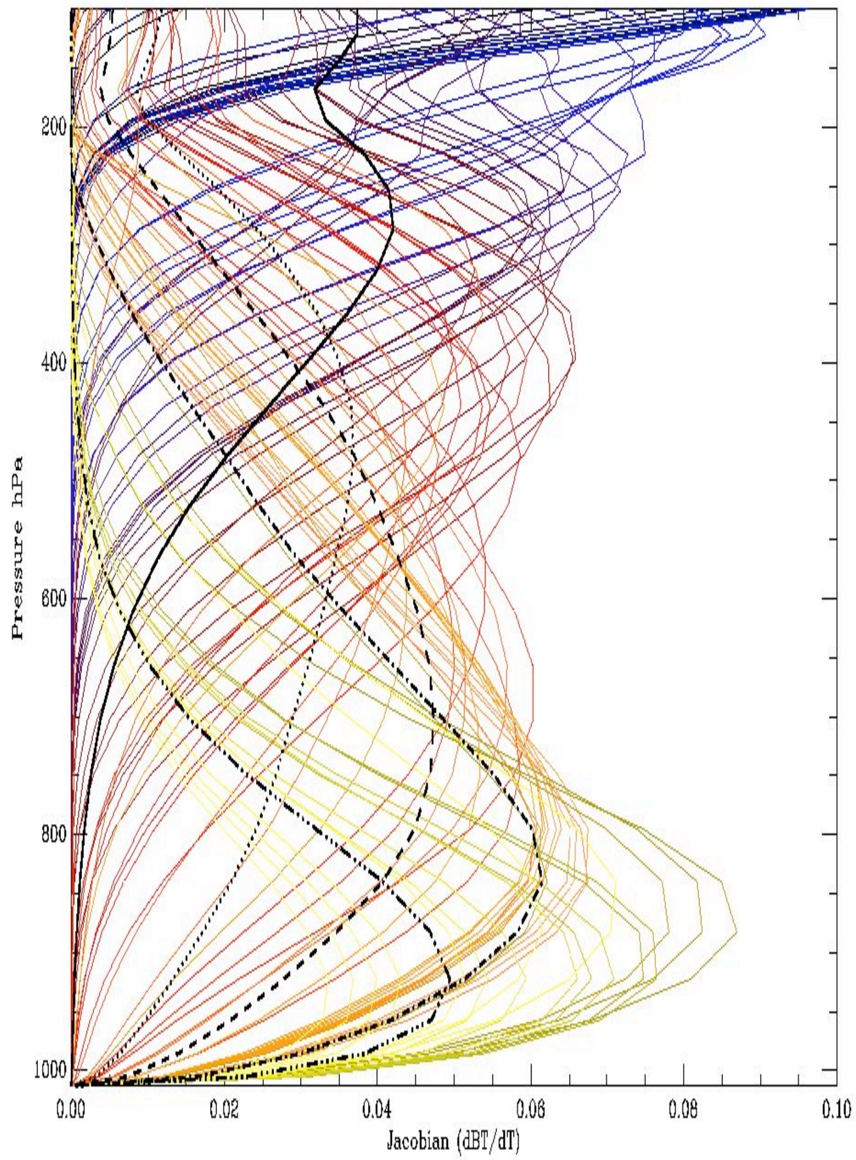
15 channels (e.g. AMSUA)



Improving vertical resolution with hyper-spectral IR instruments (AIRS / IASI)



Many thousands of channels improves things, but the vertical resolution is <u>still limited by the physics</u>



So what are the consequences of this limited vertical resolution…

?

SATELLITE RADIANCES "SEEING" AND "CORRECTING" BACKGROUND ERRORS

When we minimize a cost function of the form (in 1D / 3D / 4D-VAR)

$$J(x) = (x - x_b)^T \mathbf{B}^{-1}(x - x_b) + (y - \mathrm{H}[x])^T \mathbf{R}^{-1}(y - \mathrm{H}[x])$$

We can think of the adjustment process as radiances observations **correcting errors in the forecast background** to produce an analysis that is closer to the true atmospheric state. For example in the simple linear case...

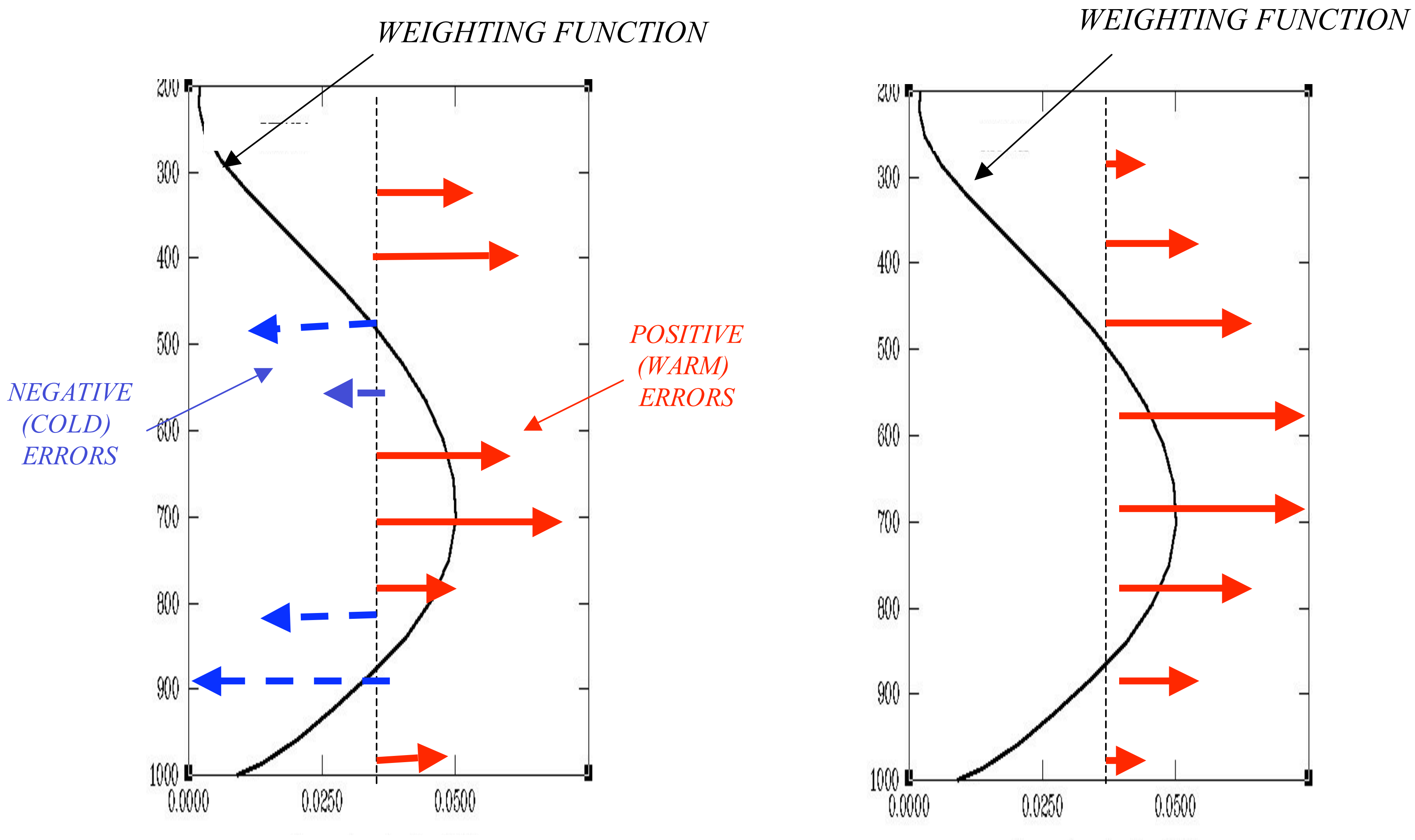
$$x_a = x_b + \underline{[\mathbf{HB}]^T[\mathbf{HBH}^T + \mathbf{R}]^{-1}(y - \mathbf{H}x_b)}$$

← **correction term**

Because of broad weighting functions the radiances have very little vertical resolution and the **vertical distribution of forecast errors** is crucial to how well they will be "seen" and "corrected" by satellite data in the analysis.

This vertical distribution is communicated to the retrieval / analysis via the **vertical correlations** implicit in the background error covariance matrix **B** (the rows of which are sometimes known as **structure functions**).

BACKGROUND ERROR VERTICAL CORRELATIONS



"Difficult" to correct

"Easy" to correct

SIMULATED RETRIEVAL / ANALYSIS PERFORMANCE WITH DIFFERENT FORECAST BACKGROUND ERRORS

Cost function:

$$J(x) = (x - x_b)^T \mathbf{B}^{-1}(x - x_b) + (y - \mathrm{H}[x])^T \mathbf{R}^{-1}(y - \mathrm{H}[x])$$

Solution:

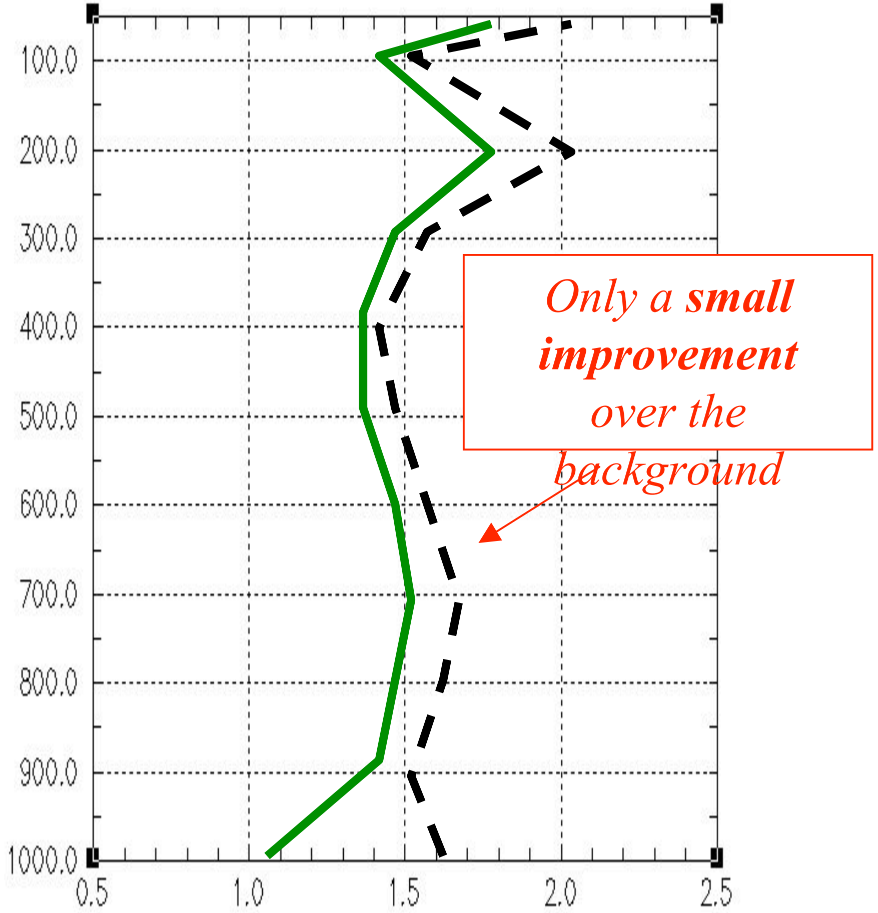
$$x_a = x_b + [\mathbf{HB}]^T [\mathbf{HBH}^T + \mathbf{R}]^{-1}(y - \mathbf{H}x_b)$$

Solution error covariance:

$$\mathbf{S_a} = \mathbf{B} - [\mathbf{HB}]^T [\mathbf{HBH}^T + \mathbf{R}]^{-1} \mathbf{HB}$$

SIMULATED RETRIEVAL / ANALYSIS PERFORMANCE WITH DIFFERENT FORECAST BACKGROUND ERRORS

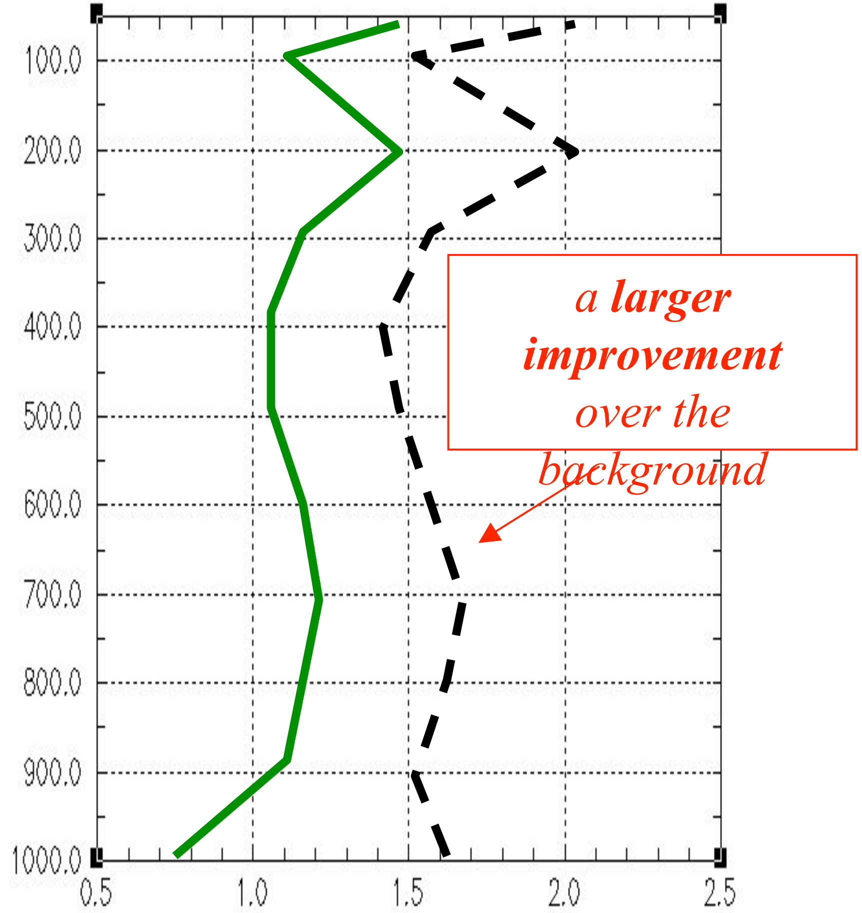
Sharp / anti-correlated background errors



Error standard deviation (K)

$\mathbf{S_a}$

Broad / deep correlated background error



Error standard deviation (K)

$\mathbf{S_a}$

ESTIMATING BACKGROUND ERROR CORRELATIONS

If the **background errors are mis-specified** in the retrieval / analysis this can lead to a complete mis-interpretation of the radiance information and badly damage the analysis, possibly producing a analysis with **larger errors than the background state** !

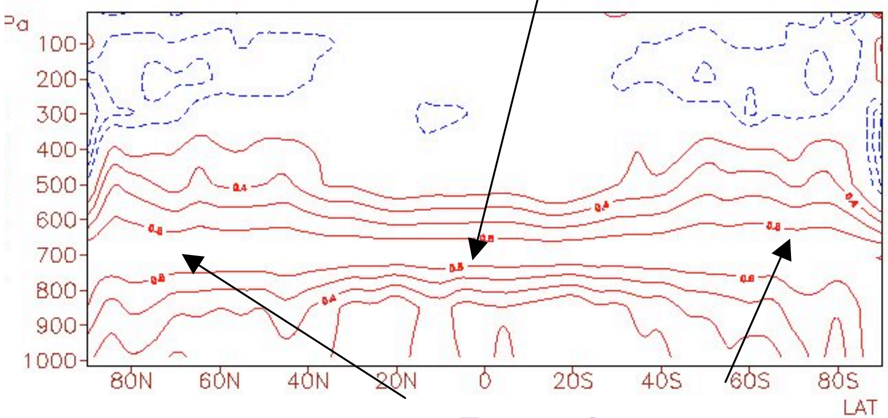
Thus accurate estimation of **B** is crucial:

•comparison with **radiosondes** (best estimate of truth but limited coverage

•comparison of e.g. 48hr and 24hr forecasts (so called ***NMC method***)

•comparison of **ensembles** of analyses made using perturbed observations

Sharp errors in the Tropics



Broad errors in the mid-lat

It is unfortunate that in remote areas where vertical correlations (in B) are are most important we have the least data available to estimate them

Ambiguity in radiance observations

AMBIGUITY BETWEEN GEOPHYSICAL VARIABLES

When the primary absorber in a sounding channel is a **well mixed gas** (e.g. oxygen) the radiance essentially gives information about variations in the **atmospheric temperature profile only**.

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz$$

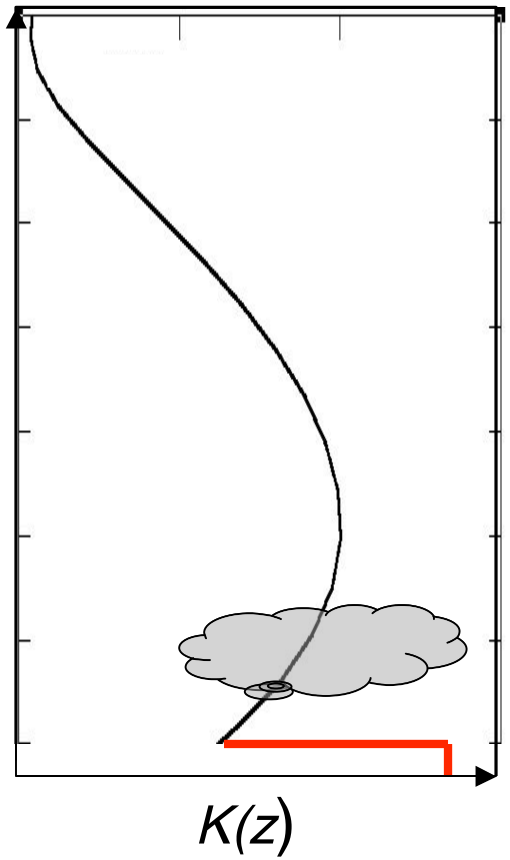
When the primary absorber is **not well mixed** (e.g. water vapour, ozone or CO_2) the radiance gives **ambiguous information** about the temperature profile and the absorber distribution. This ambiguity must be resolved by :

- differential channel sensitivity
- synergistic use of well mixed channels (constraining the temperature)
- the background error covariance (+ physical constraints)

→ *environmental monitoring – lecture 3*

AMBIGUITY WITH SURFACE AND CLOUDS

By placing sounding channels in parts of the spectrum where the absorption is **weak** we obtain temperature (and humidity) information from the **lower troposphere** (low peaking weighting functions).



BUT …

These channels (obviously) become more sensitive to surface emission and the effects of cloud and precipitation.

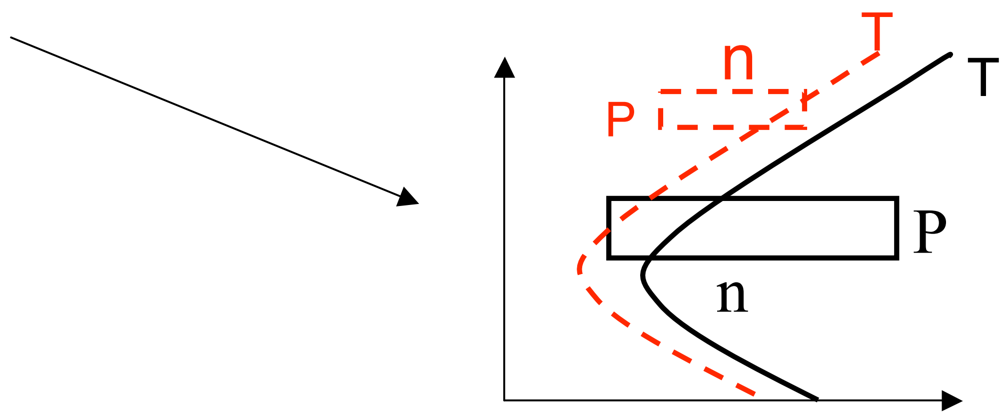
In most cases **surface or cloud** contributions will **dominate the atmospheric signal** in these channels and it is difficult to use the radiance data **safely** (i.e. we may alias a cloud signal as a temperature adjustment)

Cloud and Rain

OPTIONS FOR USING LOWER TROPOSPHERIC SOUNDING CHANNELS

1. **Screen the data carefully** and only use situations for which the surface and cloud radiance contributions can be computed very accurately *a priori* (e.g. cloud free situations over sea)

2. **Simultaneously** estimate atmospheric temperature, surface temperature / emissivity and cloud parameters within the analysis or retrieval process (need very good background statistics !)



3. **Always blacklist the data** !
   (e.g. over ice / mountains etc… where we may not trust our screening to find clouds / precipitation)

Dealing with cloud/rain:

Option 1

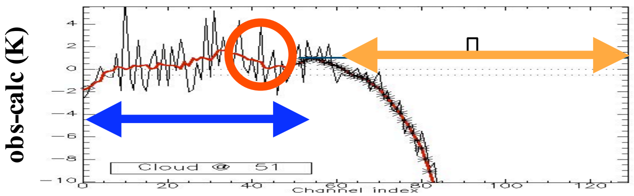
Screen the data and reject cloud/rain contamination

(currently operational)

RETAINING USEFUL INFORMATION ABOVE CLOUDS

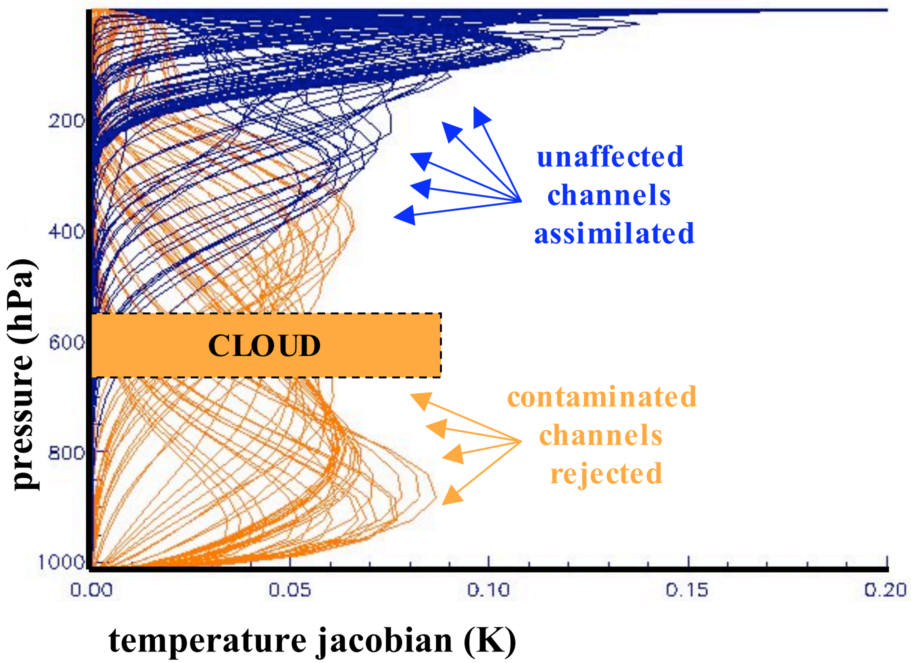
(Cloud detection scheme for AIRS / IASI)

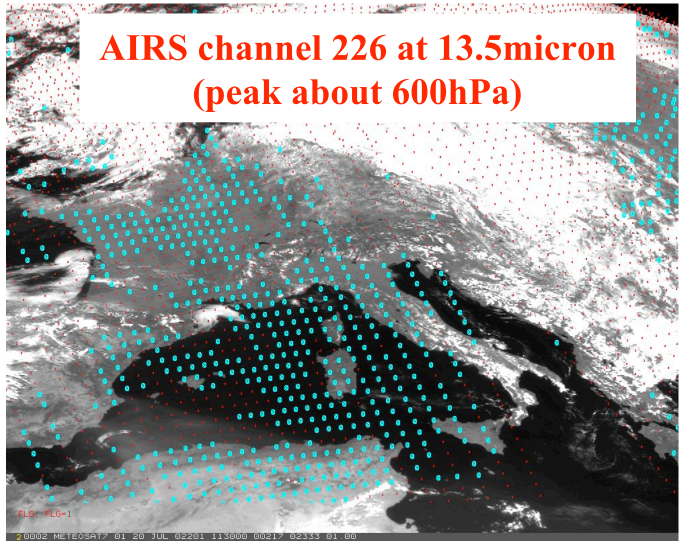
A non-linear pattern recognition algorithm is applied to departures of the observed radiance spectra from a computed clear-sky background spectra.

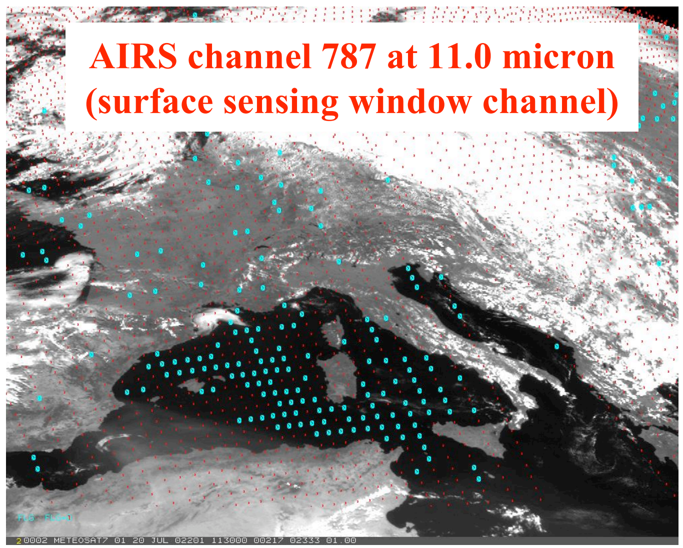


Vertically ranked channel index

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







Dealing with cloud/rain:

Option 2

Simultaneously analyze the cloud/rain information with T/Q

(MW operational* / IR experimental)

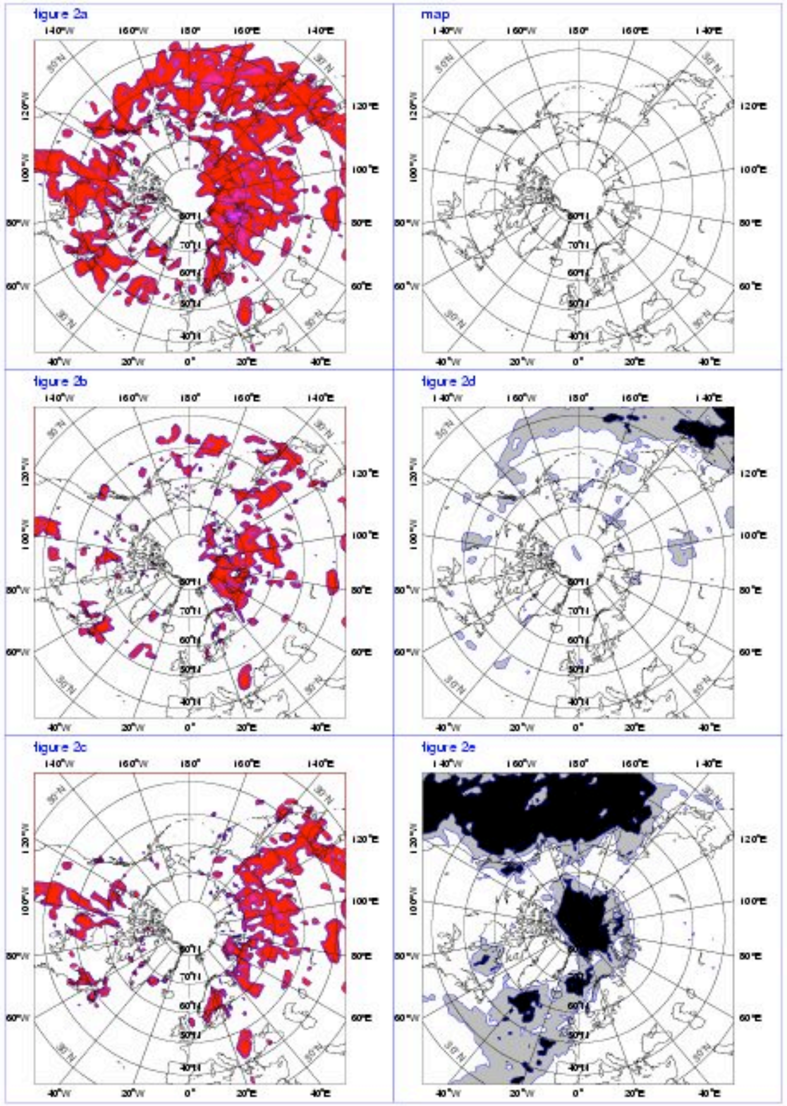
Cloud and meteorologically sensitive areas

Regions important for forecast error development can be traced using adjoint sensitivity techniques.

These sensitive areas have been found to correlate with cloud cover.

i.e. cloudy areas are very important !

sensitivity | cloud cover

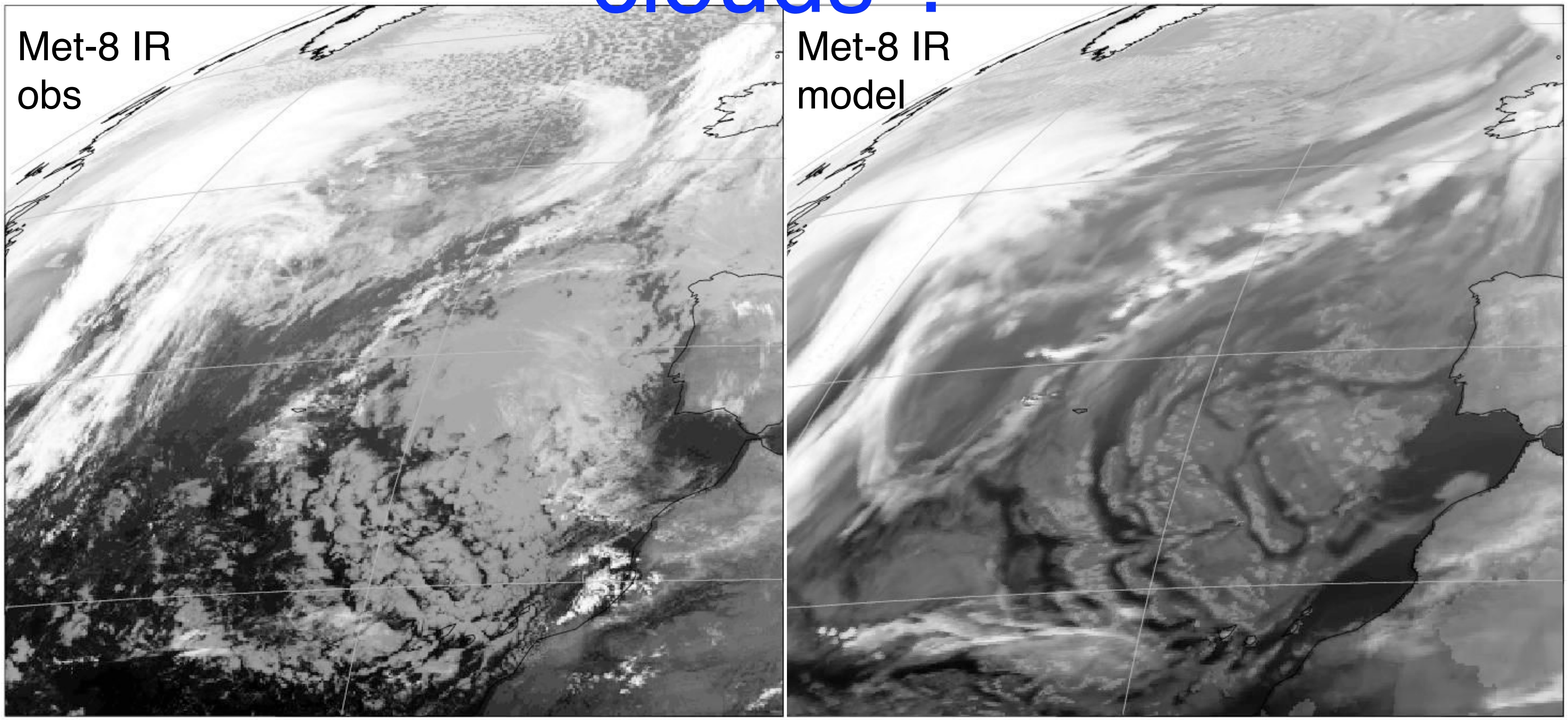


High cloud

Low cloud

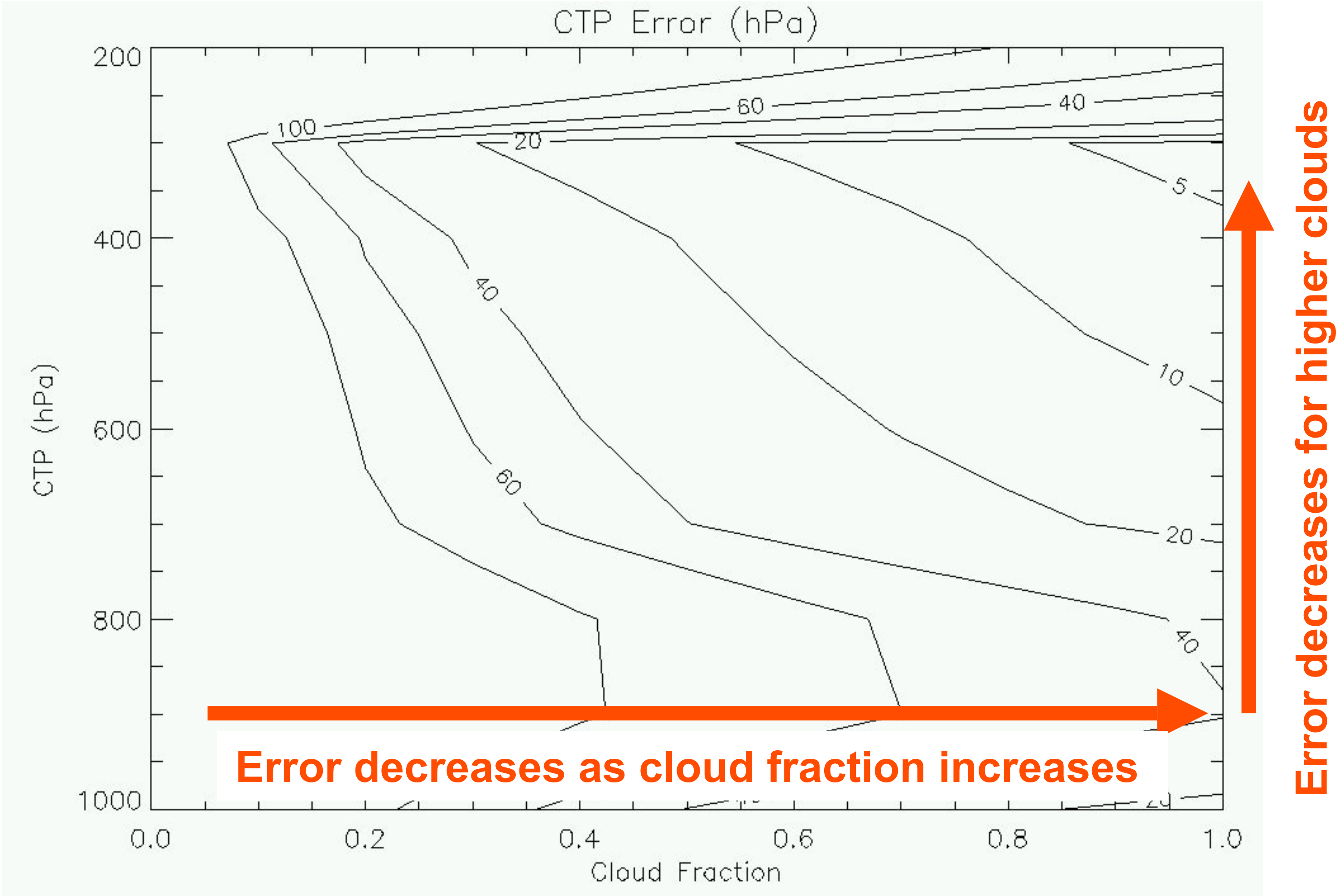
Infrared radiances and cloud

Does the NWP model provide good information on clouds ?

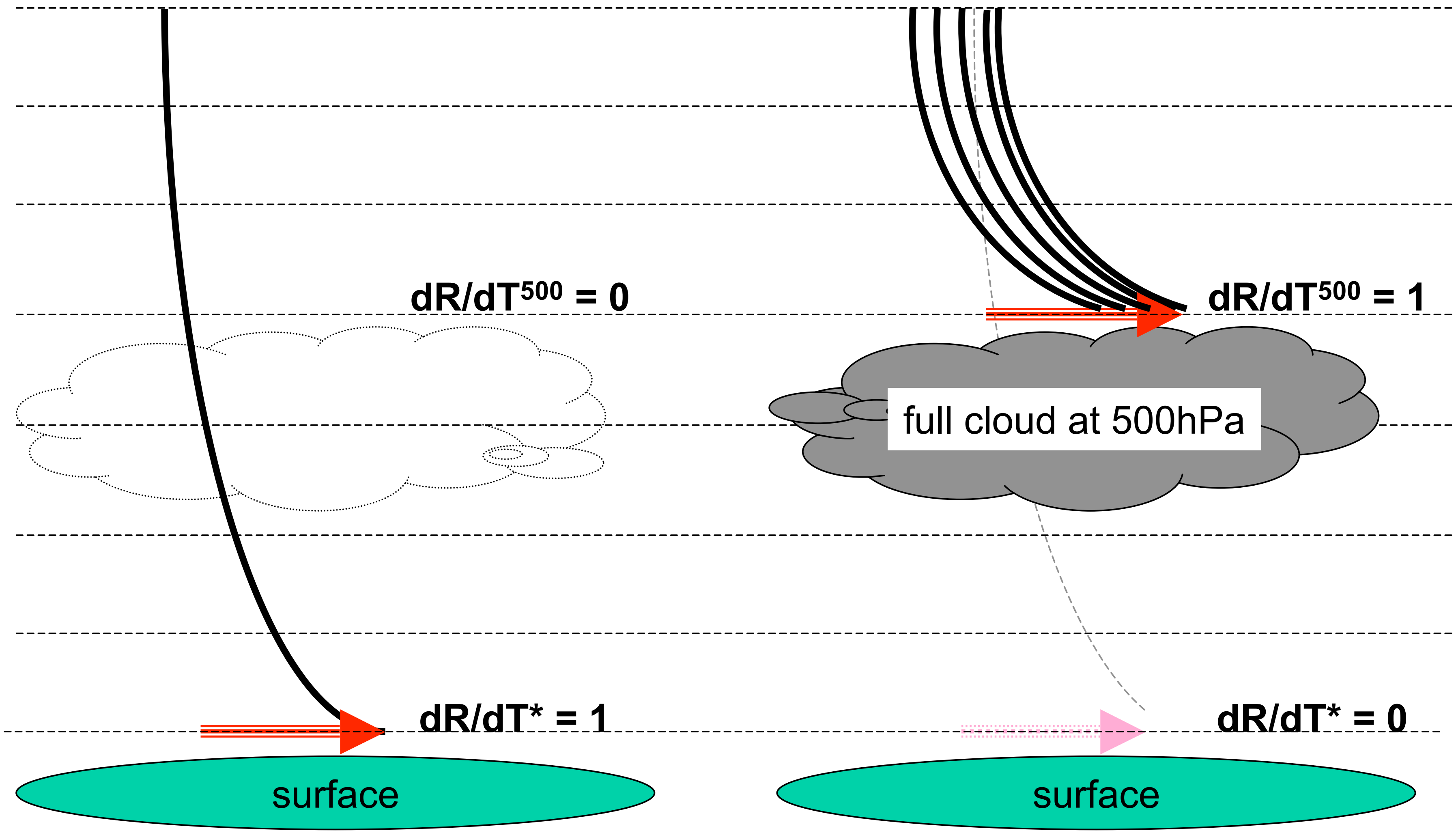


NWP model cloud simulation is now very good!

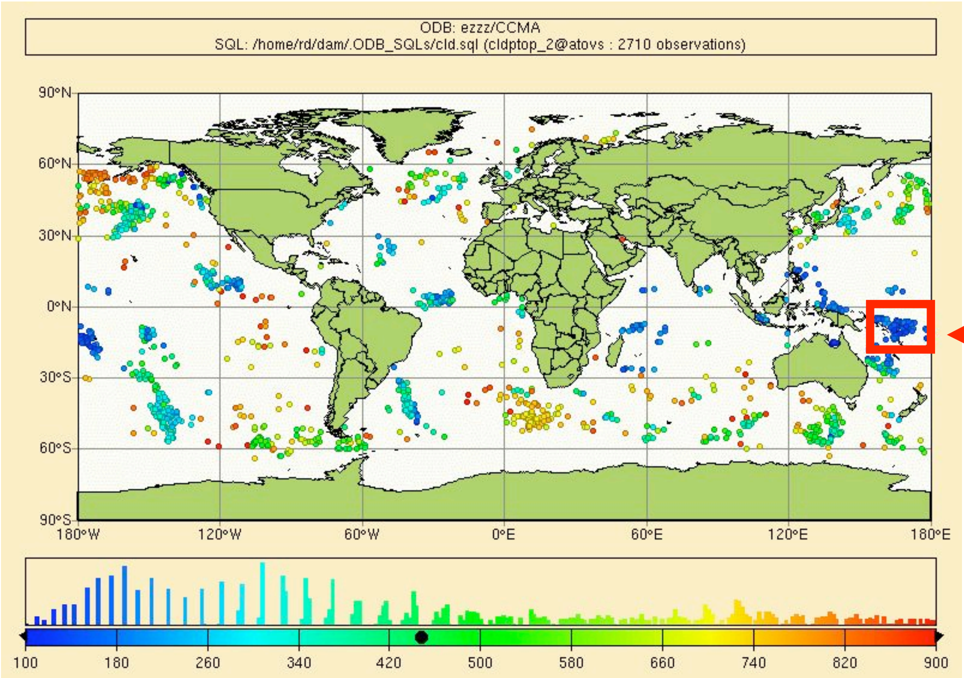
Do the observations provide good information on clouds ?



Enhanced temperature estimation at the cloud top

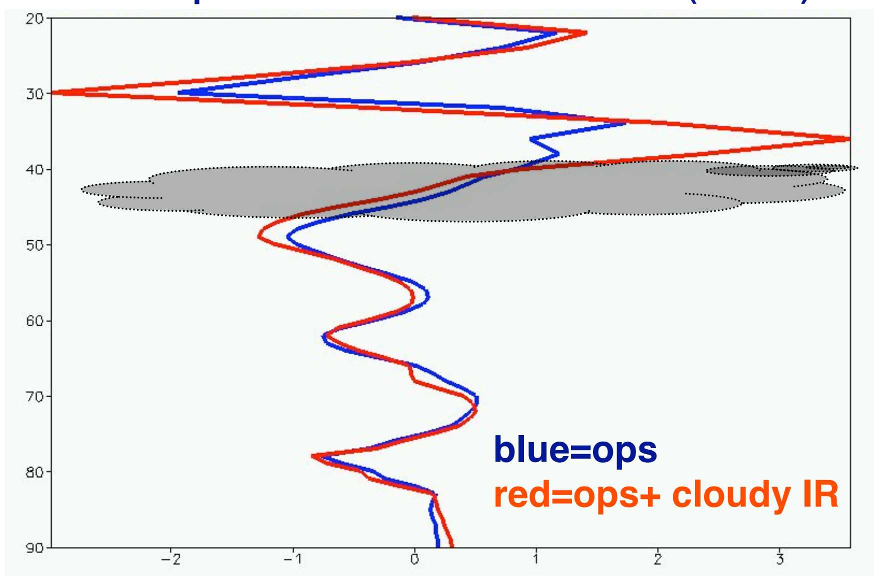


Temperature increments at the cloud top



Cell of very high overcast clouds off the coast of PNG

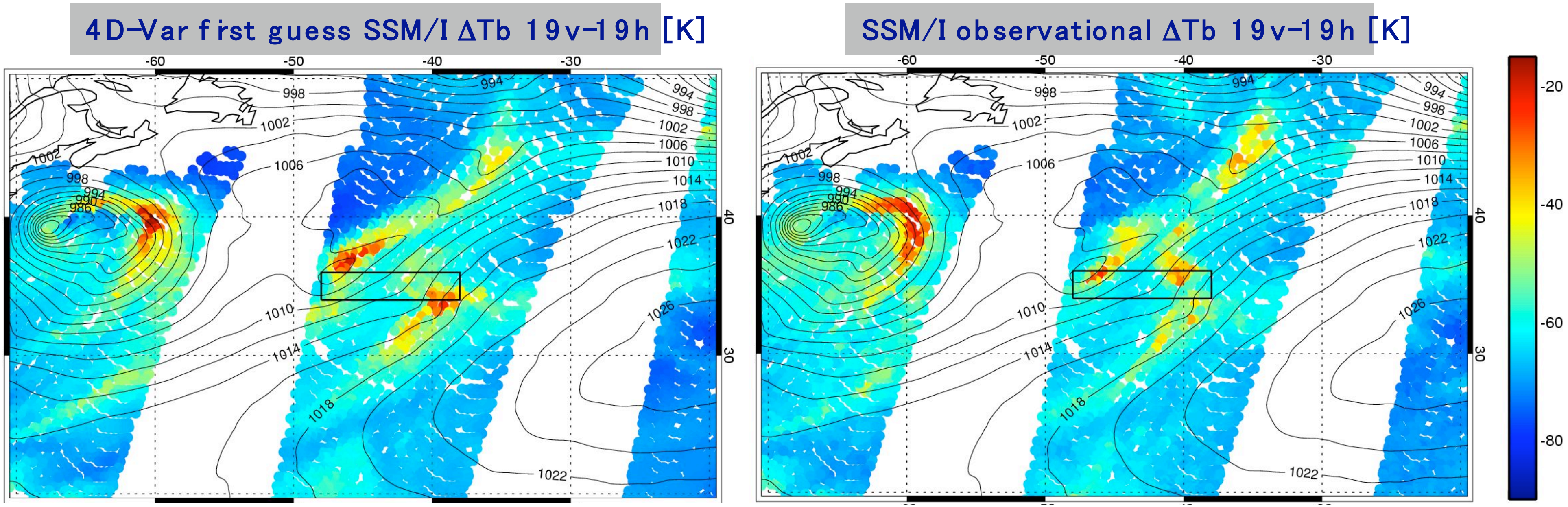
Temperature increments (IASI)



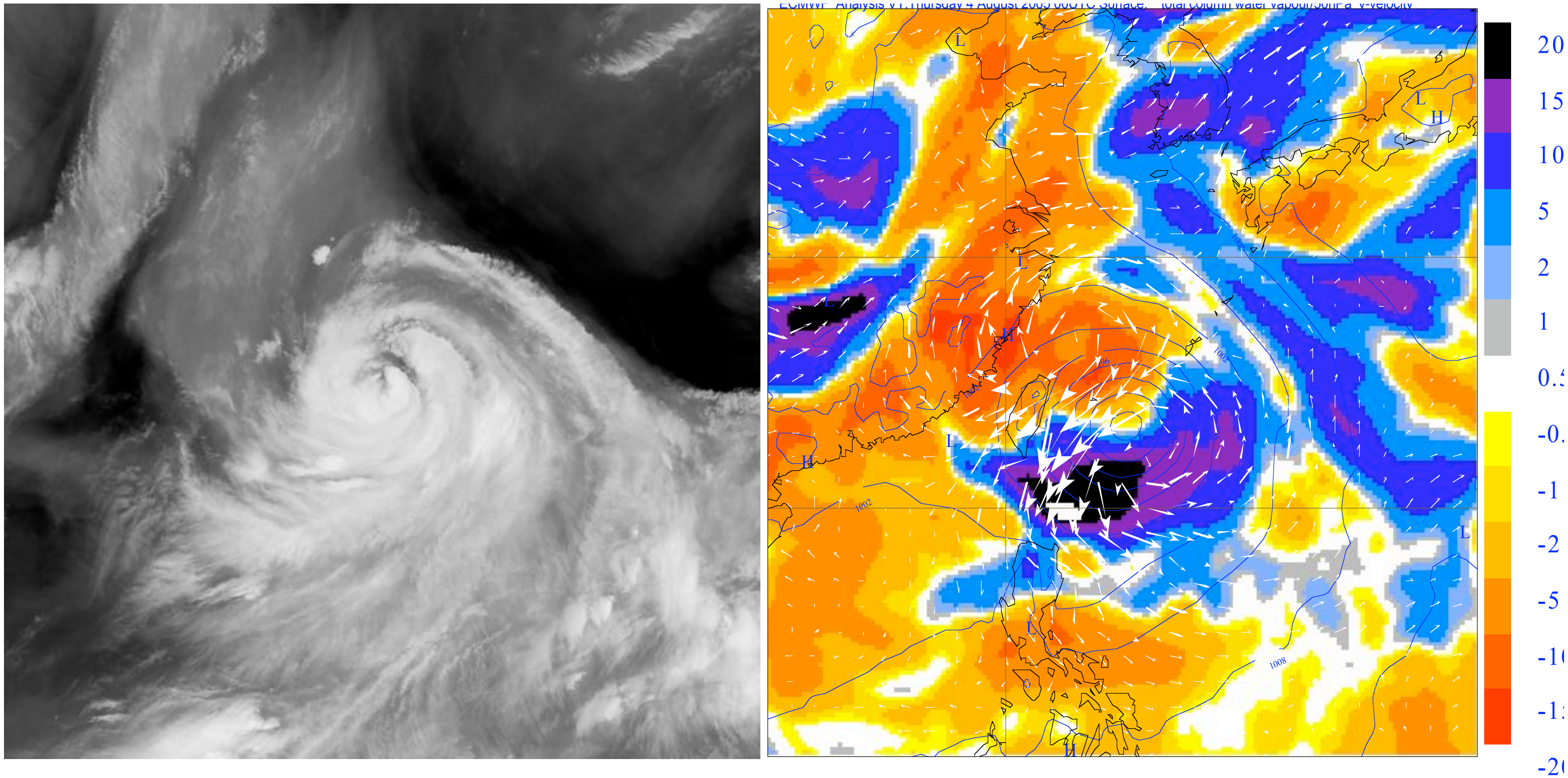
All channels collapse to near delta-functions at the cloud top giving very **high vertical resolution temperature increments** just above the diagnosed cloud

Microwave radiances and rain

Does the NWP model provide good information on rain ?



Rain-affected microwave radiances in severe weather



Left: MTSAT Infrared image of typhoon MATSA approaching Taiwanese and Chinese coast on August 4, 2005, 00 UTC. **Right:** 4D-Var moisture increments with rain assimilation (colors in %), 900 hPa wind increments (white arrows), surface pressure (isolines).

Typhoon *Matsa* (04/08/2005 00 UTC)

Potential issues for cloud / rain

- The cloud uncertainty may be an order of **magnitude** larger than the T and Q signal (i.e. 10s of kelvin compared to 0.1s of kelvin)
- The radiance response to cloud changes is **highly non-linear** (i.e. $H(x) = H_x(x)$)
- Errors in **background cloud parameters** provided by the NWP system may be difficult to quantify and model
- Conflict between having enough cloud variables for an **accurate RT calculation** while limiting the number of cloud variables to those that can be **uniquely estimated** in the analysis from the observations
- Complex interactions with **model physics**

Systematic errors in radiance observations

SYSTEMATIC ERRORS (BIASES)

Systematic errors (or biases) must be removed before the assimilation otherwise biases will propagate in to the analysis (causing **global damage** in the case of satellites!).

$$\textit{Bias} = \textit{mean}\,[\,Y_{obs} - H(X_b)\,]$$

Observed radiance

RT model

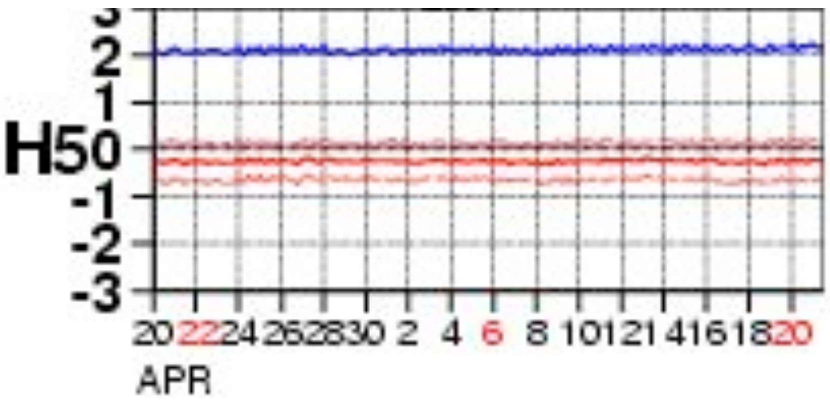
Background Atmospheric state

Sources of systematic error in radiance assimilation include:

- instrument error (calibration)
- radiative transfer error (spectroscopy or RT model)
- cloud/rain/aerosol screening errors
- systematic errors in the background state from the NWP model

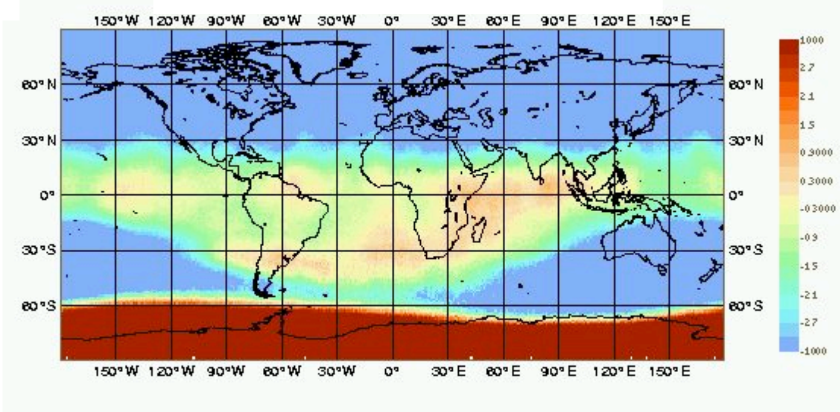
WHAT TYPE OF BIASES DO WE OBSERVE ?

HIRS channel 5



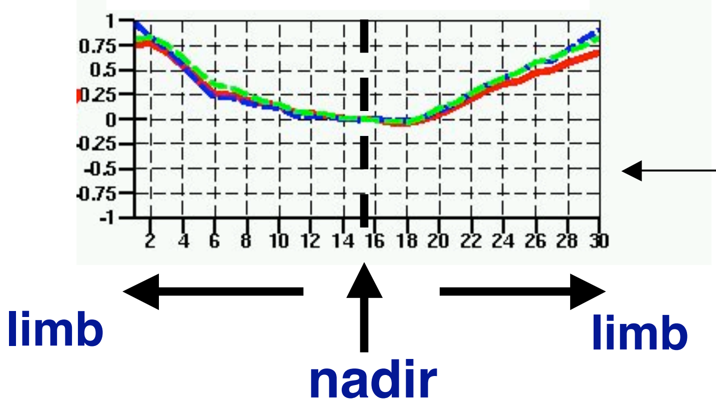
simple flat offset biases that are constant in time

AMSU-A channel 14



biases that vary depending on location or air-mass

AMSU-A channel 7

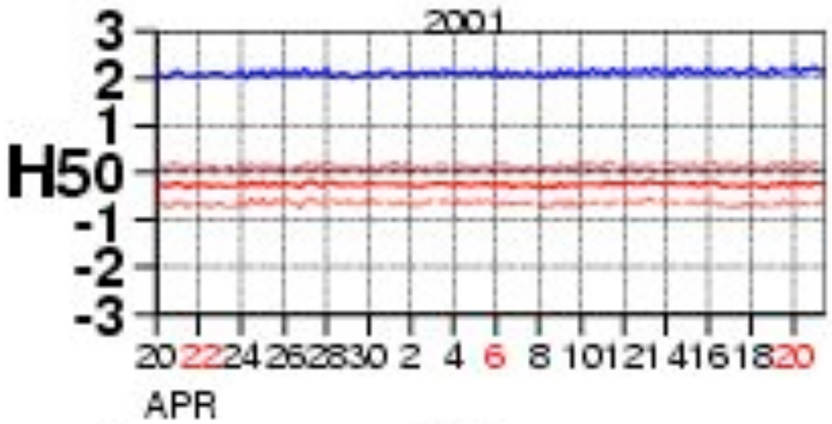


biases that vary depending on the Scan position of the satellite instrument

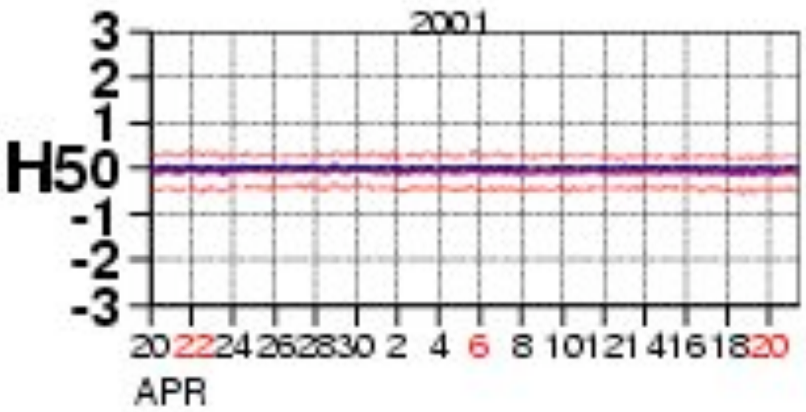
DIAGNOSING THE SOURCE OF A BIAS ...

Sometimes it is fairly obvious what is causing a particular bias…

...e.g. when the satellite instrument is wrong



HIRS channel 5 (peaking around 600hPa on NOAA-14 satellite has +2.0K radiance bias against model



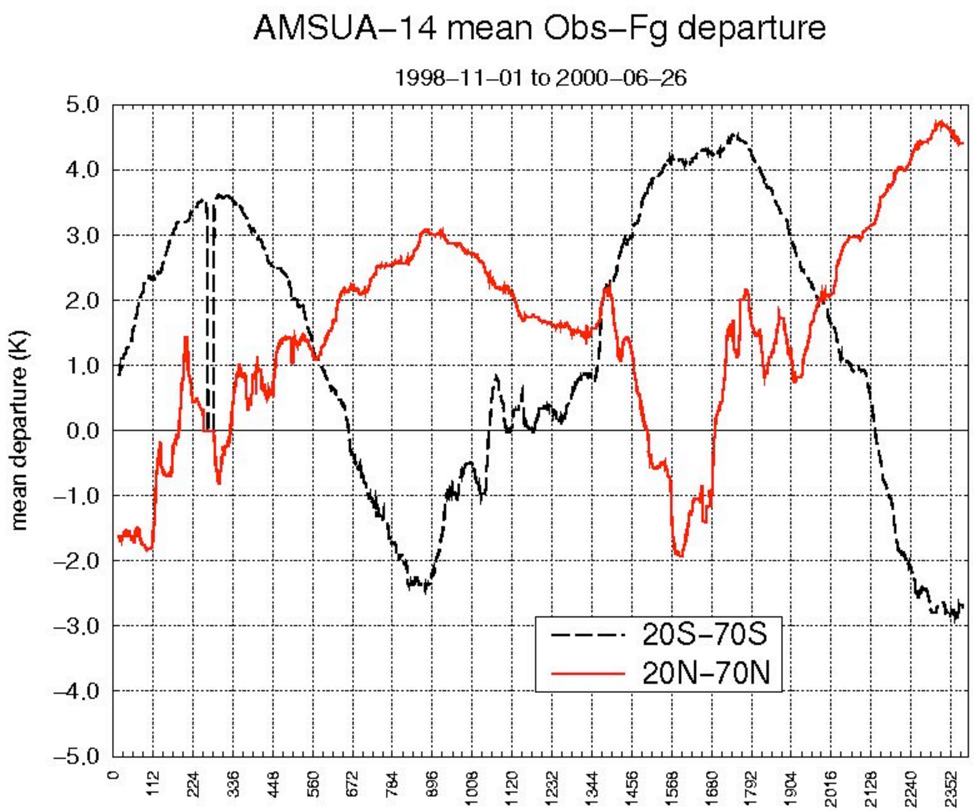
HIRS channel 5 (peaking around 600hPa on NOAA-16 satellite has no radiance bias against model.

DIAGNOSING THE SOURCE OF A BIAS …

… but what if the NWP model is wrong ?

This time series shows an **apparent time-varying bias** in AMSU channel14 (peaking at 1hPa).

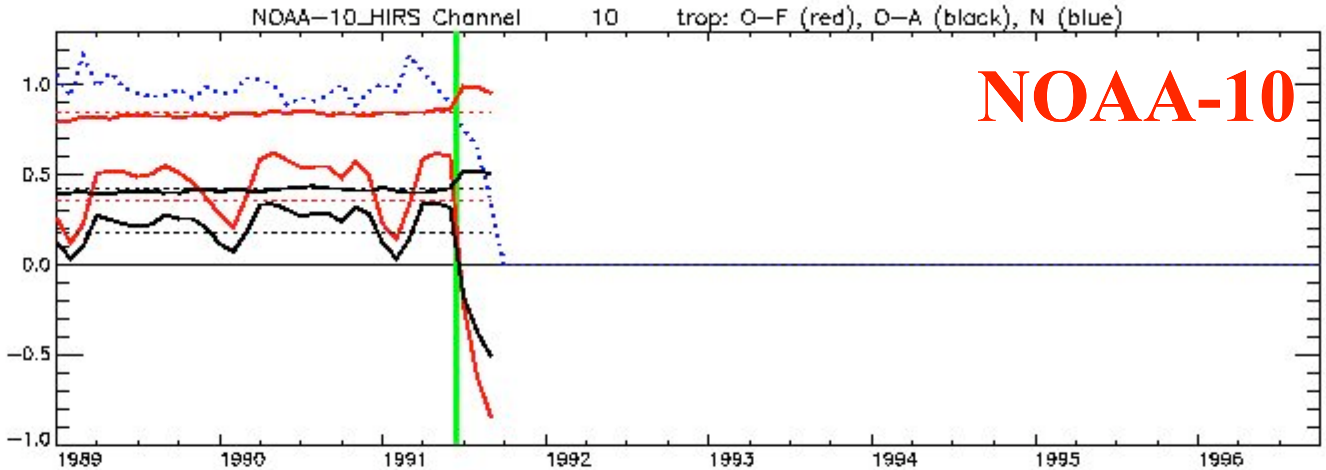
By checking against other research data (HALOE and LIDAR data) the bias was confirmed as a **NWP model temperature bias** and the channel was assimilated with **no bias correction**



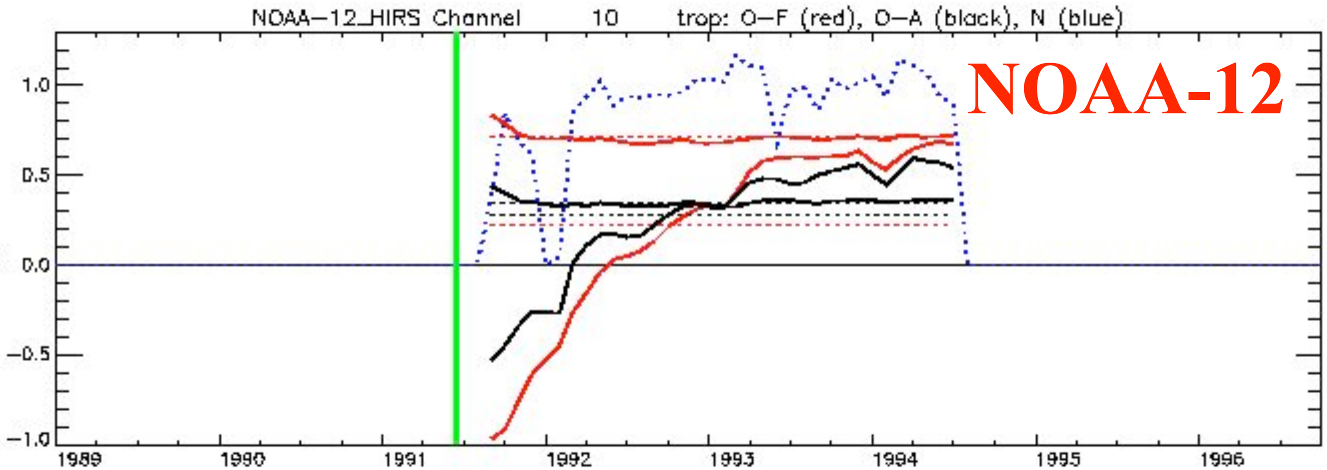
DIAGNOSING THE SOURCE OF A BIAS ...

… but what if the atmosphere is wrong … ?

The eruption of Mt Pinatubo caused huge amounts of aerosol to contaminate satellite data from NOAA-10 and render the bias corrections wrong.

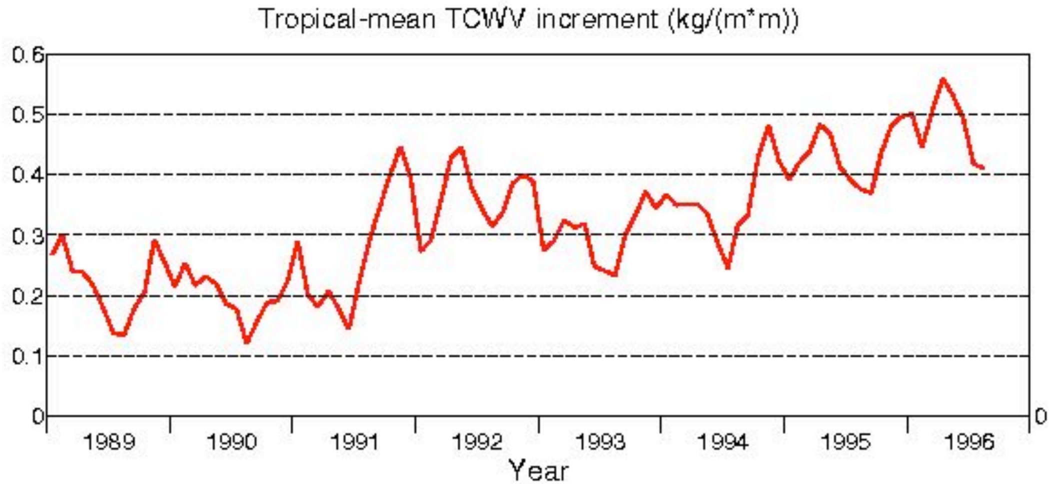


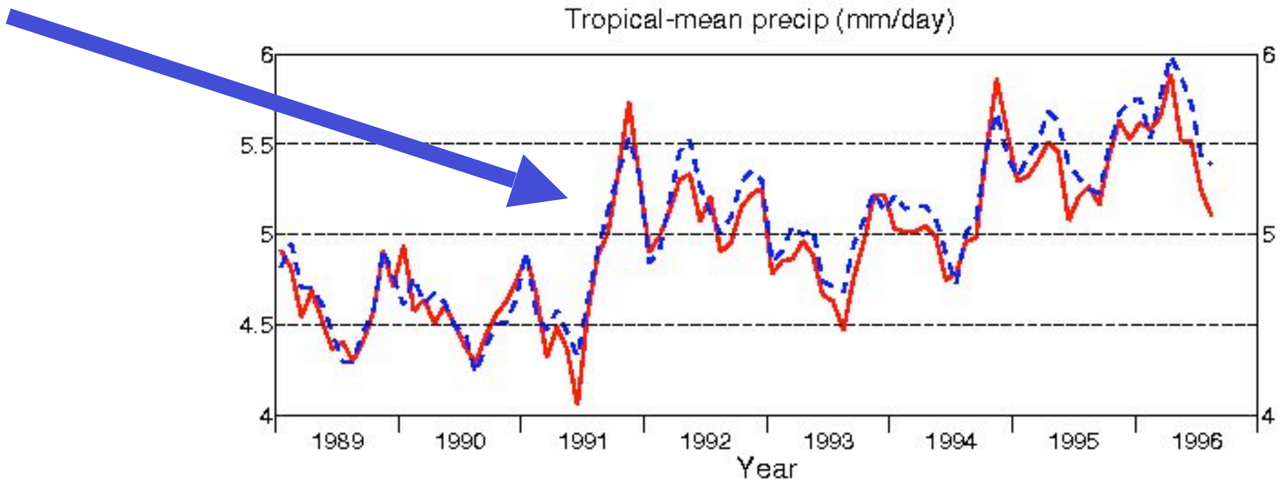
The bias corrections for the newly launched NOAA-12 were established during this period, but were wrong when the aerosol went away.



THE GLOBAL IMPACT OF BADLY HANDLED SATELLITE BIASES

The Pinatubo induced systematic cooling of HIRS channel-11 (8micron) caused an erroneous moistening of the analysis, persisted by the coincident introduction of NOAA-12 data …





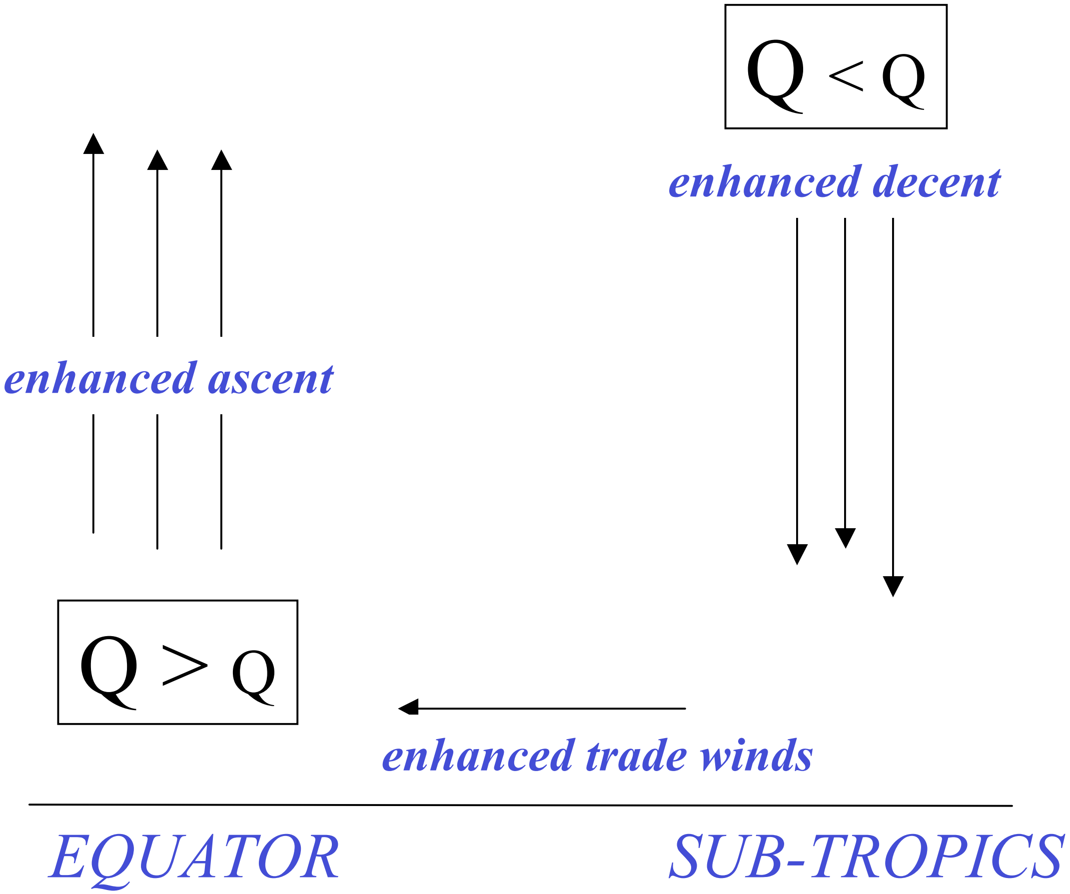
Wind adjustments from radiance observations

WIND ADJUSTMENTS WITH RADIANCE DATA

The assimilation of radiance data can influence (either directly or indirectly) the **wind** field in a number of ways:

1. directly through time analysis of **cloud imagery** (SATOBS etc..)
2. directly via **surface emissivity** changes (SCAT/SSMI...)
3. indirectly through **model physics** (initiating convection/subsidence)
4. indirectly through **passive tracing** (unique to 4DVAR)

INDIRECT FORCING OF THE WIND FIELD THROUGH MODEL PHYSICS



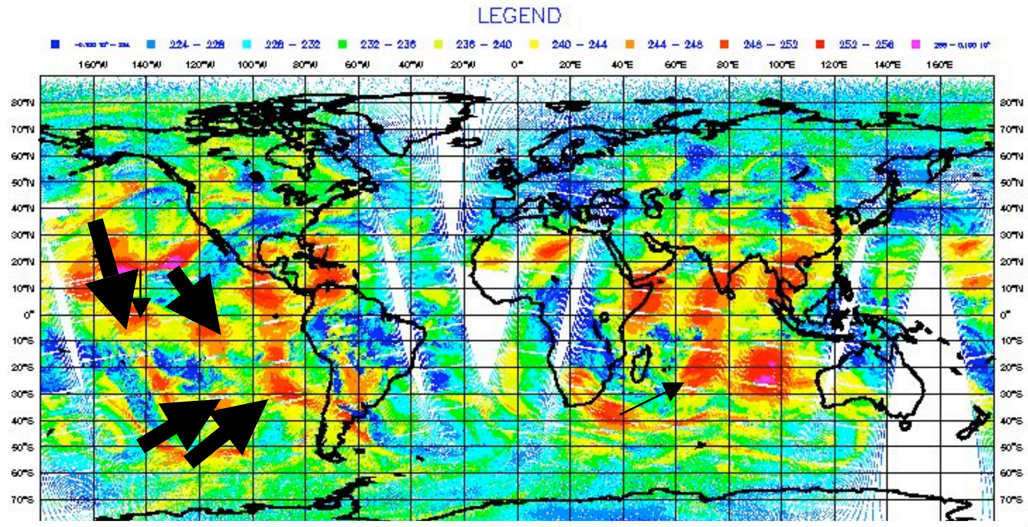
By adding humidity to the lower troposphere or removing humidity from the upper troposphere the satellite radiance information can **cause large scale wind / circulation adjustments**

..e.g. change the Hadley Circulation !!

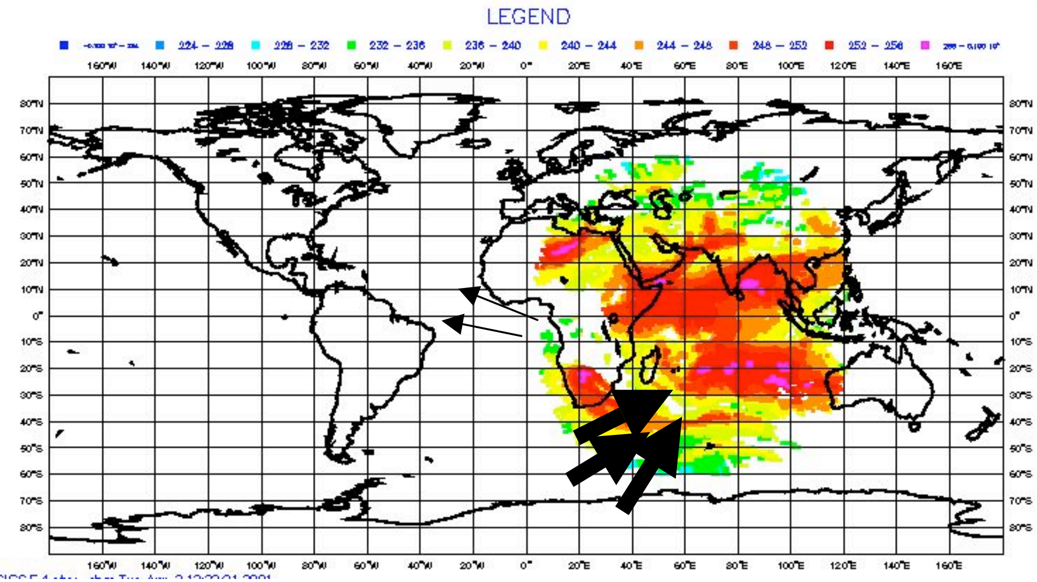
(see McNally+Vesperini 1994)

INDIRECT WIND FORCING BY PASSIVE TRACING

To fit the time and spatial evolution of humidity or ozone signals in the radiance data, the 4DVAR has the choice of creating constituents locally or **advecting** constituents from other areas. The latter is achieved with **wind adjustments**.



This is particularly true for high temporal density water vapour and ozone radiance information from GEO satellites



Summary

The assimilation of satellite radiance observations has a very powerful impact upon NWP data assimilation schemes, but…

We must pay careful attention to …

- **BACKGROUND ERROR STRUCTURES**
(what are they and are they correctly specified)

- **AMBIGUITY BETWEEN VARIABLES**
(both atmospheric and surface / cloud contamination)

- **SYSTEMATIC ERRORS**
(what are they and are they correctly specified)

- **WIND ADJUSTMENTS FROM RADIANCES**
(both direct and indirect wind adjustments)

End

Questions ?