Satellite data assimilation for Numerical Weather Prediction II

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Outline

1. Review of concepts from previous lecture
2. Background errors and vertical resolution
3. Systematic biases and bias correction
4. Ambiguity in radiance observations
5. Current research topics:
   1. Assimilation of data affected by clouds and precipitation
   2. Surface-sensitive channels over land/sea-ice
6. Summary

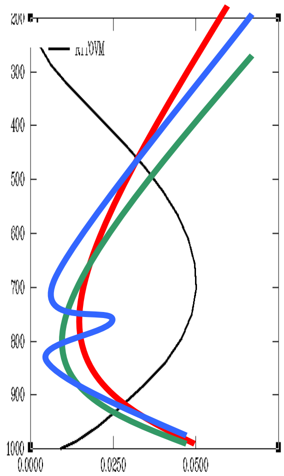
Review of some key concepts

- **Satellite data are extremely important in NWP.**
- **Data assimilation combines observations and a priori information in an optimal way and is analogous to the retrieval inverse problem.**
- **Passive nadir sounders have the largest impact on NWP forecast skill:**
  - Nadir sounders measure radiance (not T,Q or wind).
  - Sounding radiances are broad vertical averages of the temperature profile (defined by the weighting functions).
  - The retrieval of atmospheric temperature from the radiances is ill-posed and all retrieval algorithms use some sort of prior information.
  - Most NWP centres assimilate raw radiances directly due to their simpler error characteristics. 4DVAR is now widely used.

2.) Background errors and vertical resolution

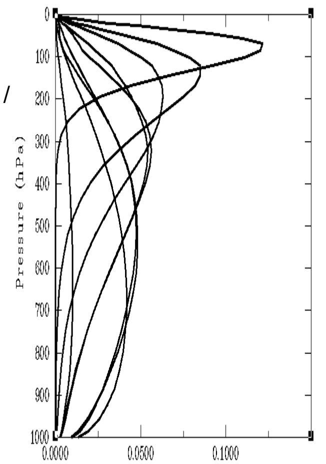
Lecture 1: Satellite radiances have limited vertical resolution

Single channel



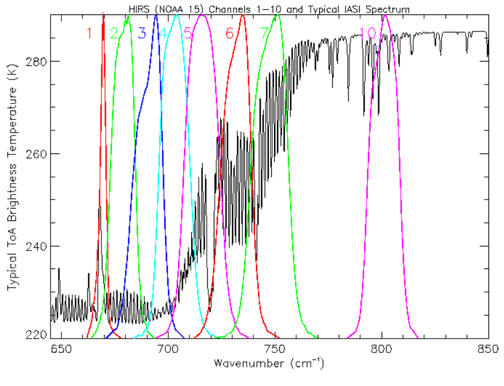
Selecting radiation in a number of frequencies / channels improves vertical sampling and resolution

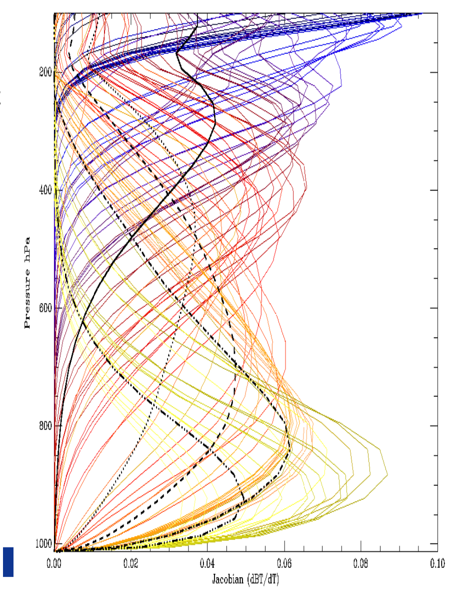
Several channels (e.g. AMSUA)



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

These instruments sample the spectrum extremely finely and thus generate many thousands of channels peaking at different altitudes.
However, vertical resolution still limited by the physics.





Satellite radiances "seeing" and "correcting" background errors

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

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

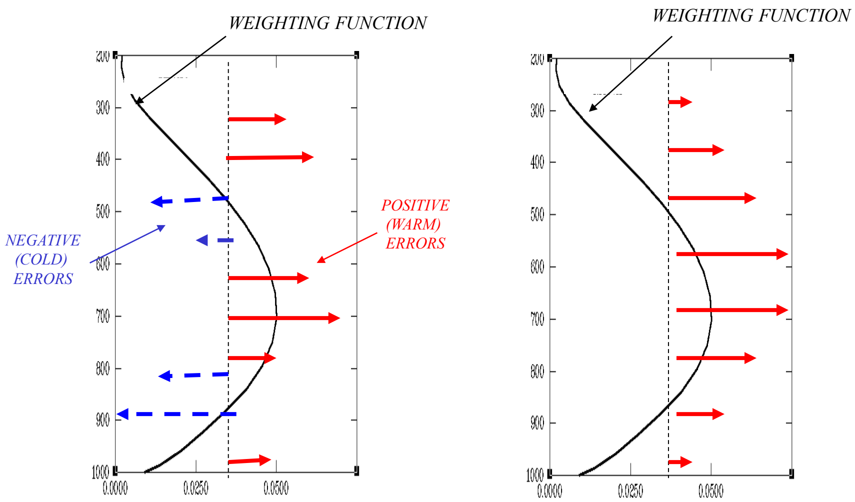
We can think of the adjustment process as radiances observations **correcting errors in the forecast background** to produce an analysis that is closer to the true atmospheric state. For example in the simple linear case...

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

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**).

Correcting errors in the background

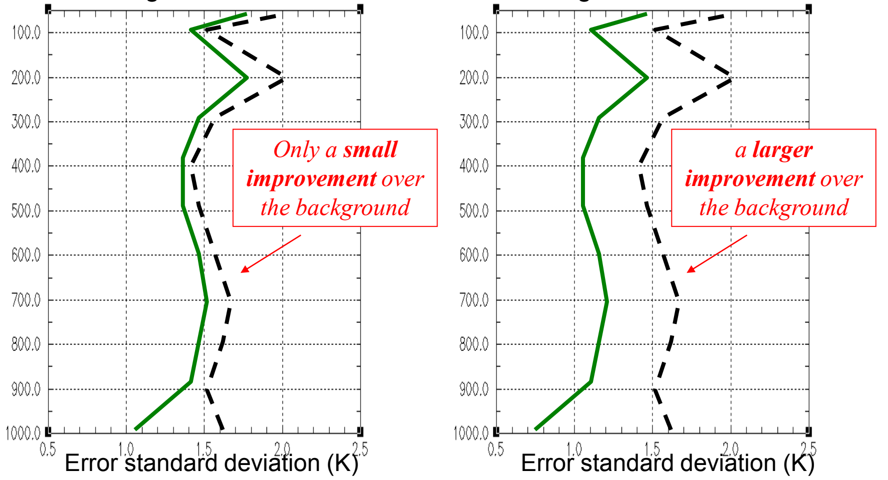


"Difficult" to correct *"Easy"* to correct

Analysis performance for different background errors

Sharp / anti-correlated background errors

Broad / deep correlated background error



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 an analysis with **larger errors than the background state** !

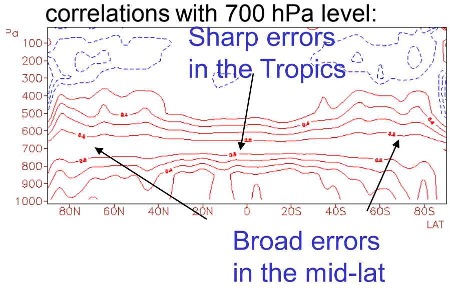
Thus accurate estimation of **B** is crucial:

- Comparison with **radiosondes** (best estimate of truth but limited coverage)

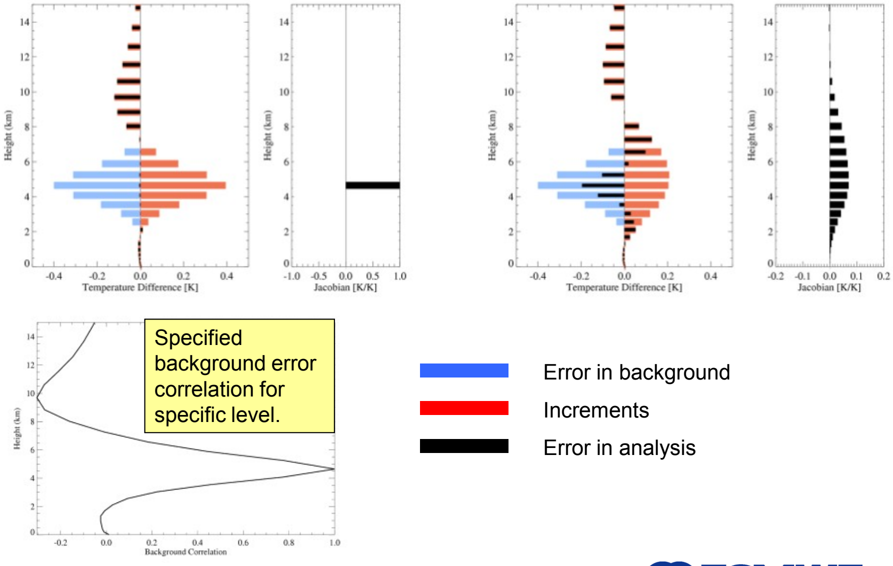
- Comparison of e.g. 48hr and 24hr forecasts (so called ***NMC method***)

- Comparison of **ensembles** of analyses made using perturbed observations

Temperature background error correlations with 700 hPa level:



Example of background constraint



3.) Systematic errors and bias correction

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!).

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

Observed radiance — RT model — Background atmospheric state

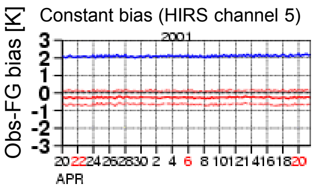
Sources of systematic error in radiance assimilation include:

- 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

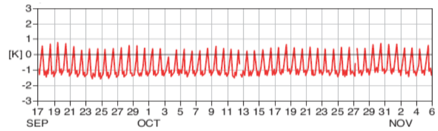
What kind of biases do we see? (I)

Biases are obtained from long-term monitoring of observation minus background.

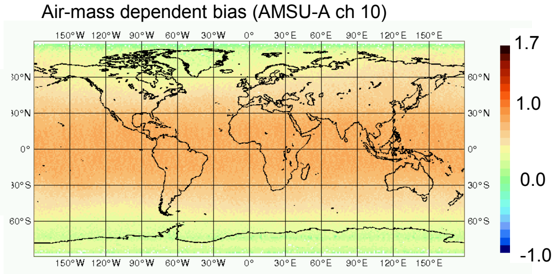
Constant bias (HIRS channel 5)



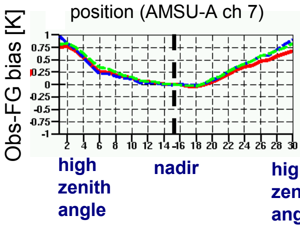
Diurnal bias variation in a geostationary satellite



Air-mass dependent bias (AMSU-A ch 10)

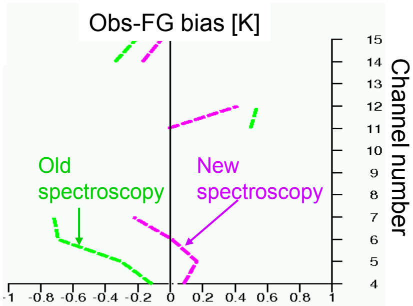


Bias depending on scan position (AMSU-A ch 7)



What kind of biases do we see? (II)

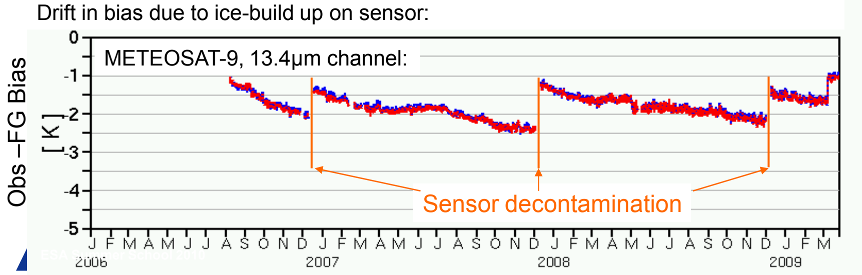
Different bias for HIRS due to different spectroscopy in the radiative transfer model:



Other common causes for biases in radiative transfer:

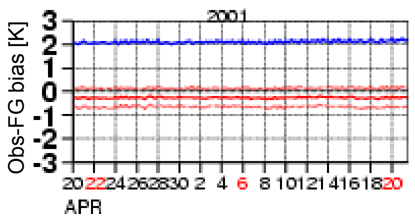
- Bias in assumed concentrations of atmospheric gases (e.g., CO_2)
- Neglected effects (e.g., clouds)
- Incorrect spectral response function
- ….

Drift in bias due to ice-build up on sensor:

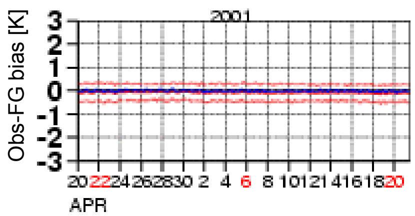


Diagnosing the source of bias (I)

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



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



Same channel on NOAA-16 satellite has no radiance bias against FG.

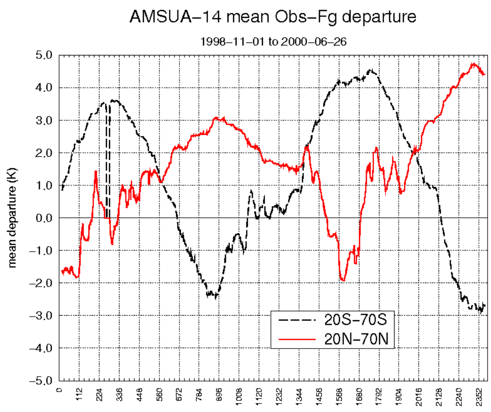
→ **NOAA-14 channel 5 has an instrument bias.**

Diagnosing the source of bias (II)

What about biases in the forecast model?

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

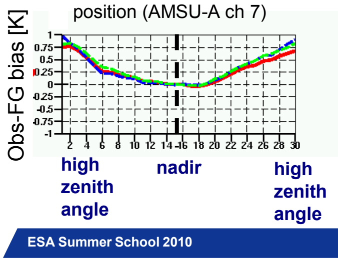
By checking against other research data (HALOE and LIDAR data) the bias was confirmed as an **NWP model temperature bias** and the channel was assimilated with **no bias correction**



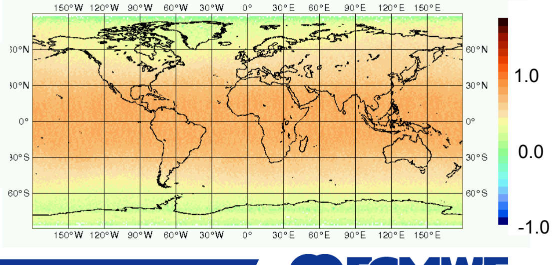
Bias correction

- Biases need to be corrected before or during the assimilation.
- Usually based on a “model” for the bias, depending on a few parameters.
  - ➢ Ideally, the bias model “corrects only what we want to correct”.
  - ➢ If possible, the bias model is guided by the physical origins of the bias.
  - ➢ Usually, bias models are derived empirically from observation monitoring.
- Bias parameters can be estimated offline or as part of the assimilation (“variational bias correction”)

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

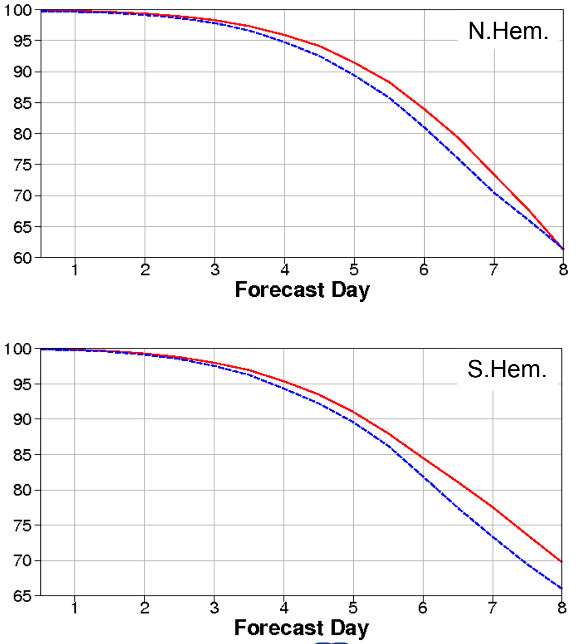


Air-mass dependent bias (AMSU-A ch 10)



Importance of bias correction

Forecast impact comparing
operational bias correction
vs
bias correction with static global constant only



4.) 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) 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)

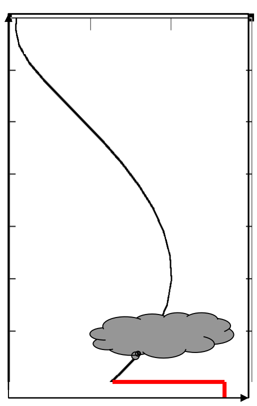
Ambiguity with surface and clouds

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).

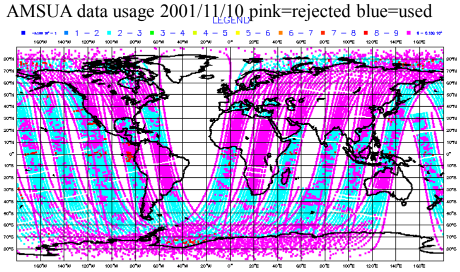


K(*z*)

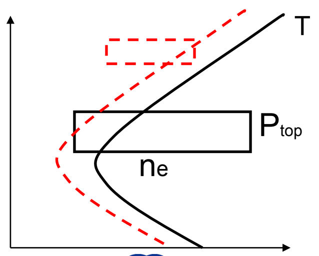
Options for using lower-tropospheric sounding channels

• 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). But meteorologically important areas are often cloudy!

AMSUA data usage 2001/11/10 pink=rejected blue=used



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



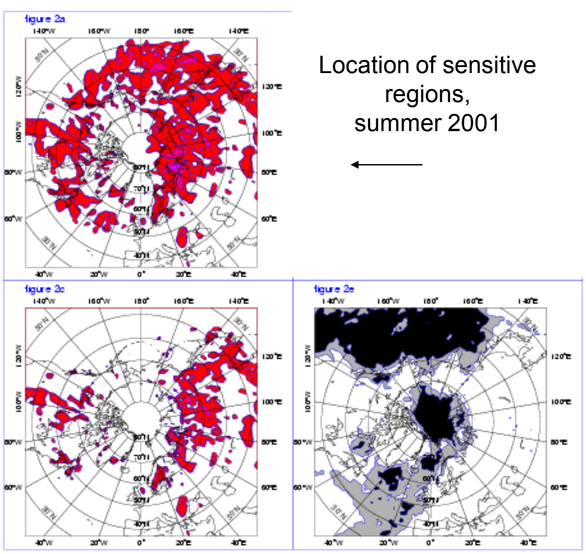
5.) Some current research topics

Assimilation of cloud/rain affected radiances

Assimilation of cloud/rain-affected radiances

- **Currently, more than 90 % of the radiances assimilated at ECMWF are from clear-sky regions.**
  - **A lot of radiances are thrown out just because they observe clouds or rain.**
- **But meteorologically sensitive regions are often cloudy…**

Importance of cloud observations



Location of sensitive regions, summer 2001

Sensitivity surviving low cloud cover

Monthly mean low cloud cover

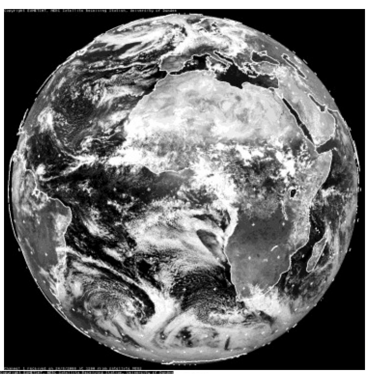
Potential issues for cloud/rain

- 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. $H = H_x$), esp. in infrared.
- 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.

Visible

SEVIRI channel 1

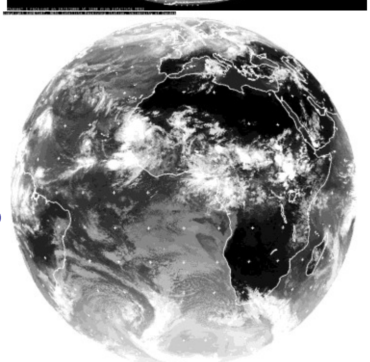
0.56-0.71 µm



Infrared

SEVIRI channel 10

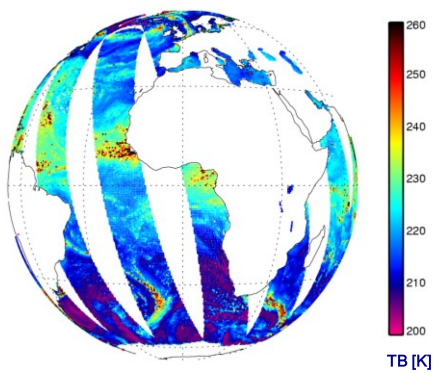
11-13 µm



Microwave

AMSR-E channel 37v

8108 µm (37 GHz v-pol)



24th August 2008

around 12UTC

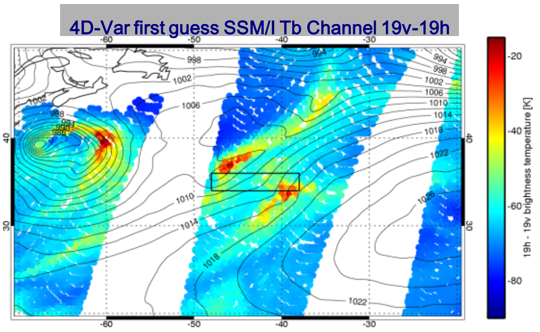
Two current approaches to assimilation of cloudy/rainy radiances

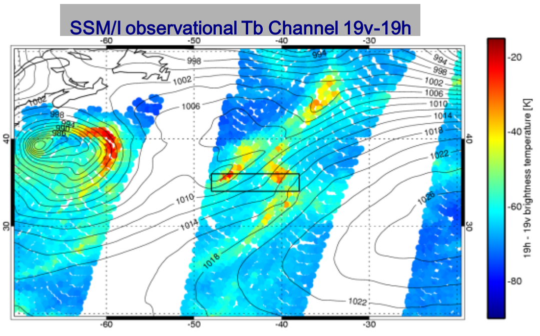
Microwave:

- "Allsky" system
- Use radiative transfer that includes effects of cloud/rain
- Use observations in all conditions
- Include fields for cloud/rain from model physics
- Operational for SSMI, AMSRE (imagers with MW window channels)

Infrared:

- Restriction to overcast data
- Estimate basic cloud parameters (cloud top pressure, cloud fraction) from observations, and use in radiative transfer
- Use data for totally overcast scenes only
- No feedback on model cloud fields
- Operational for IR sounding instruments



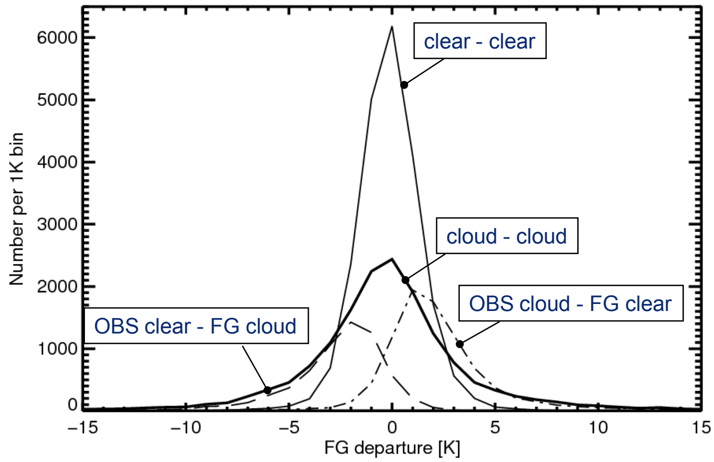


Does the NWP model provide good information on cloud/rain?

First guess

versus SSM/I observations

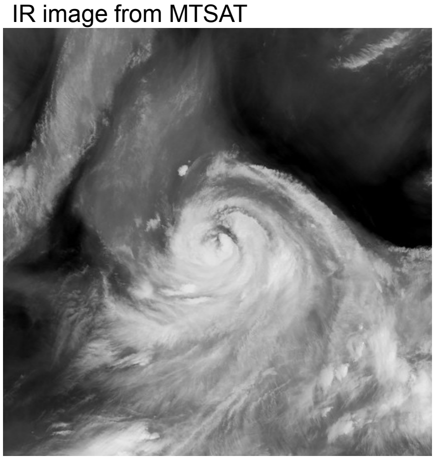
Why all-sky?



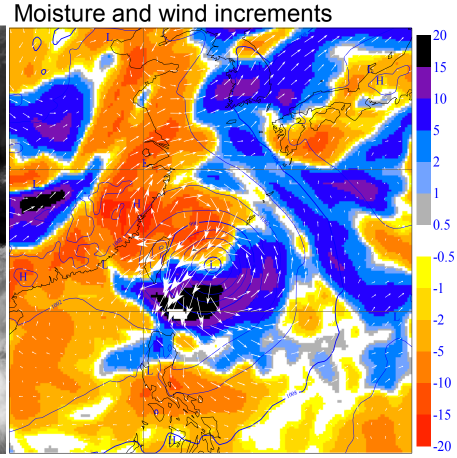
Impact of rain-affected microwave radiances in severe weather

Typhoon Matsa (04/08/2005 00 UTC)

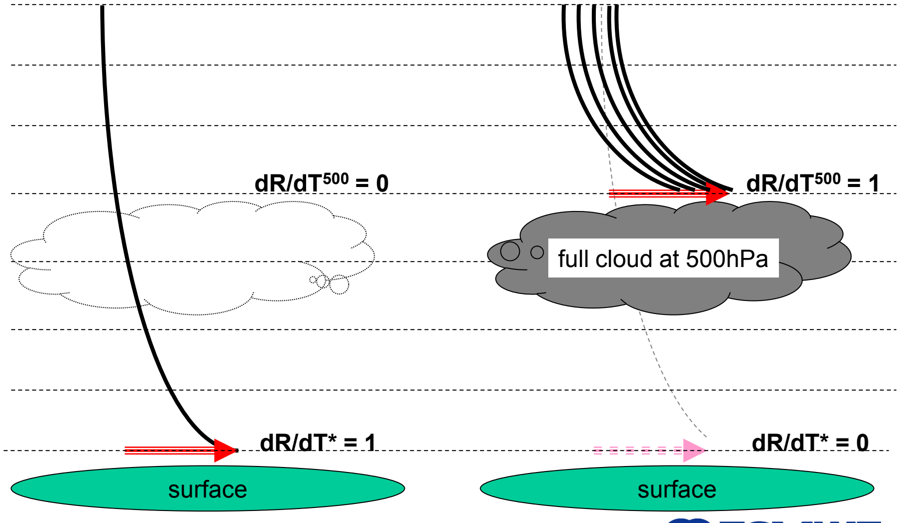
IR image from MTSAT



Moisture and wind increments



Enhanced temperature estimation at cloud top for IR



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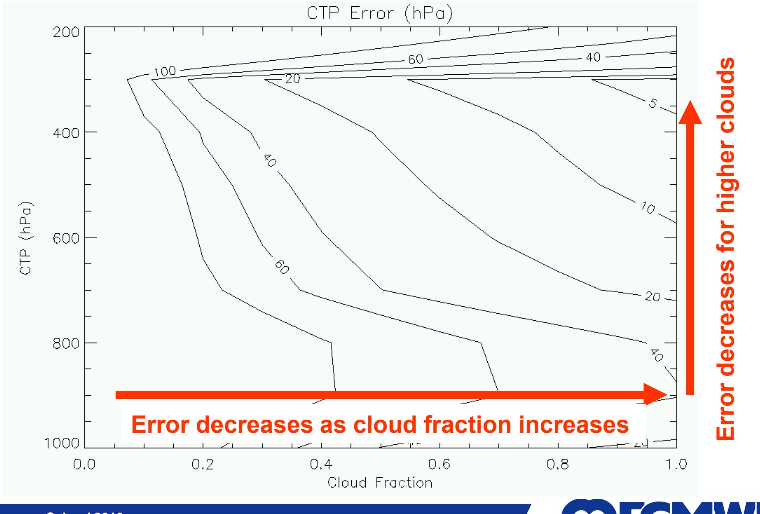
Estimation of cloud top pressure with IR data



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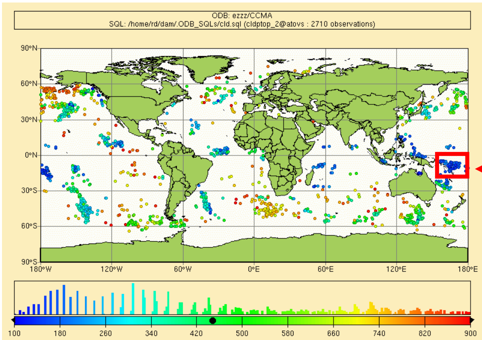
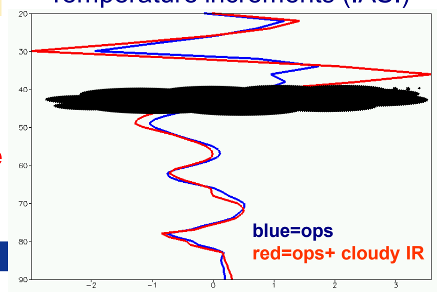
Temperature increments at the cloud top



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

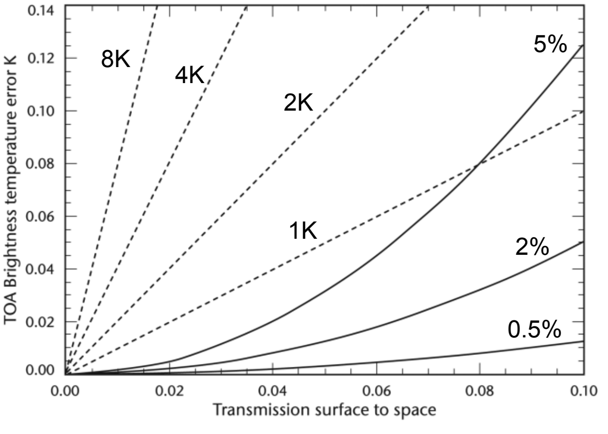
5.) Some current research topics

Assimilation of surface-sensitive channels over land

Assimilation of surface-sensitive channels over land

- **For surface-sensitive channels, assimilation is most mature for data over sea.**
  - Advantages:
    - Surface emission relatively well known, as errors in sea-surface temperatures and emissivity relatively small (~0.5 K, 1 %).
    - For the microwave, sea surface emissivity is relatively low (0.5-0.6)
  - Also, few conventional observation are available over sea!
- **Use of surface-sensitive channels over land or sea-ice more difficult:**
  - Errors in land surface temperature relatively larger (~5-10 K)
  - Surface emissivity less well known.
  - Cloud-screening more difficult.

Influence of emissivity and skin temperature error



Solid: influence of emissivity error
Dashed: influence of skin temperature error

Approaches to use surface-sensitive channels over land/sea-ice

- **Use window channels to constrain surface emissivity and/or skin temperature.**
  - **Use previously derived emissivity atlas.**
  - **Retrieve surface emissivity or skin temperature prior to main assimilation.**
  - **Retrieve surface emissivity or skin temperature within the main analysis.**

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?)

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

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