The assimilation of cloud affected IR radiances

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ECMWF

Outline of talk…

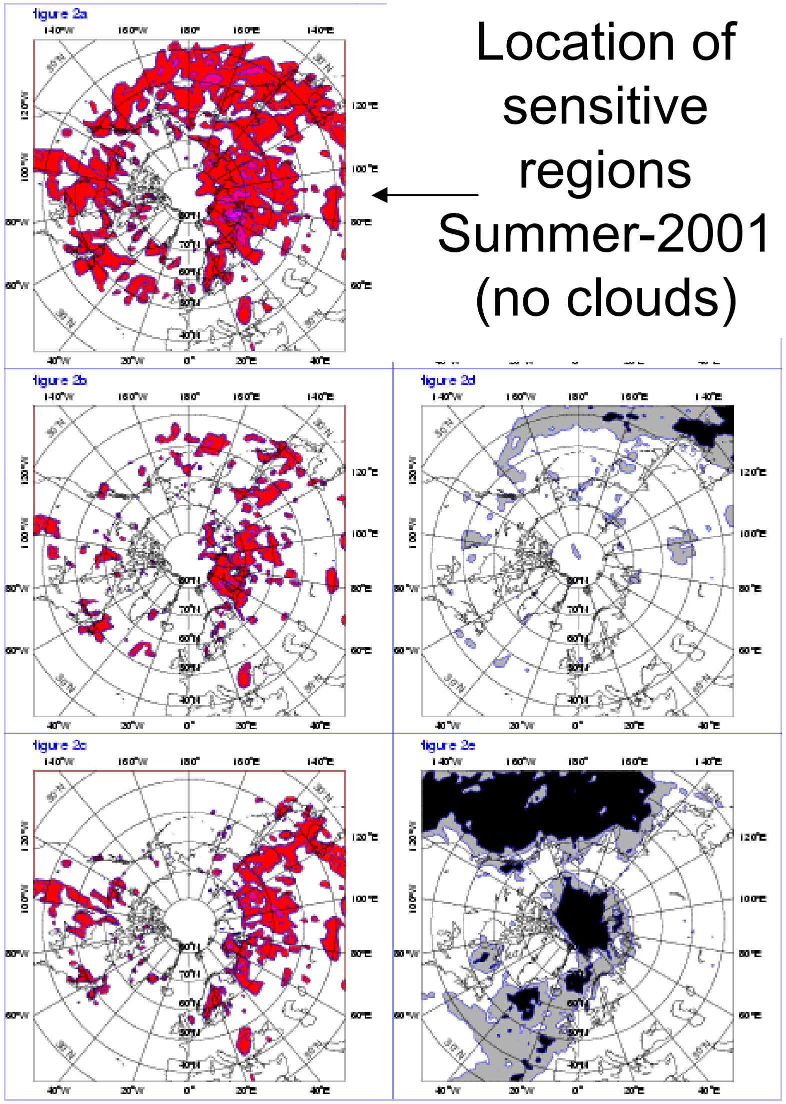
- Issues related to the assimilation of cloudy data
- The scheme developed at ECMWF
- Performance of the cloudy scheme
- Summary and view to the future

Why do we want to use cloud affected data ?

1. Only using clear-sky data represents a major under-use of high cost instruments such as AIRS and IASI

2. It is important to constrain analysis errors in cloudy regions as they are believed to be meteorologically sensitive

Sensitive areas and cloud cover



Location of sensitive regions Summer-2001 (no clouds)

sensitivity surviving **high** cloud cover

monthly mean **high** cloud cover

sensitivity surviving **low** cloud cover

monthly mean **low** cloud cover

From *McNally (2002) QJRMS* ***128***

Two potential approaches to handle clouds

1. Use cloud affected radiance observations that have been pre-corrected to remove the cloud signal (i.e. *cloud cleared data*)

2. Extend the NWP analysis to estimate cloud parameters simultaneously with temperature and humidity (*either interacting with model cloud physics or not*)

Two potential approaches to handle clouds

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2. Extend the NWP analysis to estimate cloud parameters simultaneously with temperature and humidity (*either interacting with model cloud physics or not*)

Fundamental issues

- The cloud uncertainty in radiance terms 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 too large to provide an accurate linearization point and very difficult to model
- Trade off 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

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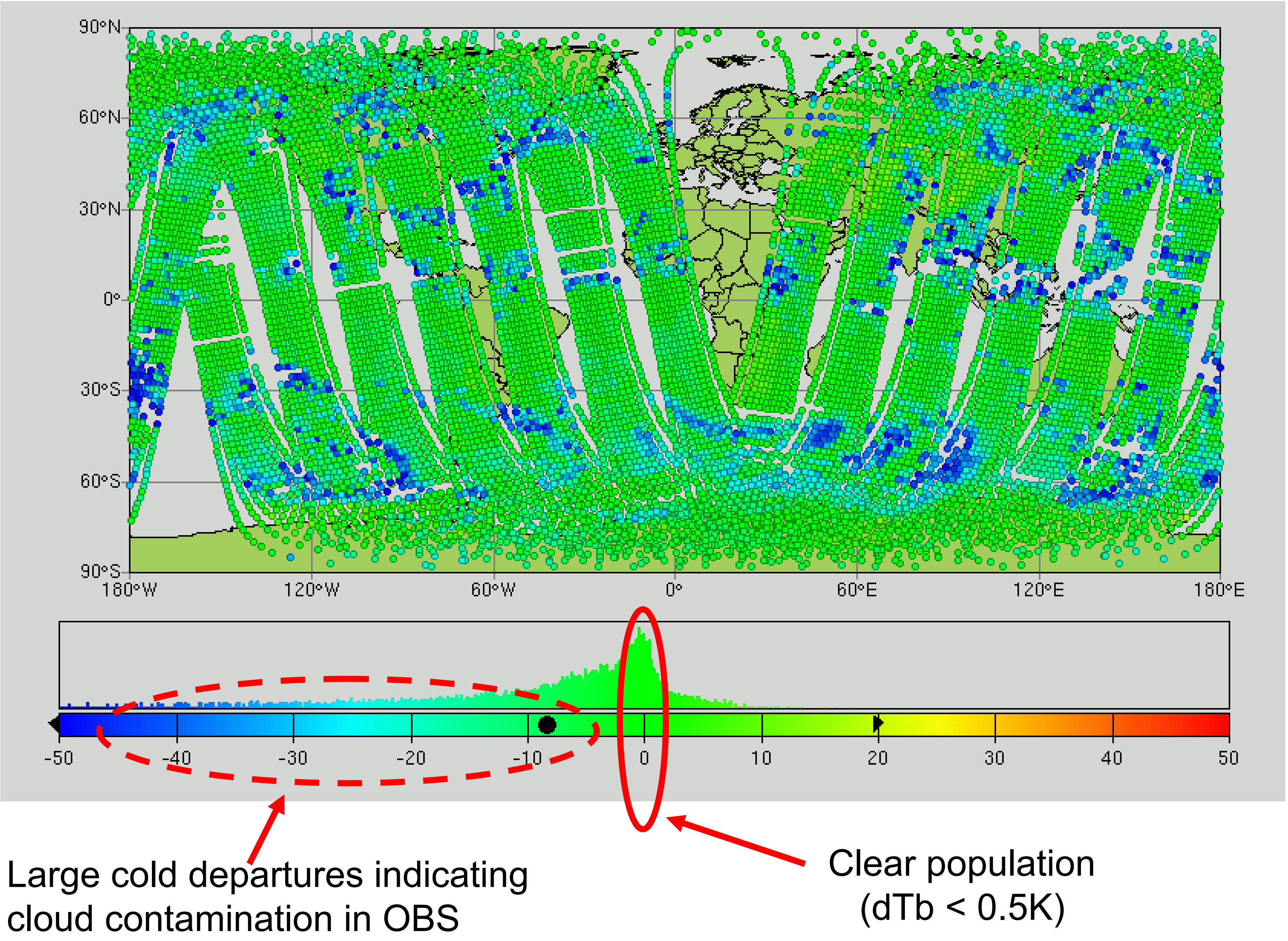
Observed radiance at 11 microns minus radiance calculated in clear sky



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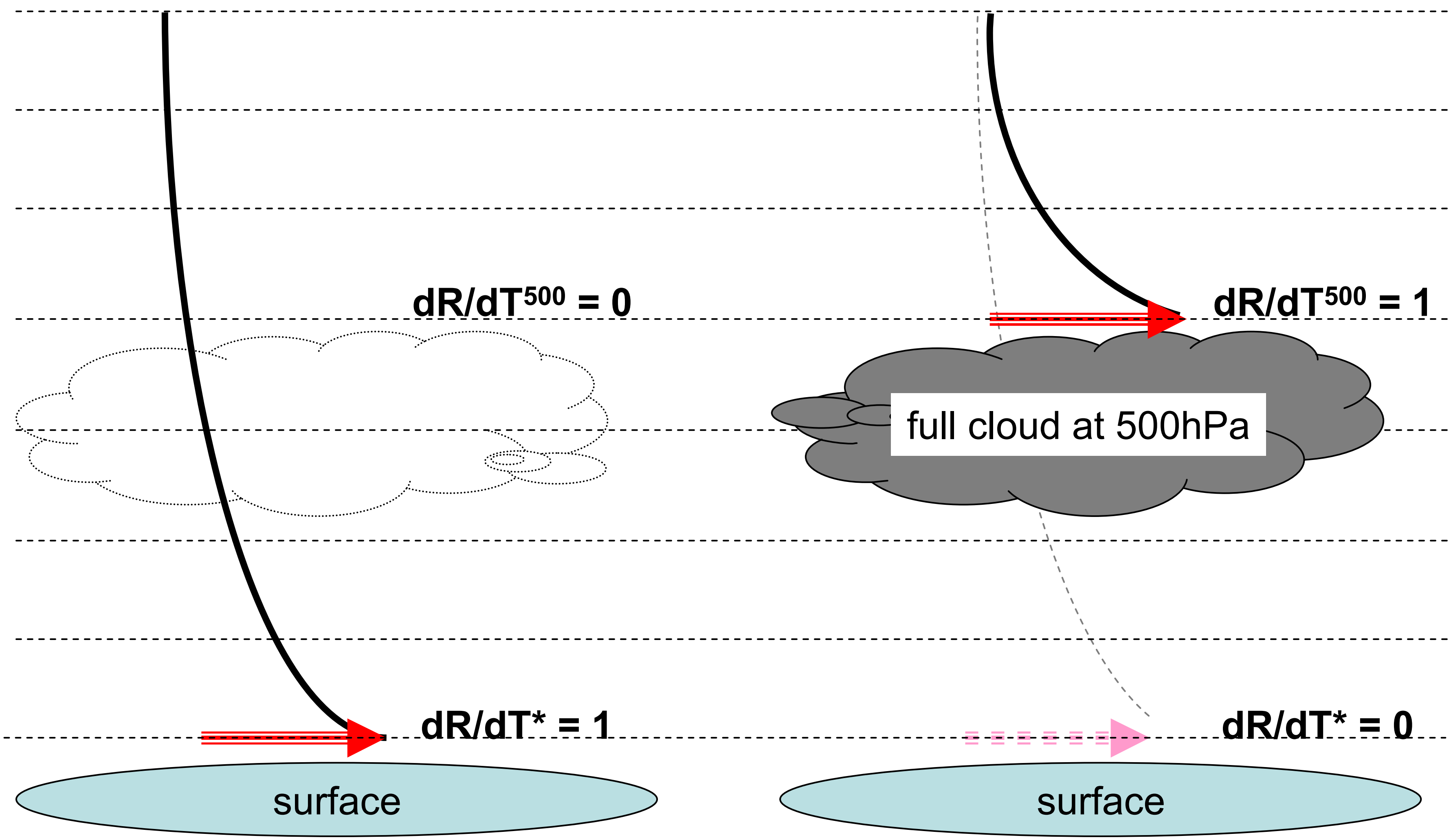
Clear and Cloudy Jacobians



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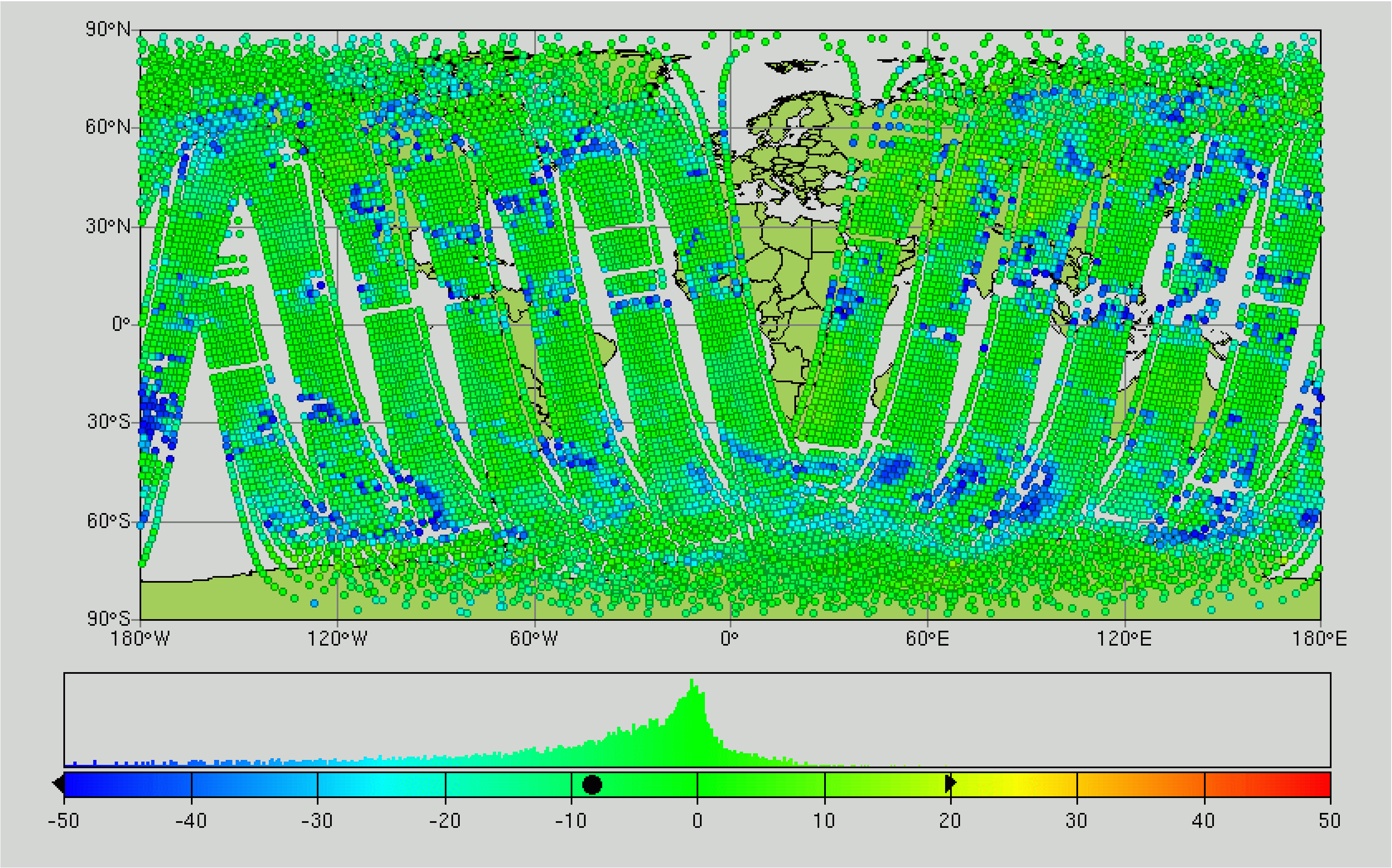
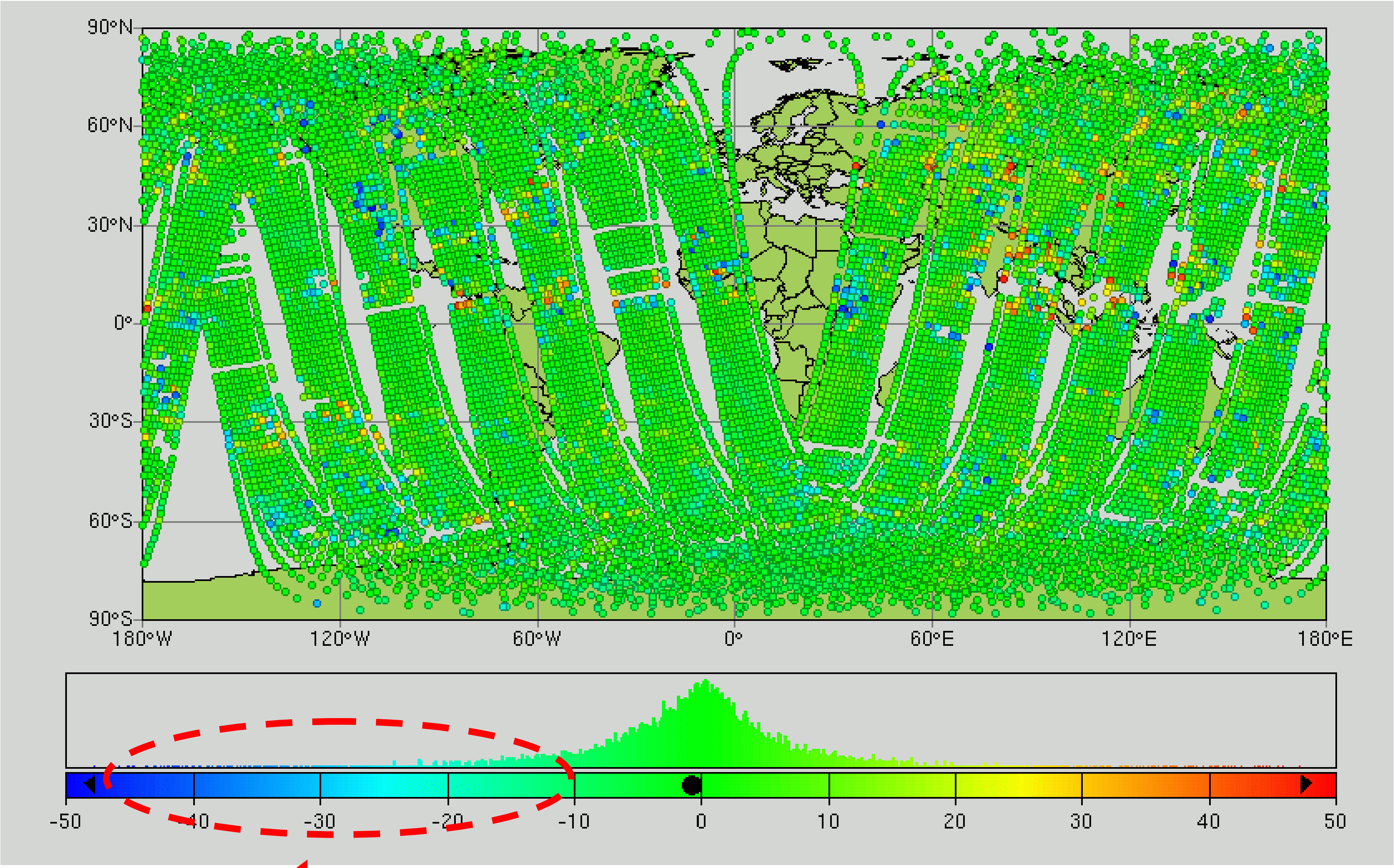


Observed radiance at 11 microns minus radiance calculated from NWP cloud background profile



Many clouds with significant radiance signals are accurately represented by the NWP model and RT modelled !

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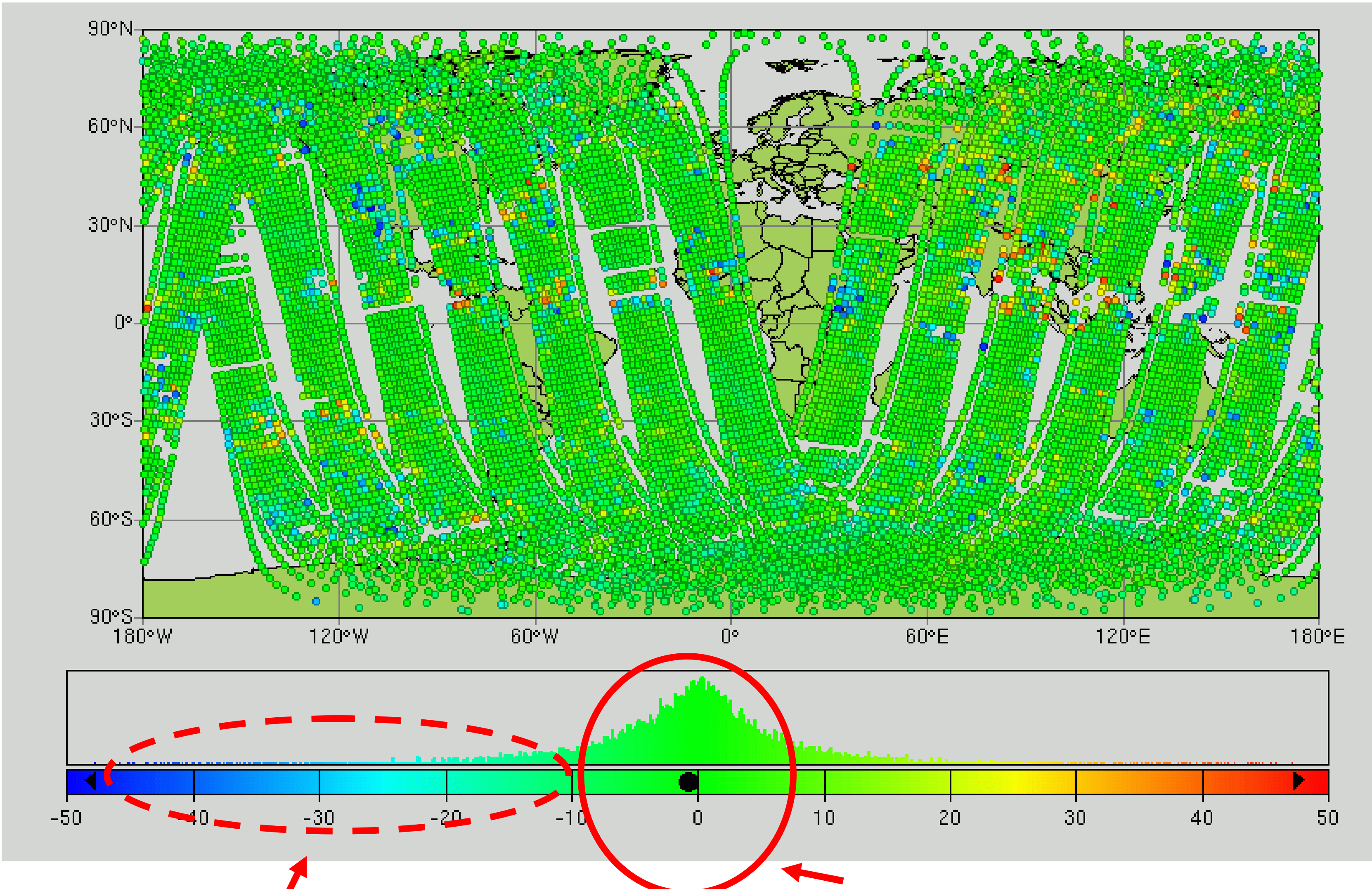

Many clouds with significant radiance signals are accurately represented by the NWP model and RT modelled !

…but the spread is still very large!

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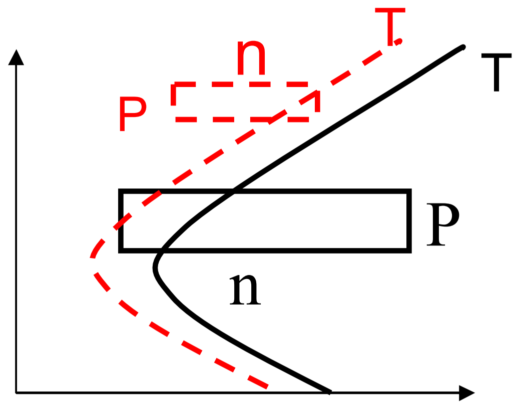
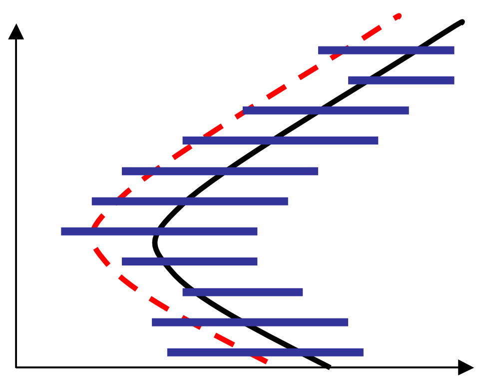
Complexity of cloud description and ambiguity with T and Q

A very simple cloud model (e.g. single layer grey cloud amount and pressure) should more readily estimated from the data (independently of T and Q), but will make the forward RT calculation very inaccurate in many cloud conditions



A more complex cloud model (e.g. cloud liquid and ice at each model level) will allow a more accurate forward RT calculation, but the parameters may be difficult to estimate independently of each other and T and Q and may alias into erroneous increments



Extension of the ECMWF 4D-Var to assimilate cloud affected infrared radiances

Described in McNally 2009 QJRMS

Key features of the cloudy scheme

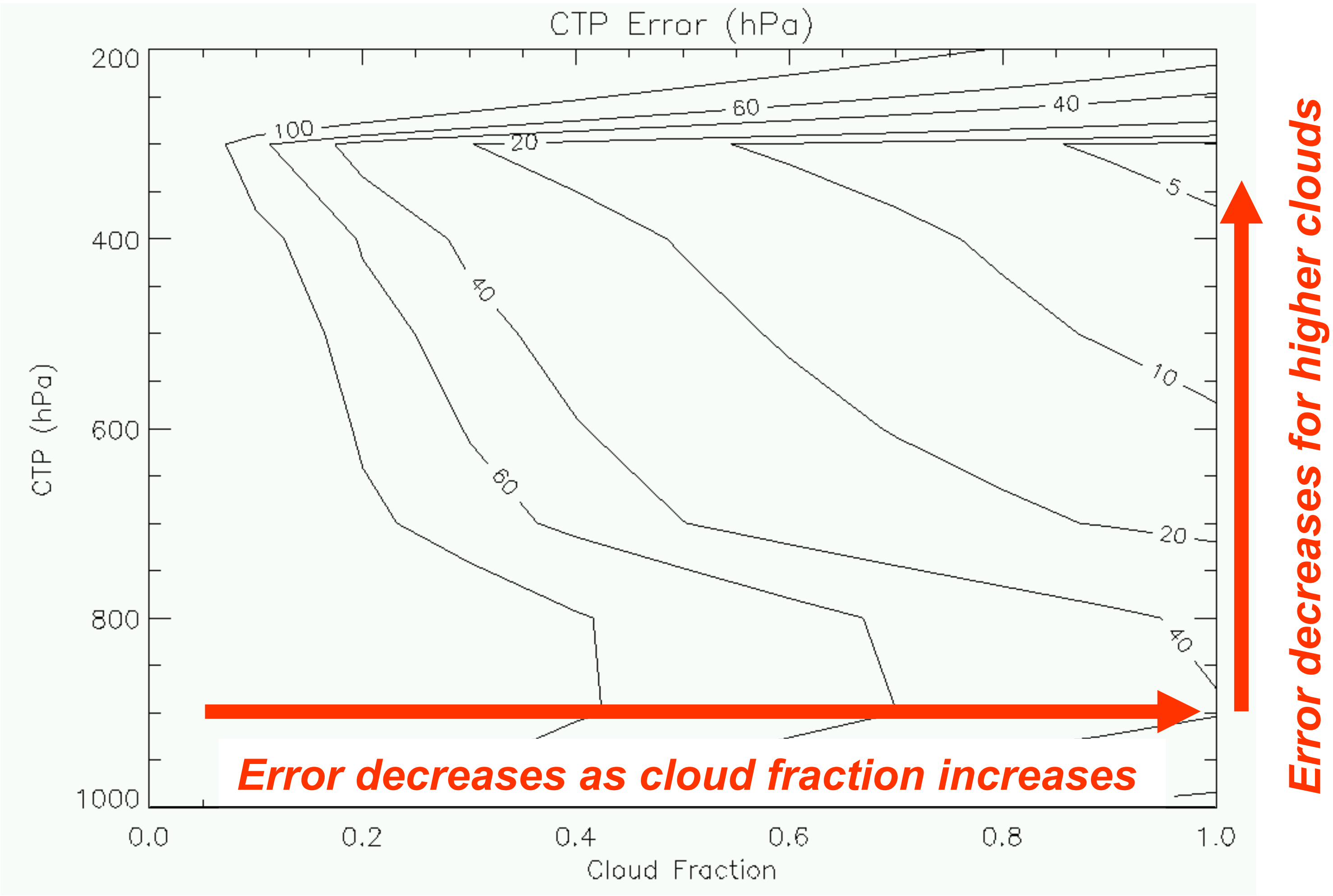
- Only cloudy IR radiances from completely overcast scenes are used
- One additional variable (local) added to 4D-Var control vector (P_{CTOP})
- Background values estimated from the observations (not NWP model)
- QC rejection of marine inversion / physically unreasonable clouds
- All IR sensors treated identically (AIRS / IASI / HIRS)
- Cloud information not fed back to NWP model

Why overcast scenes…?

Why use cloudy radiances only in overcast conditions ?

- Overcast conditions are least ambiguous in the radiance data*
- Cloud control vector collapses to a single number (P_{CTOP})
- Problems with cloud overlap assumptions vanish
- Termination of jacobians at cloud top provides new information*
- We can measure temperature above clouds better than in clear sky
- No cross-talk between cloud and surface skin sink variables

Error in estimation of cloud top pressure



Thanks Andrew…

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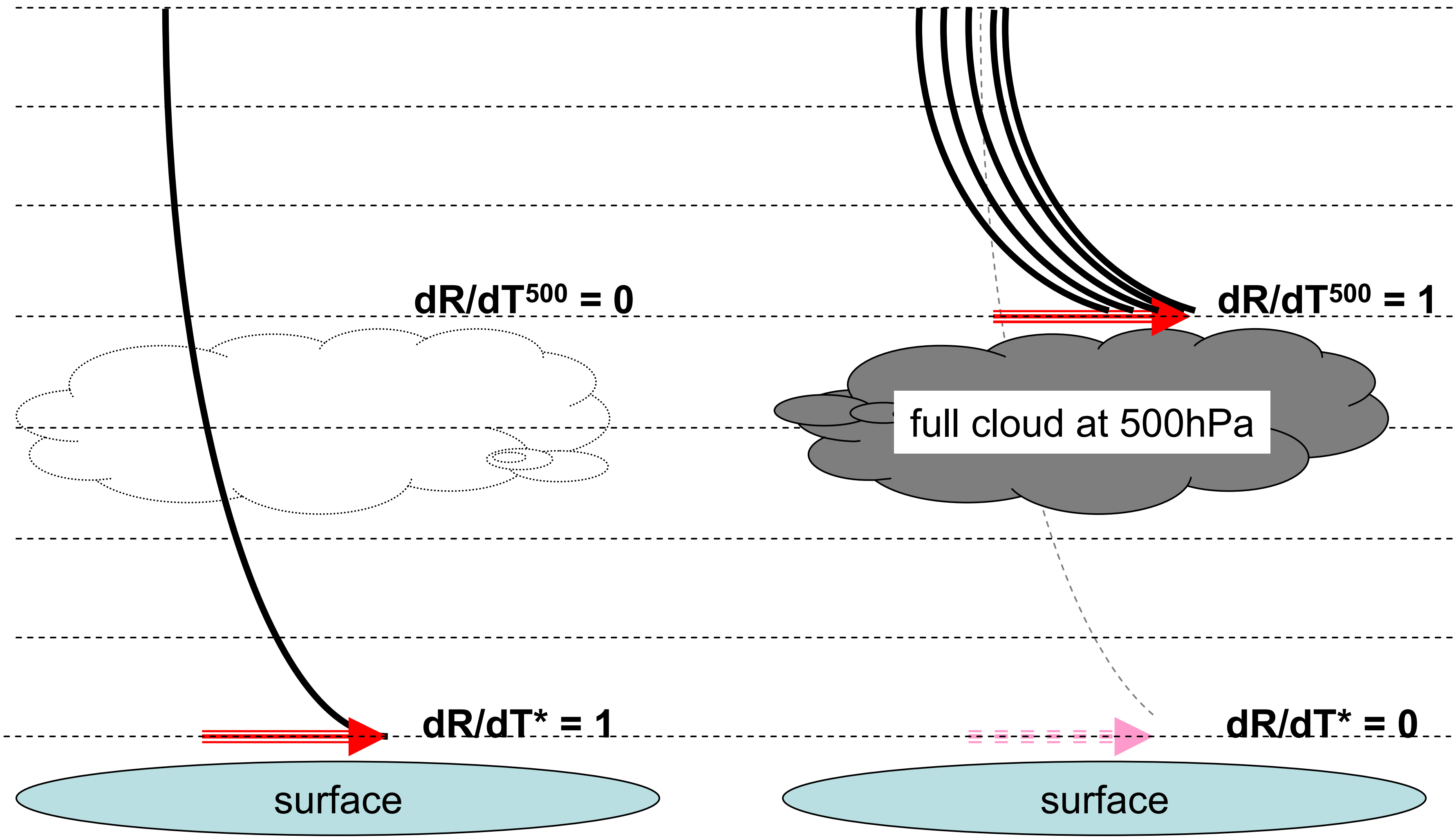
Enhanced temperature estimation at the cloud top



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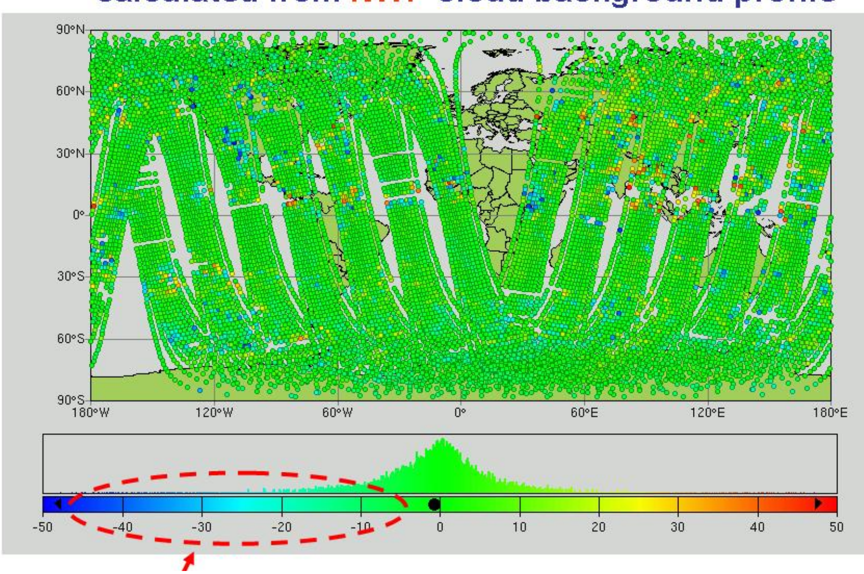
Background cloud parameters…

Why not use the NWP model for background cloud parameters ?

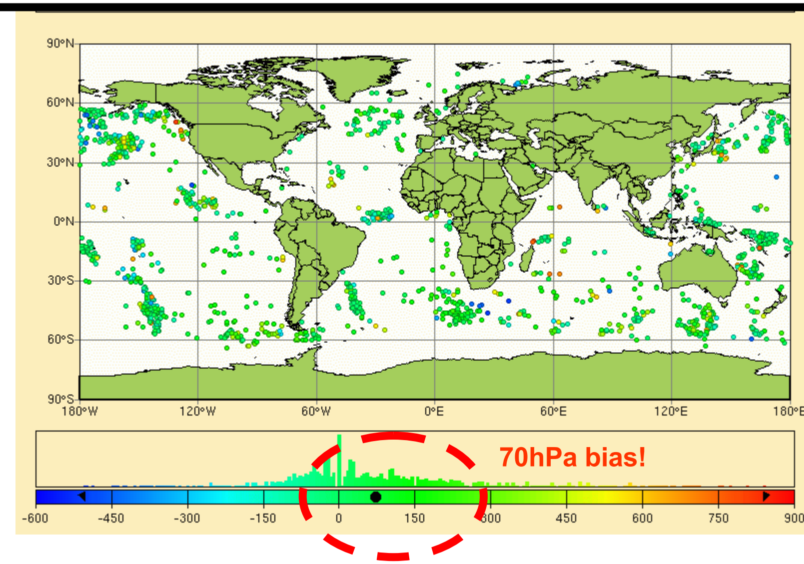
The disagreement between the OBS and the model is not excessive, but still **large enough** to often stretch the TL approximation and limit convergence

There also a difficulty in post- processing the model cloud profile variables to the quantity **representative** of that seen by the radiance observations

Observed radiance at 11 microns minus radiance calculated from **NWP** cloud background profile



CTOP: NWP minus 2D least squares



Background cloud parameters
(2D least squares method)

We find ***N*** (*cloud fraction*) and **P** (*cloud top pressure*) which minimize the squared radiance departures summed over *J* (currently *J*=3) channels:

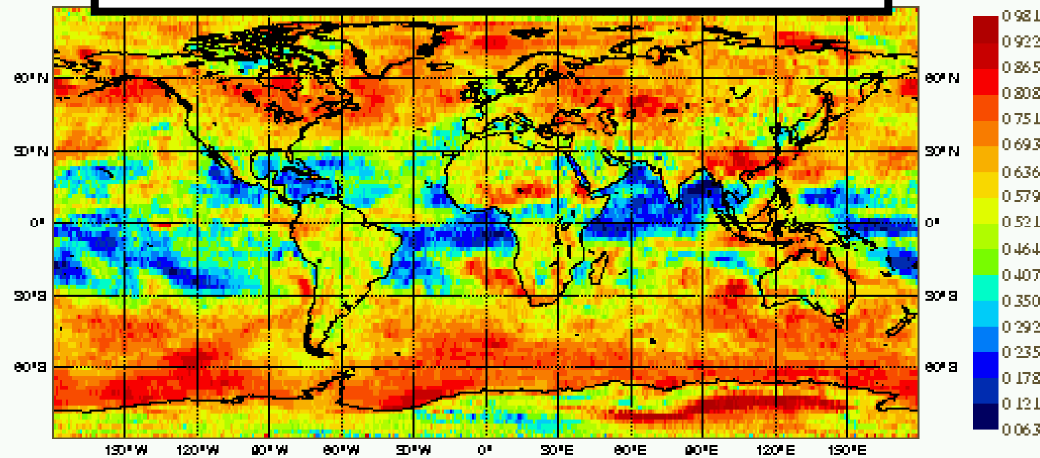
$$\sum_j \delta^2 = \sum_j [(R_j^{obs} - R_j^\circ) - N(R_j^\bullet(p) - R_j^\circ)]^2$$

Analytically solving for N:

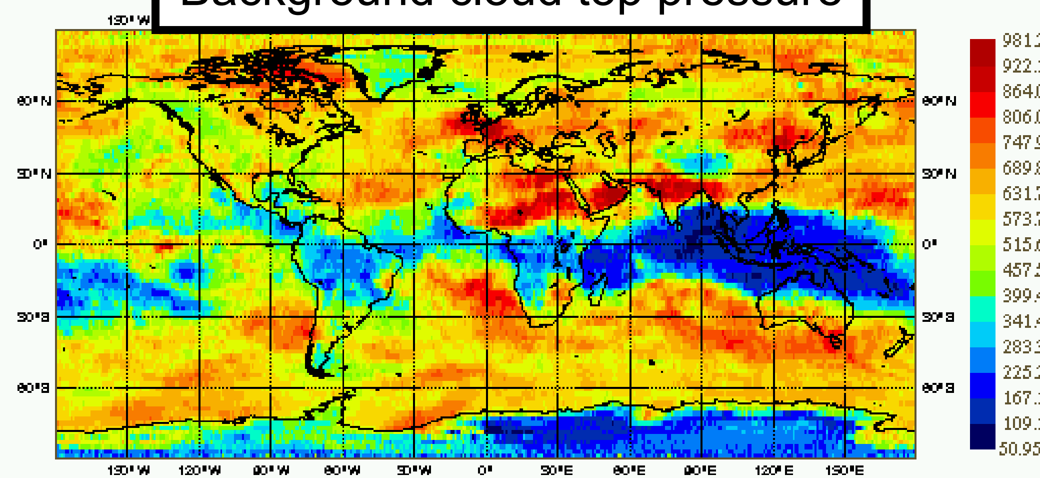
$$N_p = \frac{\sum_j [(R_j^{obs} - R_j^\circ)[R_j^\bullet(p) - R_j^\circ)]}{\sum_j \, [R_j^\bullet(p) - R_j^\circ)]^2}$$

and numerically finding the value of *P* that gives the overall minimum departure.

Background effective cloud fraction

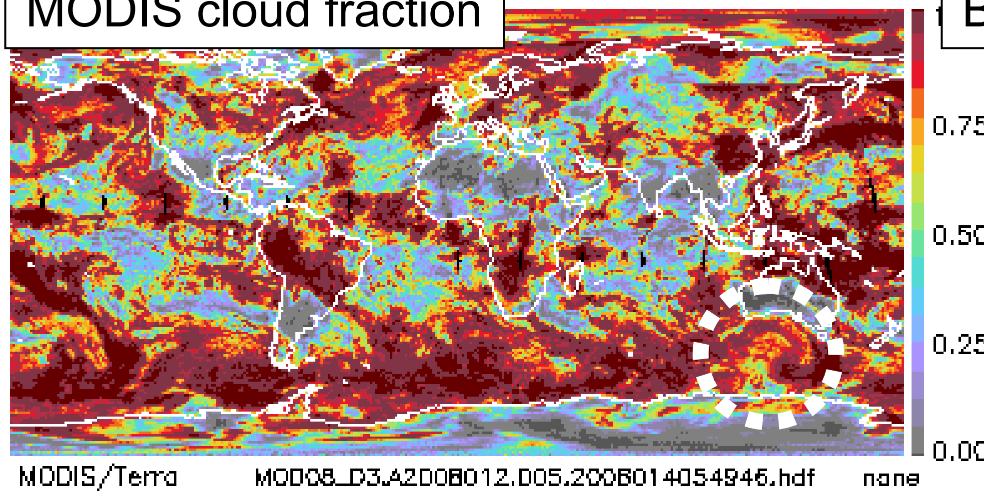


Background cloud top pressure

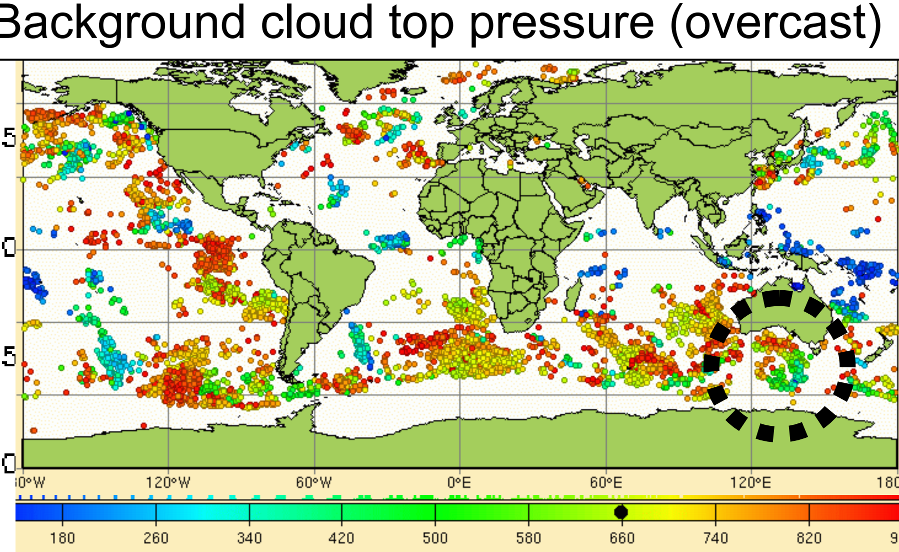


Background 2D cloud parameters
(comparison to MODIS values)

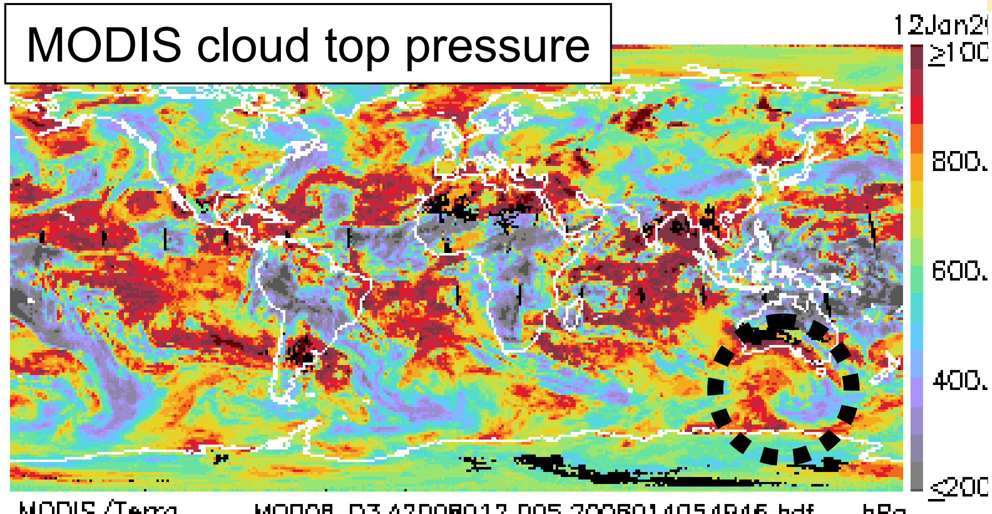
MODIS cloud fraction



Background cloud top pressure (overcast)



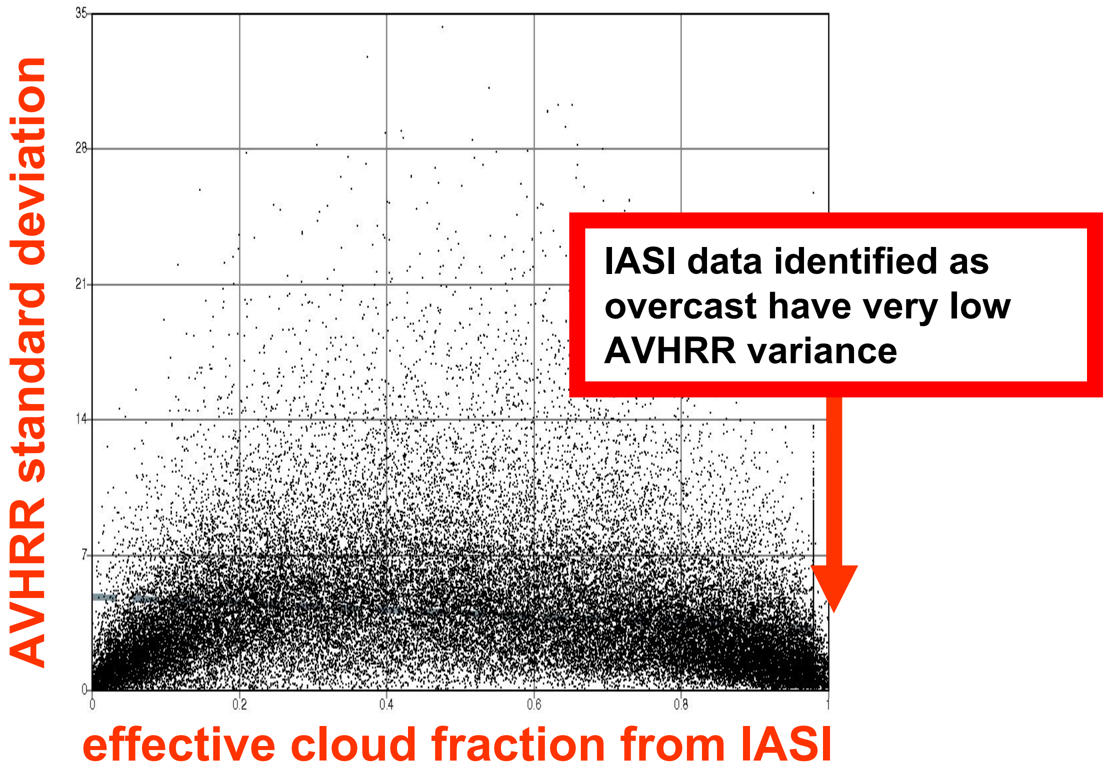
MODIS cloud top pressure



Qualitatively – the location and altitude of **overcast** locations seems reasonable when compared to MODIS equivalent products

Background 2D cloud parameters (comparison with AVHRR)

AVHRR cluster analysis based on imager pixels within the IASI filed of view – one week of data 2008-08-07 to 2008-08-14



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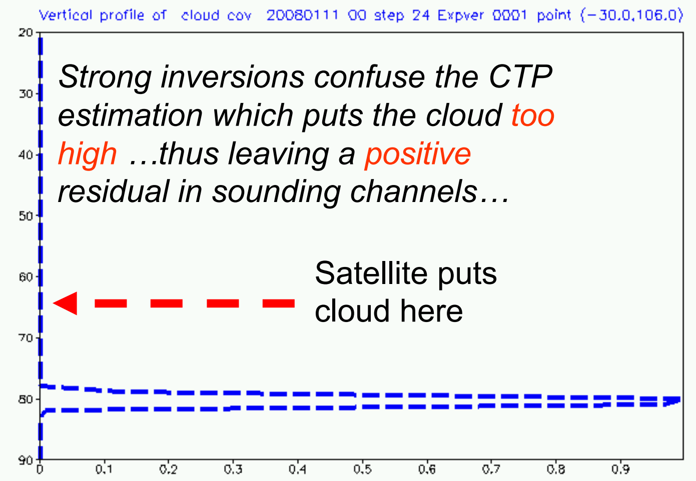
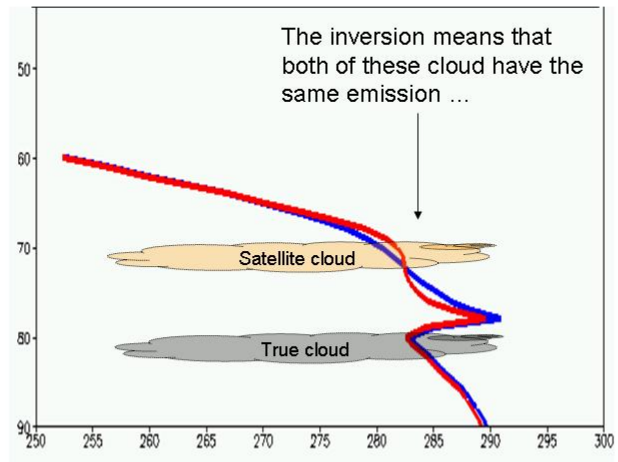
Quality Control…

Problem in MSC regions / inversions

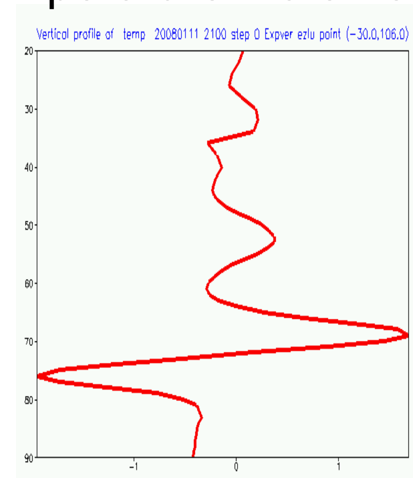
Model cloud cover

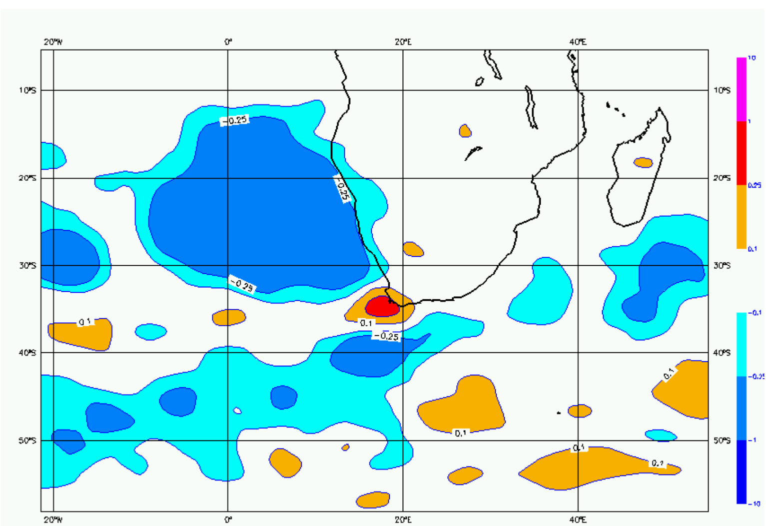


Temperature profiles



Temperature increments





Note: there is some **LIDAR evidence to suggest the model clouds are too low** in the (SH) MSC regions and thus the associated model temperature / humidity profile (from which initial cloud parameters are computed) is unlikely to be correct!

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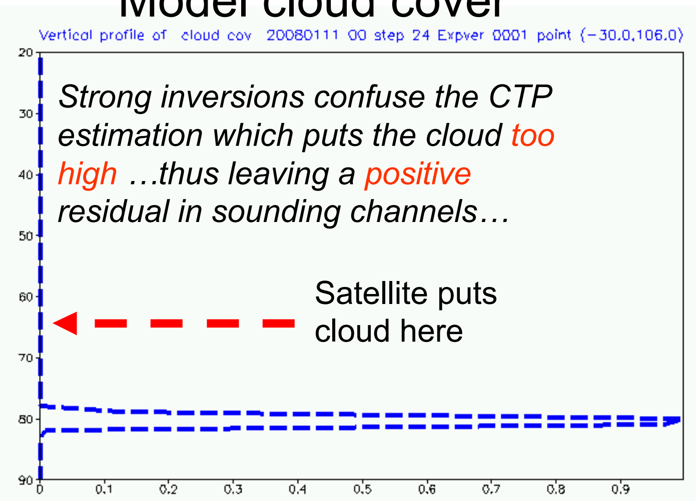

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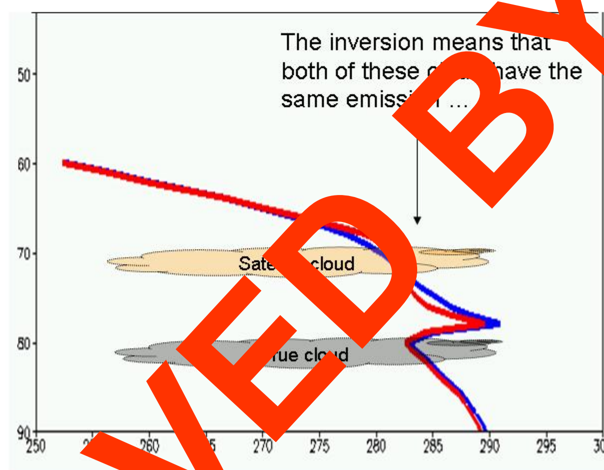

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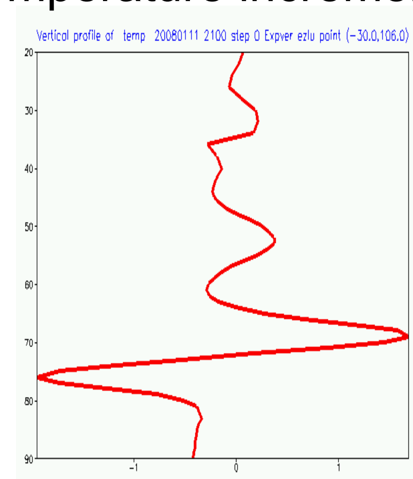

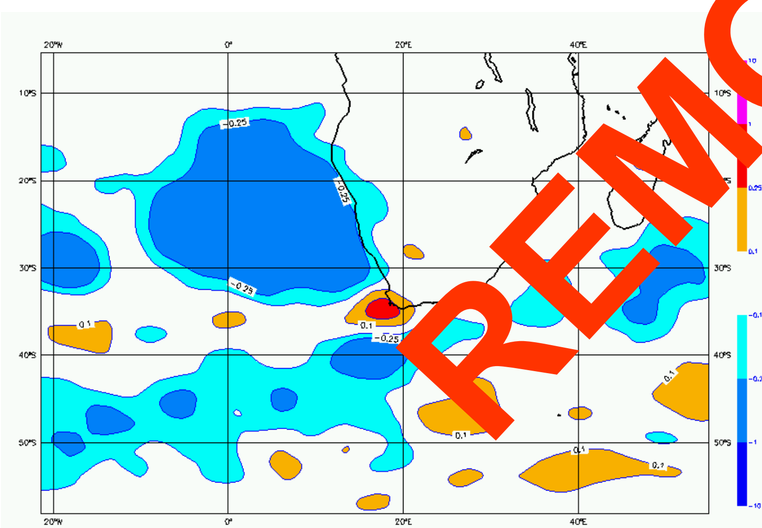

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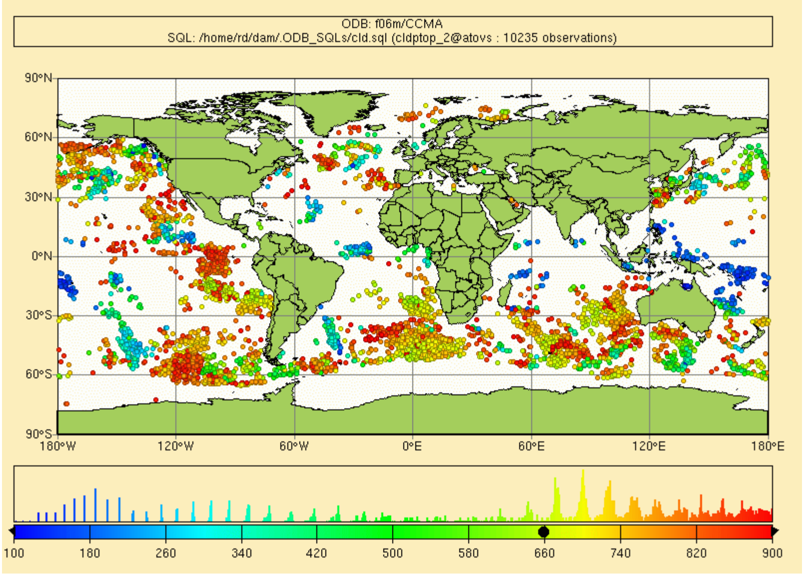
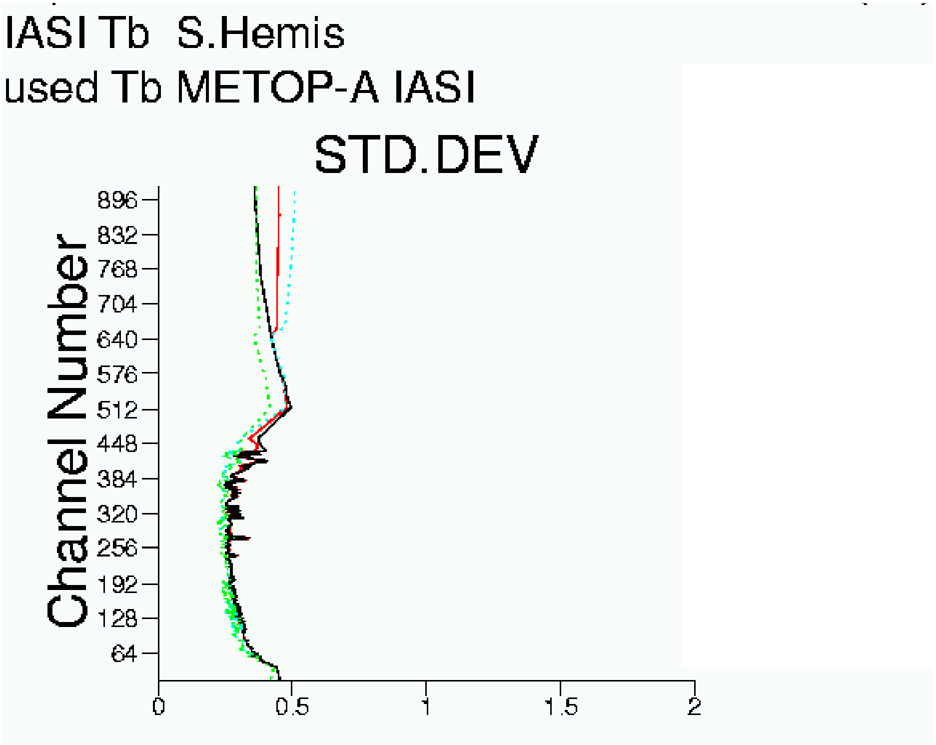
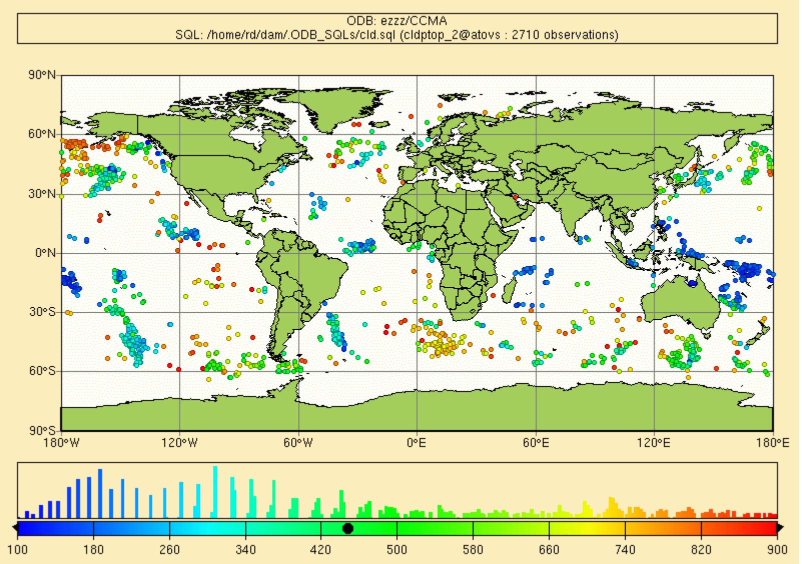
Non-physical cloud solutions

Initial cloud fraction estimates are sometimes found to stray outside **physical bounds** (i.e. 0 < Ne < 1). These are removed as a QC step from further assimilation (as they may indicate multi-level cloud situations and show a degraded fit to the observations)







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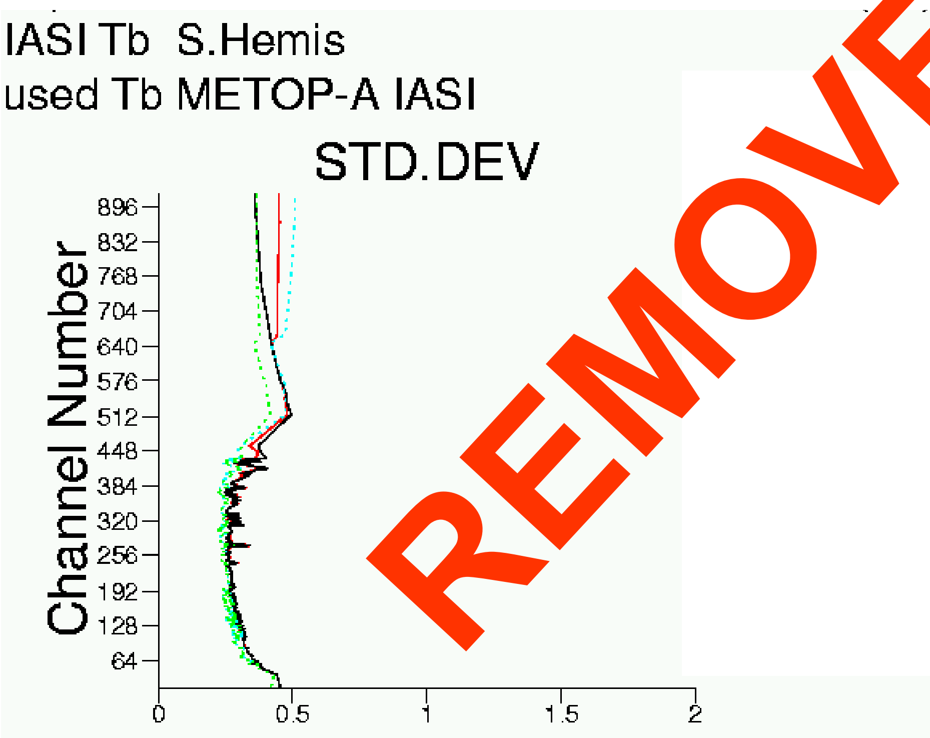

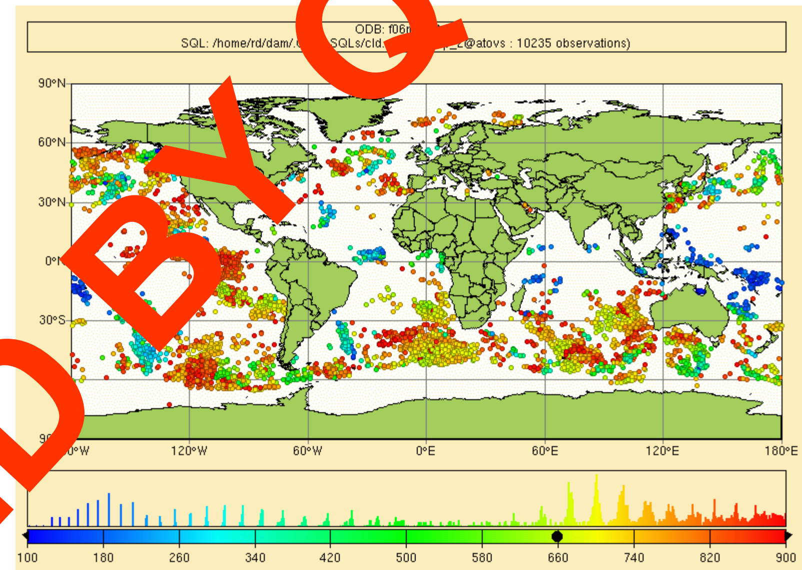

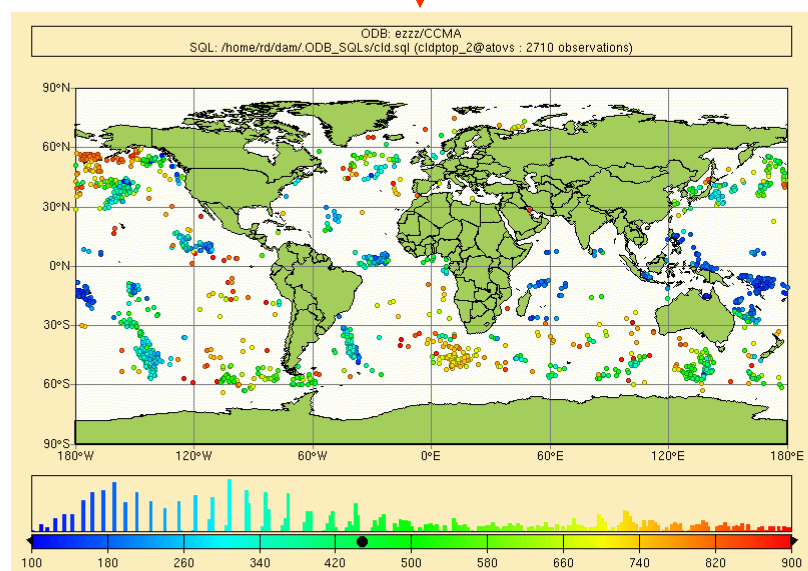

Cloudy assimilation system applied to combined HIRS / AIRS / IASI

Experiment design

Period = 3 months in January/February/March 2008

Resolution = T255

HIRS radiances from METOP-A and NOAA-17 used (LW)
AIRS radiances from AQUA used (LW/WB/SW)
IASI radiances from METOP-A (LW)

CNTRL = ECMWF operations (clear channels from HIRS / AIRS / IASI)

EXPT = CNTRL + HIRS / AIRS / IASI in overcast locations

Background cloud conditions from 2D least squares fit to 4 channels

Background errors CTOP = 5hPa and CFRAC = 0 (local sink variables)

QC applied rejecting low clouds and “bad” 2D solutions

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Background errors CTOP = 5hPa and CFRAC = 0 (local sink variables)

QC applied rejecting low clouds and “bad” 2D solutions

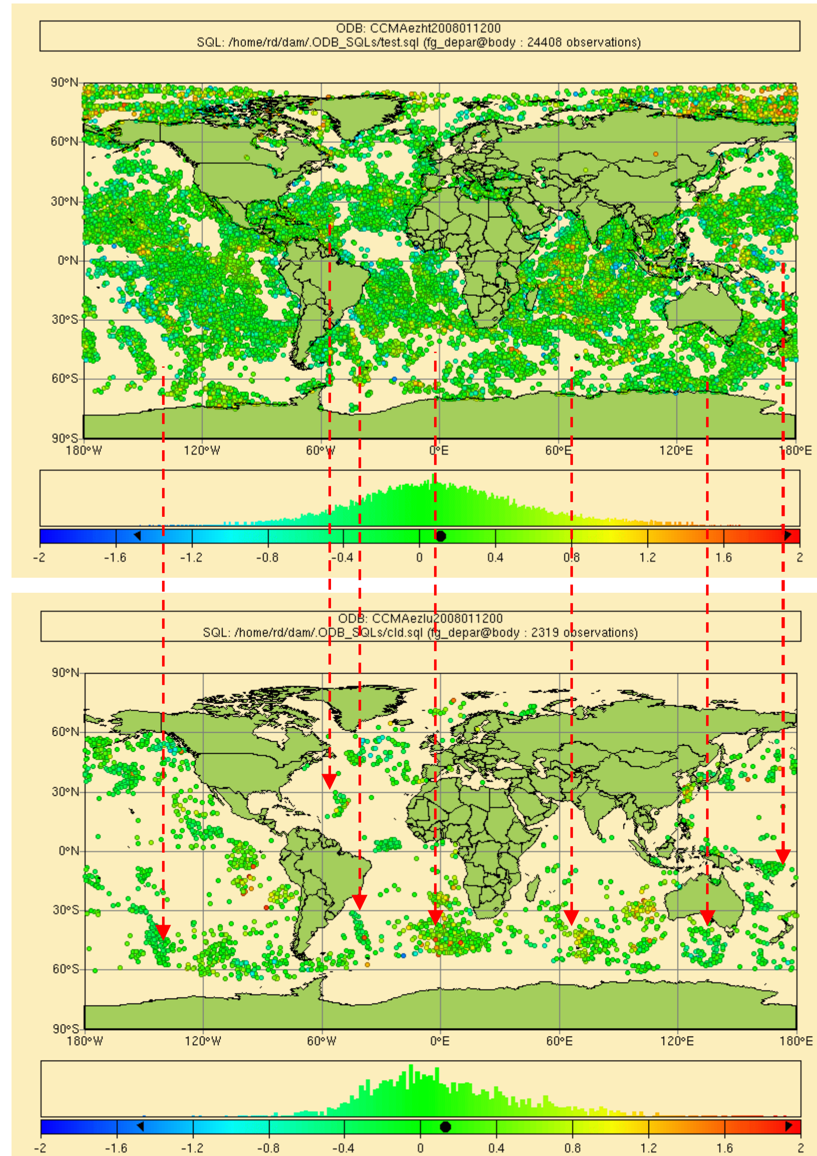
Where are the extra data ?

Combined clear data coverage of mid/lower tropospheric sounding radiances:

IASI channel 434 (METOP-A)
AIRS channel 355 (AQUA)
HIRS channel 7 (NOAA-17 / METOP-A)

Additional overcast locations where cloudy radiance analysis **fills gaps** due to cloud detection rejections:

IASI channel 434 (METOP-A)
AIRS channel 355 (AQUA)
HIRS channel 7 (NOAA-17 / METOP-A)

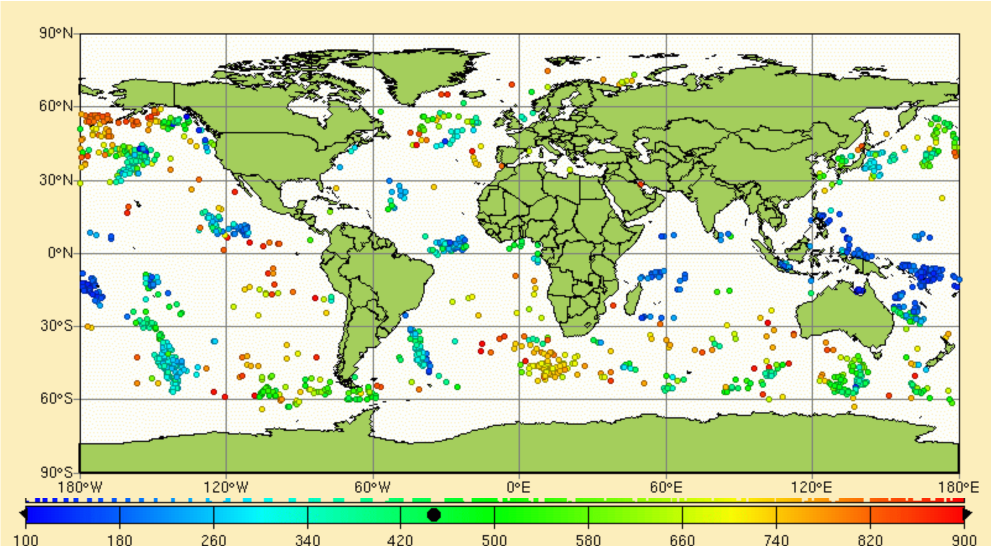


Typically the overcast locations only provide an extra 10% to the total data

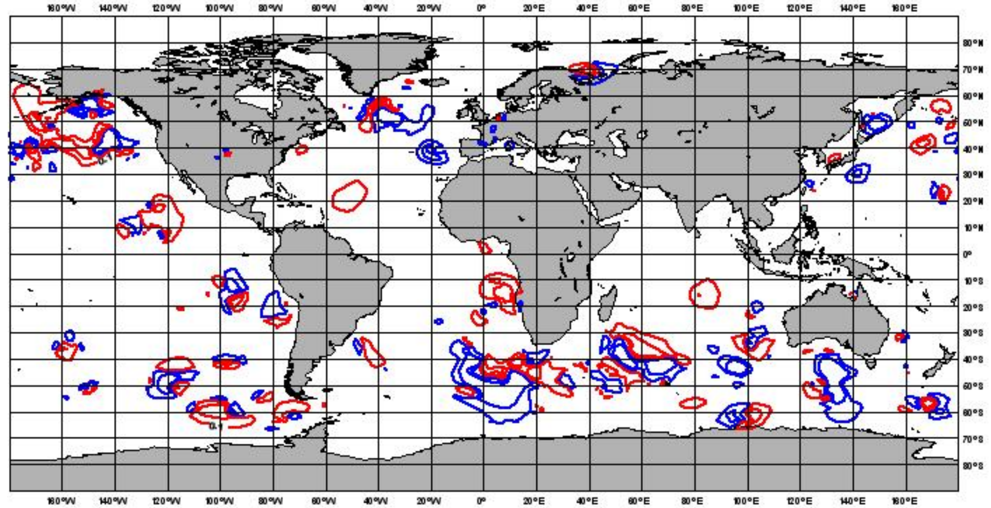
Impact of overcast data on the analysis…

Temperature increments above low clouds

Overcast data coverage and Cloud top pressure

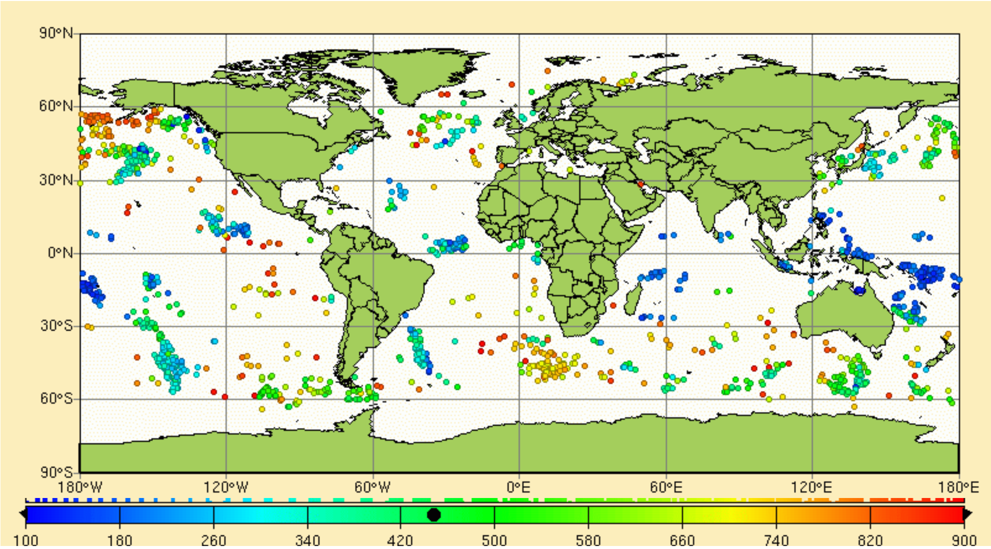


Analysis temperature increments at 700hPa

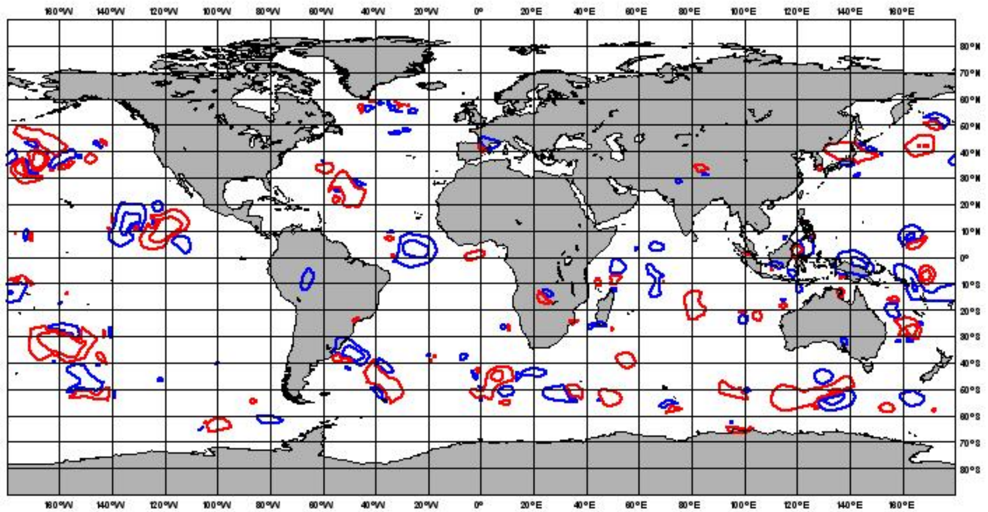


Temperature increments above high clouds

Overcast data coverage and Cloud top pressure

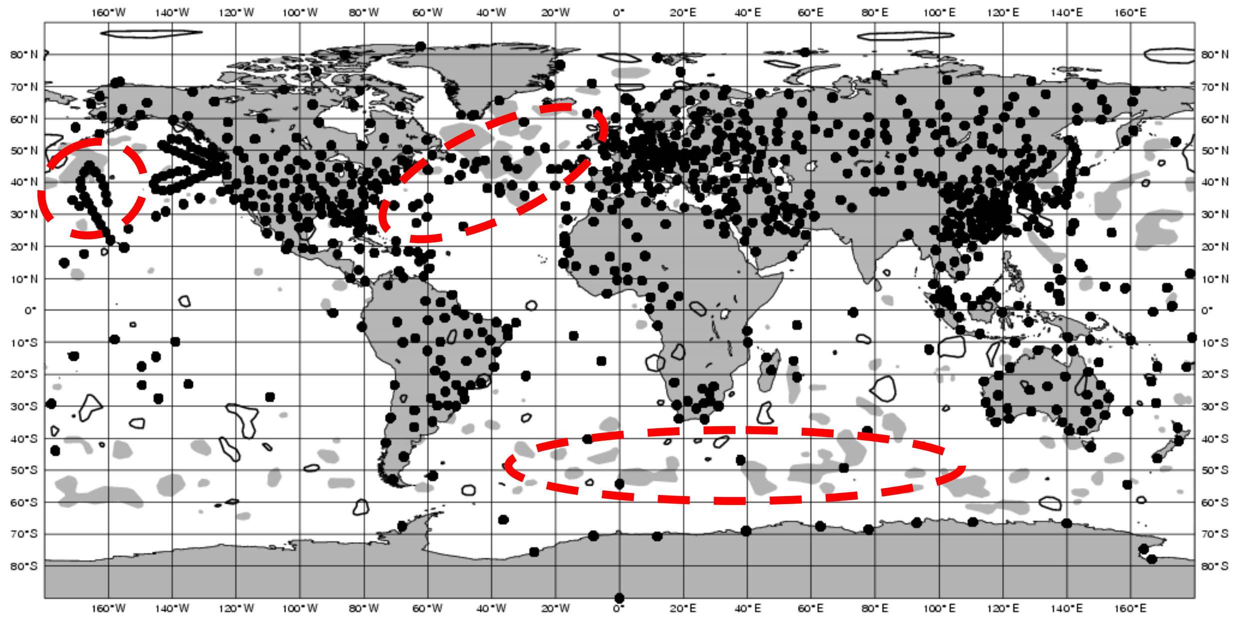


Analysis temperature increments at 250hPa

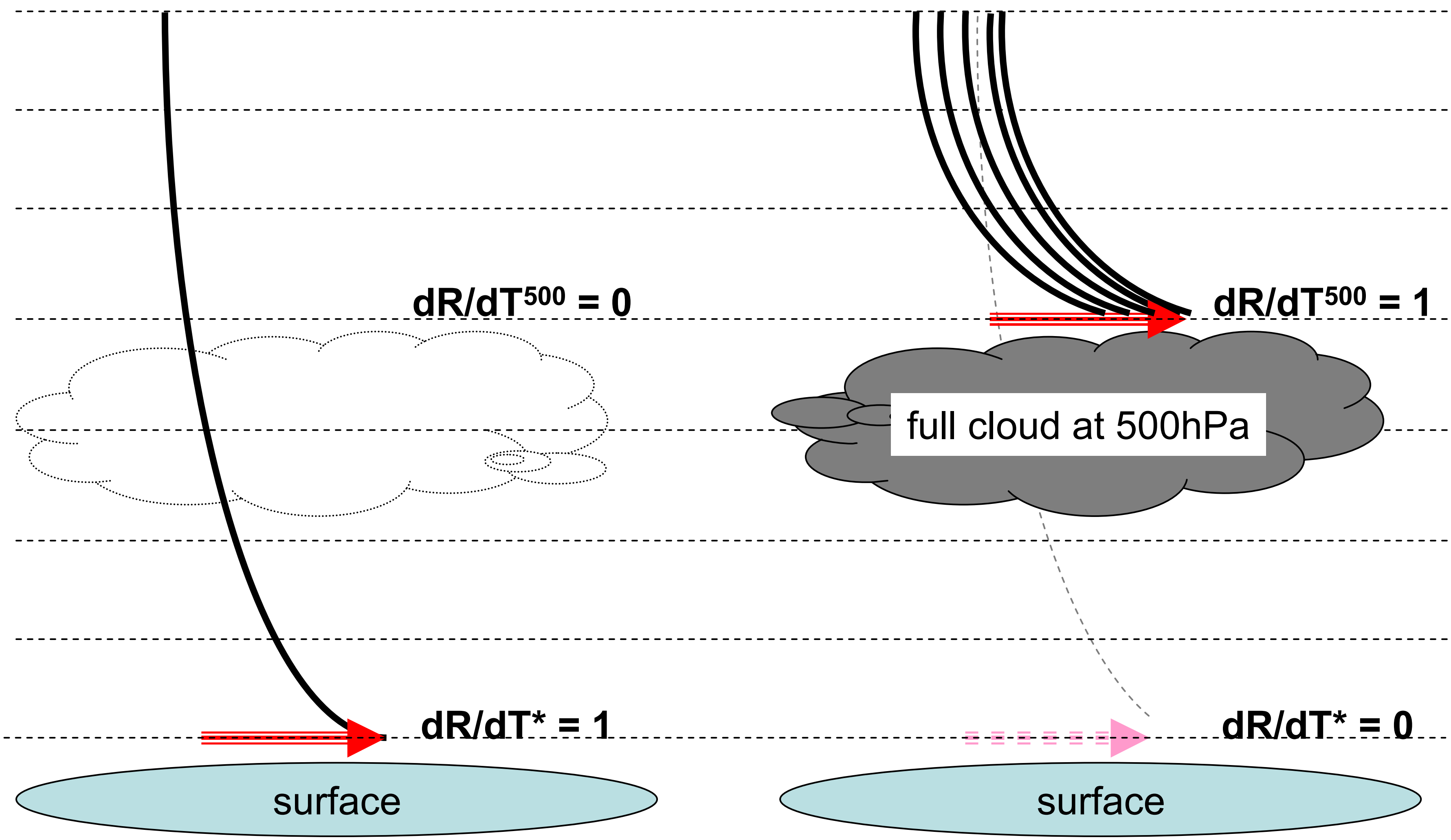


Reduced temperature increments at isolated observation locations

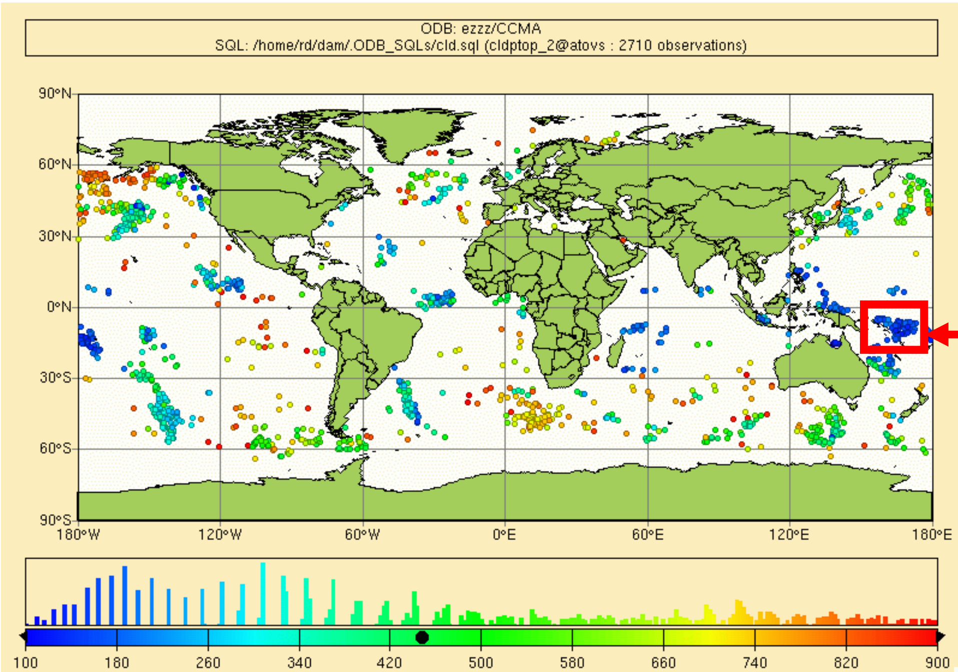
Monthly averaged RMS temperature increment difference (CLOUDY minus CTRL). Shaded areas indicate a reduction in increments in excess of 0.1K when the cloud radiances are assimilated.



…remember this …?

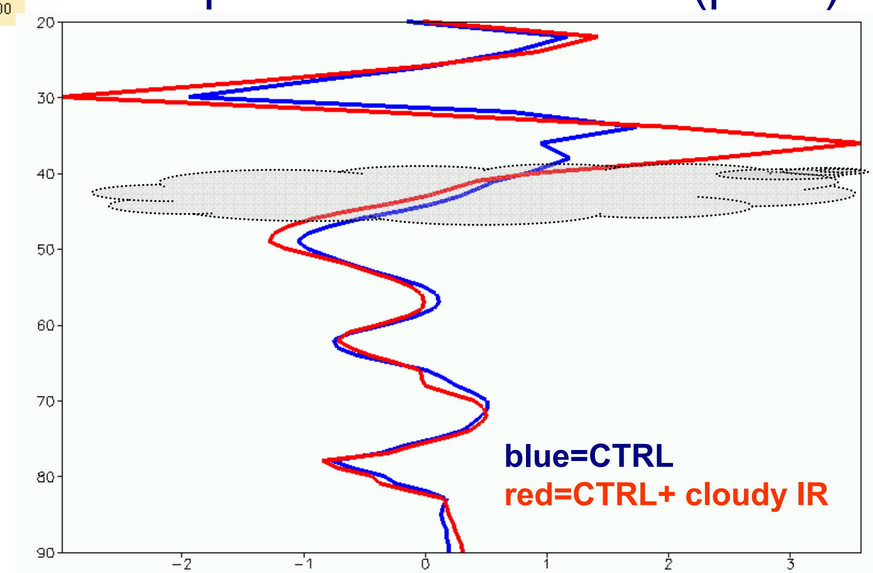


Temperature increments at the cloud top



Cell of very high overcast clouds off the coast of PNG seen by IASI

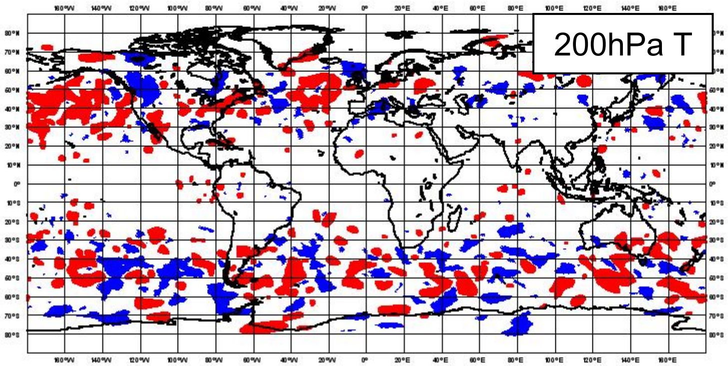
Temperature increments (point)

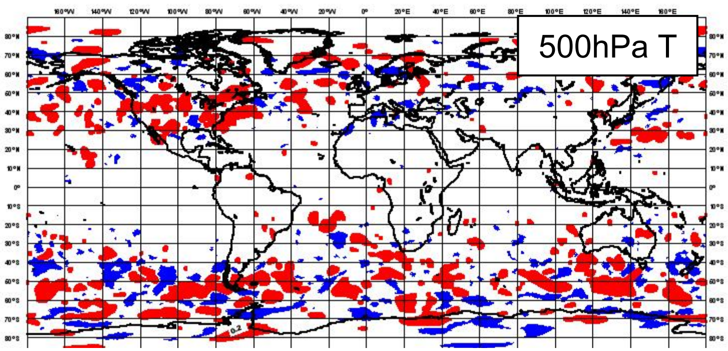


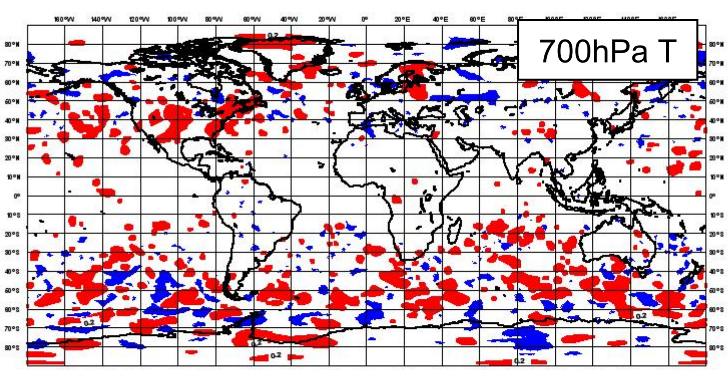
All IASI channels collapse to near **delta-functions** at the cloud top giving very **high vertical resolution** temperature increments just above the diagnosed cloud

Impact of overcast data on forecasts …

Forecast error statistics with cloudy data

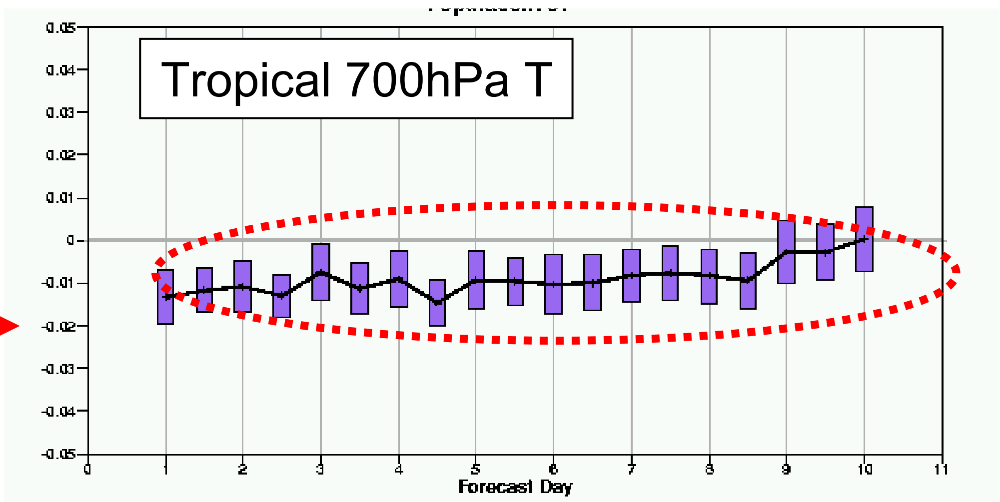






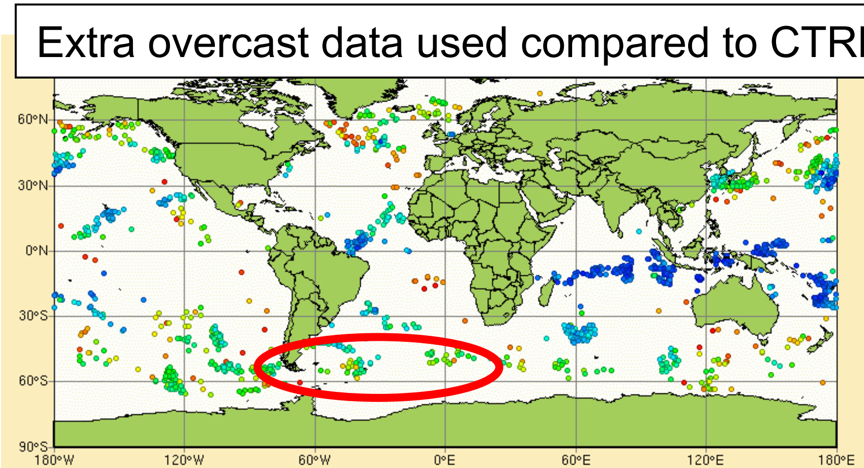
Generally the impact of the extra overcast data on the hemispheric forecast error scores is neutral or slightly positive (with no statistical significance).

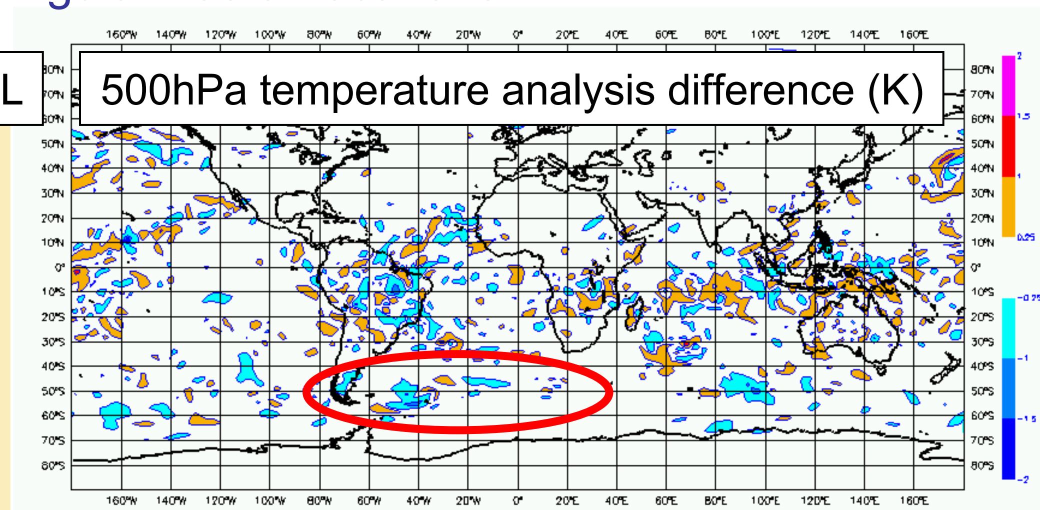
However, statistically significant forecast impacts are obtained in the Tropics where temperature forecasts are improved at all ranges

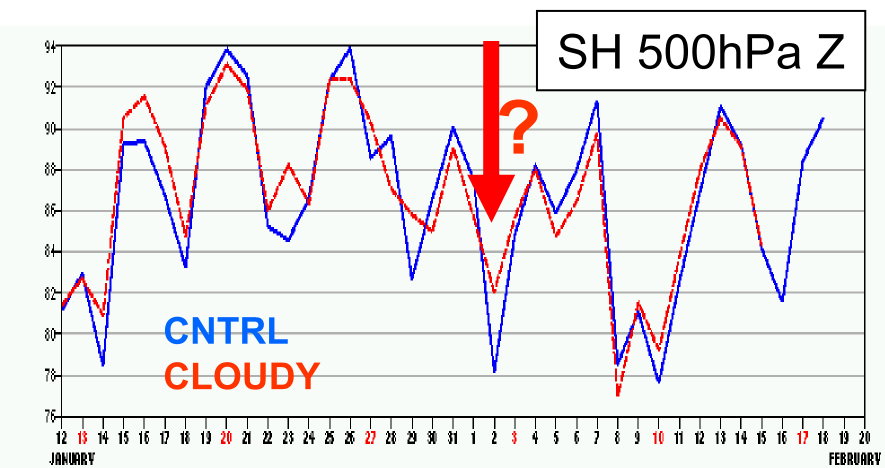


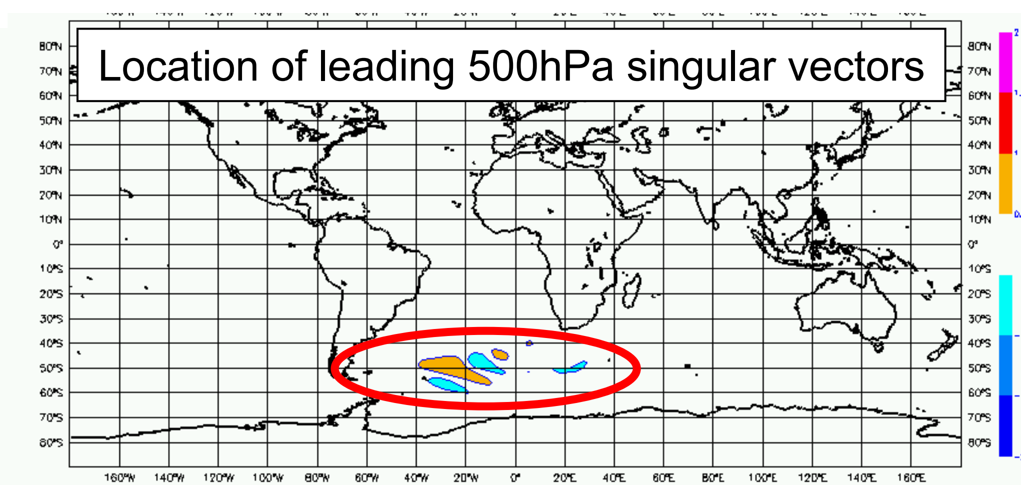
Cloud obscured singular vector ?

In this case the use of overcast observations resulted in analysis differences in an area suggested to be sensitive by the singular vector locations









Summary

- The ECMWF 4D-Var has successfully been extended to make additional use of overcast radiance data

- The restriction to overcast scenes and the strict QC currently yields < 10% extra radiance data

- The small amount of additional data do not significantly influence the bulk characteristics of the analysis or departure statistics – although some isolated reduction of increments is observed.

- At locations where there are extra radiance observations - high vertical resolution increments (above overcast cloud top) look reasonable, but need further detailed validation

- No statistically significant impact on forecast performance apart from improved Tropical temperature scores

Next Steps

- Use imager data (MODIS/AVHRR) to validate 2DLS background cloud estimates and investigate the possibility of using imager identification of overcast scenes for data selection / QC rejection

- Use CLOUSAT data to validate the 2DLS background cloud top estimates in overcast conditions (particularly MSC)

- Continue to search for individual cases of forecast impact – possibly using singular vectors or adjoint sensitivity diagnostics

- Investigate use of a post-processed NWP cloud background for the cloudy IR analysis to replace the 2DLS

- *Investigate the options for feeding the cloud information back to the model physics (e.g. via cloud fraction ?)*

- *Understand how this approach to using cloudy data blends (or not) with other future developments (rainy radiances)*

End

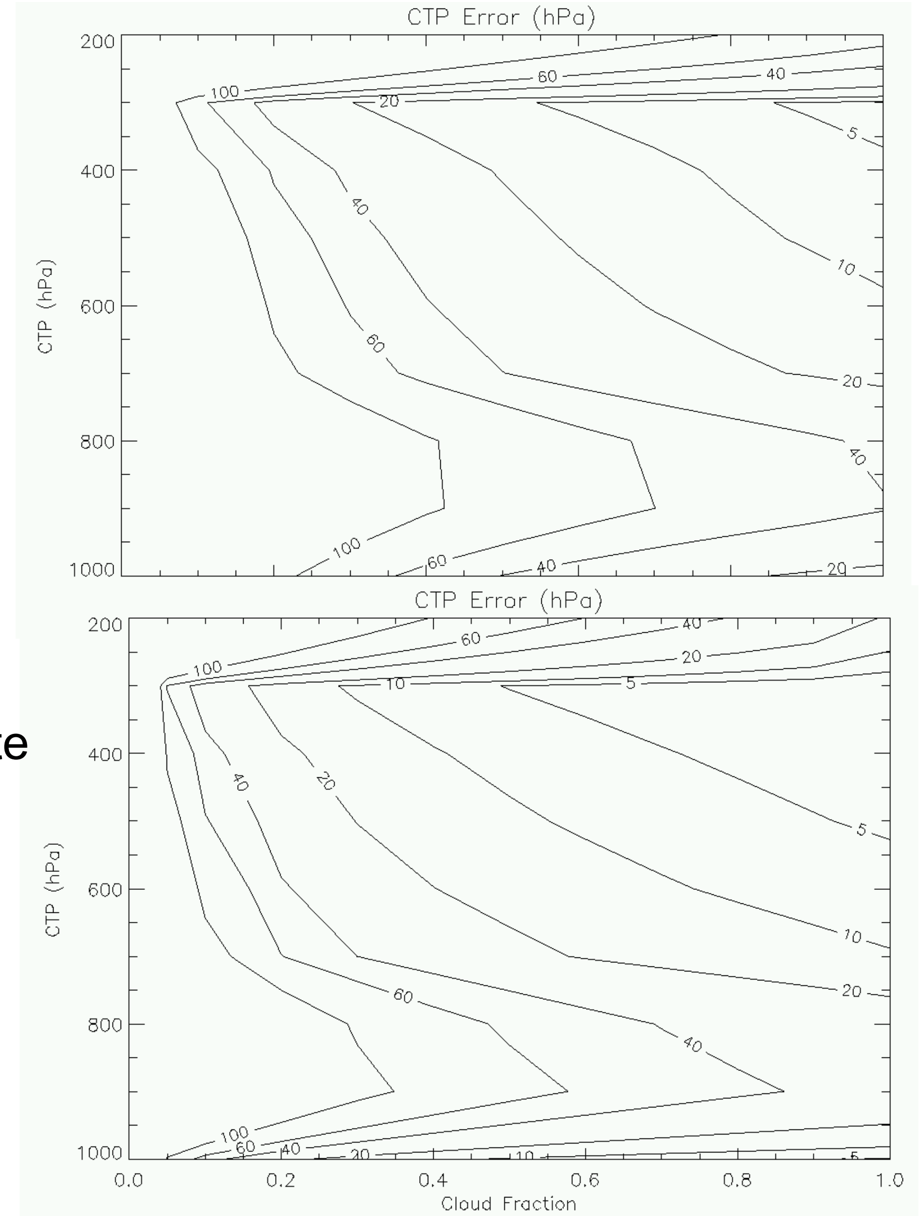
Some questions ?

- What are the implications of channels used in the 2DLS and then in the 4DVAR (potentially all T/Q information could be removed by inserting a cloud. Is the problem biggest for HIRS and does the overcast limitation help ?
- Can we make better use of post-processed NWP cloud parameters to provide independent background for cloud analysis ?
- Can we make use of imager cloud information – either as a background of to at least verify other background cloud parameters (2DLS or NWP) – or as a QC mechanism
- Must study the (O-B) stats for unambiguously clear data and cloudy data with the 2DLS estimated cloud signal removed. If the latter is very small it suggest that a lot of T/Q signal is being dumped into cloud in 2DLS.
- The neutral forecast impact – is it a mix of good and bad or just small ?
- Two possible sources of improvement in analyses and forecasts ?
  - dumping erroneous signal from cloud detection into cloud sink variable
  - real new useful T/Q information above overcast clouds.

The effect of T,Q error on the estimation of cloud top pressure

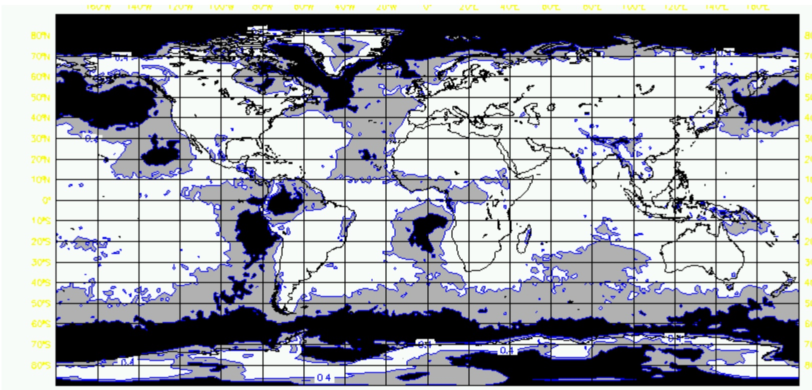
Realistic errors placed on T,Q from B for the simultaneous estimation of cloud top pressure from AIRS / IASI

However, the cloud top pressure estimate is not significantly affected by these T,Q errors and the accuracy is similar even when the T,Q are known perfectly

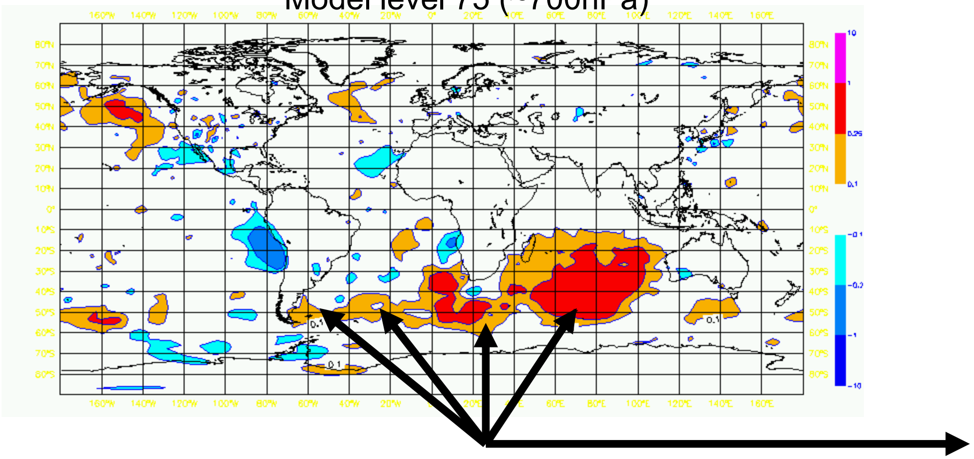


Experiments with overcast HIRS data only

Monthly mean (model) low cloud cover

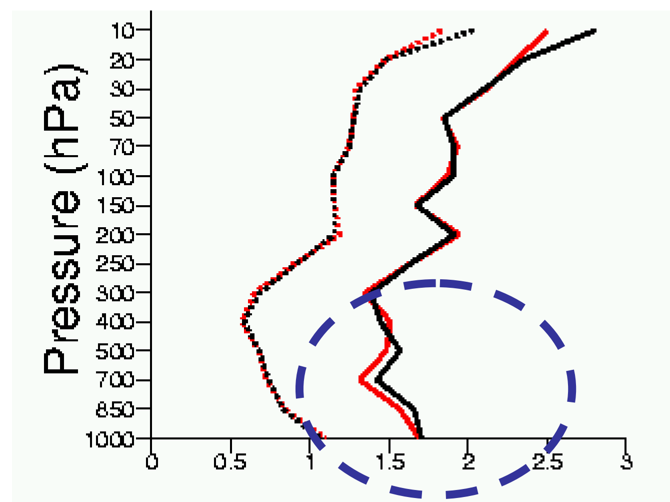


Monthly averaged RMS T increments (CNTRL minus EXPT)
Model level 75 (~700hPa)



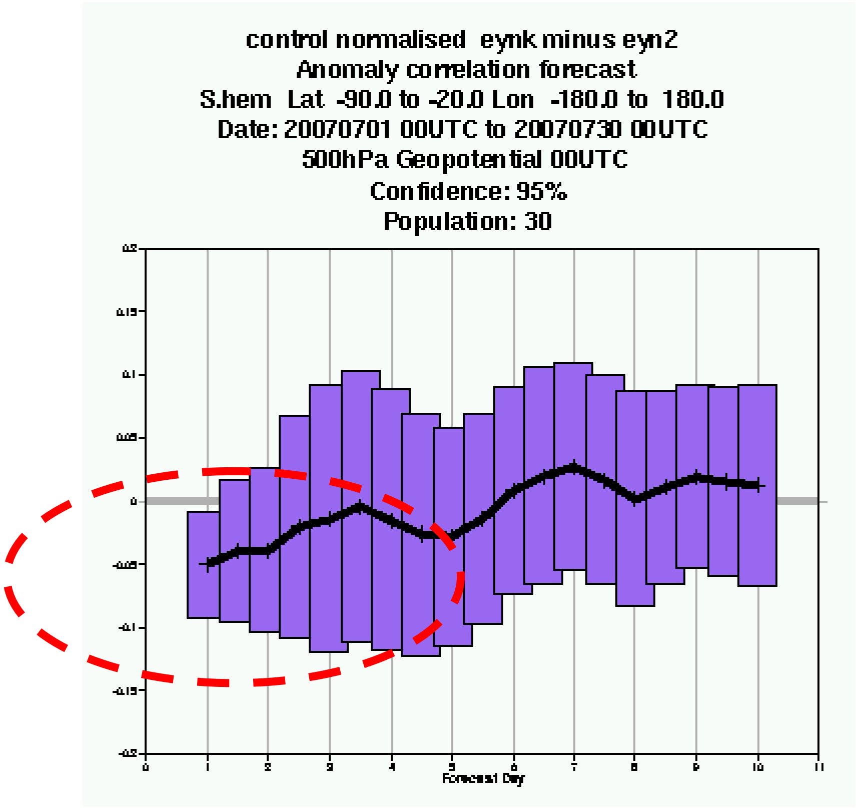
Temperature increments

Improved fit to isolated TEMP data (averaged over 1 month)



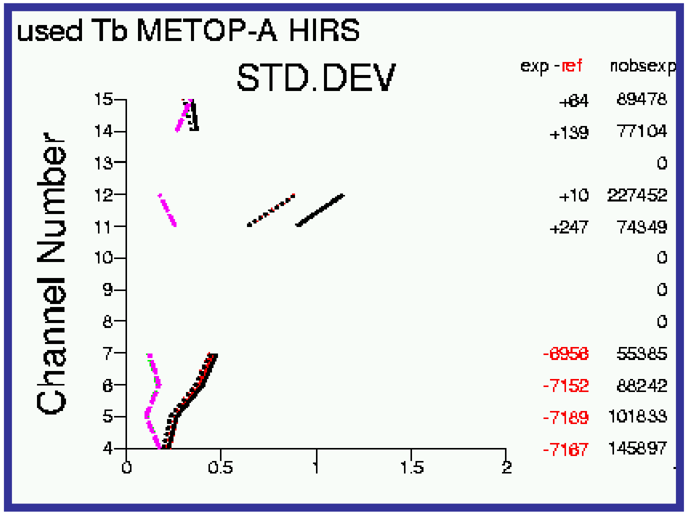
Experiments with overcast HIRS data only

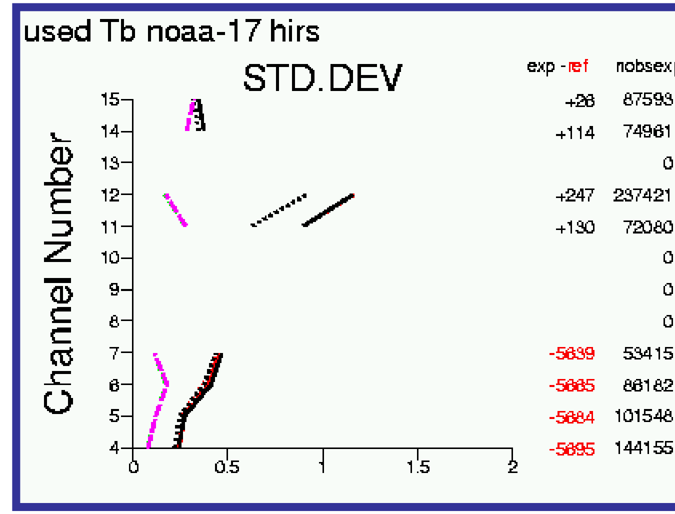
Forecast scores averaged over **1 month** generally neutral – but some improvement in S. Hemisphere short-range forecasts at the 95% significance level



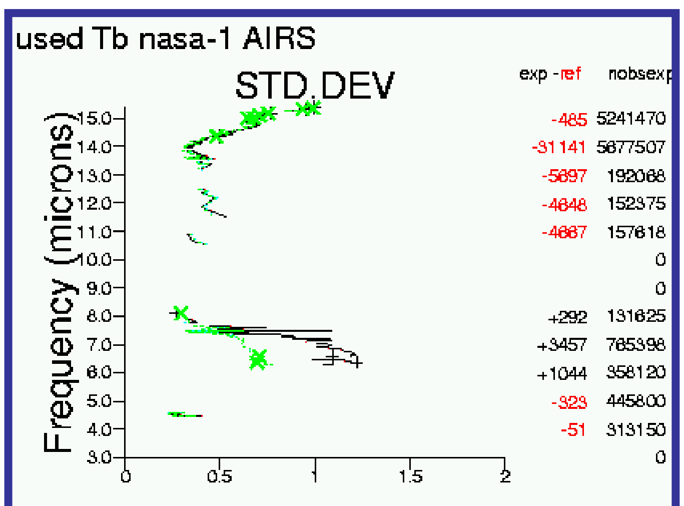
Extra IR data from overcast locations

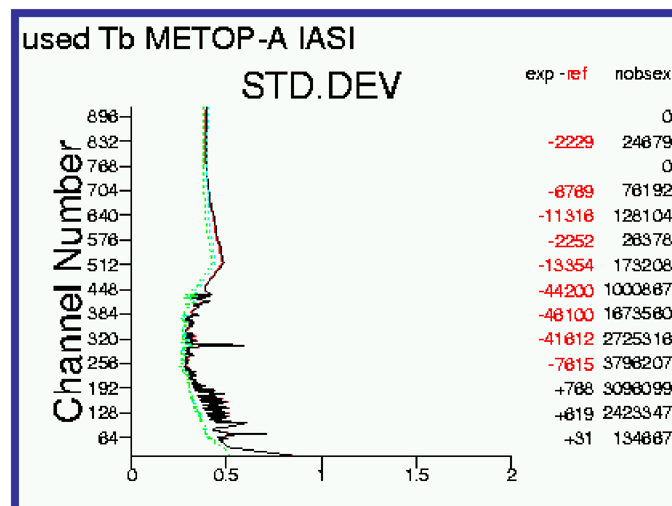
(after QC typically < 10% shown in red)





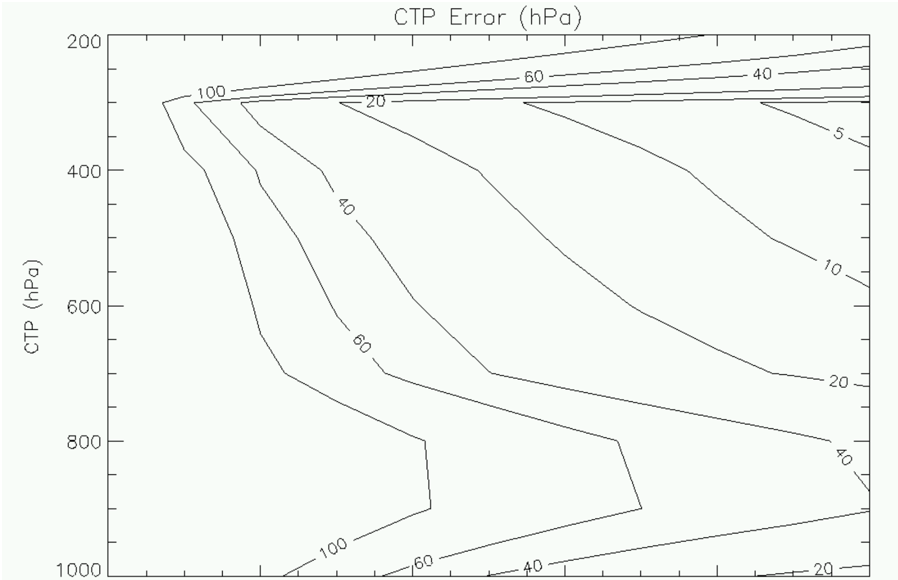
Note that the extra overcast radiances do not alter the overall (O – B) statistics





The effect of T,Q error on the estimation of cloud top pressure

Realistic errors placed on T,Q from B for the simultaneous estimation of cloud top pressure from AIRS / IASI



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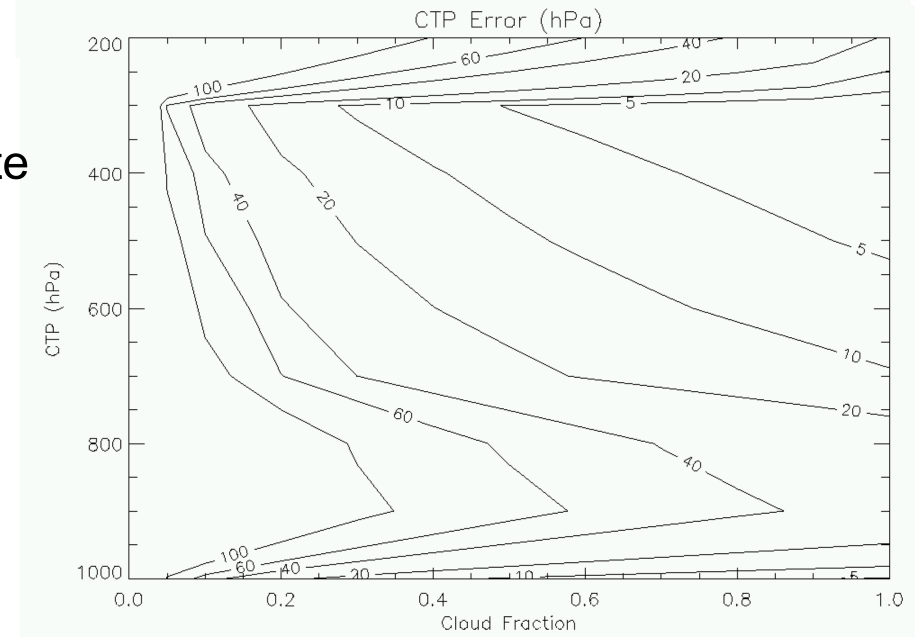
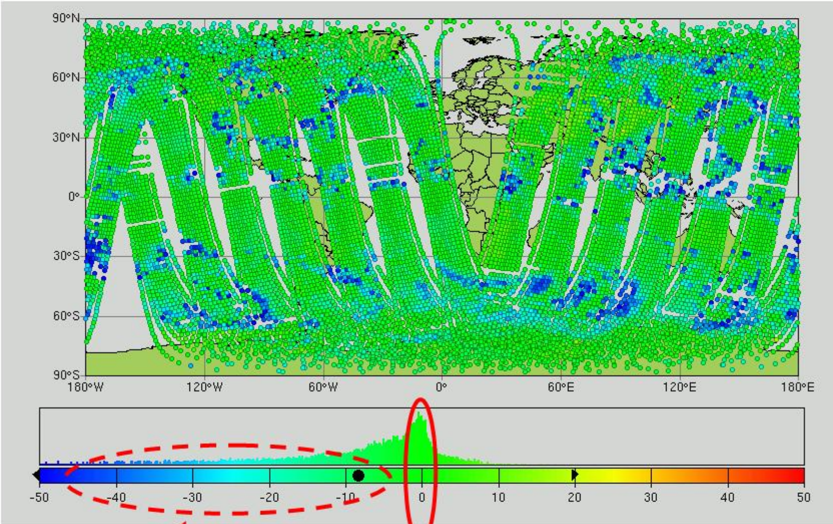


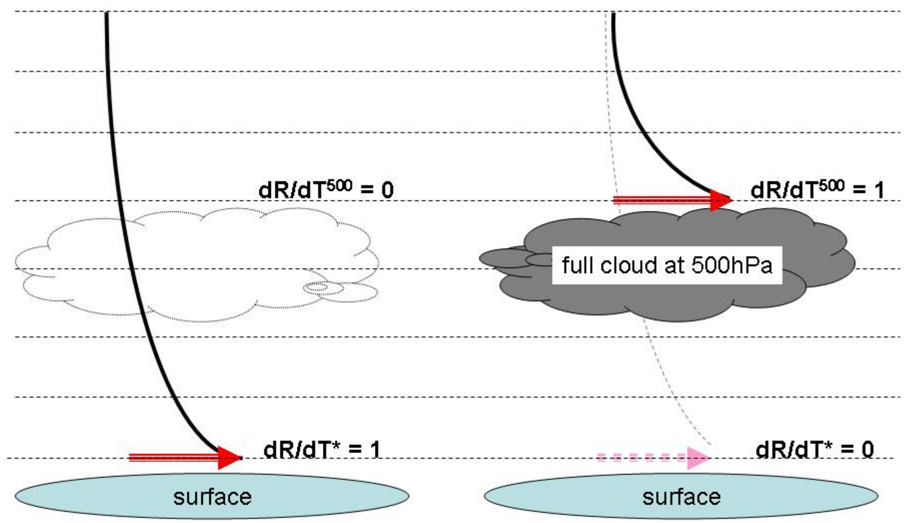
Observed radiance at 11 microns minus radiance calculated in clear sky



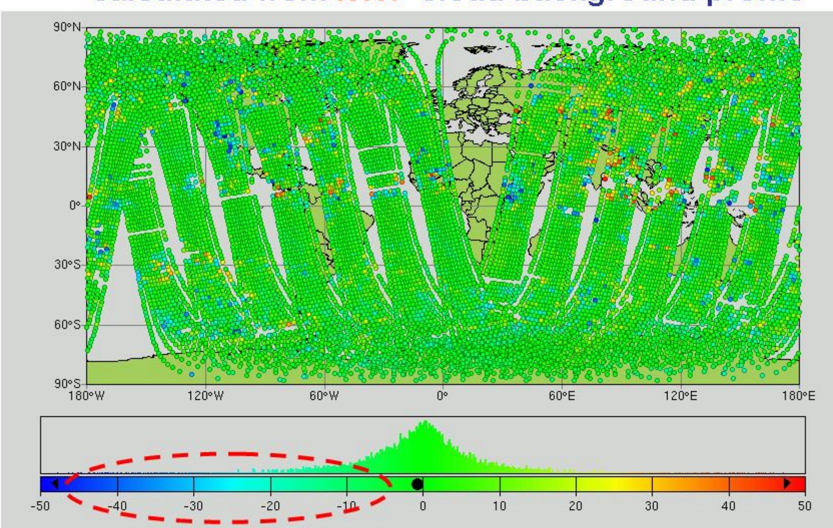
Cold departures indicating cloud contamination in OBS

Clear population

Clear and Cloudy Jacobians



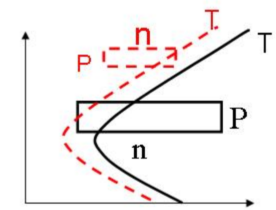
Observed radiance at 11 microns minus radiance calculated from NWP cloud background profile



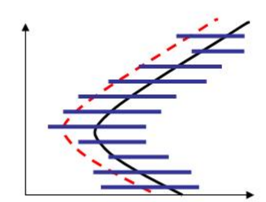
Many clouds with significant radiance signals are accurately represented by the NWP model and RT modelled !

Choice of cloud parameters and ambiguity with T and Q

A very simple cloud model (e.g. single layer grey cloud amount and pressure) should more readily estimated from the data (independently of T and Q), but will make the forward RT calculation very inaccurate in many cloud conditions



A more complex cloud model (e.g. cloud liquid and ice at each model level) will allow a more forward RT calculation, but may be difficult to estimate independently of T and Q and may alias into erroneous increments



Two potential approaches to handle clouds

1. Use cloud affected radiance observations that have been pre-corrected to remove the cloud signal (i.e. *cloud cleared data*)

2. Extend the NWP analysis to estimate cloud parameters simultaneously with temperature and humidity (*either interacting with model cloud physics or not*)

… note that fundamentally the estimation problem is the same …