Assimilation of Infrared Sounder Radiances

Andrew Collard
IMSG@NOAA/NCEP/EMC

Slide 1

Overview

Introduction

The Infrared Spectrum

Infrared Hyperspectral Sounders and their Performance

Channel Selection

O-B Comparisons

Clouds

Humidity Assimilation

Overview of IR Sounder Performance in NWP

Slide 2

Conclusions

Introduction

Scope of Talk

- Infrared satellite sounders have long been part of the satellite observing system: The first HIRS was launched on NIMBUS-6 in 1975.
- However, the launch of EOS-Aqua AIRS in 2002, marked a paradigm shift in the use of these data resulting in the infrared sounders (AIRS, IASI, CrIS) being among the most important sensors in global data assimilation systems
- For this reason, this talk will focus exclusively on the use of hyperspectral sounders.

Scope of Talk

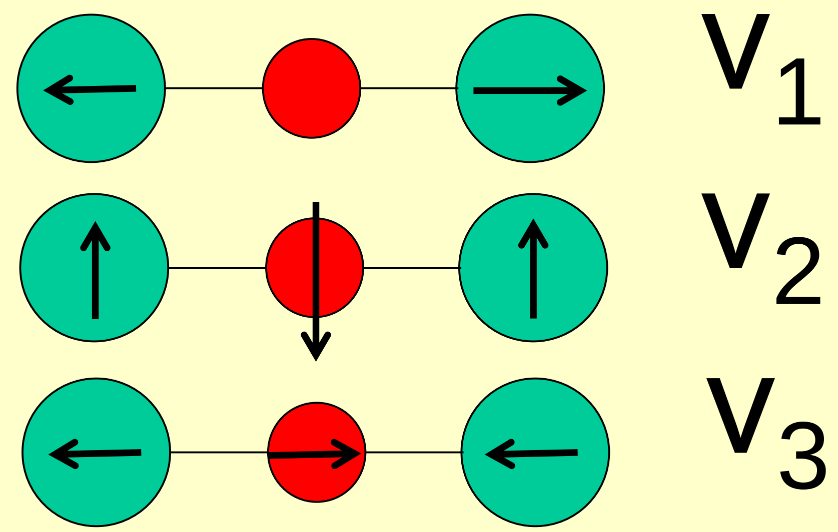
- Important issues in the assimilation of infrared radiances are discussed in other talks in this seminar and so will not be discussed here in detail:
- Observation errors (including spectrally correlated errors): Niels Bormann
- Instrument characterisation: Dieter Klaes and Bill Bell
- Cloudy radiance assimilation:
  Jean-Francois Mahfouf, Alan Geer, Jérôme Vidot
- Convective scale DA: Thomas Auligné
- Principal components and reconstructed radiances:
  Marco Matricardi
- Surface Emissivity: Fatima Karbou

The Infrared Spectrum

Slide 6

The clear sky infrared spectrum is dominated by emission and absorption by atmospheric molecules

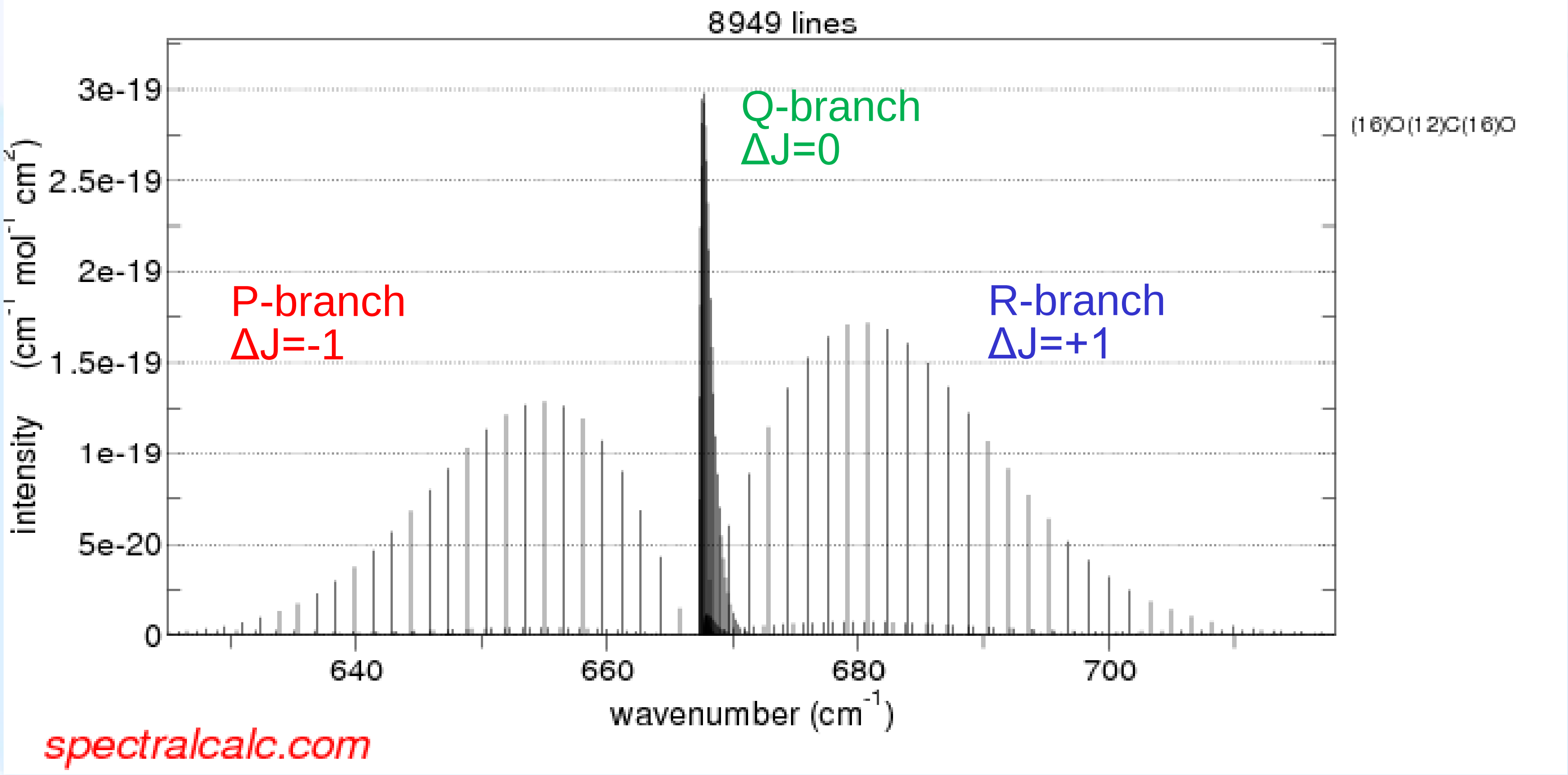
- Molecules in the atmosphere have energy stored as rotational,vibrational and electronic components
- The energy states are quantised and may be transformed through emission or absorption of electromagnetic radiation. This results in discrete spectral emission/absorption features in the spectrum.



Vibrational Modes for CO_2

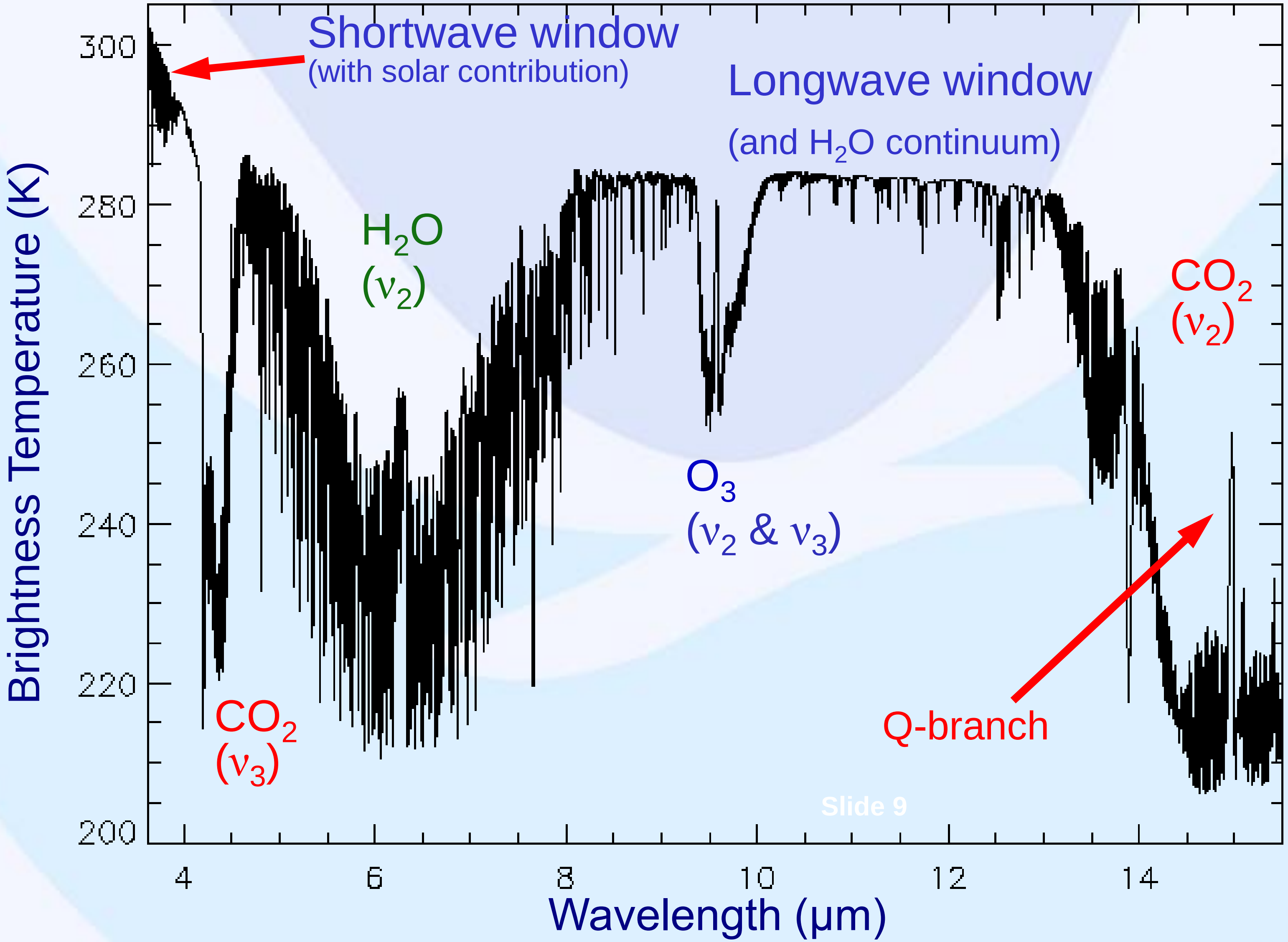
  - In the microwave these are due to rotational transitions
  - In the infrared these are rotational and vibrational transitions
  - Electronic transitions manifest themselves in the visible and ultraviolet

Vibration-Rotation Spectrum Ground→ν2 transition for CO_2



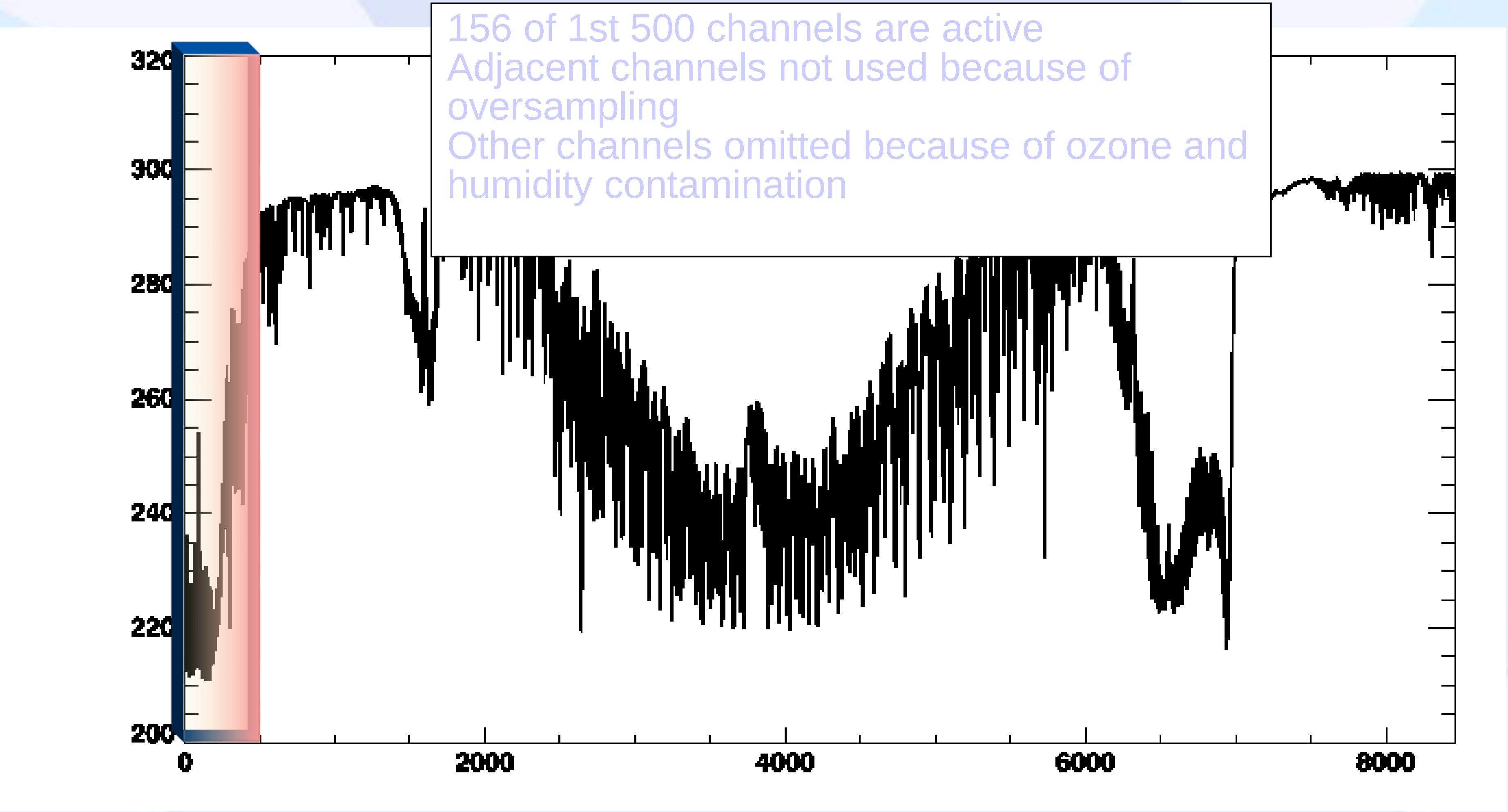
An example of a vibration-rotation band in the infrared CO_2 spectrum. Due to considerations of angular momentum, only changes in the rotational quantum number, J, of -1,0 or 1 are optically active, producing the characteristic three branch structure to the band (some linear molecules have the Q-branch missing).

An Infrared Spectrum



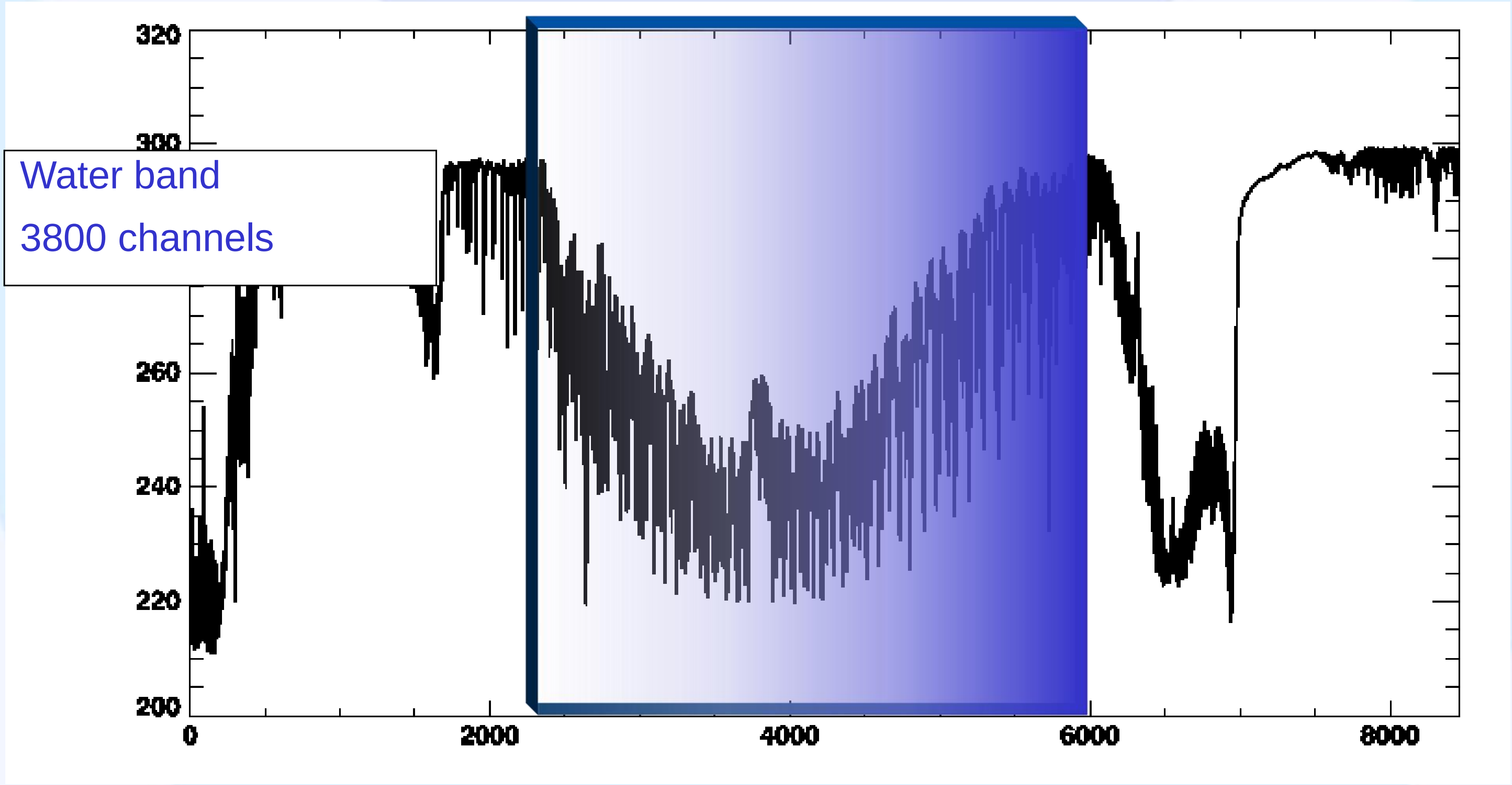
Regions of the Infrared Spectrum

Longwave CO_2 Band



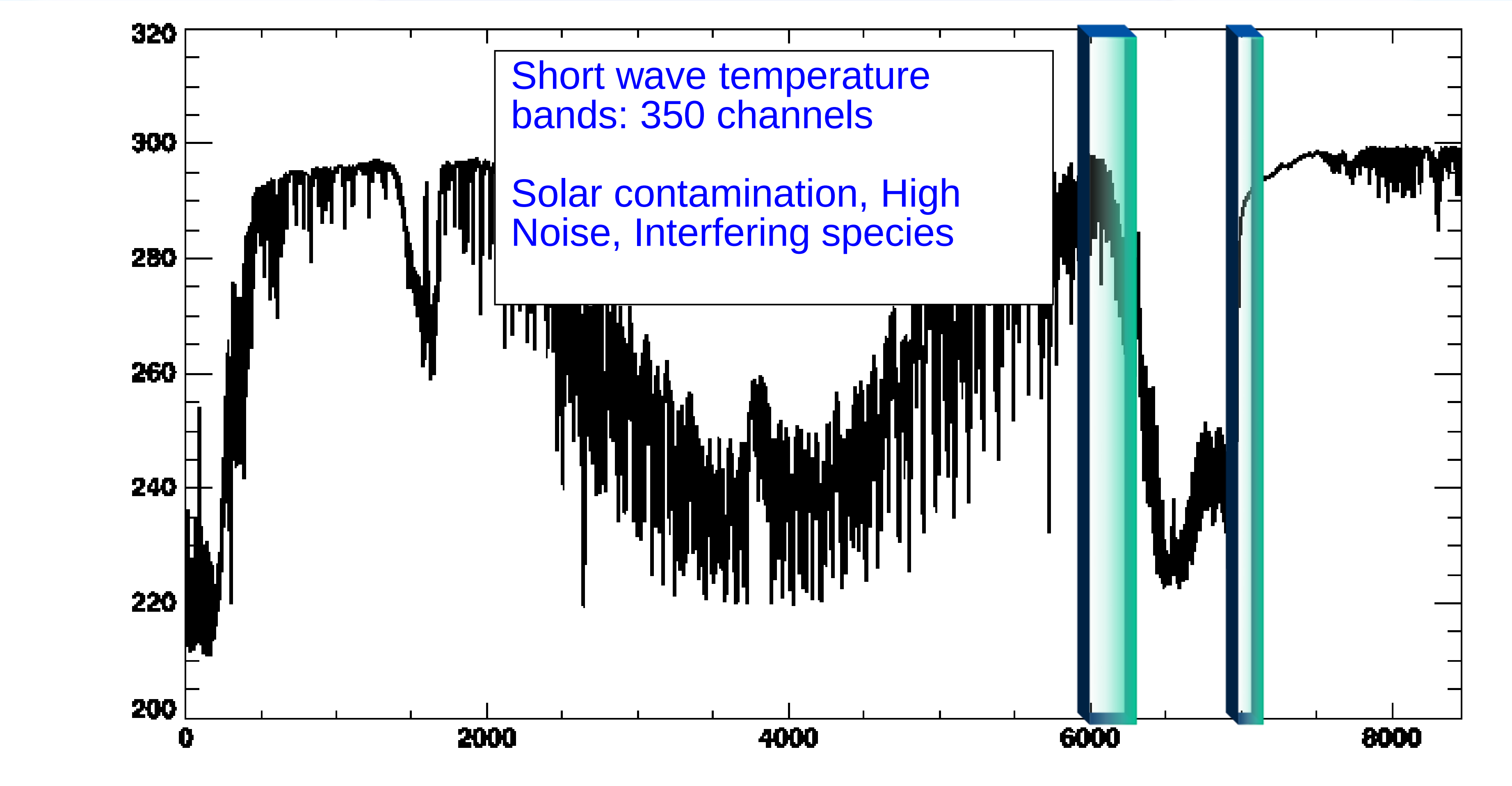
Regions of the Infrared Spectrum

The 6.3µm Water Band



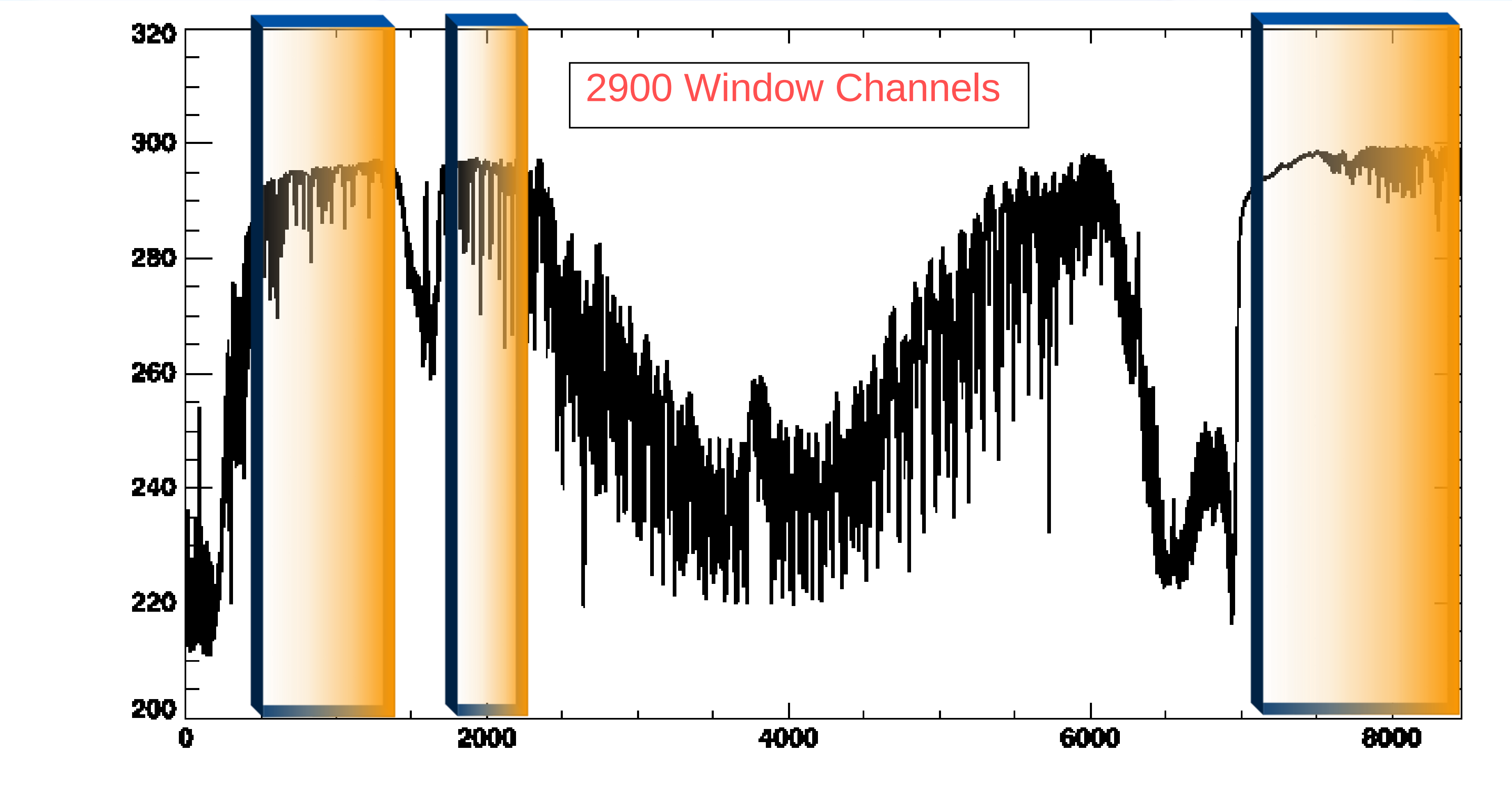
Regions of the Infrared Spectrum

Shortwave CO_2 Band



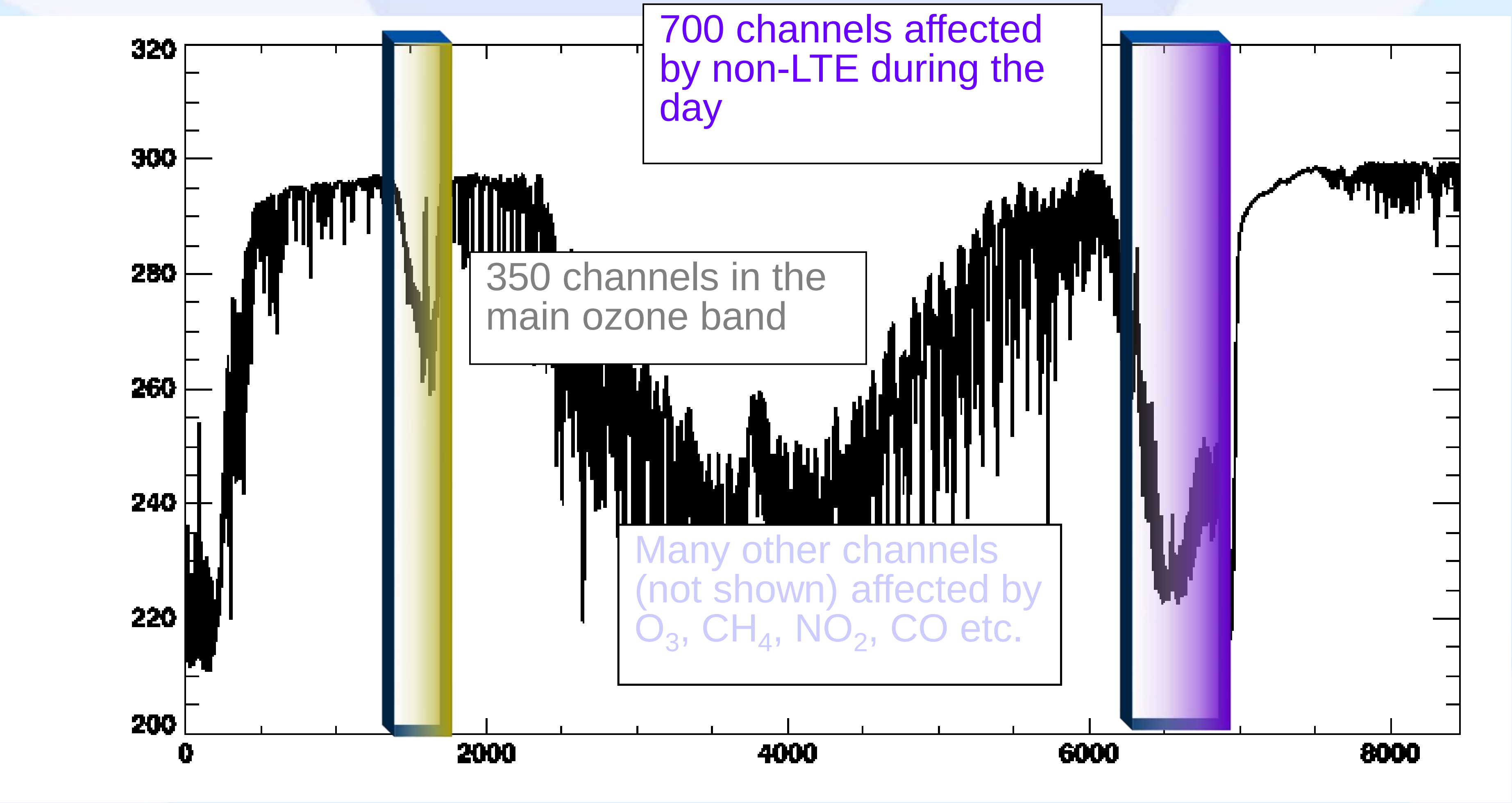
Regions of the Infrared Spectrum

Channels Primarily Sensitive to the Surface

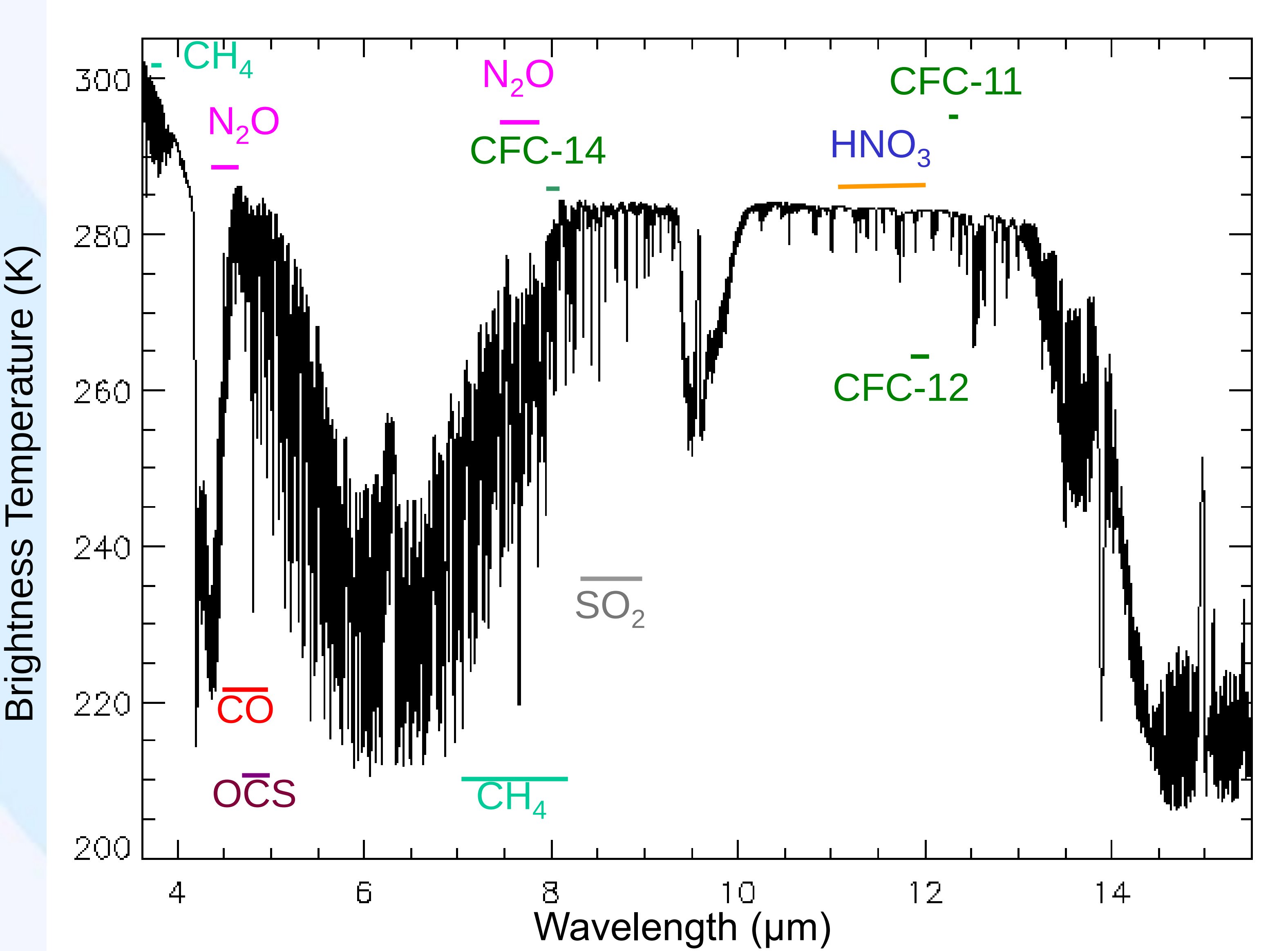


Regions of the Infrared Spectrum

Trace Gases and RT Challenges



Regions of the Infrared Spectrum
Trace Gases

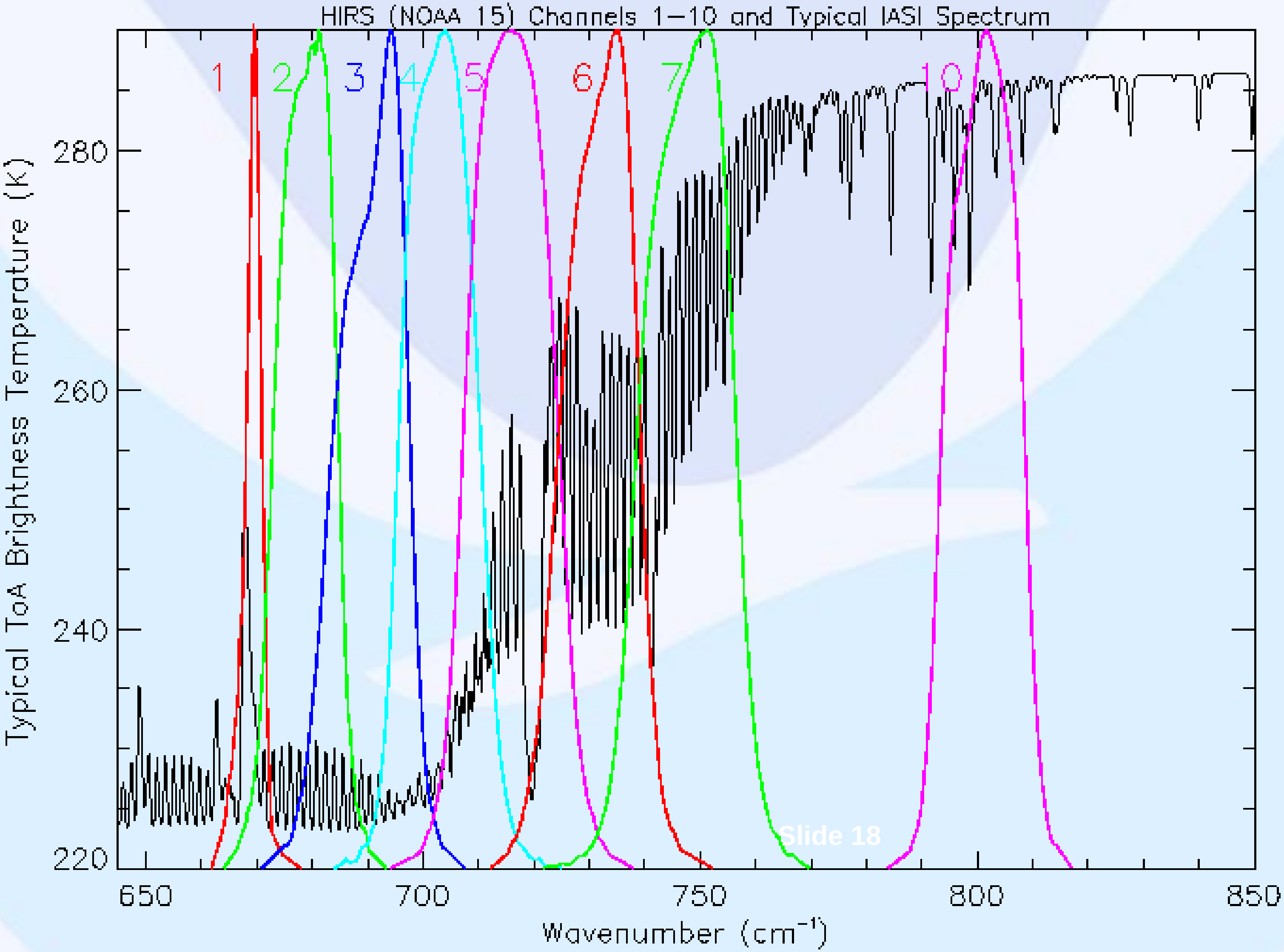


Infrared Hyperspectral Sounders and their Performance

Current and Future High-Spectral Resolution InfraRed Sounders

Instrument/ Satellite/ Launch	No. of Channels	Spectral Range	Spectral Resolution	IFOV	Type/ Orbit
AIRS/ Aqua(EOS-PM)/ May 2002	2378	650-2760cm^{-1}	~1cm^{-1}	13.5km	Grating Spectrometer/ Polar
IASI/ MetOp/ October 2006	8461	645-2760cm^{-1}	0.5cm^{-1}	12km	Interferometer/ Polar
CrIS/ NPP & JPSS/ October 2011	1400	635-2450cm^{-1}	1.125-4.5cm^{-1}	12km	Interferometer/ Polar
MTG-IRS 2018	1720	700-2175cm^{-1}	0.5-0.625cm^{-1}	4km	Interferometer/ Geostationary
IASI-NG 2021	16920	645-2760cm^{-1}	0.25 cm^{-1}	12km	Interferometer/ Polar

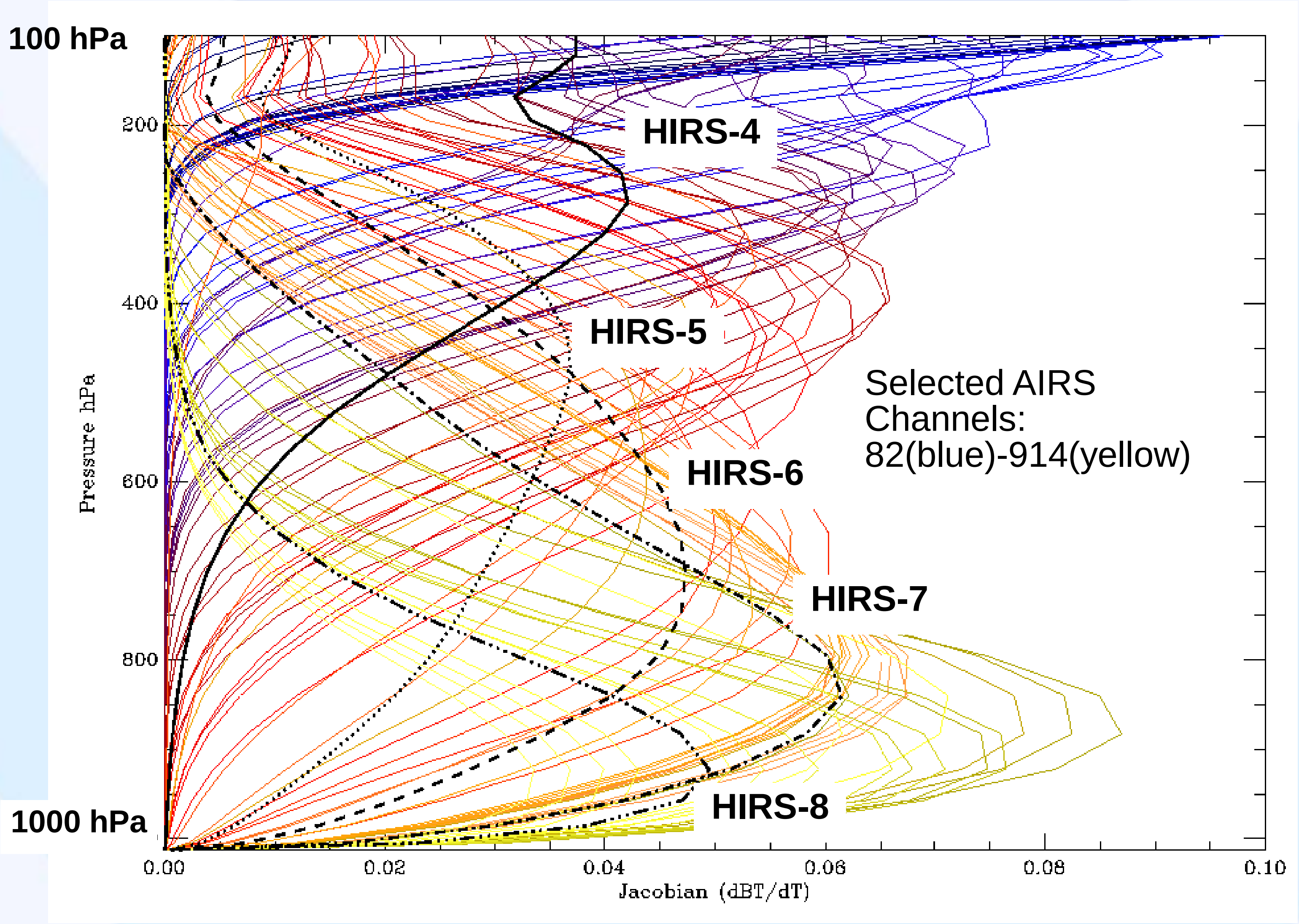
IASI vs HIRS: The Thermal InfraRed



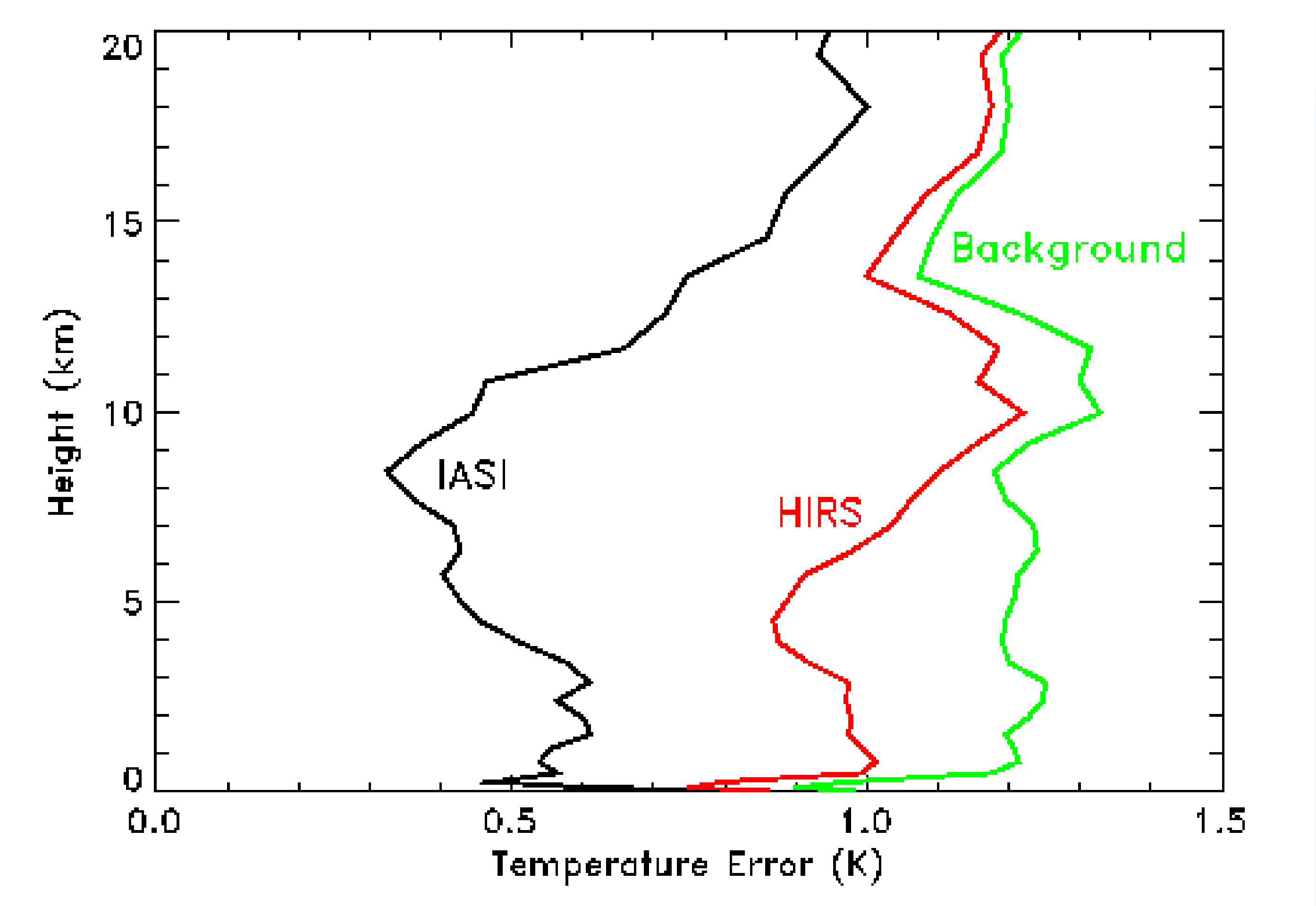
Slide 18

AIRS vs HIRS Jacobians

in the 15µm CO_2 band

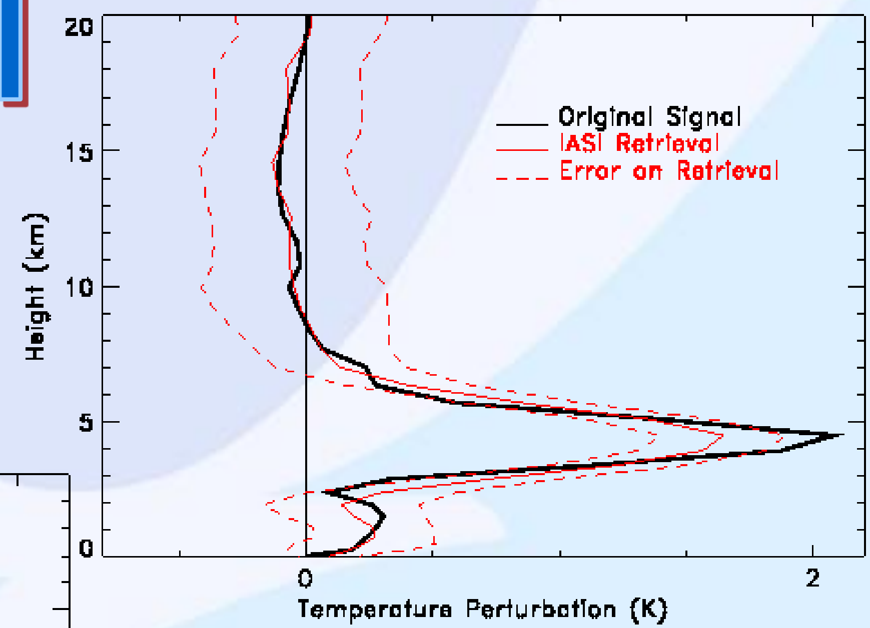


HIRS vs IASI: Temperature Retrieval Accuracy

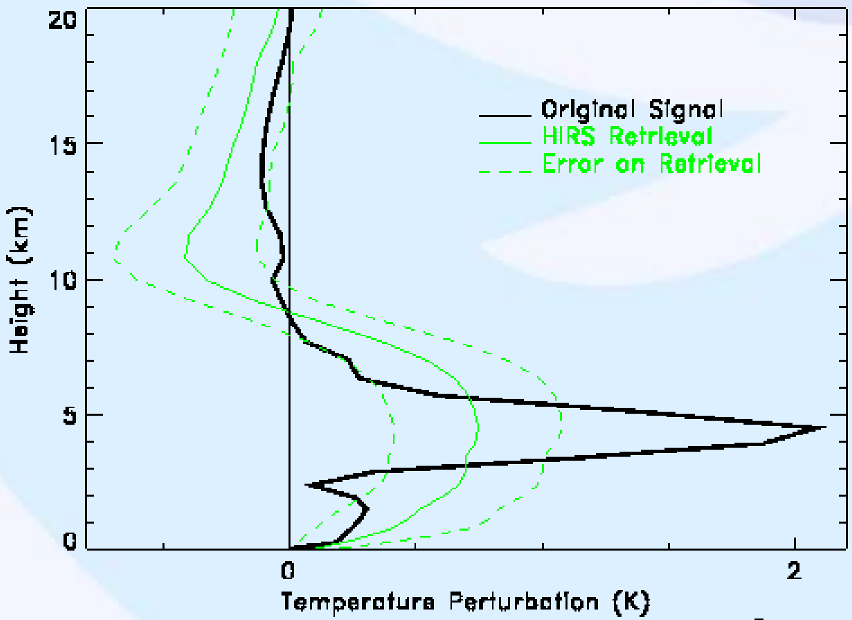


HIRS vs IASI: Response to Important Atmospheric Structure

IASI



HIRS



Response to a structure the observation of which would have improved the forecast of the reintensification of Hurricane Floyd over SW France and SW England on 12th September 1993. (Rabier et al., 1996)

Channel Selection

Why Select Channels?

The volume of hyperspectral IR data available is such that we do not have the computational resources to simulate and assimilate all these data in an operational timeframe

Not all channels are of equal use when assimilated into an NWP system

We choose channels that we wish to monitor (often with a view to future use)

We choose a subset of these channels which we actively assimilate

The following describes the channel selection performed for IASI (Collard, 2007, based on Rodgers, 2000)

IASI Channel Selection

Pre-screen channels

- Ignore channels with large contribution from un-assimilated trace gases.

Use the channel selection method of Rodgers (1996)

- Iterative method which adds each channel to the selection based on its ability to improve a chosen figure of merit (in this case degrees of freedom for signal).
- Determine the channels which contribute most information to a number of atmospheric states and view angles.
- Use multiple runs to reduce the effect of non-linearity and to focus on particular species.
- Impose additional selection criterion: No channel adjacent to one already chosen may be selected to reduce the impact of inter-channel correlated errors due to apodisation

Add extra channels that the Rogers method cannot choose

- E.g. Cloud detection channels.

IASI Channel Selection

Pre-screen channels

- Ignore channels with large contribution from un-assimilated trace gases.

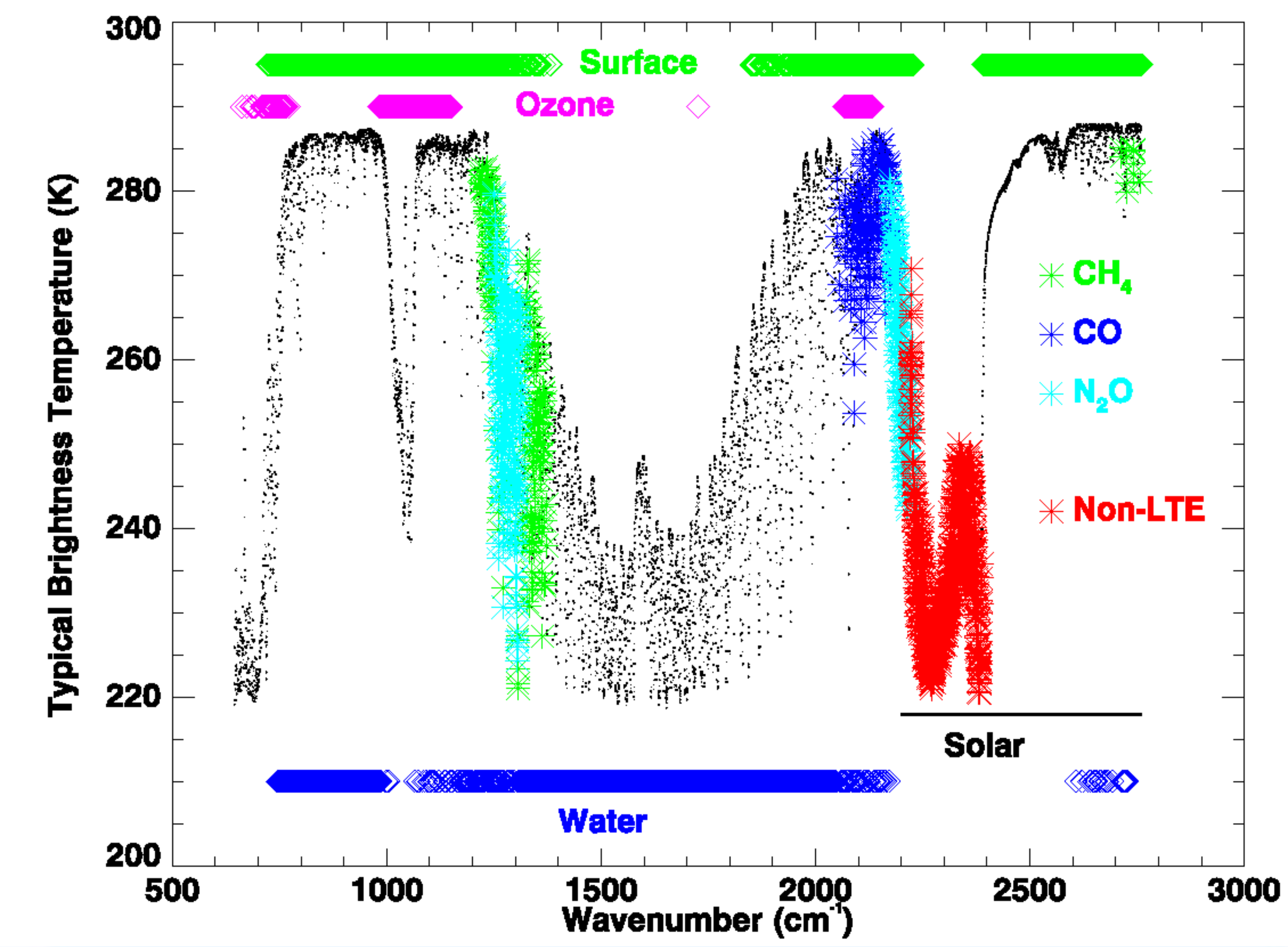
Use the channel selection method of Rodgers (1996)

- Iterative method which adds each channel to the selection based on its ability to improve a chosen figure of merit (in this case degrees of freedom for signal).
- Determine the channels which contribute most information to a number of atmospheric states and view angles.
- Use multiple runs to reduce the effect of non-linearity and to focus on particular species.
- Impose additional selection criterion: No channel adjacent to one already chosen may be selected to reduce the impact of inter-channel correlated errors due to apodisation

Add extra channels that the Rogers method cannot choose

- E.g. Cloud detection channels.

Pre-screened channels



IASI Channel Selection

- Pre-screen channels
  - Ignore channels with large contribution from un-assimilated trace gases.
- Use the channel selection method of Rodgers (1996)
  - Iterative method which adds each channel to the selection based on its ability to improve a chosen figure of merit (in this case degrees of freedom for signal).
  - Determine the channels which contribute most information to a number of atmospheric states and view angles.
  - Use multiple runs to reduce the effect of non-linearity and to focus on particular species.
  - Impose additional selection criterion: No channel adjacent to one already chosen may be selected to reduce the impact of inter-channel correlated errors due to apodisation
- Add extra channels that the Rogers method cannot choose
  - E.g. Cloud detection channels.

Figure of merit for channel selection

- Rogers (2000) suggests two possible figures of merit for channel selection:
- The degrees of freedom for signal (DFS) for the retrieval is given by:

$$DFS=Tr(\mathbf{I}-\mathbf{AB}^{-1})$$

- and, the entropy reduction

$$ER=-\tfrac{1}{2}Ln|\mathbf{AB}^{-1}|$$

- Past experience has shown very similar results from these and in this study the former is used.

Efficient calculation of A-matrix

- The Rogers (2000) channel selection technique requires repeated calculation of the A matrix every time a new channel is being tested. Rogers notes that for a diagonal observation error covariance, the change in A matrix on adding a new channel *i* is calculated efficiently thus:

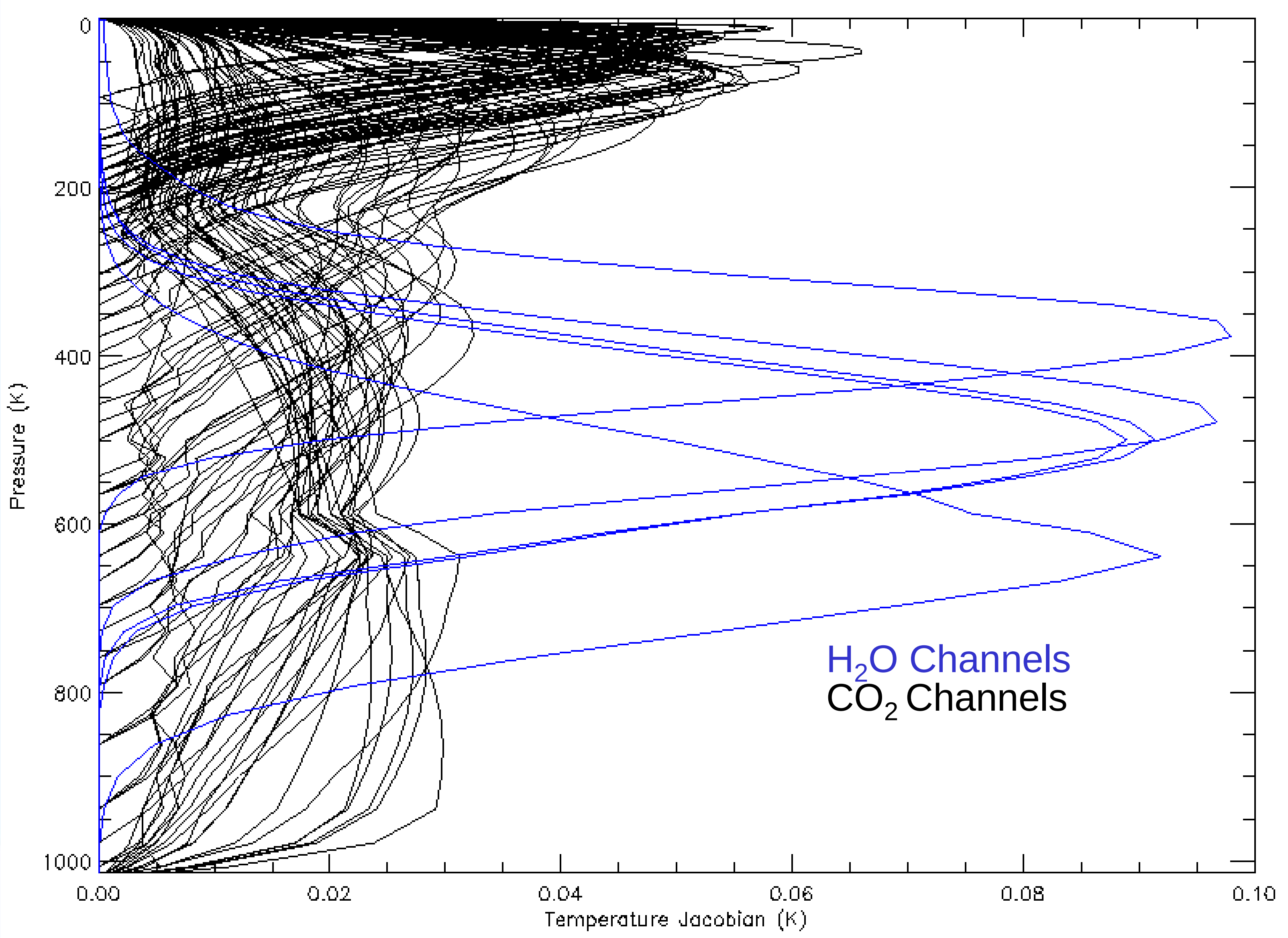
$$\mathbf{A}_{i-1} = \mathbf{A}_{\mathbf{i}-1}\left(1 + \frac{\mathbf{h}_{\mathbf{i}}(\mathbf{A}_{\mathbf{i}-1}\mathbf{h}_{\mathbf{i}})^{T}}{1+(\mathbf{A}_{\mathbf{i}-1}\mathbf{h}_{\mathbf{i}})^{T}\mathbf{h}_{\mathbf{i}}}\right)$$

- where h_i is the Jacobian of the *i*th channel in observation noise-normalised units.

IASI Channel Selection

- Pre-screen channels
  - Ignore channels with large contribution from un-assimilated trace gases.
- Use the channel selection method of Rodgers (1996)
  - Iterative method which adds each channel to the selection based on its ability to improve a chosen figure of merit (in this case degrees of freedom for signal).
  - Determine the channels which contribute most information to a number of atmospheric states and view angles.
  - Use multiple runs to reduce the effect of non-linearity and to focus on particular species.
  - Impose additional selection criterion: No channel adjacent to one already chosen may be selected to reduce the impact of inter-channel correlated errors due to apodisation
- Add extra channels that the Rogers method cannot choose
  - E.g. Cloud detection channels.

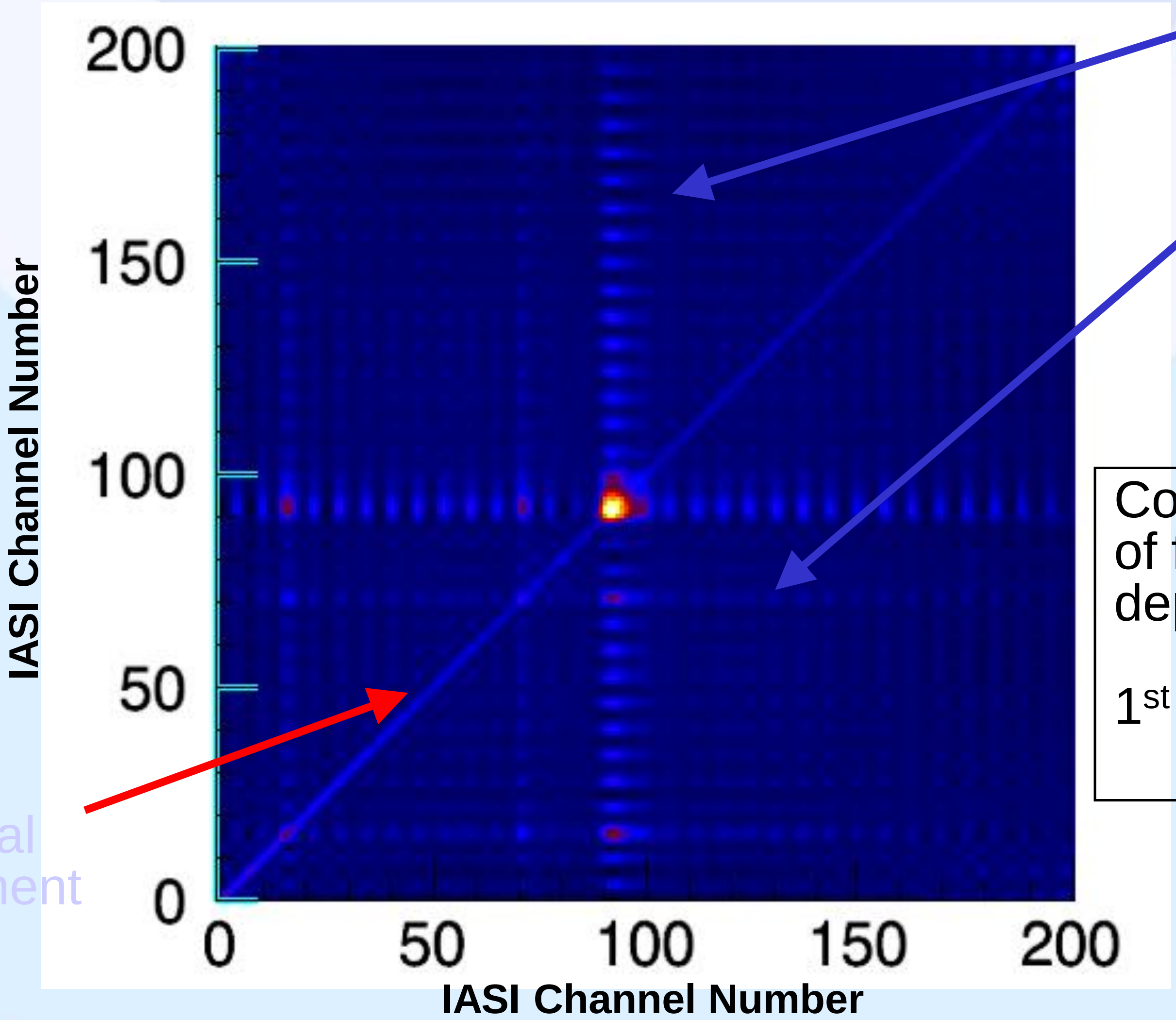
Temperature Jacobians of Used Channels



IASI Channel Selection

- Pre-screen channels
  - Ignore channels with large contribution from un-assimilated trace gases.
- Use the channel selection method of Rodgers (1996)
  - Iterative method which adds each channel to the selection based on its ability to improve a chosen figure of merit (in this case degrees of freedom for signal).
  - Determine the channels which contribute most information to a number of atmospheric states and view angles.
  - Use multiple runs to reduce the effect of non-linearity and to focus on particular species.
  - Impose additional selection criterion: No channel adjacent to one already chosen may be selected to reduce the impact of inter-channel correlated errors due to apodisation
- Add extra channels that the Rogers method cannot choose
  - E.g. Cloud detection channels.

IASI Spectral Correlation



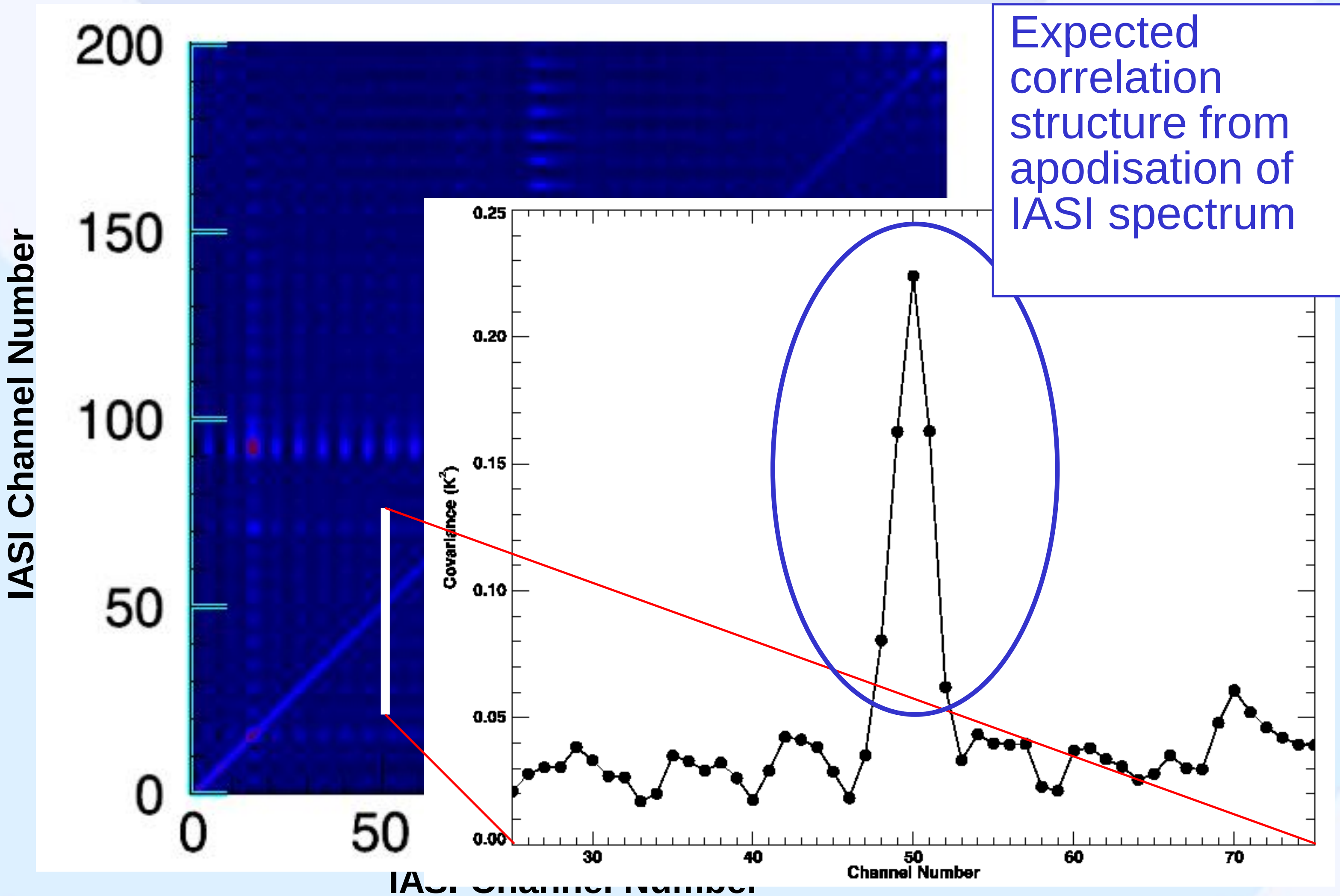
Correlations from forecast model

Covariance of first-guess departures

1^{st} 200 channels

Nearly diagonal instrument noise

IASI Spectral Correlation



Expected correlation structure from apodisation of IASI spectrum

Selected Channels (1)

30 channels chosen from 15µm CO_2 band considering temperature assimilation only

36 channels from 707-760cm^{-1} region – found to be particularly important when assimilating AIRS.

252 channels considering temperature and water vapour together

15 ozone channels

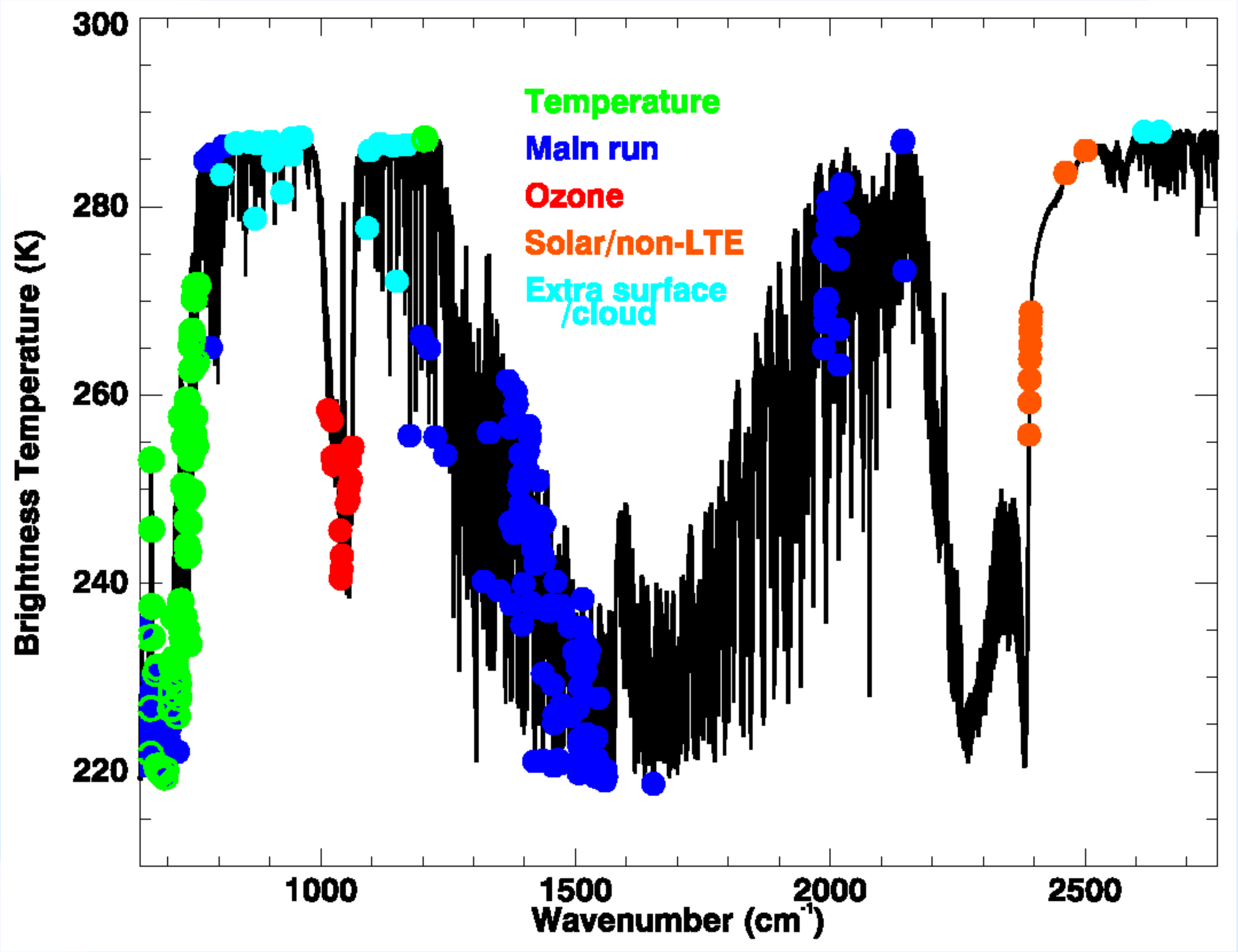
13 Channels in the solar-affected shortwave region

In ECMWF selection only:

22 channels used for monitoring (HIRS analogues and requested by CNES)

Another 44 channels in the 707-760cm^{-1} region

Selected Channels (2)



Improved treatment of correlated error

- In their 2013 paper, Ventress and Dudhia, are able to extend the calculation of the A matrix – and thus the degrees of freedom for signal – to the more realistic situation where the assumed observation error covariance is diagonal but the real error covariance is correlated.
- This allows one, for example, to explicitly allow for the correlated observation error term arising from uncertain molecular abundances and for channels to be chosen that are more robust against these sources of error.

Extension to cloudy scenes

- Martinet et al. (2014) has extended the selection of 366 IASI channels that are currently used to 500, with the other channels being chosen based on their use in obtaining cloud properties with particular reference to the AROME regional model.
  - A range of situations covering low liquid clouds, opaque ice clouds and semi-transparent ice clouds were considered with RTTOV-CLD used to generate the spectra.
- Migliorini is also considering channel selection in cloudy situations, with particular focus on correlated observation errors and a flow-dependent estimate of forecast uncertainty.

Extension to reconstructed radiances.

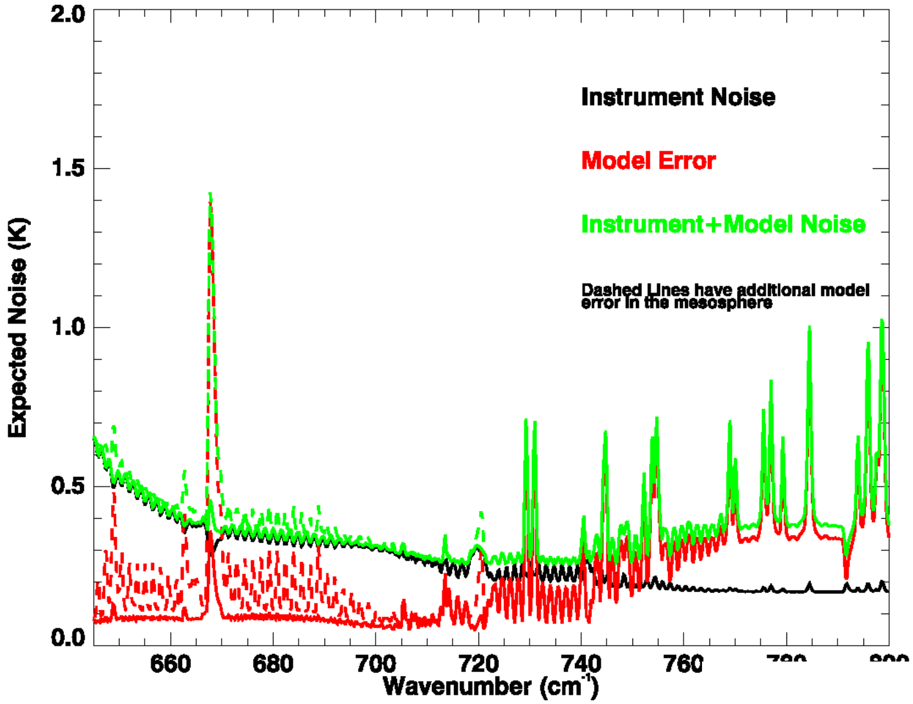
- As part of her thesis work, Fiona Hilton has considered channel selection in the context of reconstructed radiances.
- The transformation of instrument noise into reconstructed radiances will result in a singular R-matrix. We therefore need to consider whether the R-matrix associated with a particular channel selection is suitably well-conditioned.

More efficient ways of representing the spectrum

- It is often pointed out that channel selection where we select ~5-10% of the channels for monitoring and even fewer for assimilation is an inefficient way of representing the hyperspectral infrared spectrum.
- More sophisticated methods such as Principal Component Analysis and Reconstructed Radiances will be the subject of the following talk by Marco Matricardi.

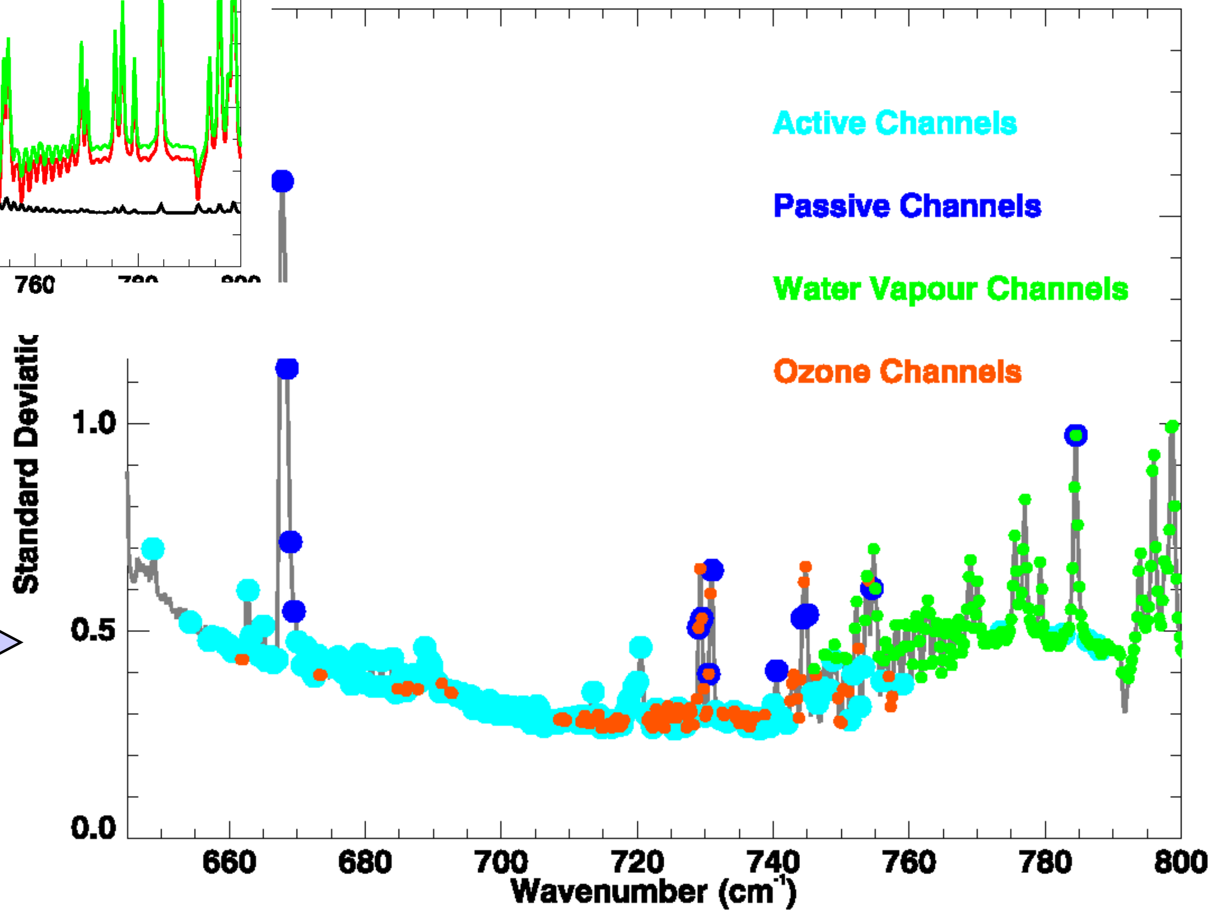
O-B Comparisons

First –Guess Departure Standard Deviations in 15µm CO_2 Band

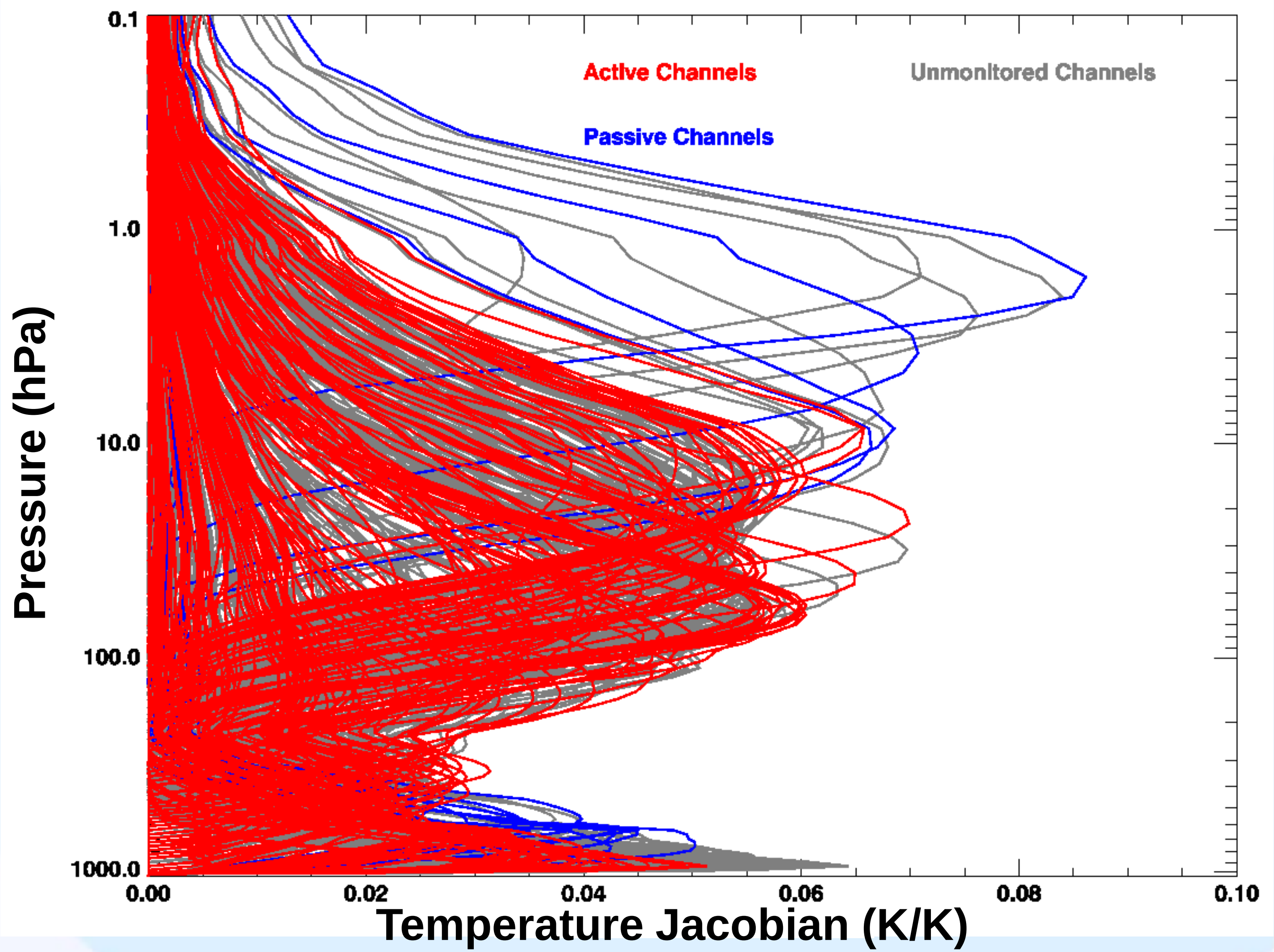


Calculated Std. Dev.

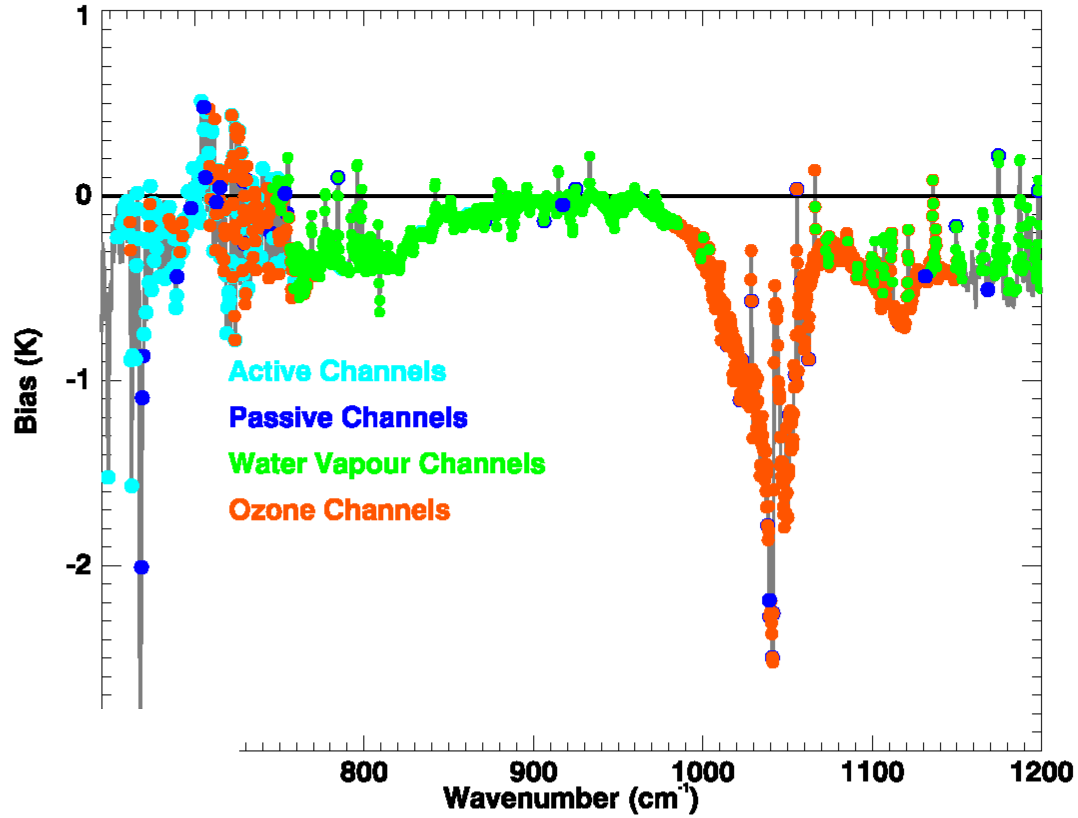
Observed Std. Dev.

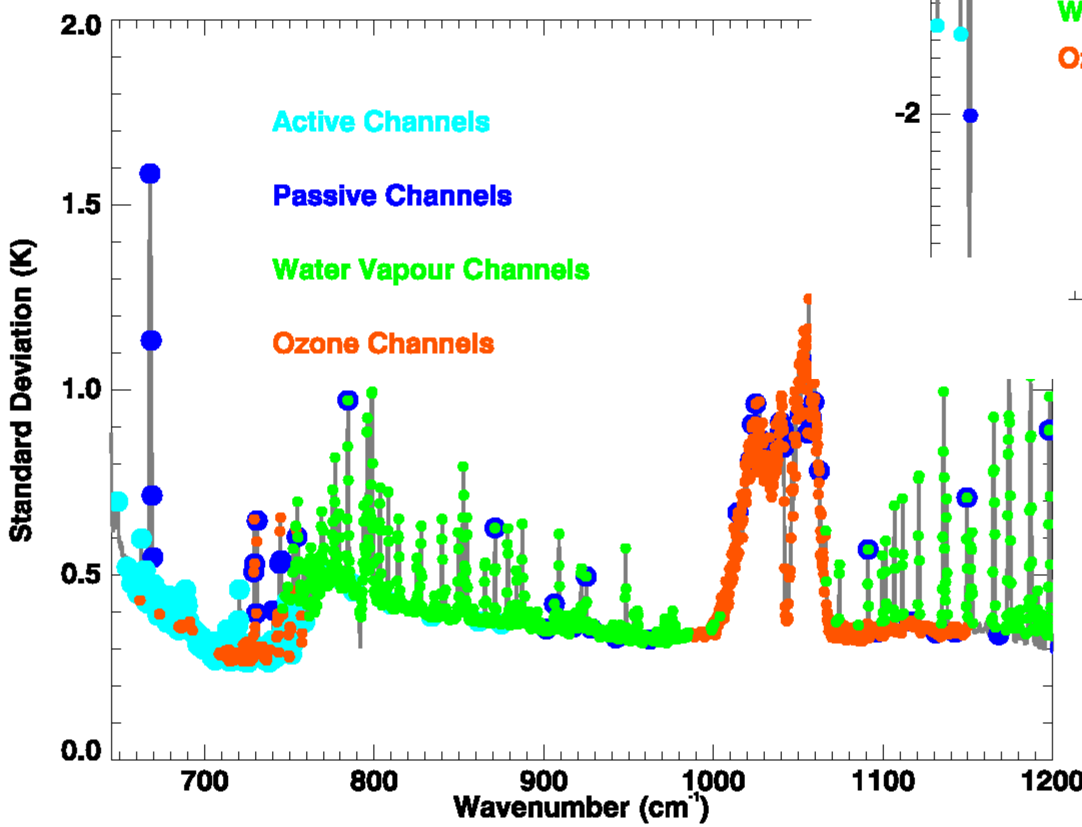


Jacobians of 15µm CO_2 Band



First Guess Departure Standard Deviations and Biases in the Longwave Window

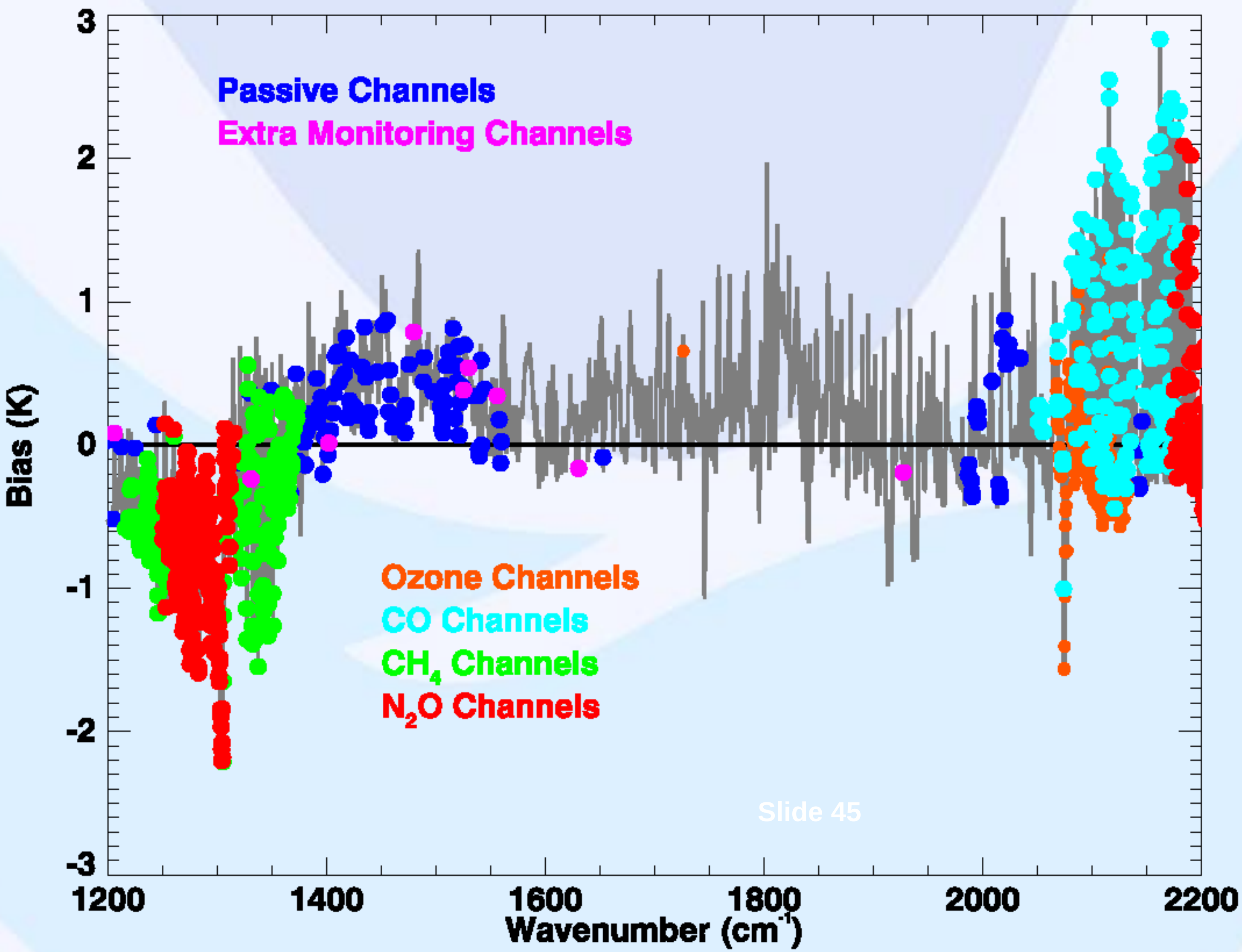




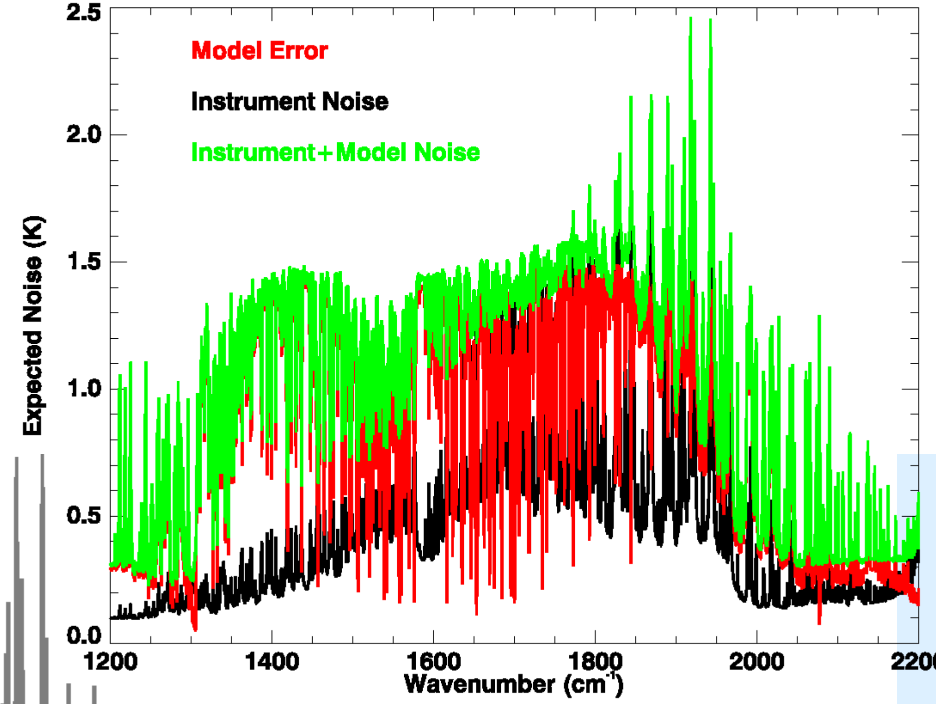
Bias

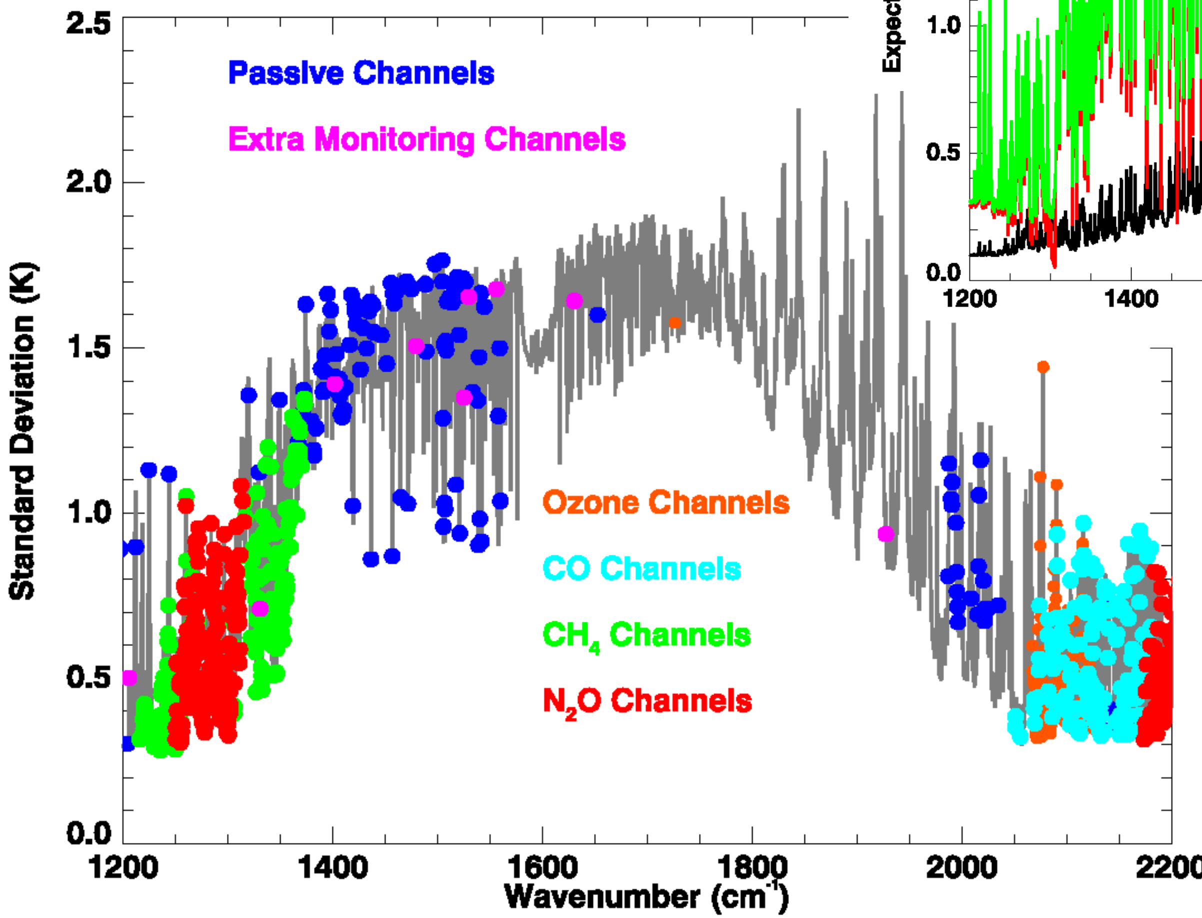
Standard Deviation

First-Guess Departure Biases in Water Band



First –Guess Departure Standard Deviations in Water Band

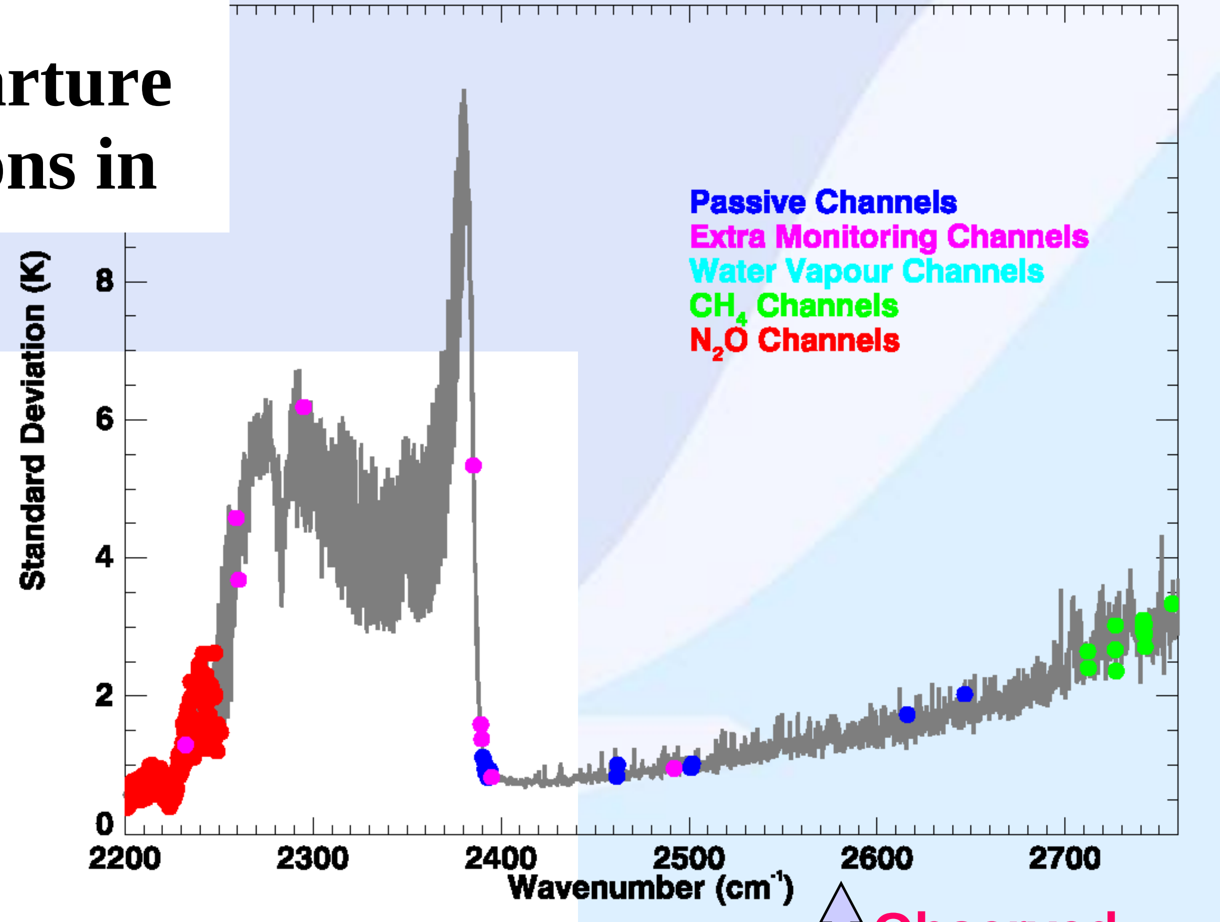


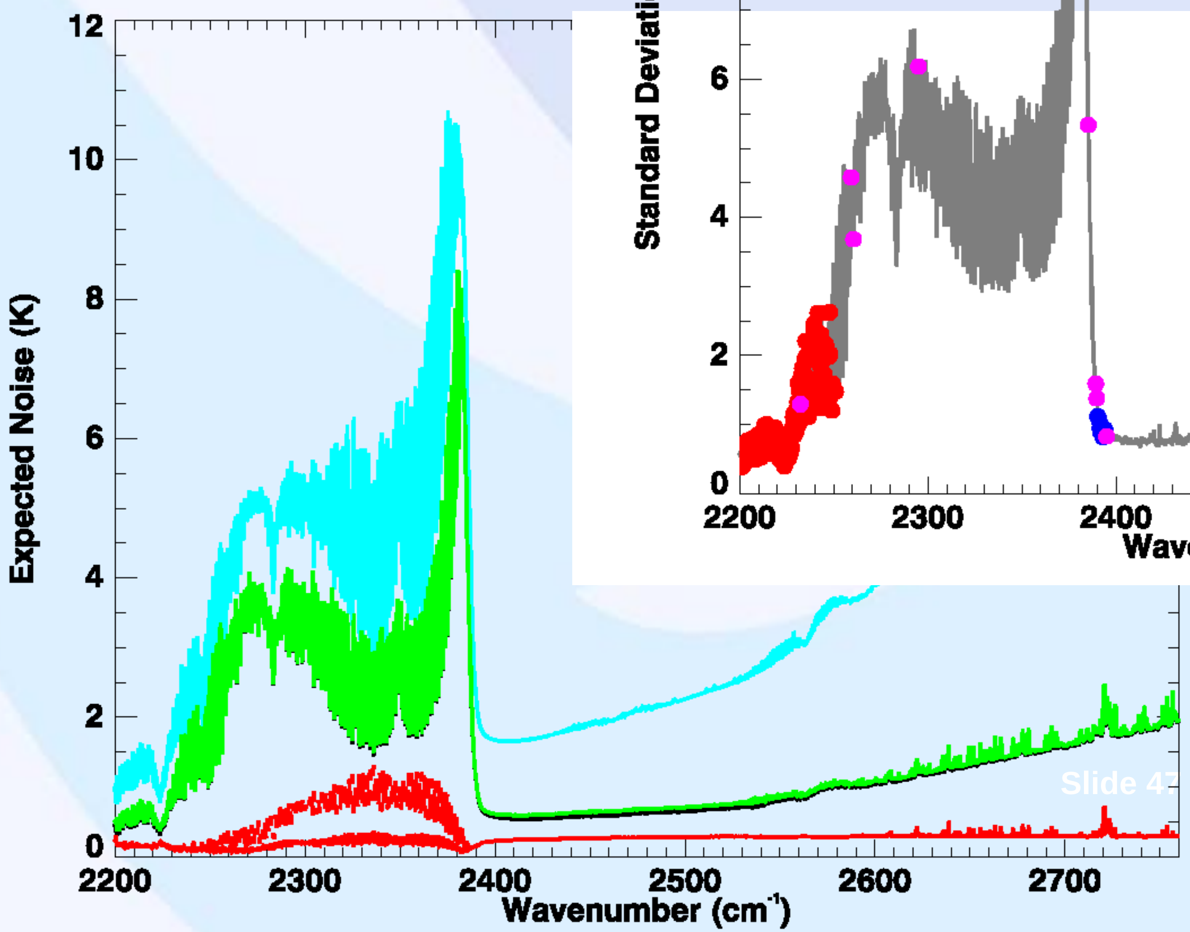


Calculated Std. Dev.

Observed Std. Dev.

First –Guess Departure Standard Deviations in Shortwave Band





Clouds

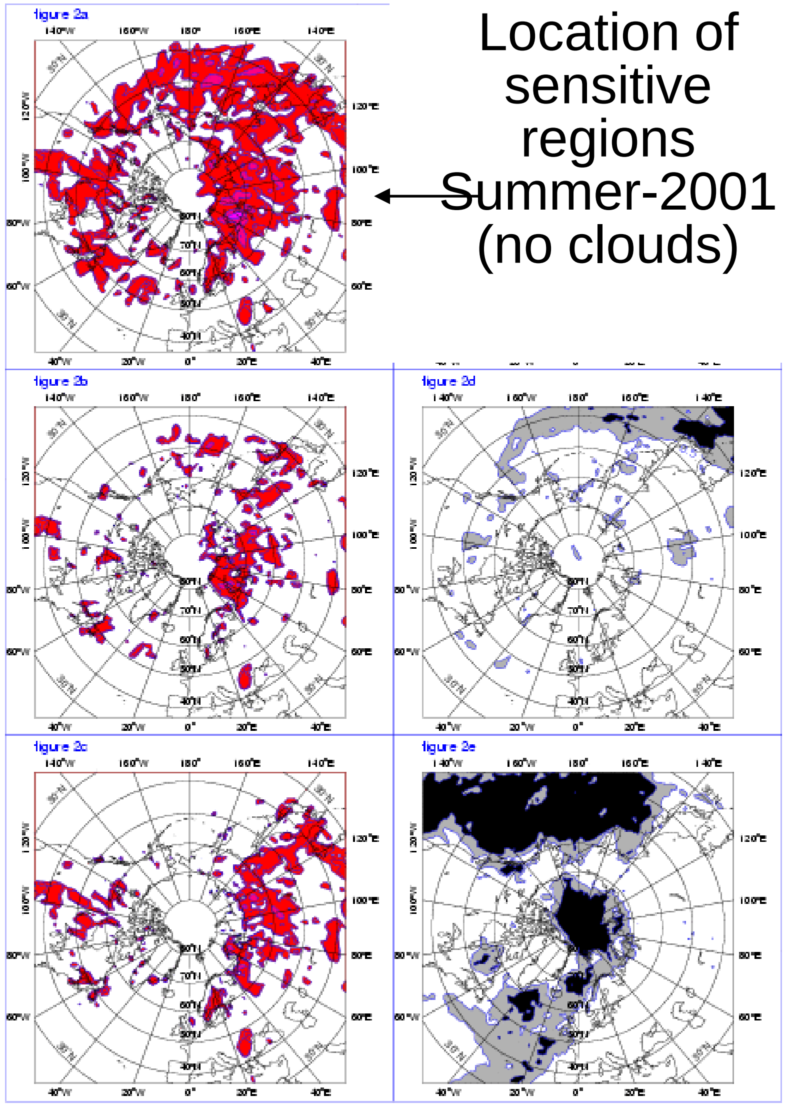
Slide 48

Dealing with Cloud

Cloud can be treated in five ways:

1) Avoid all FOVs with cloud (“hole hunting”)
2) Only assimilate channels that are insensitive to cloud
3) Correct the observations to remove the effect of clouds (“cloud-clearing”)
4) Explicitly model the effect of cloud on the radiances either during pre-processing or as a sink variable. But DO NOT assimilate the cloud properties.
5) Initialise model cloud variables from the cloudy radiances.

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

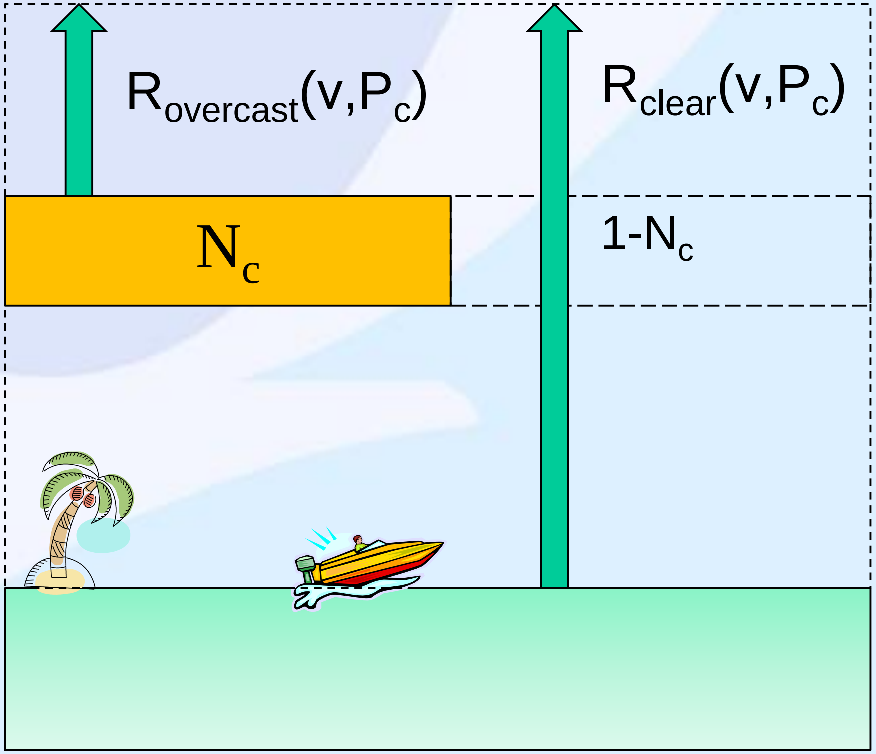
monthly mean **low** cloud cover

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

Eyre and Menzel, 1989

Cloud Detection in the GSI

- Assume the cloud is a single layer at pressure P_c and with unit emissivity and coverage within the FOV, N_c.
- $0 \le N_c \le 1$
- P_c is below the tropopause and above the ground
- Find P_c and N_c so that the RMS deviation, $J(N_c,P_c)$, of the calculated cloud from the model (over a number of channels) is minimized.
- Remove all channels that would be radiatively affected by this cloud.



$$R_{cld}(v,P_c)=N_c R_{overcast}(v,P_c)+(1-N_c)\ R_{clear}(v,P_c)$$

$$J(N_c,P_c)=\Sigma v\ (R_{cld}(v,P_c)-R_{obs}(v)/\sigma(v))^2$$

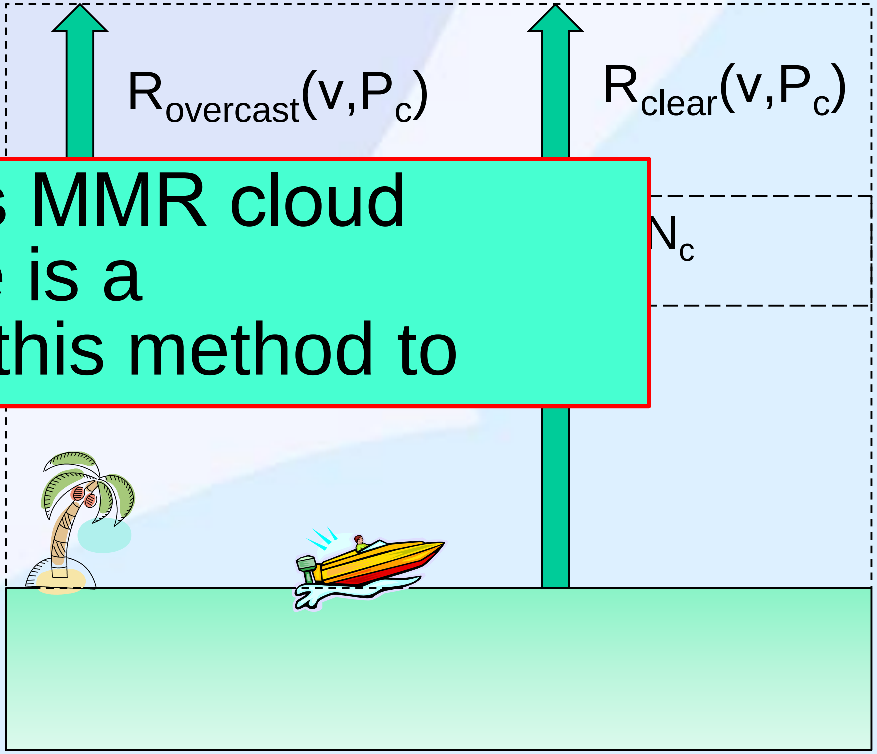
$\sigma(v)$ is the assumed observation error for channel v
This calculation should be done in radiance, not brightness temperature space.

Eyre and Menzel, 1989

Cloud Detection in the GSI

- Assume the cloud is a single layer at pressure P_c and with unit emissivity and coverage within the FOV, N
- $0 \le N_c \le 1$
- P_c is belo… above the…
- Find P_c a… deviation, … calculated cloud from the model (over a number of channels) is minimized.
- Remove all channels that would be radiatively affected by this cloud.

Thomas Auligne's MMR cloud detection scheme is a generalisation of this method to multi-level clouds



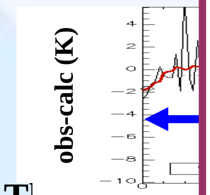
$R_{cld}(v,P_c)=N_c R_{overcast}(v,P_c)+(1-N_c)\ R_{clear}(v,P_c)$

$J(N_c,P_c)=\Sigma v\ (R_{cld}(v,P_c)-R_{obs}(v)/\sigma(v))^2$

$\sigma(\nu)$ is the assumed observation error for channel v
This calculation should be done in radiance, not brightness temperature space.

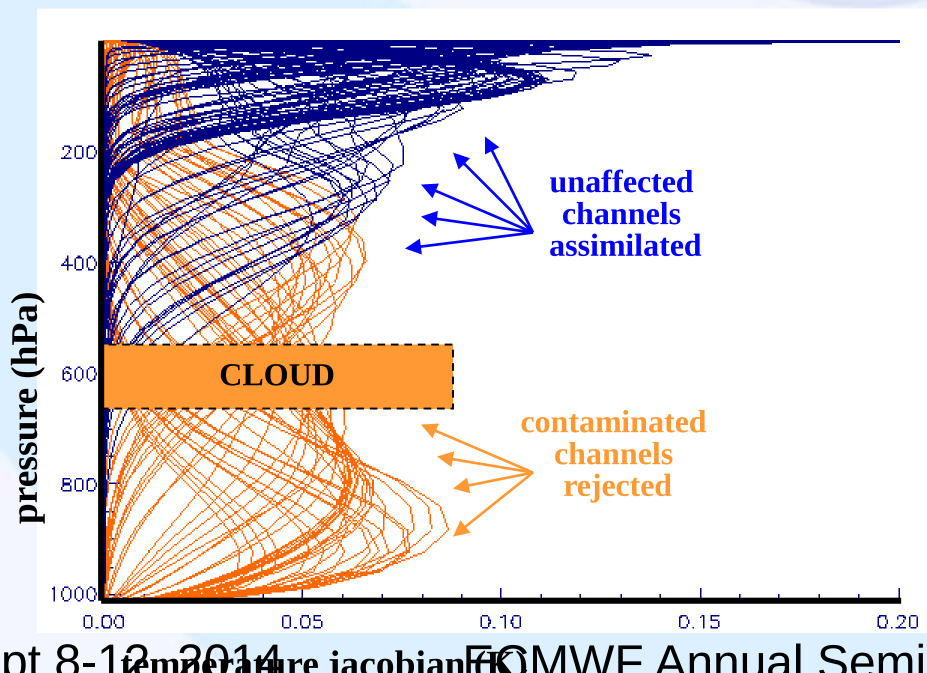
Cloud detection scheme for Advanced Sounders

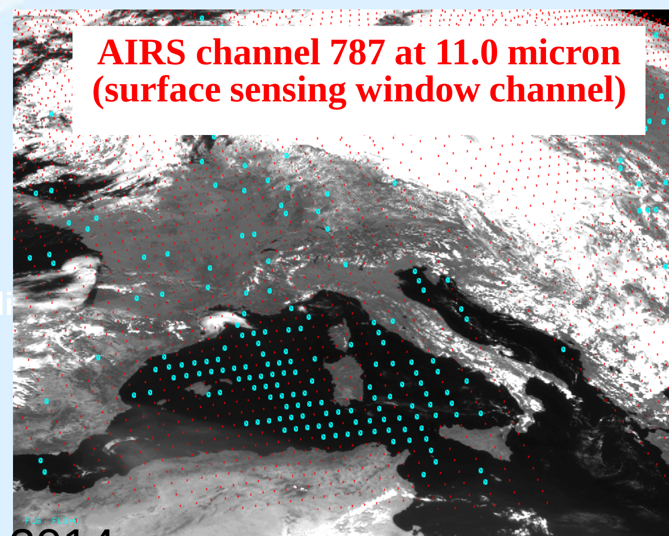
A non-linear pattern recognition algorithm is applied to departures of the observed radiance spectra from a computed clear-sky background spectra.



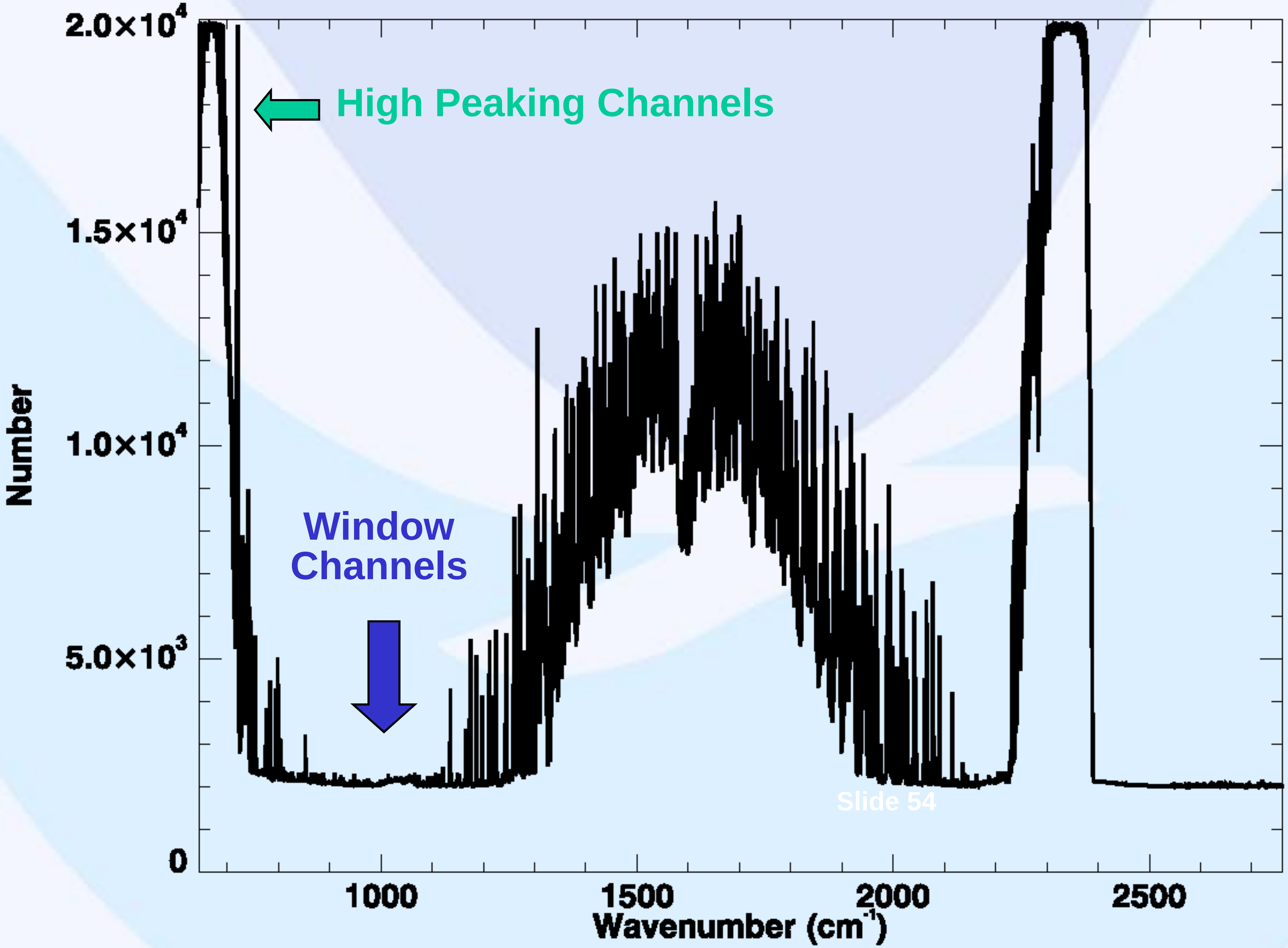
This identi… data and al…

The large number of AIRS or IASI channels allows improved measurement of the cloud-top height compared to HIRS



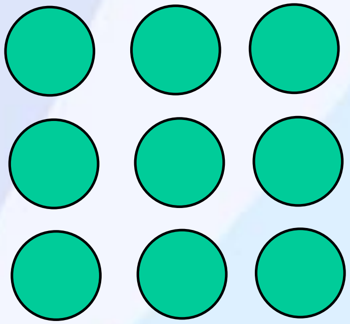


Number of Clear Channels



Cloud Cleared Radiances

Cloud Cleared Radiances derive a single “clear” spectrum from an array of partially cloudy fields-of-view (9 in the case of AIRS and CrIS)



Assumes the cloud height in each FOV is identical and only cloud fraction varies between the FOVs.

Needs to be initialised with a high quality first guess, usually either a regression from AMSU-A radiances or an NWP model field.

Can calculate a noise amplification factor which is the basis of the QC flag

Cloud-clearing methodology

Following Chahine (1977) and Joiner and Rokke (2000), the observed radiance at channel i from field of view (FOV) j can be written as

$$R_j^i = \left(1 - \sum_{k=1}^{K} \boldsymbol{\alpha}_{j,k}\right) \times R_{clr}^i + \sum_{k=1}^{K} \boldsymbol{\alpha}_{j,k} \times R_{cld}^{i,k}$$

$\boldsymbol{\alpha}_{j,k}$ is the cloud type k fraction in FOV j, R_{clr}^i is the clear-sky radiance at channel i and $R_{cld}^{i,k}$ is the radiance at channel i from the cloud type k with fraction $\boldsymbol{\alpha}_{j,k}$.

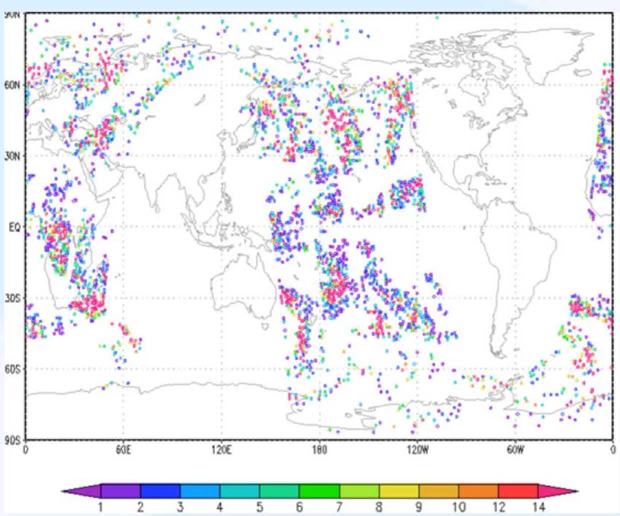
The cloud-cleared radiance can be derived if assuming R_{clr}^i and $R_{cld}^{i,k}$ are the same in the 3x3 FOVs in a single CrIS field of regard (FOR) and eliminating $R_{cld}^{i,k}$,

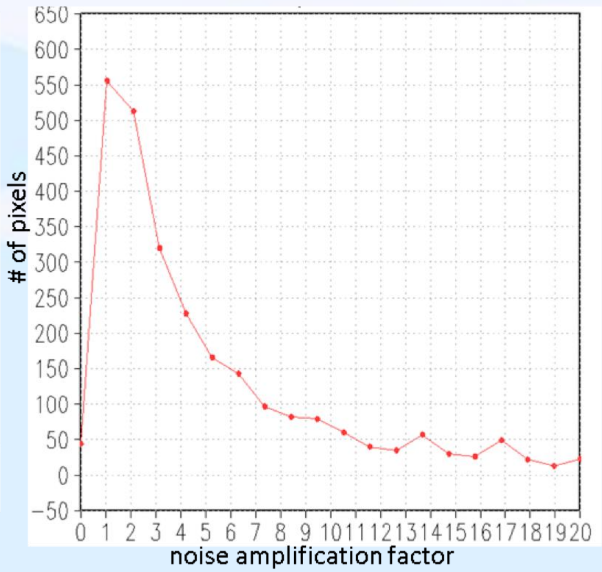
$$R_{ccr}^i = R_1^i + \boldsymbol{\eta}_1 \times \left(R_1^i - R_2^i\right) + \boldsymbol{\eta}_2 \times \left(R_1^i - R_3^i\right) + \cdots + \boldsymbol{\eta}_k \times \left(R_1^i - R_{k+1}^i\right)$$

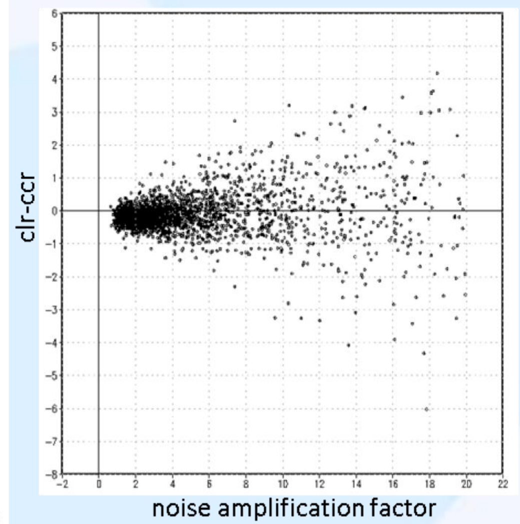
$\boldsymbol{\eta}_k$ are the cloud-clearing parameters. They depend on the cloud fraction $\boldsymbol{\alpha}_{j,k}$ only, so they are channel-independent. These parameters can be solved by using model guess simulated clear-sky radiances and observed radiances in adjacent pixels at cloud sounding channels in a least-square sense.

Noise amplification factor

The reconstructed clear-column radiances will be treated as other IR clear-sky radiances when being assimilated except for amplifying the observation error by a factor of $A = \sqrt{\left(1 + \sum_{k=1}^{K} \eta_k\right)^2 + \sum_{k=1}^{K} \eta_k^2}$.



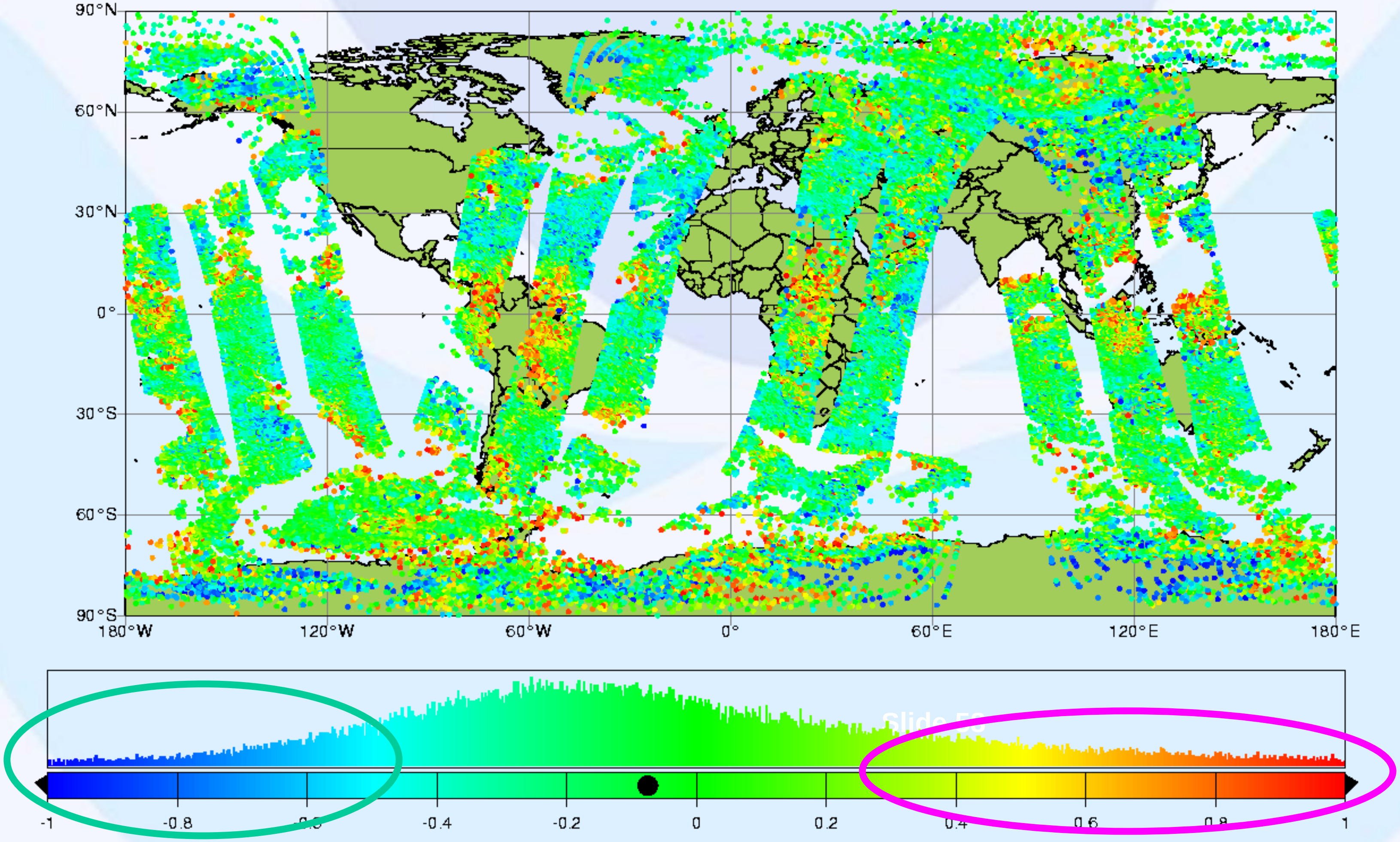




Haixia Liu

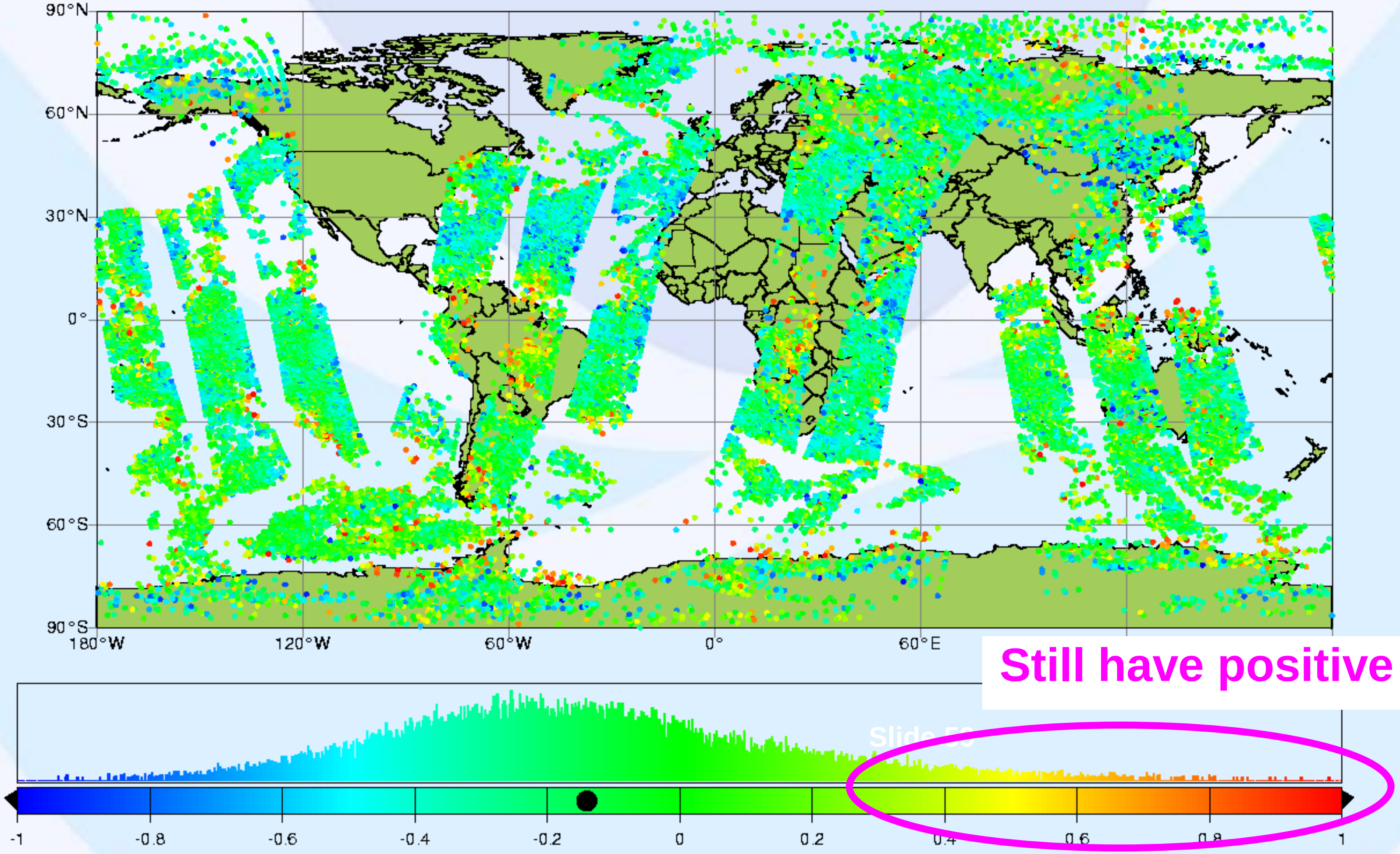
Cloud-Cleared Radiances

AIRS Ch. 221. QC Flag Used. No Cloud Detection



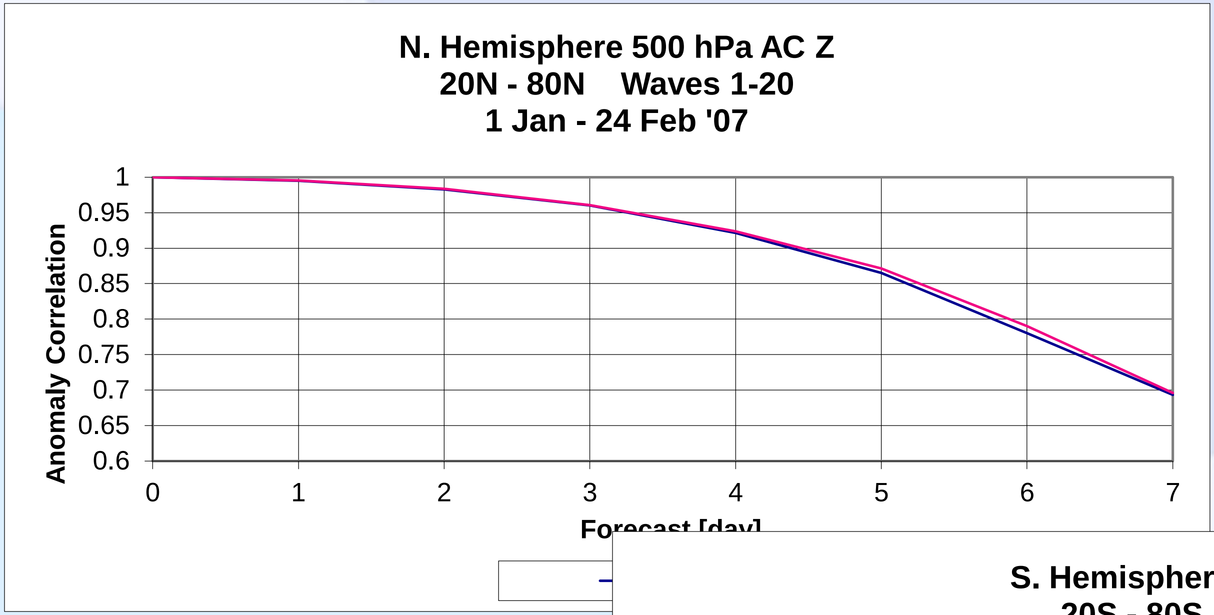
Cloud Cleared Radiances

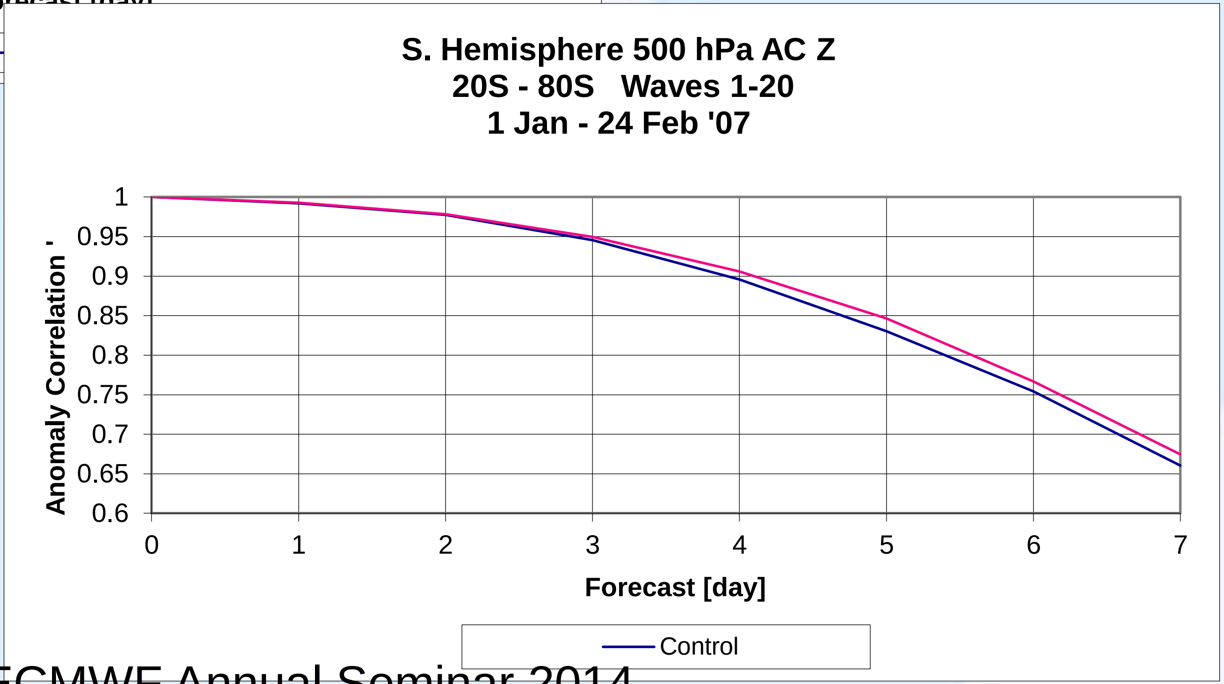
AIRS Ch. 221. QC Flag Used. With Cloud Detection



Still have positive tail

Impact of CCRs on Forecast?





Results from Jim Jung using NCEP GFS model.

Simultaneous Analysis of Cloud Properties (Tony McNally)

Derive a cloud-top pressure (CTP) and cloud fraction from observed radiances with a 2-D least-squares fit in the screening run

For overcast FOVs use all channels (that are currently used for clear sky case)

This has the advantage of reducing the degrees of freedom

For other FOVs revert to operational cloud-detection scheme to identify clear channels

Assimilate these radiances with CTP as a sink variable

Using data in cloudy areas

Tony McNally

Clear data coverage of mid/lower tropospheric sounding radiances:

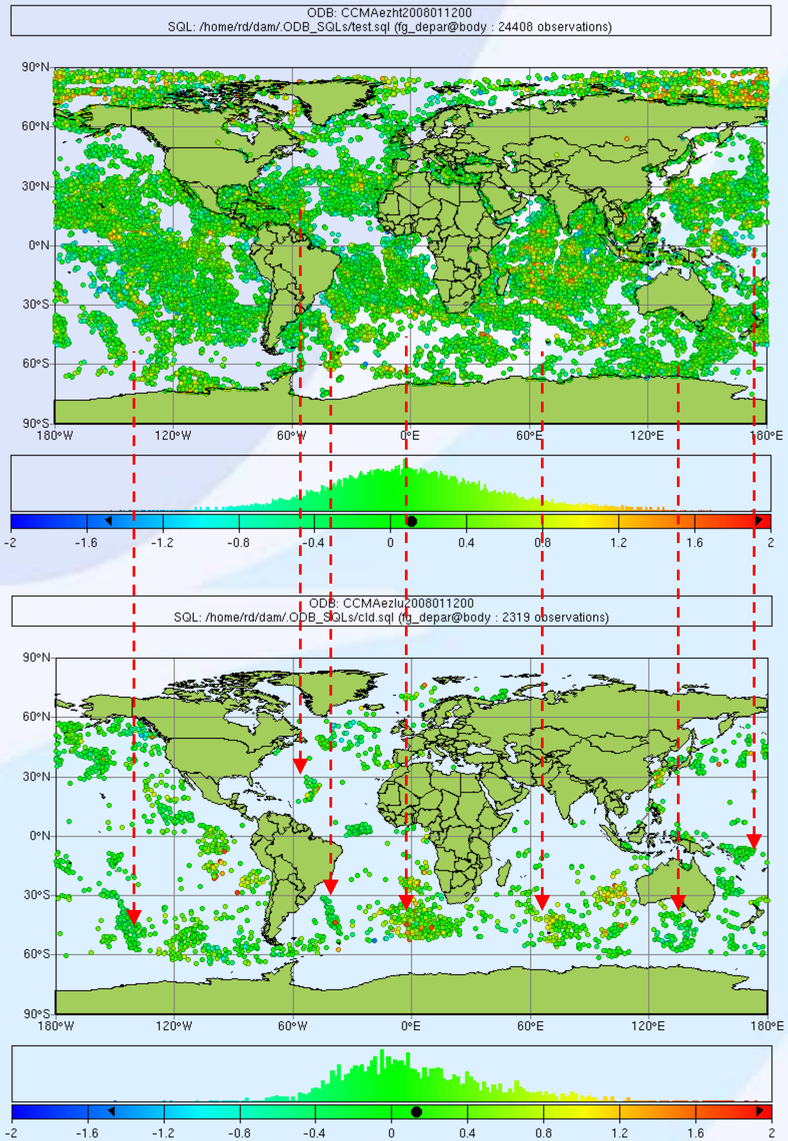
IASI 434 (METOP-A)
AIRS 355 (AQUA)
HIRS 7 (NOAA-17 / METOP-A)

Colour indicates first guess departure

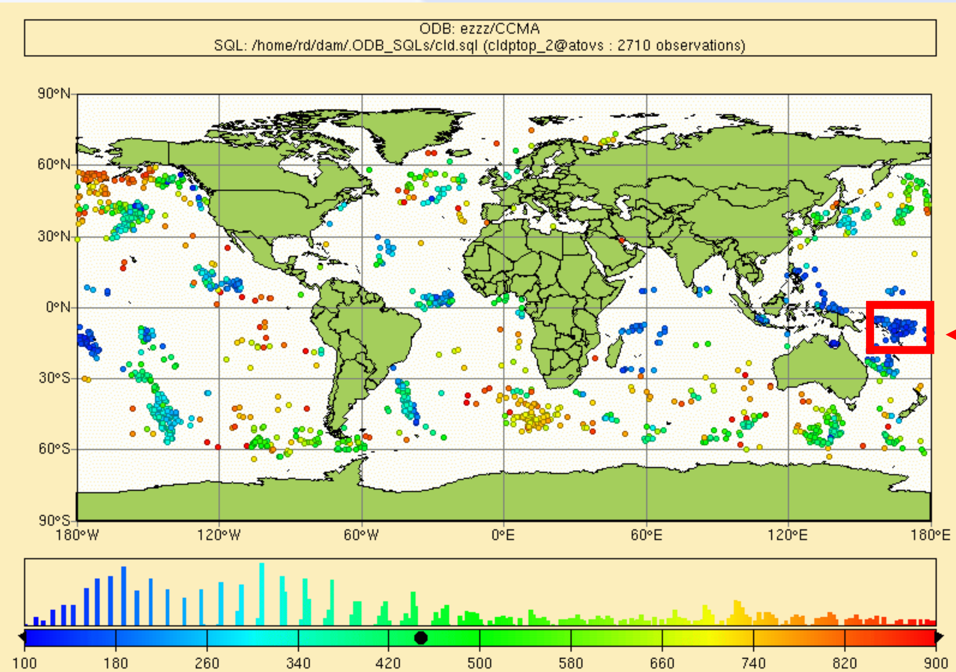
Additional overcast locations where cloudy radiance analysis fills gaps due to cloud detection rejections:

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

First guess departures similar to clear data after QC of *complex* clouds



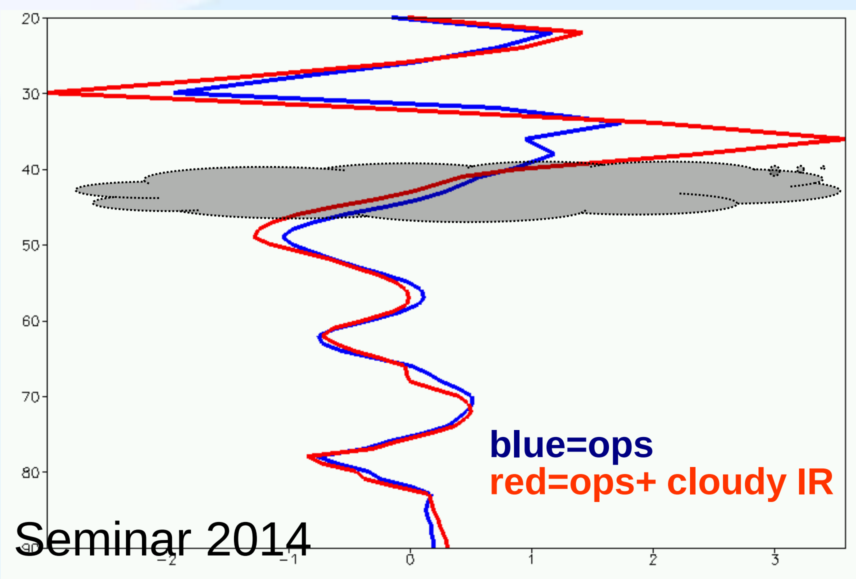
Temperature increments at the cloud top



Tony McNally

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

Direct Assimilation of IR Cloudy Radiances

- The direct use of the cloudy information in IR cloudy radiances is the ultimate aim. A number of centres are starting to get encouraging results in this area.
- The main challenges are:
  - Non-linearity of the observation operator (particularly for opaque clouds where the Jacobian is essentially a delta-function at the cloud top).
  - Radiative transfer accuracy
  - Partially cloudy scenes
  - Propagation of cloudy errors into other fields (such as temperature).

Direct Assimilation of IR Cloudy Radiances

- Pauline Martinet is exploring the direct assimilation of IR radiances in the AROME model. Analyses are limited to schemes where the model and observations agree that the cloud field is homogeneous. Some initial encouraging results.
- Stefano Migliorini has shown positive impact through the assimilation of cloudy radiances in the ECMWF IFS. To minimize the risk of cloudy signal adversely affecting the temperature field, this work focuses on the use of humidity-sensitive channels.

Humidity Assimilation

Humidity assimilation (1)

Some centres have demonstrated positive impact from assimilating H2O channels (with reduced weight) to the analysis and 1-2 day forecast

NWP models have a hard time keeping impact of assimilation after 1-2 days.

Ambiguity with humidity Jacobians - the water vapor (WV) channels have strong sensitivity to humidity and temperature

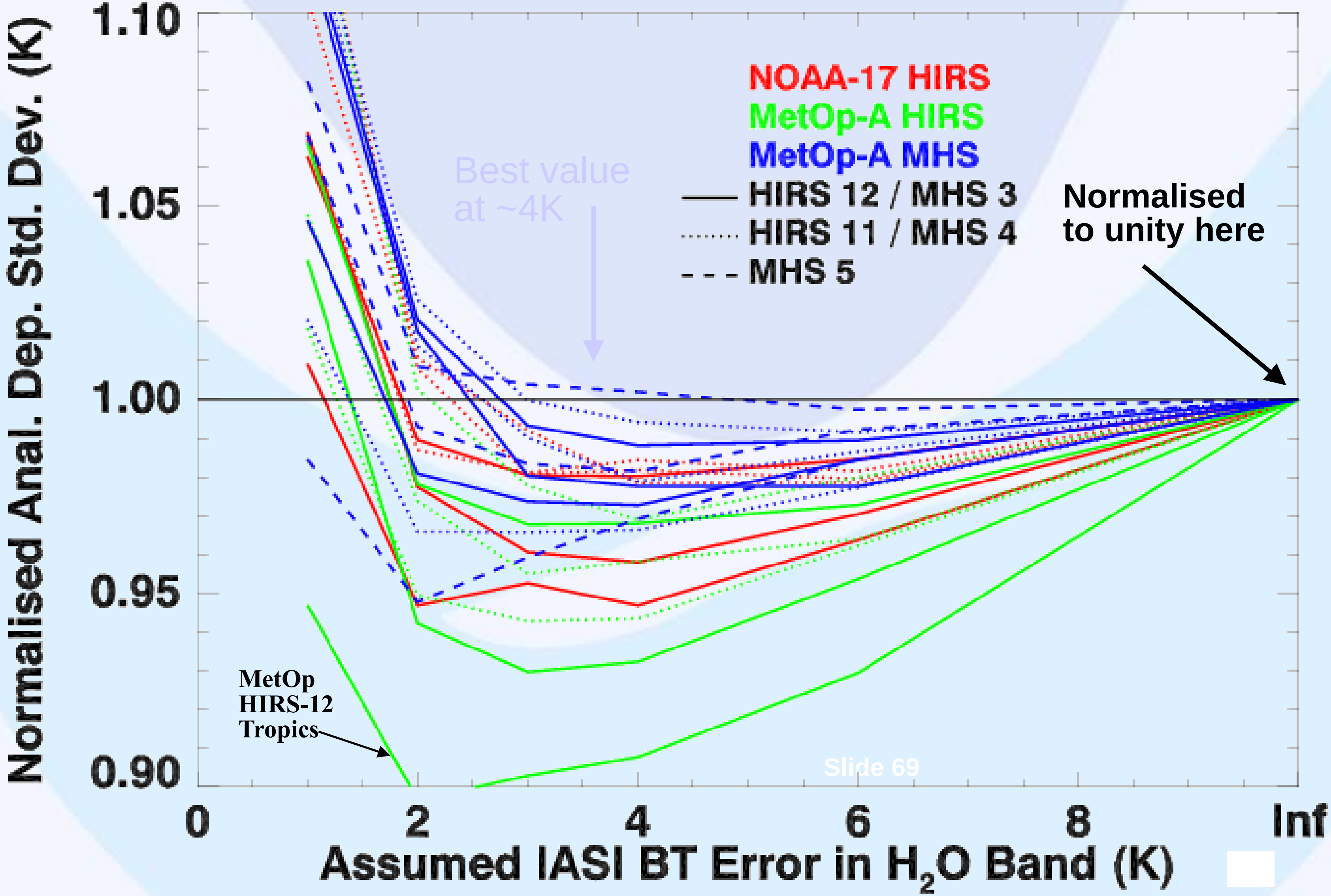
Humidity Jacobians are non-linear; i.e., the Jacobians themselves are a function of the humidity field

Representivity error is probably the most important contributor to the observation error covariance in the water band (at least for global DA). This takes the form of a highly correlated error covariance with amplitude of 1-2K, which therefore dominates the instrument noise.

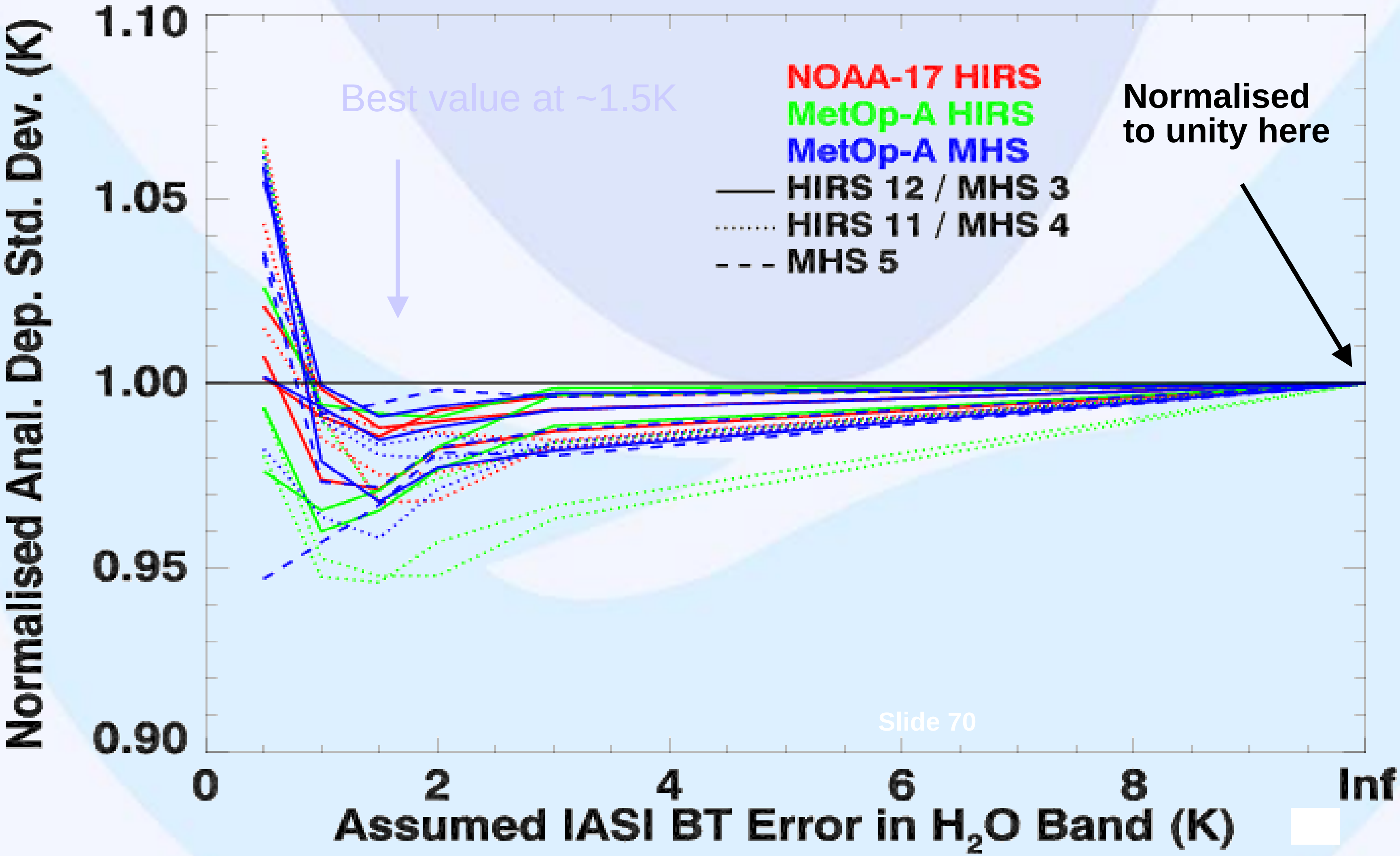
Humidity assimilation (2)

- Large bias relative to NWP model (model bias). Bias correction algorithms remove this bias.
  - RT model errors/biases may contribute as well.
  - Variational bias correction algorithms need to have suitable anchoring observations.
  - Radiance departures should be used to inform forecast model changes (Hilton et al., 2012)
- Above issues are mitigated through inflated observation errors; reduced number of channels, tight QC and explicit representation of correlated observation errors.
  - NCEP use tight QC (~1K) but increase data useage through re-evaluation of QC every outer loop.
  - The Met Office explicitly specifies the correlated observation error for IASI (Bormann talk).

Fit to other observations
84 IASI Water Channels



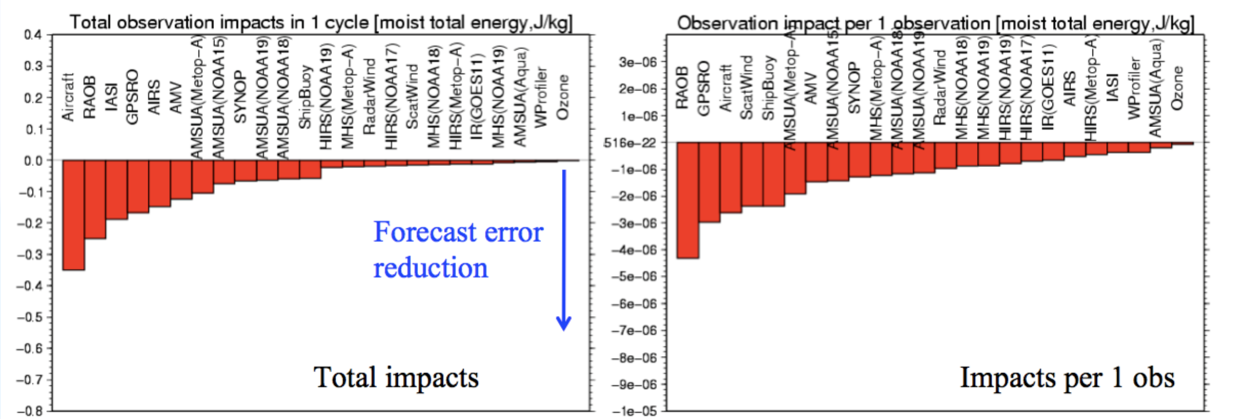
Fit to other observations:
10 IASI Water Channels



Overview of IR Sounder Performance in NWP

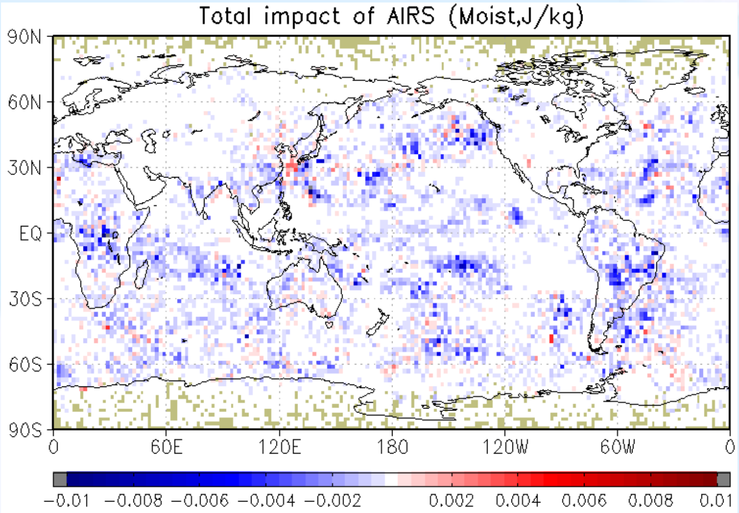
Slide 71

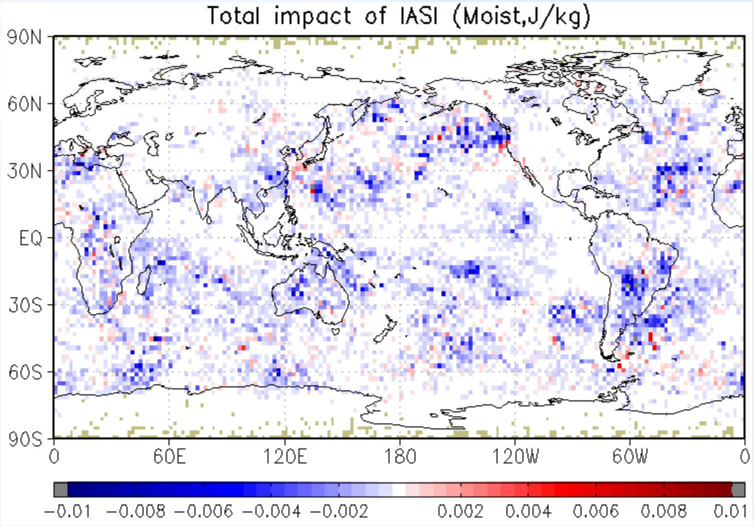
Global NWP Data Impacts



All observation types have positive impacts on average.
For the total impact, 1: aircraft, 2: AMSU-A, 3: radiosonde, 4: IASI, 5: GPSRO
For impact per 1 obs., 1: radiosonde, 2: GPSRO, 3: aircraft, 4: Scattrometer wind, 5: marine surface observation

Ensemble FSO at NCEP

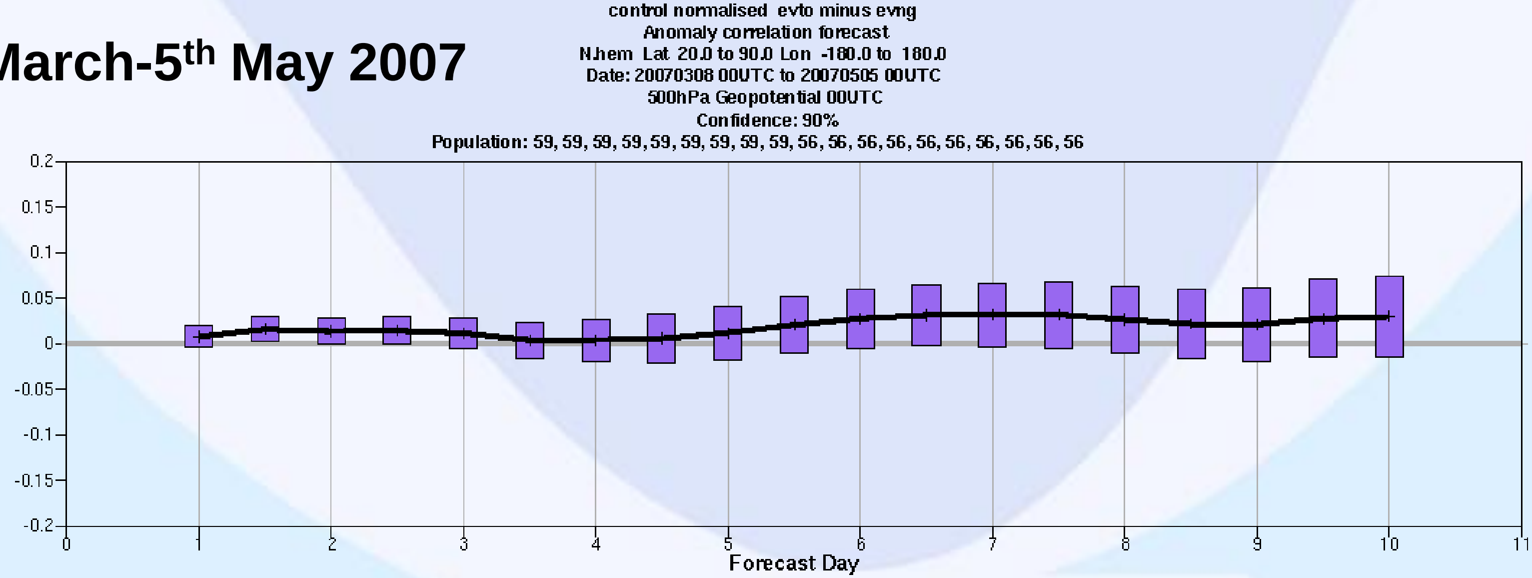




IASI Forecast Scores: 500hPa Geopot. AC

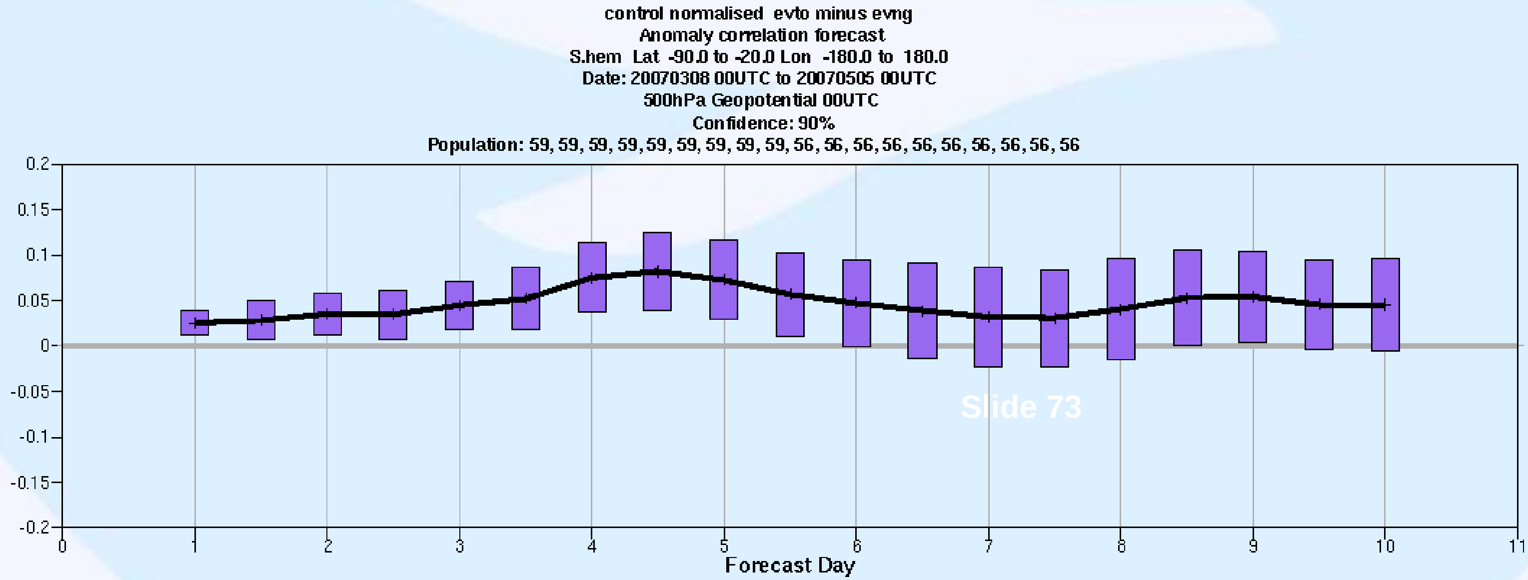
8th March-5th May 2007

NH



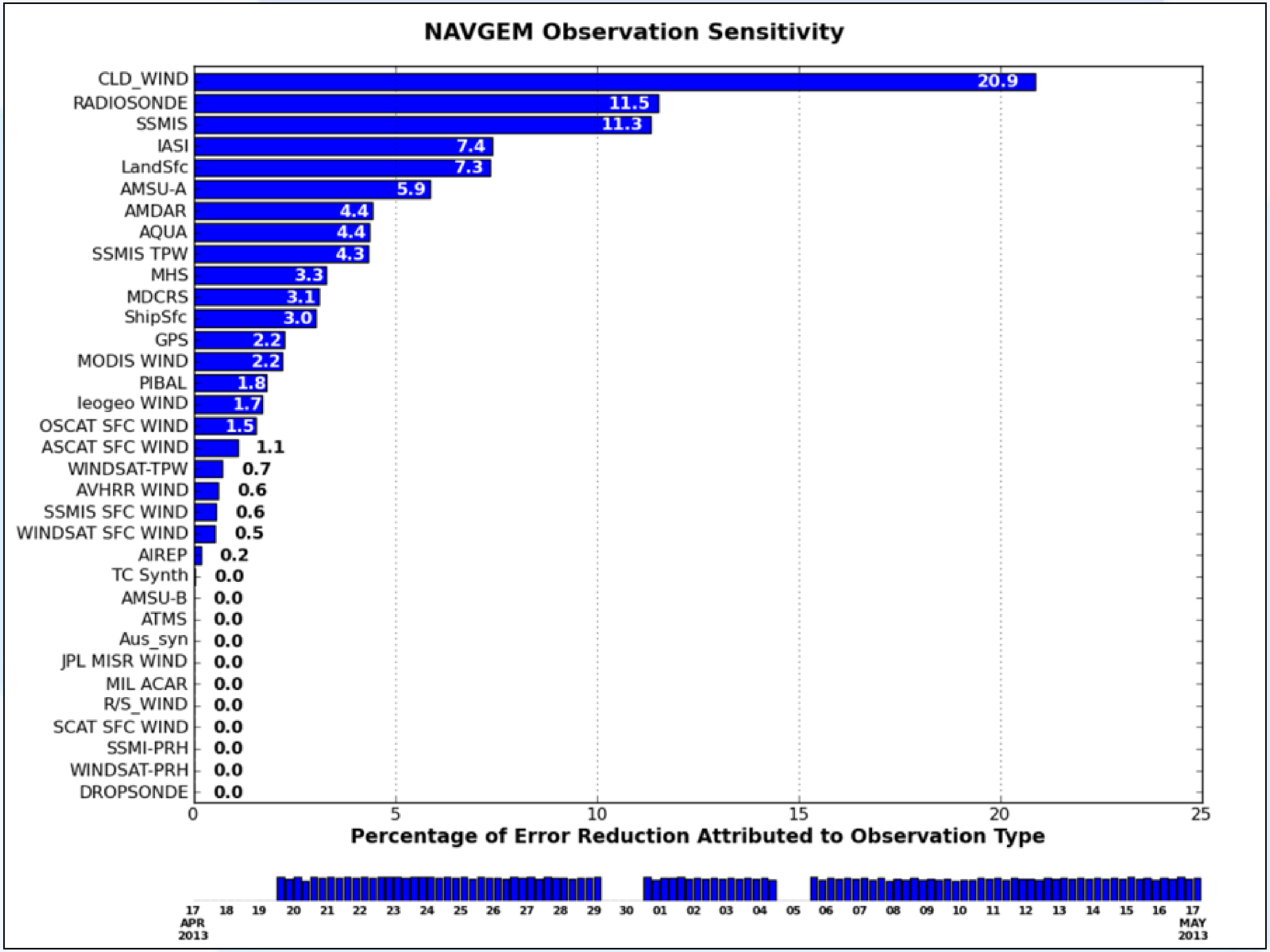
IASI Better

SH

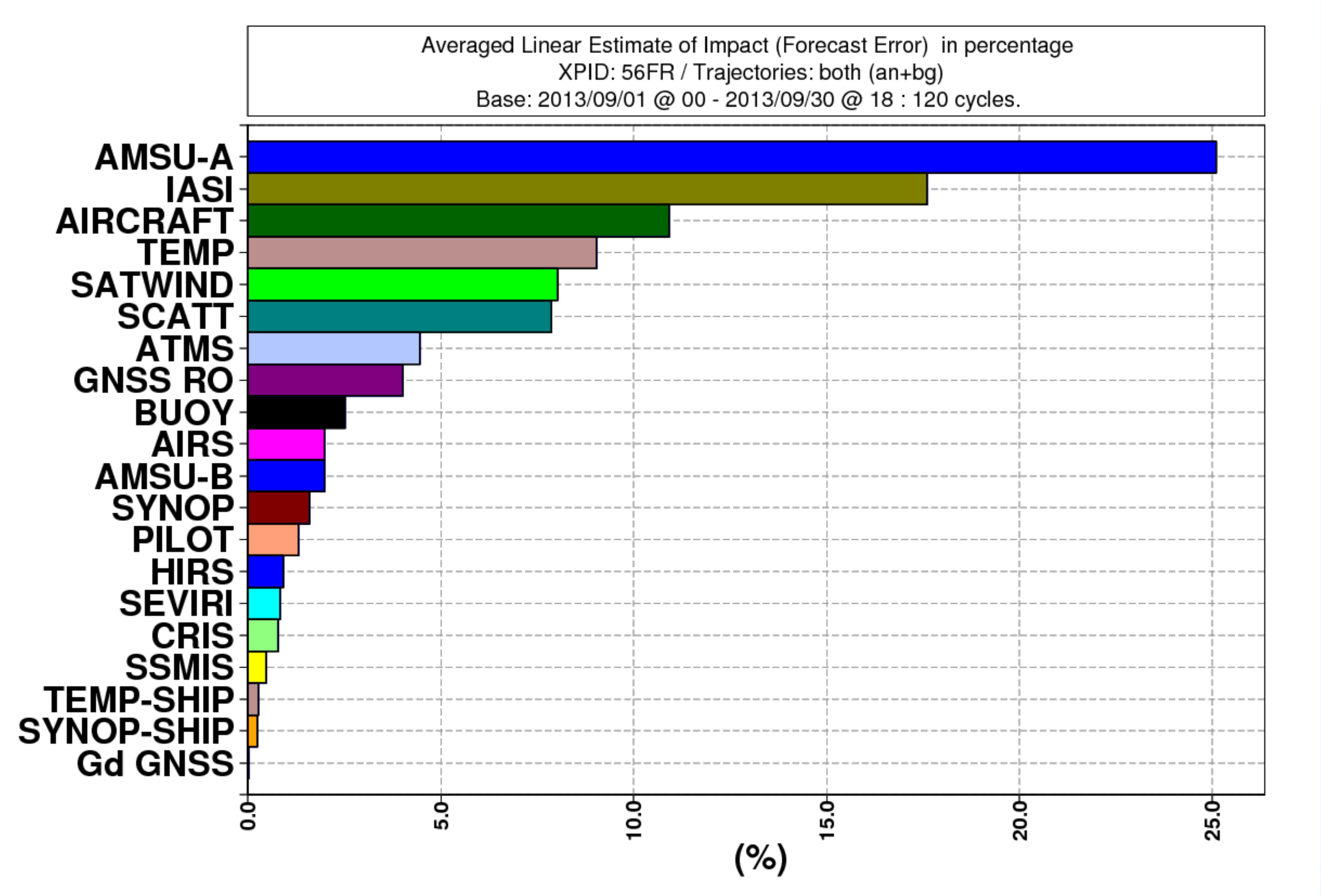


IASI Worse

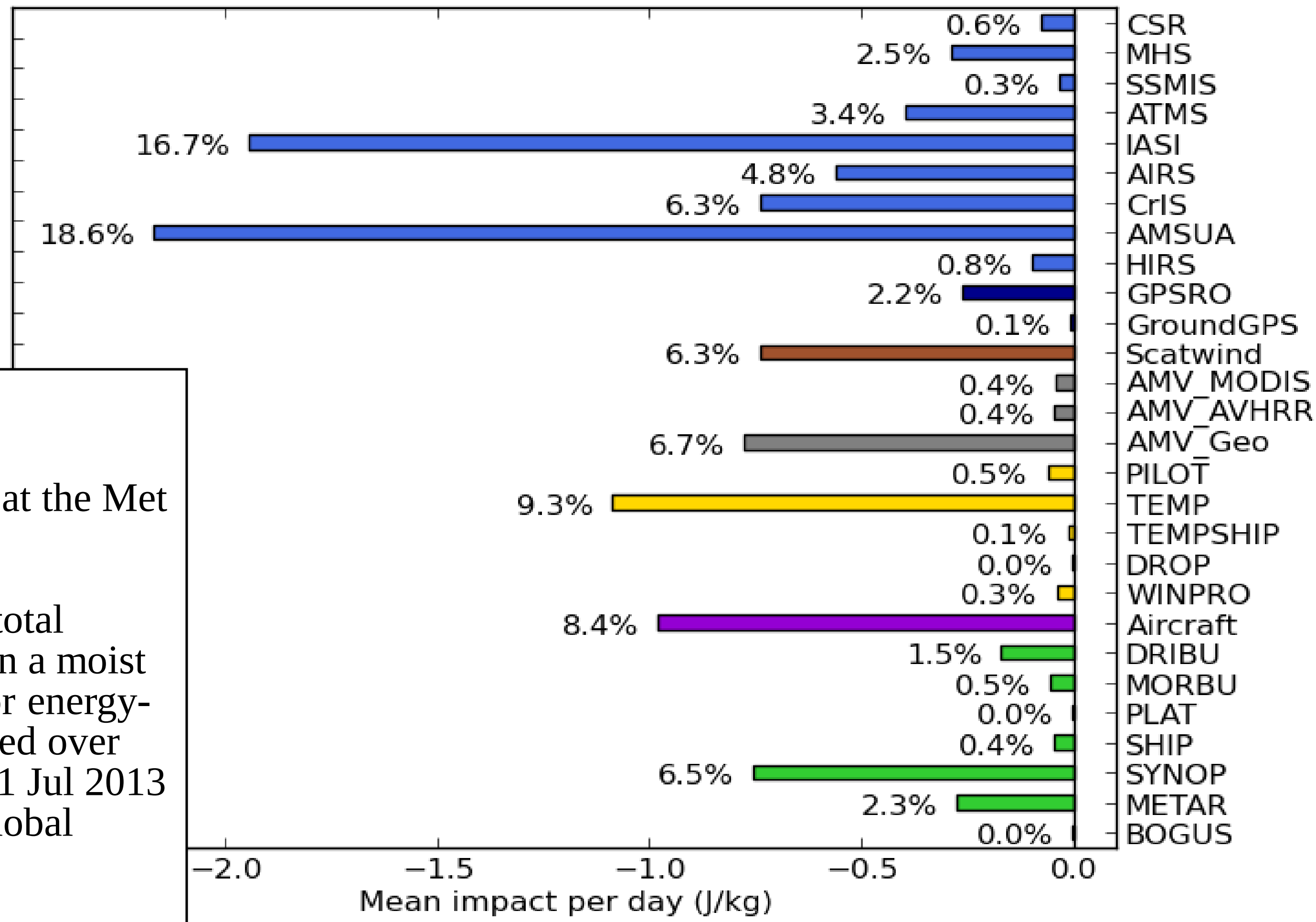
Global NWP Data Impacts: NRL



Global NWP Data Impacts: Météo-France



Global NWP Data Impacts: Met Office



Observation impacts at the Met Office – FSO results

Contributions to the total observation impact on a moist 24-hour forecast-error energy-norm per day, averaged over the period 01 Apr - 31 Jul 2013 for the Met Office Global Model

Conclusions

Conclusions

- Since the launch of AIRS in 2002, hyperspectral infrared sounders have become some of the leading contributors to forecast accuracy.
- Most NWP centres assimilate a large number of 15µm CO_2 channels with a smaller number of humidity and ozone channels.
- Areas of study include:
  - Use of cloudy radiances
  - Efficient use of information (channel selection, PCs, Reconstructed Radiances)
  - Specification of observation errors (including correlations).