Assimilation of AIRS & IASI at ECMWF

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Acknowledgements to Tony McNally, Richard Engelen & Rossana Dragani

Overview

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- Assimilation Configuration
  - Channel Selection
  - Cloud Detection
- IASI First Guess Departures
- AIRS & IASI Forecast Impacts
- Challenges
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  - Data Compression
- “Trace” Gases
- Conclusions

Introduction

What are Advanced Infrared Sounders?

- **Infrared Spectrometers with high spectral resolution and thousands of channels.**
- **Allows sounding of the atmosphere with improved vertical resolution and accuracy.**
- **All such instruments are** interferometers **(except for the NASA/EOS Atmospheric Infrared Sounder (AIRS) which is a grating spectrometer).**

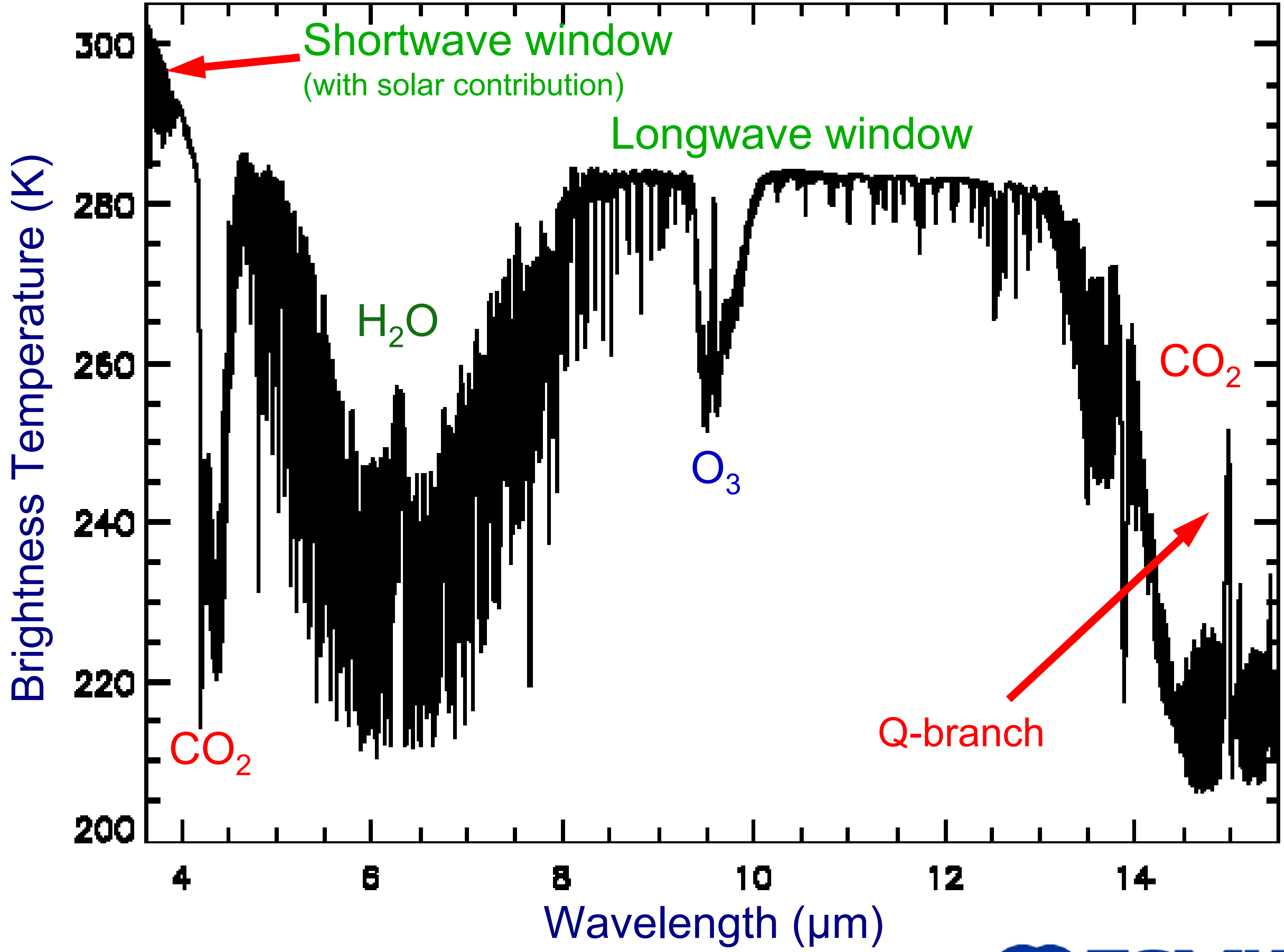
Current and Future High-Spectral Resolution InfraRed Sounders

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/ NPOESS/ ??? ????	1400	635-2450cm^{-1}	1.125-4.5cm^{-1}	12km	Interferometer/ Polar
GIFTS/ ??????/?????	1724	685-1130cm^{-1} 1650-2250cm^{-1}	0.6cm^{-1}	4km	Imaging Interferometer/ Geostationary
HES/ GOES-R/ 2012	?	650-1200 [1650-2150cm^{-1} or 1210-1740cm^{-1}] 2150-2250	0.6cm^{-1}	4-10km	Interferometer?/ Geostationary

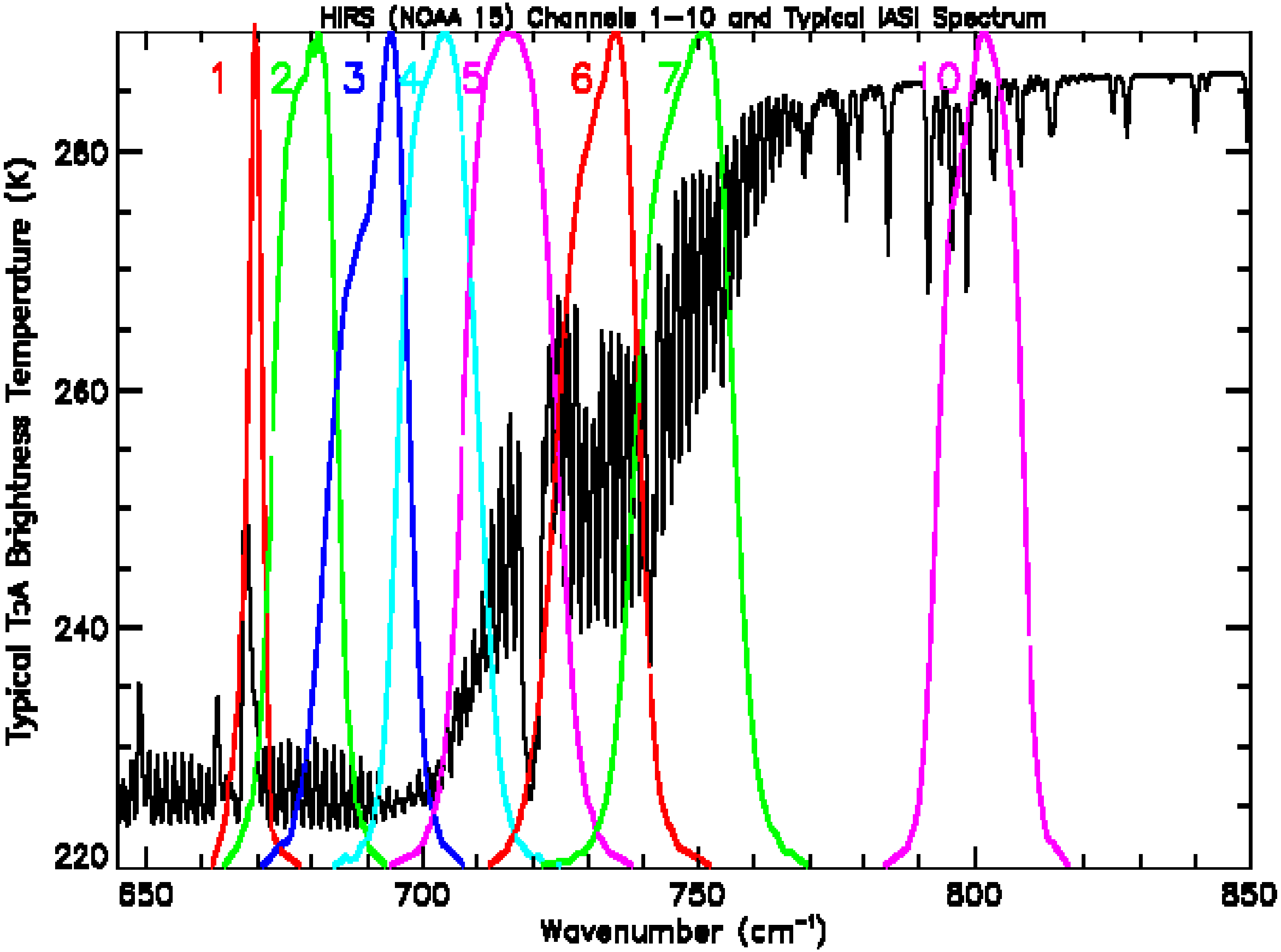
Other Examples of Interferometers in Space

- The following have been used for atmospheric sounding but (for various reasons) their observations have not been assimilated into NWP models:
  - IRIS on NIMBUS 3 & 4 (1969-70)
  - IRIS on Mariner 9 (Mars, 1971)
  - IRIS on Voyager 1 & 2 (Giant Planets, 1979-89)
  - IMG on ADEOS (1996-97)
  - CIRS on Cassini (Saturn, 2004-)
  - PFS on Mars Express (Mars, 2003-)
  - TES on EOS-AURA (limb sounder, 2004-)

An IASI Spectrum

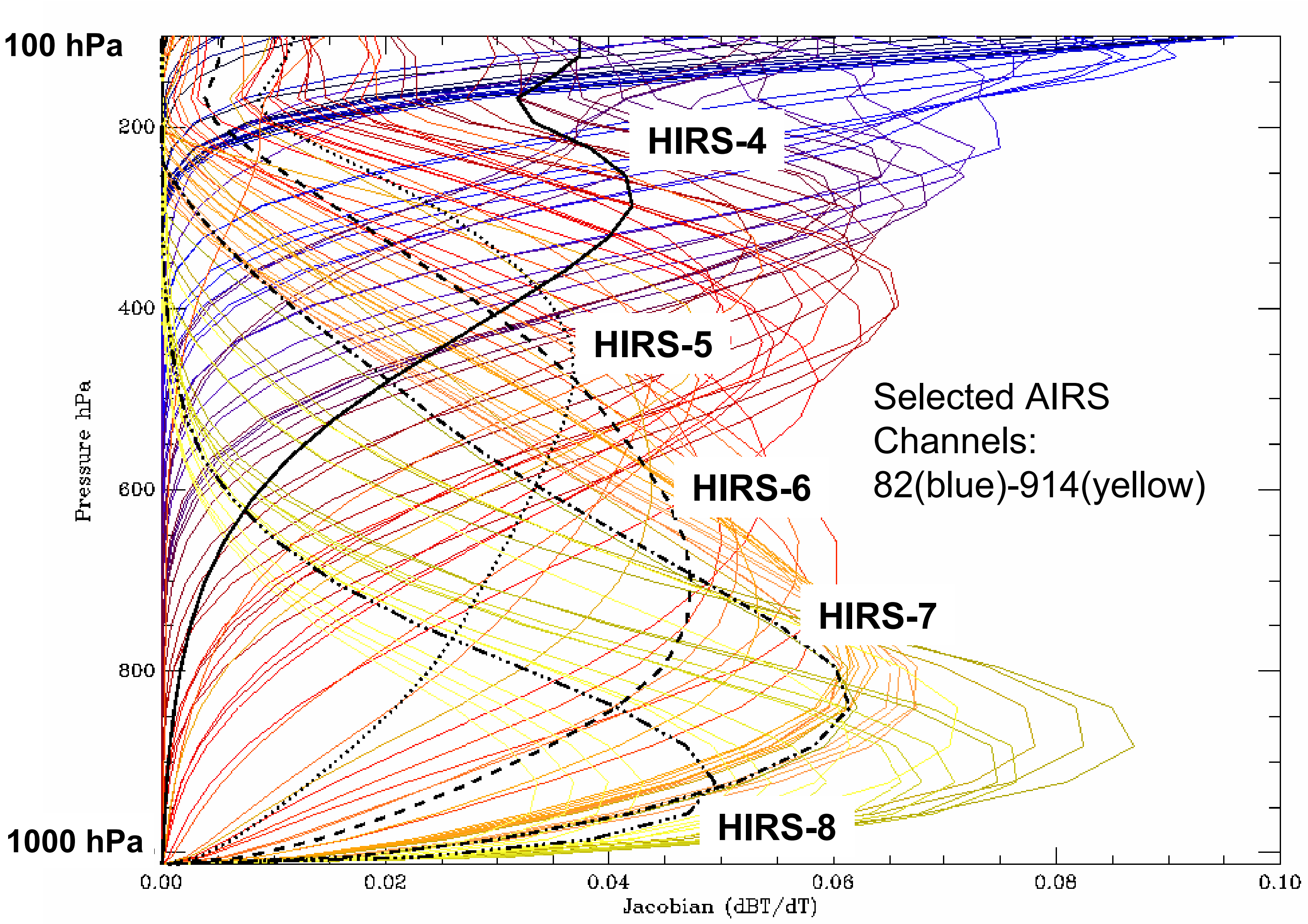


IASI vs HIRS: The Thermal InfraRed



AIRS vs HIRS Jacobians

in the 15μm CO_2 band



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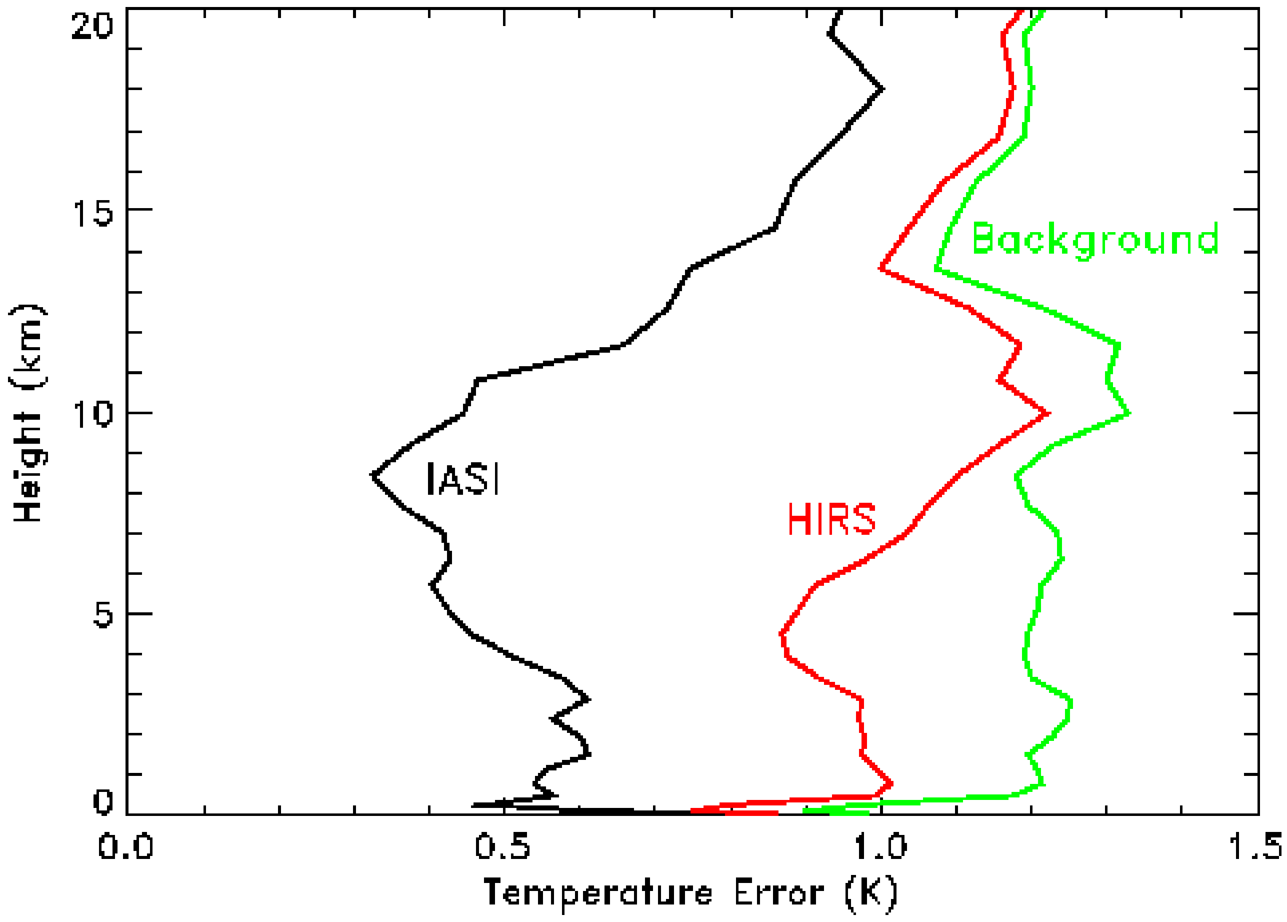
HIRS vs IASI: Temperature Retrieval Accuracy



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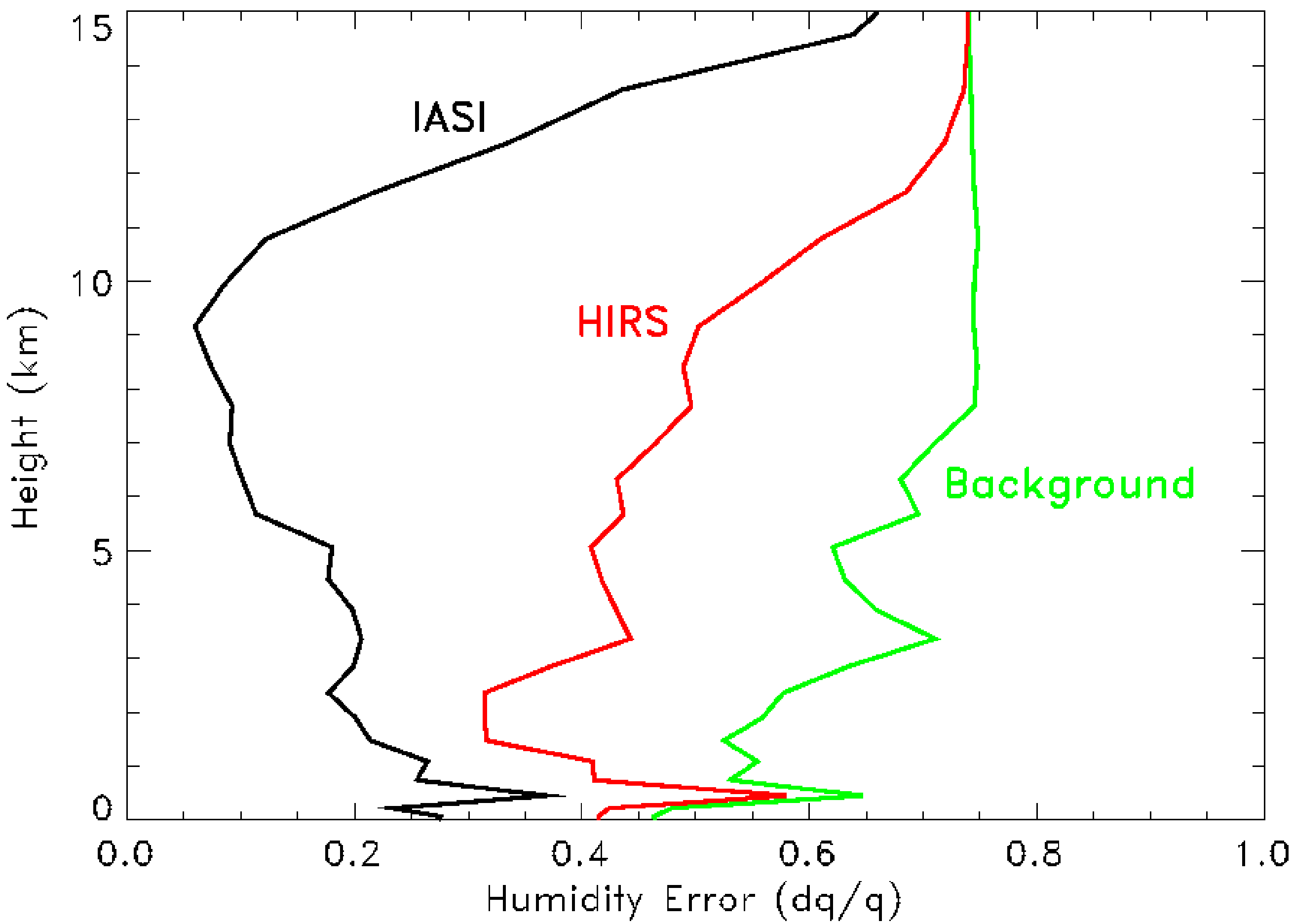
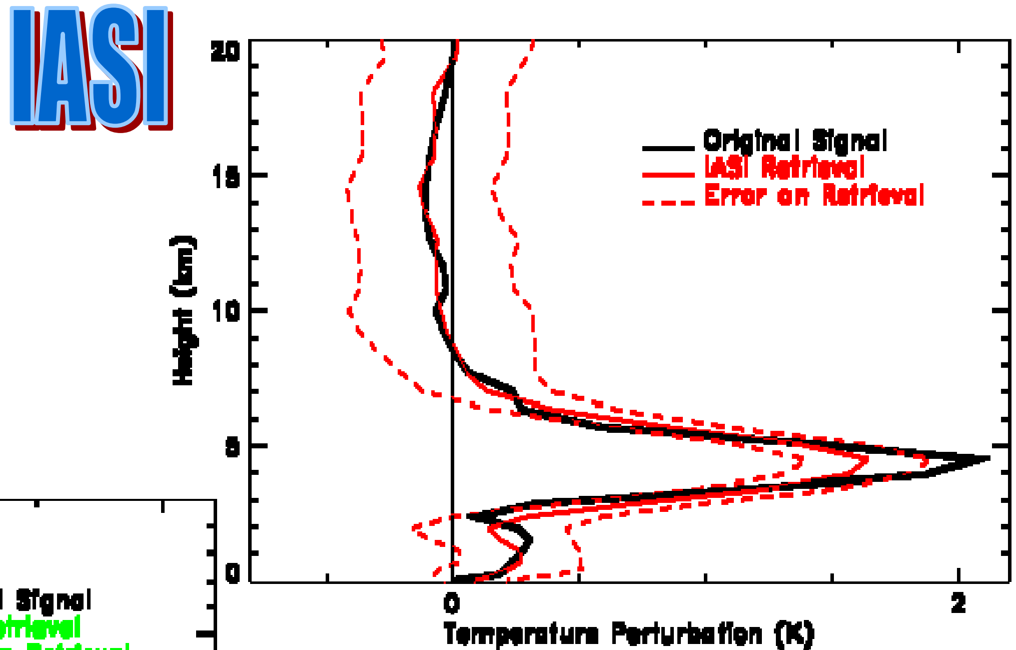
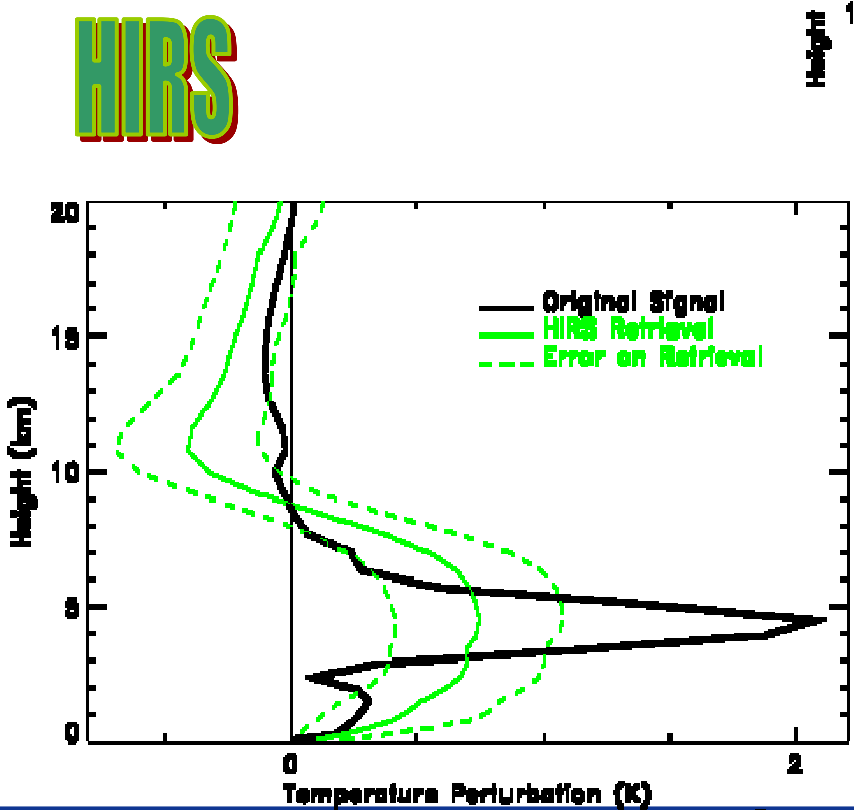
HIRS vs IASI: Humidity Retrieval Accuracy



HIRS vs IASI: Response to Important Atmospheric Structure





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)

Assimilation Configuration

Current Operational Configurations

AIRS

- Operational at ECMWF since October 2003
- 324 Channels Received in NRT
- One FOV in Nine
- Up to 155 channels may be assimilated (CO_2 and H_2O bands)

IASI

- Operational at ECMWF since 12th June 2007
- 8461 Channels Received in NRT
- All FOVS received; Only 1-in-4 used
- 366 Channels Routinely Monitored
- Up to 168 channels may be assimilated (CO_2 band only)

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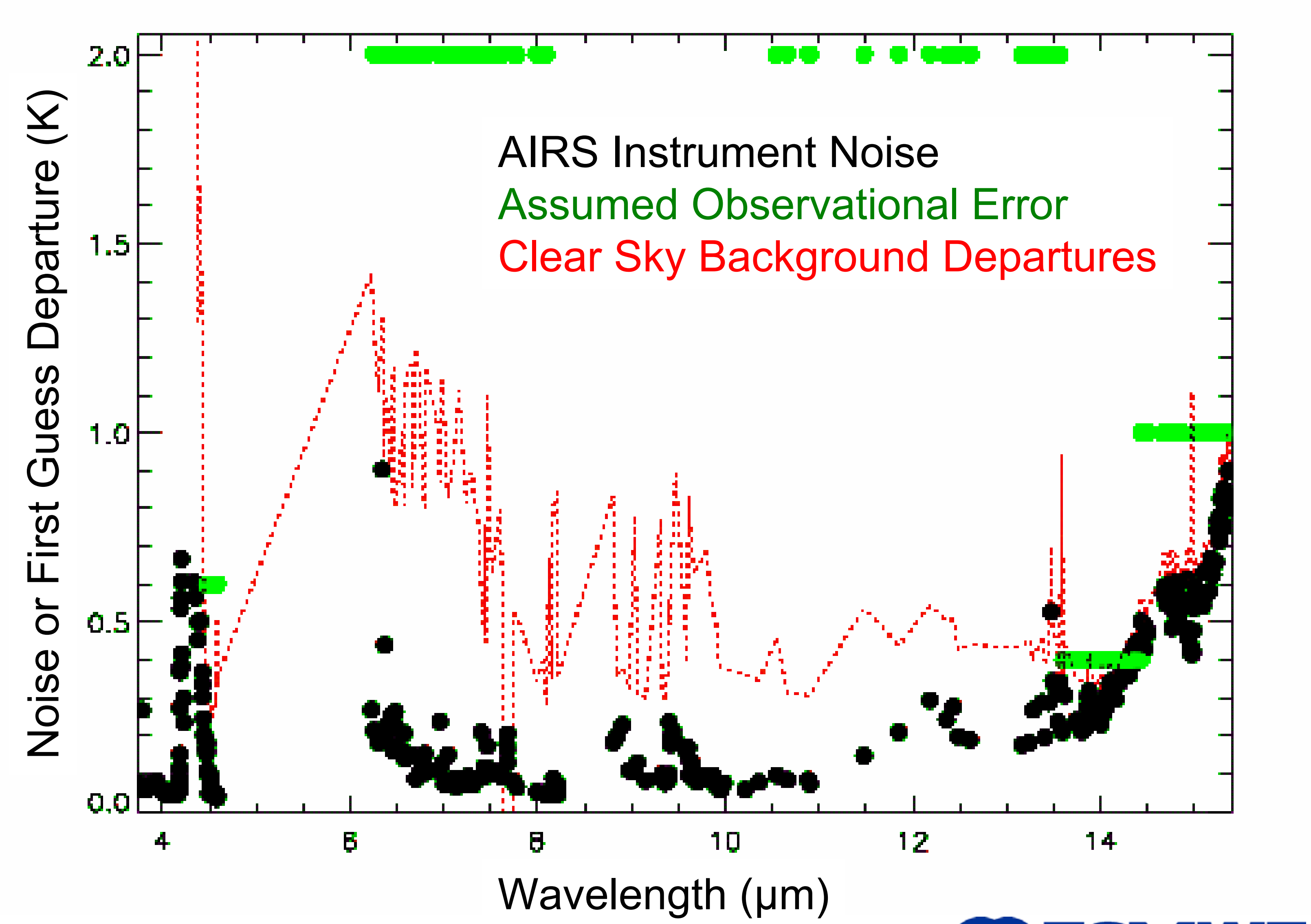
Assumed Noise for AIRS & IASI Assimilation



Assimilation Configuration:
Channel Selection

Why Select Channels?

- The volume of IASI 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

AIRS and IASI Channel Selection

- The 324 AIRS channels distributed by NOAA/NESDIS were chosen based on inspection of Jacobian widths and expected noise levels. (Susskind, Barnet & Blaisdell, 2003).

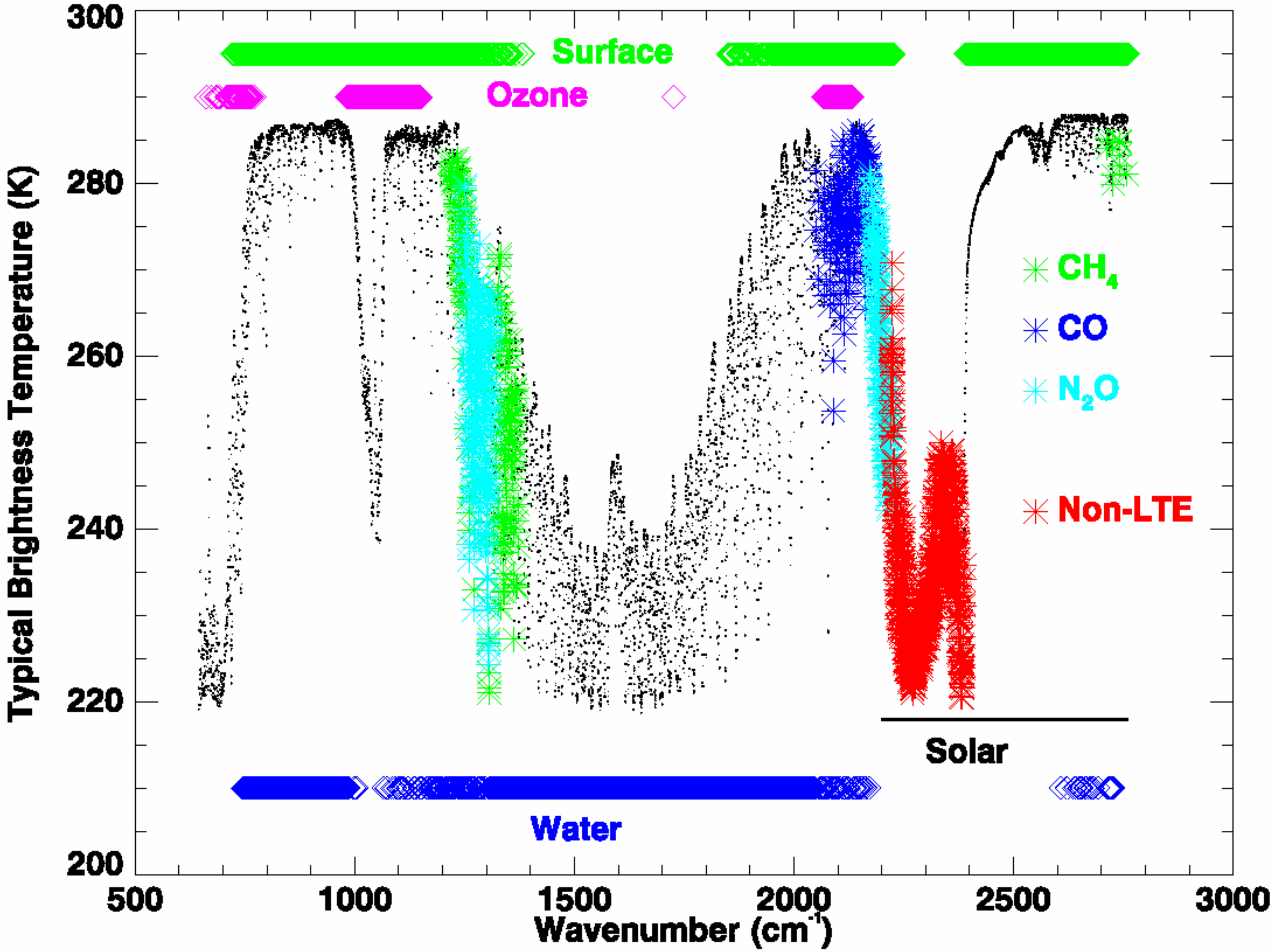
- All IASI channels are distributed to European Users via EUMETCAST. Distribution of IASI radiances via GTS is for 300 channels chosen according to Collard (2007).
- At ECMWF, for IASI we use the 300 channels above plus a further 66 channels….

These are the channels that are routinely monitored – not all are actively assimilated (see later)

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.
- Add extra channels that the Rogers method cannot choose
  - E.g. Cloud detection channels.

Pre-screened channels



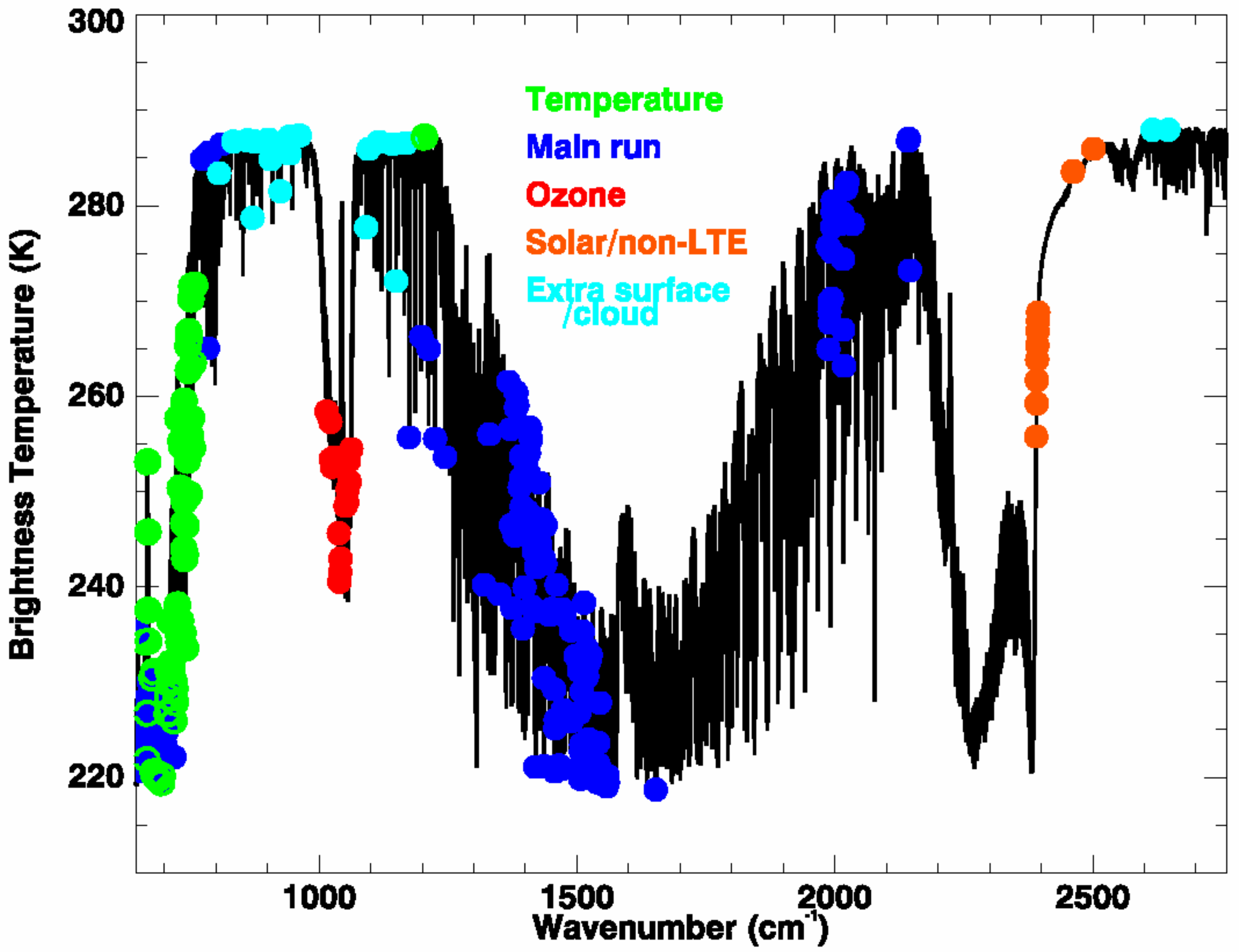
Selected Channels (1)

- 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)



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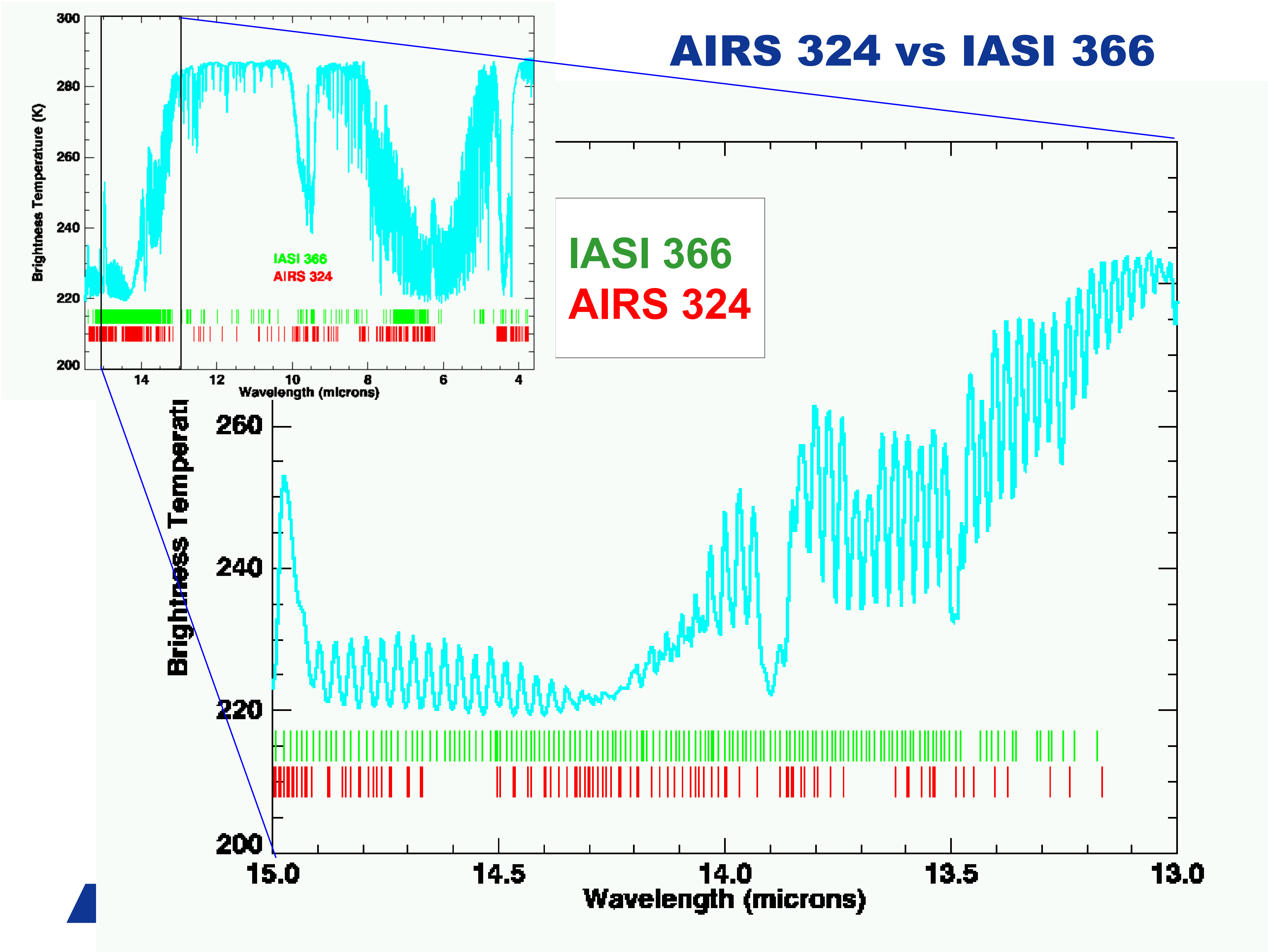
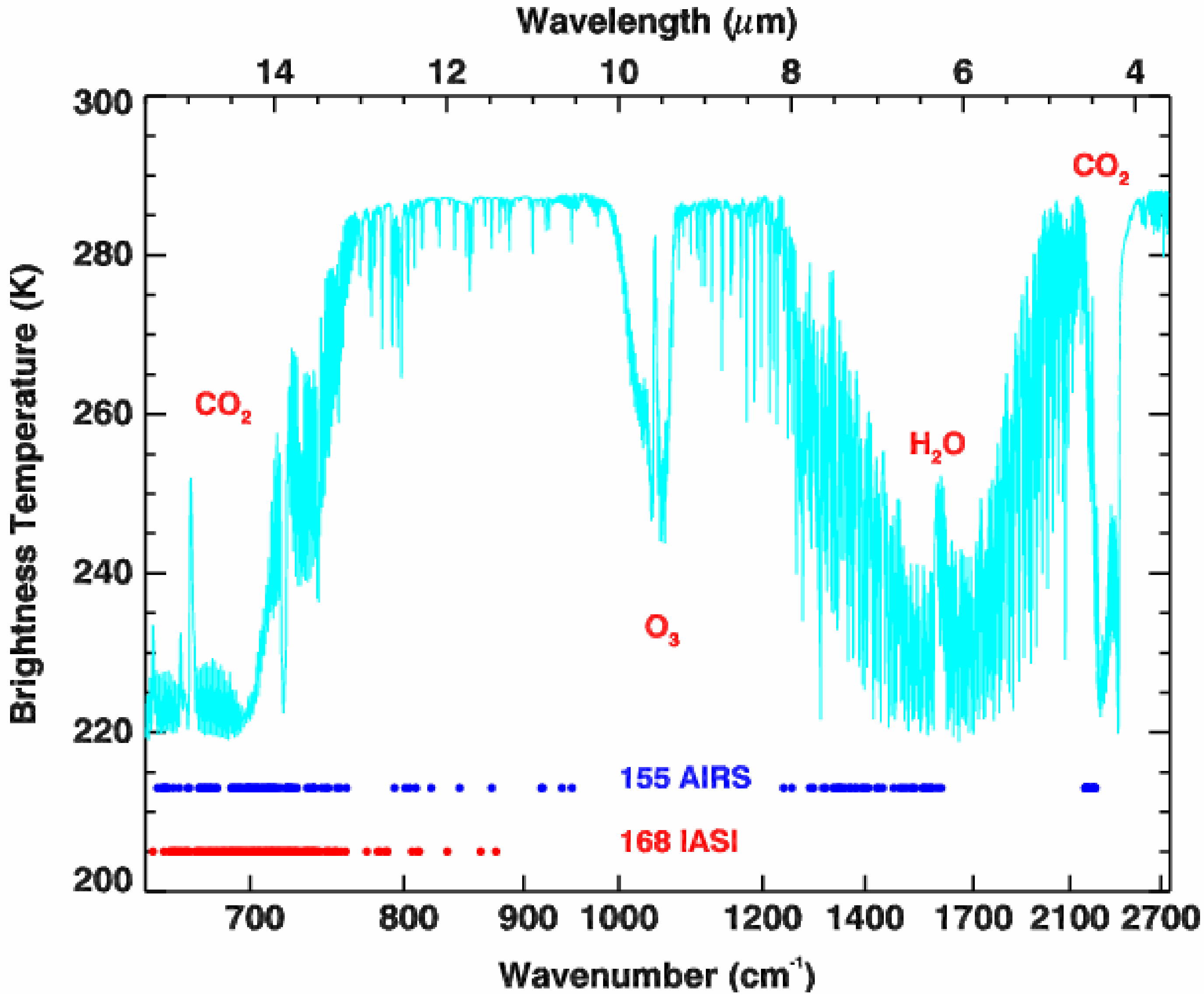
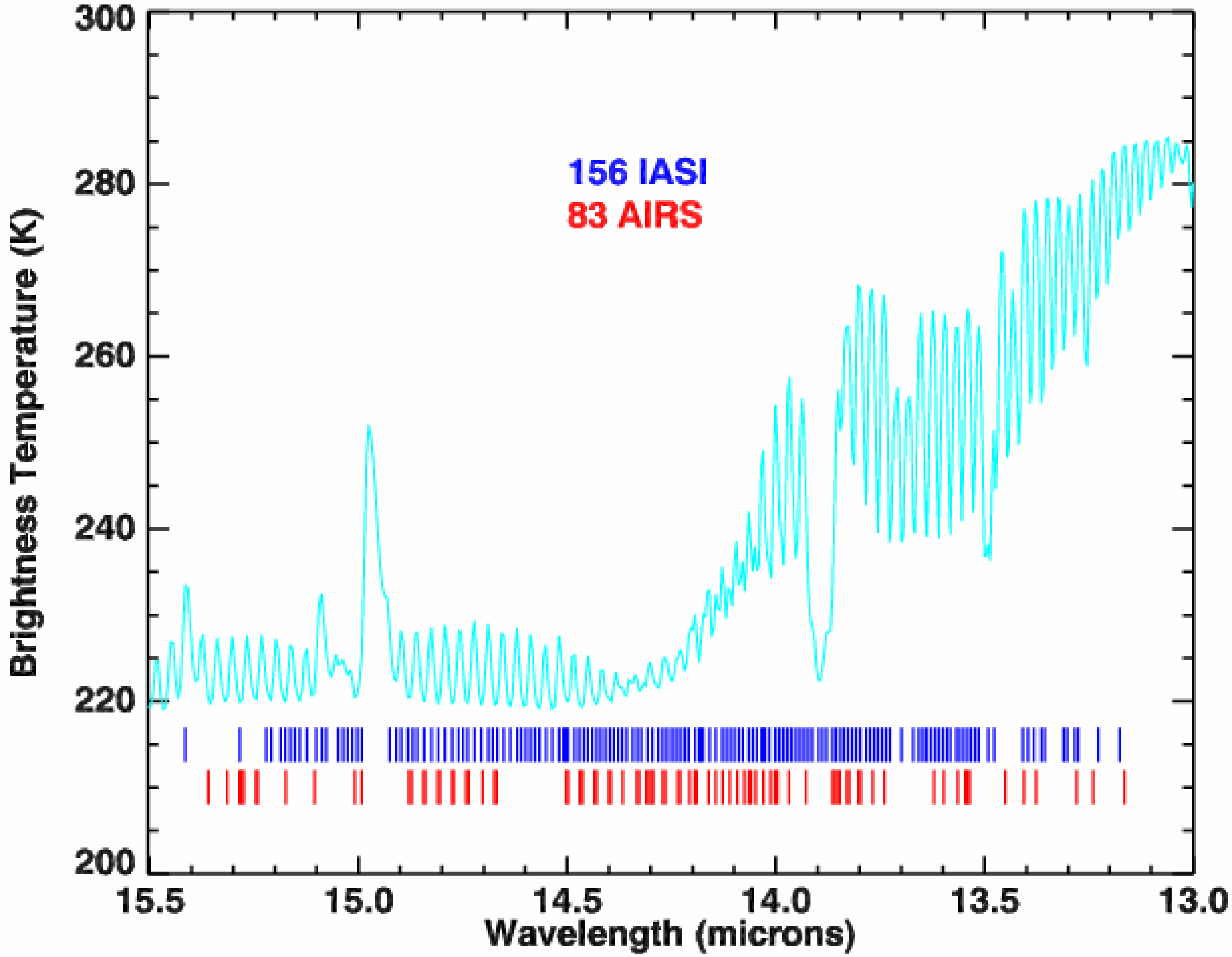
AIRS 324 vs IASI 366



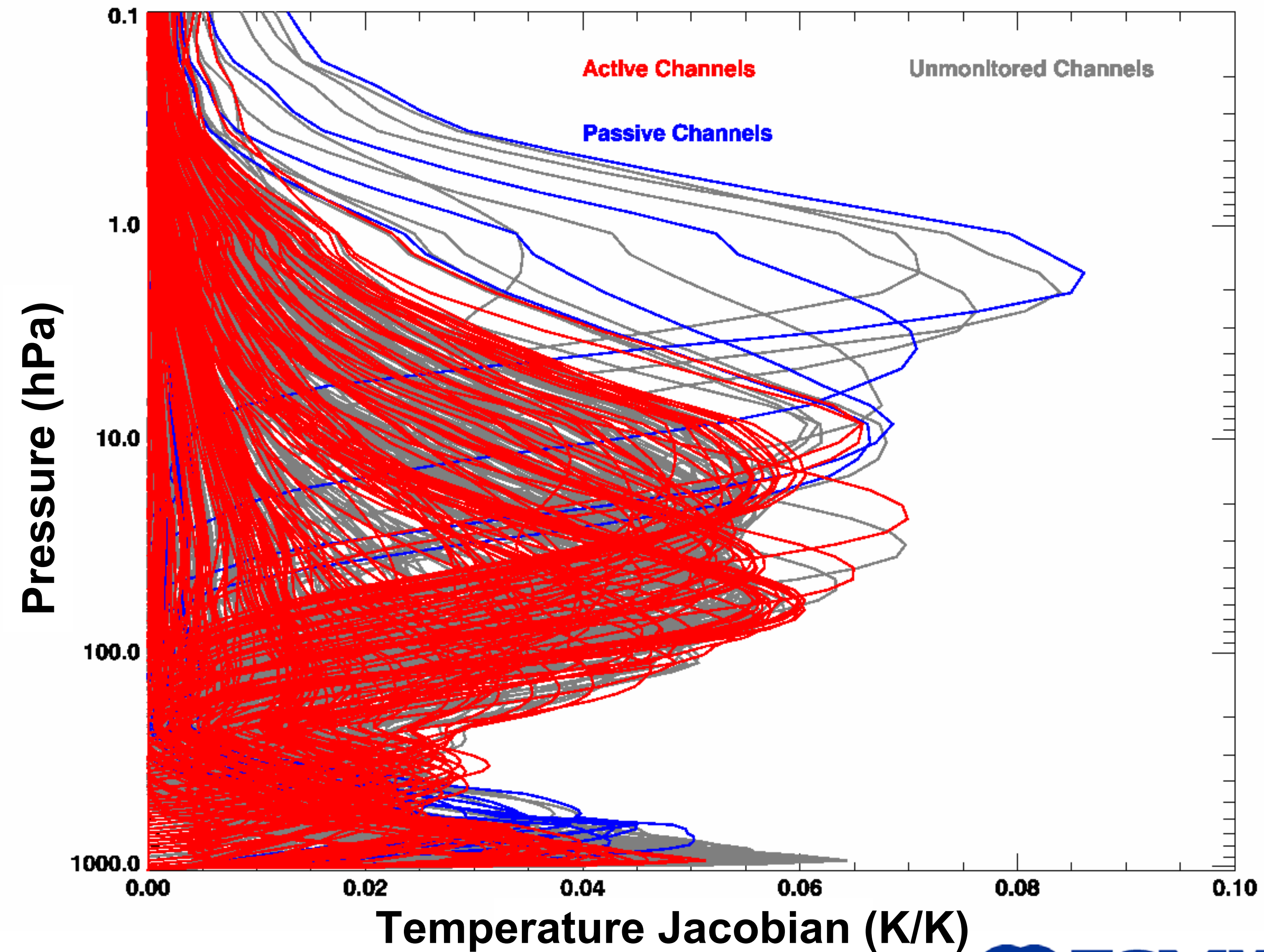
Comparison of Actively Assimilated Channels (1)



Comparison of Actively Assimilated Channels (2)



Jacobians of 15µm CO_2 Band



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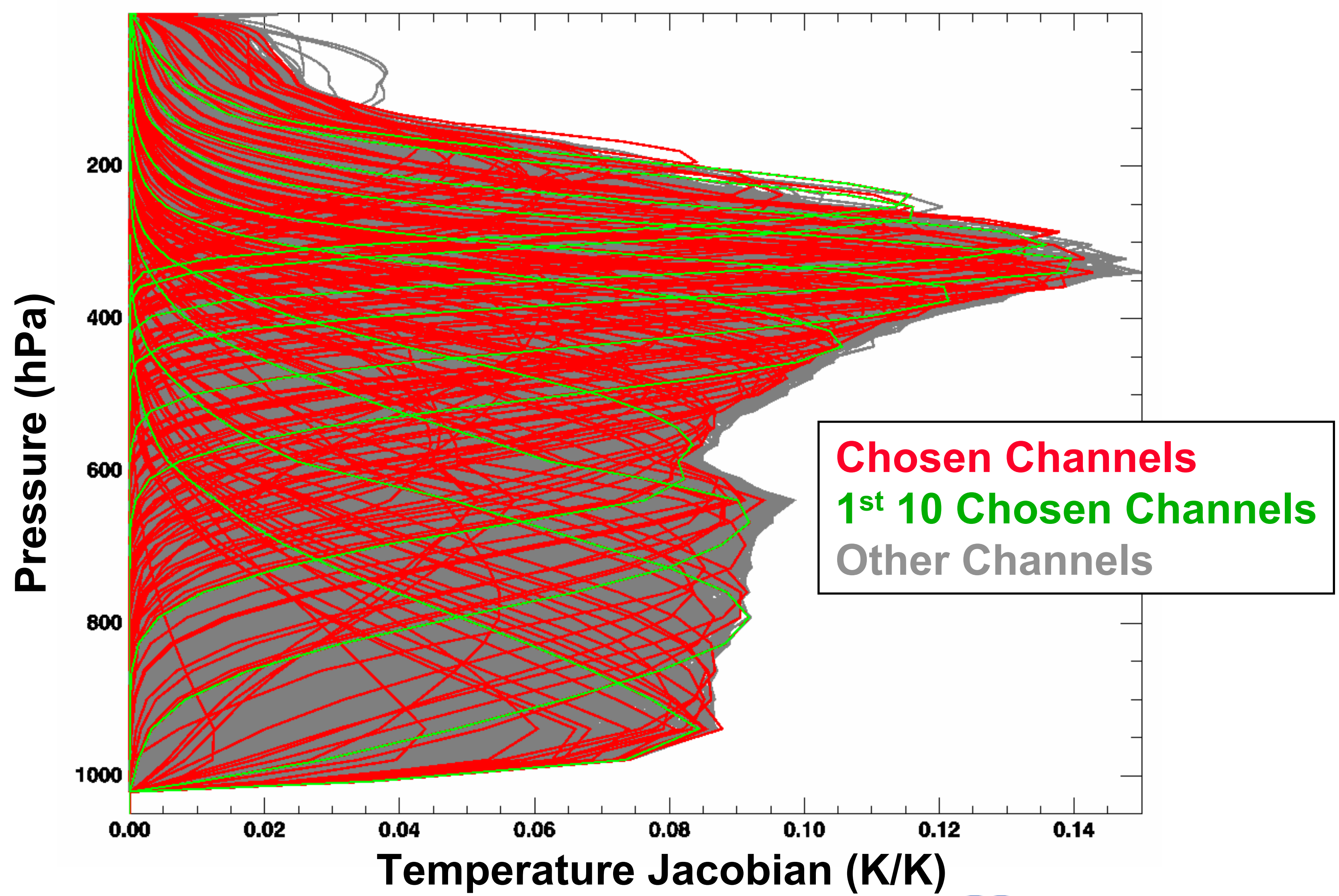
Jacobians of 6.3μm H_2O Band



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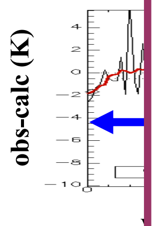
Assimilation Configuration: Cloud Detection

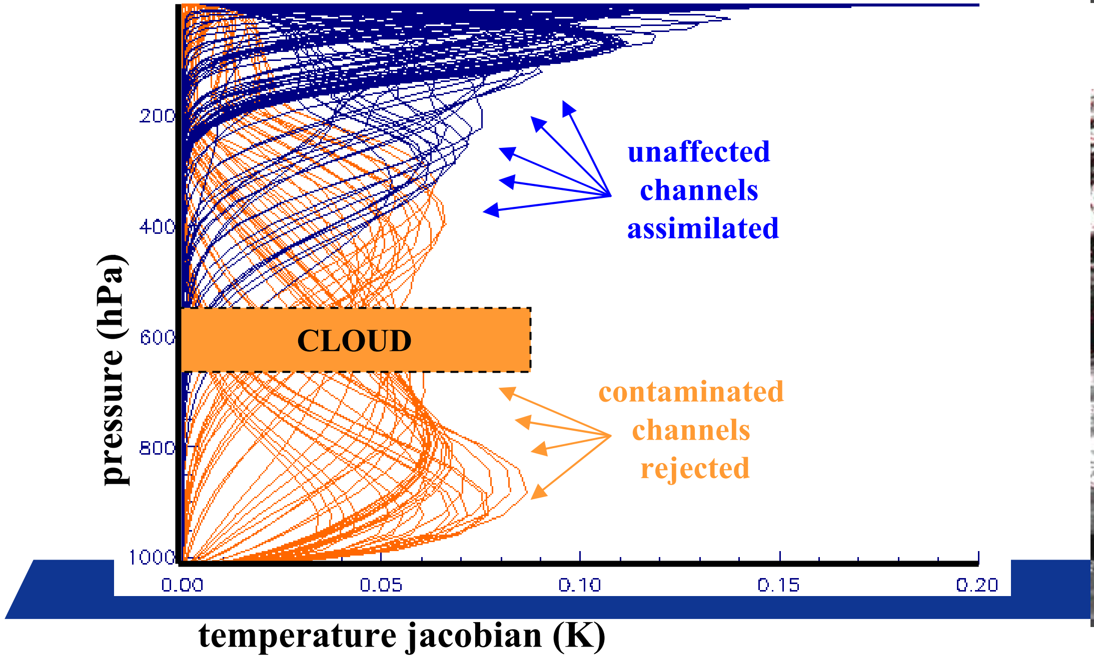
Cloud detection scheme for Advanced Sounders

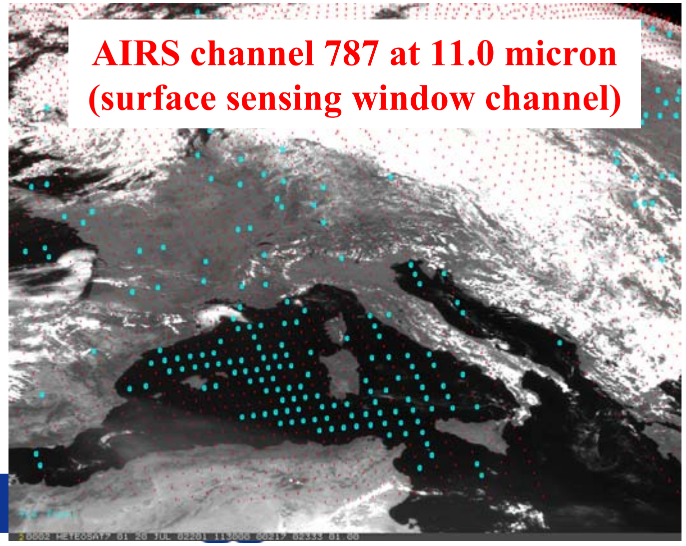
A non-linear pattern recognition algorithm is applied to departures of the observed radiance spectra from a computed clear-sky background spectra.



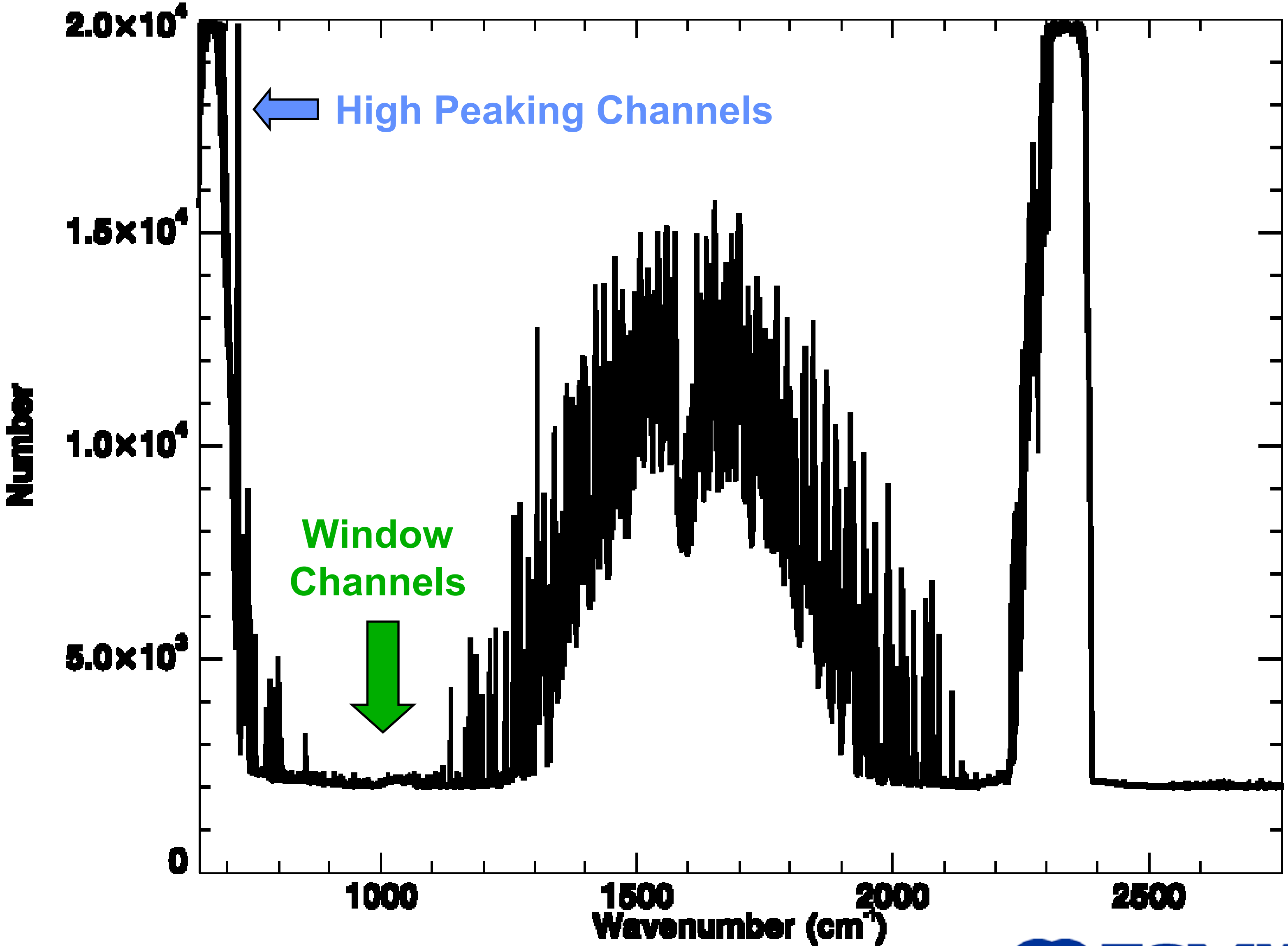
The large number of AIRS or IASI channels allows improved measurement of the cloud-top height compared to HIRS

This identifi… data and allows contaminated channels to be rejected





Number of Clear Channels



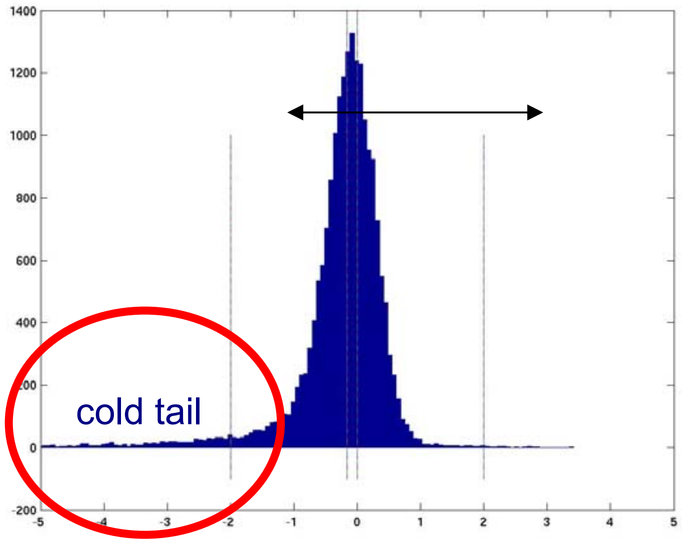
Cloud Detection Software is Available

- Cloud detection has been re-written to allow greater portability and to allow cloud detection of IASI

- *It is available for all to use from the NWPSAF*

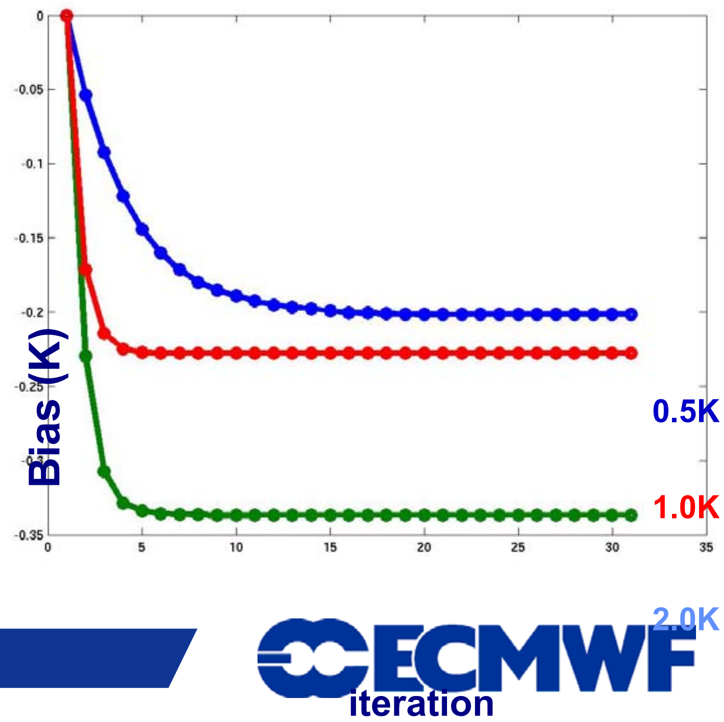
- http://www.metoffice.gov.uk/research/interproj/nwpsaf/

Adaptive bias correction and QC



A typical distribution of (Obs-Calc) departures has a cold / warm tail due to residual cloud contamination. A boxcar QC window is often applied to remove the tail before estimating the bias.

However, successive applications of this (as in adaptive bias correction leads to a "dragging" of the mean by the cold tail. The speed and size of the drag depends on the number of iterations and the size of the boxcar window QC.



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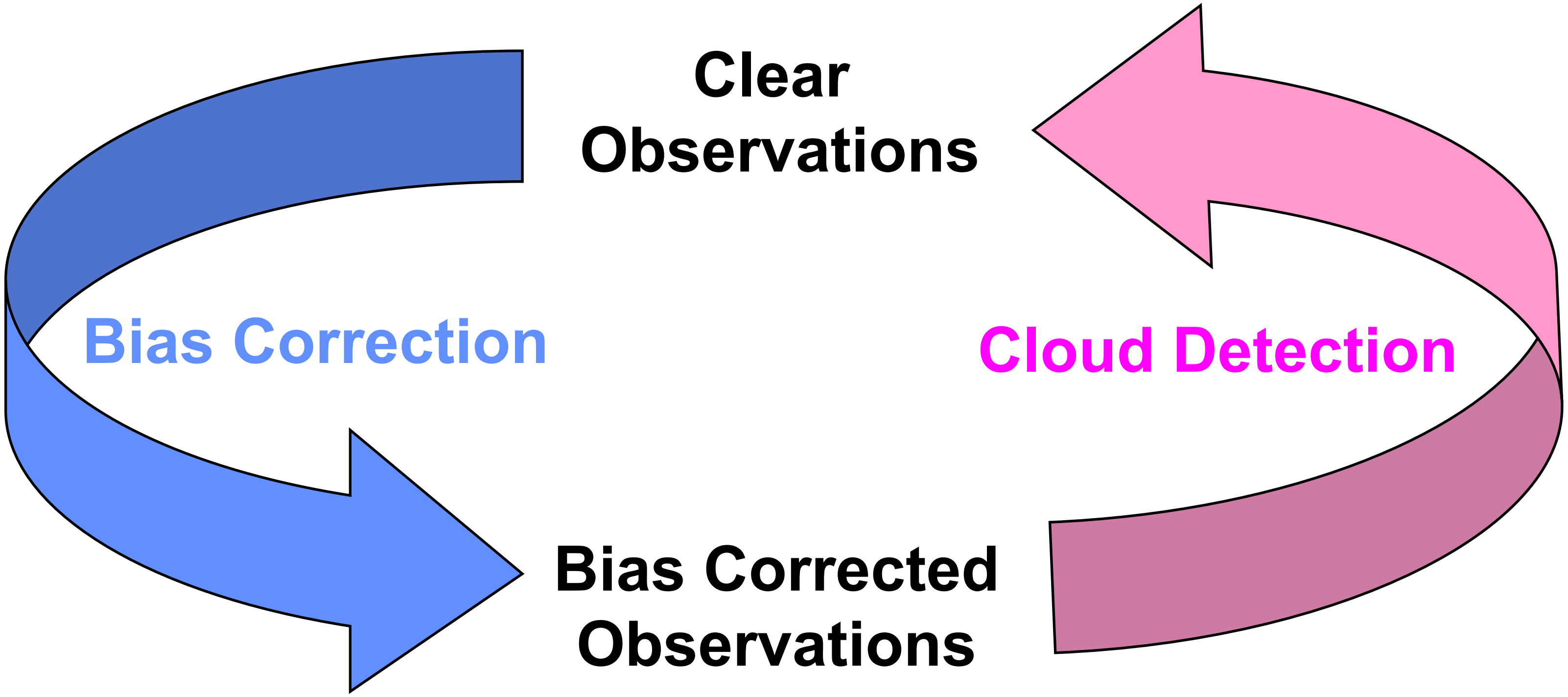
Cloud Detection and Bias Correction Interact



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IASI First Guess Departures

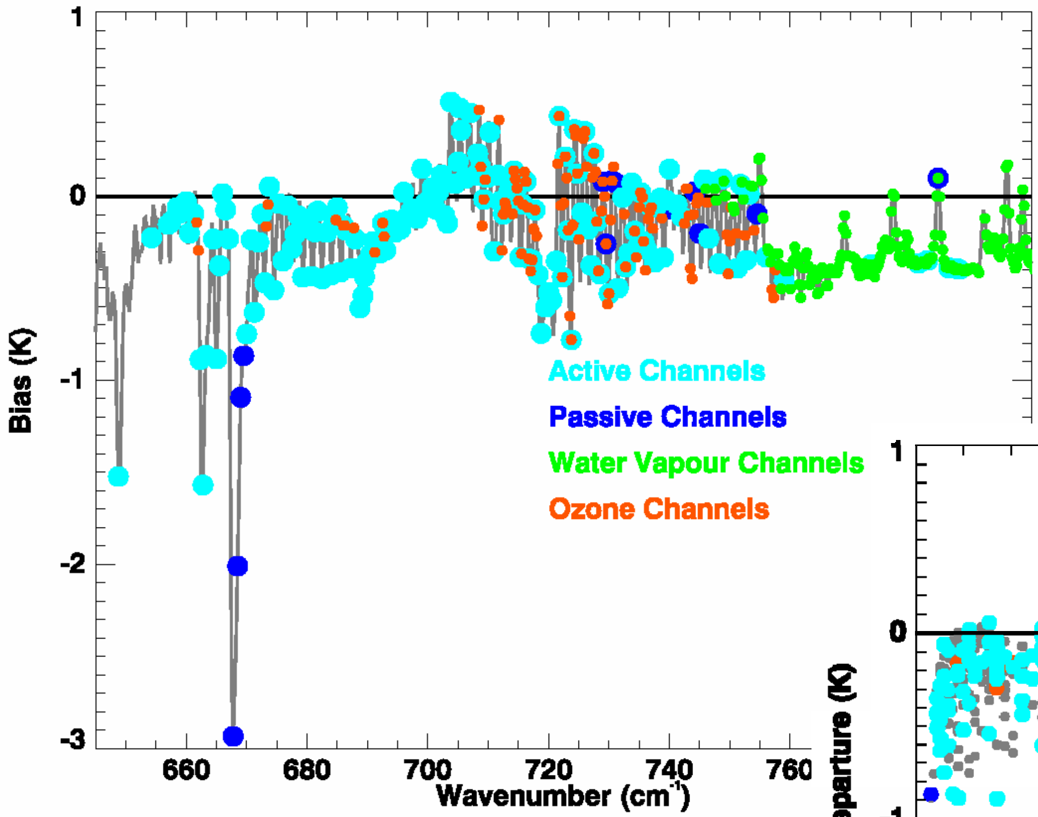
Looking at First Guess Departures

- Observed Radiances minus Radiances Predicted from Short Range Forecast from Previous Cycle
- First Guess Departures drive the increments

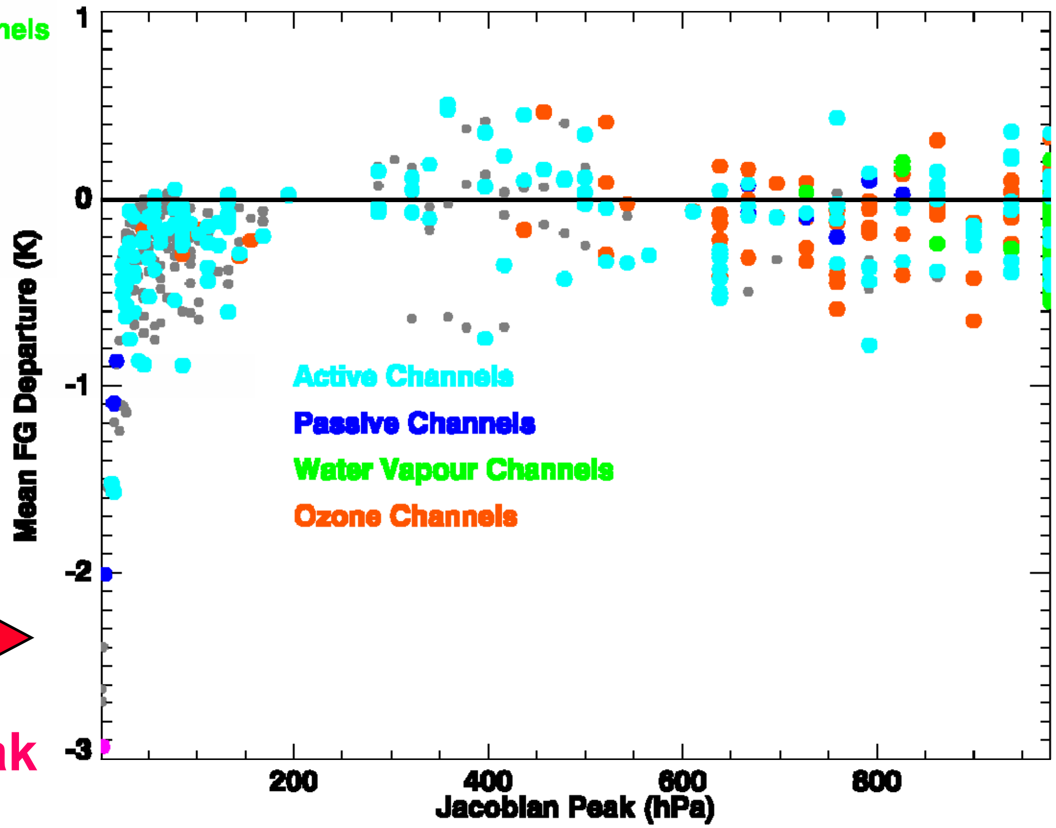
In the following slides:

- Clear-sky first guess departures
- The cloud detection uses the operational bias-correction
- The first-guess departures are NOT bias-corrected

First Guess Departure Biases in 15µm CO_2 Band



Ordered by Wavenumber



Ordered by Jacobian Peak Pressure

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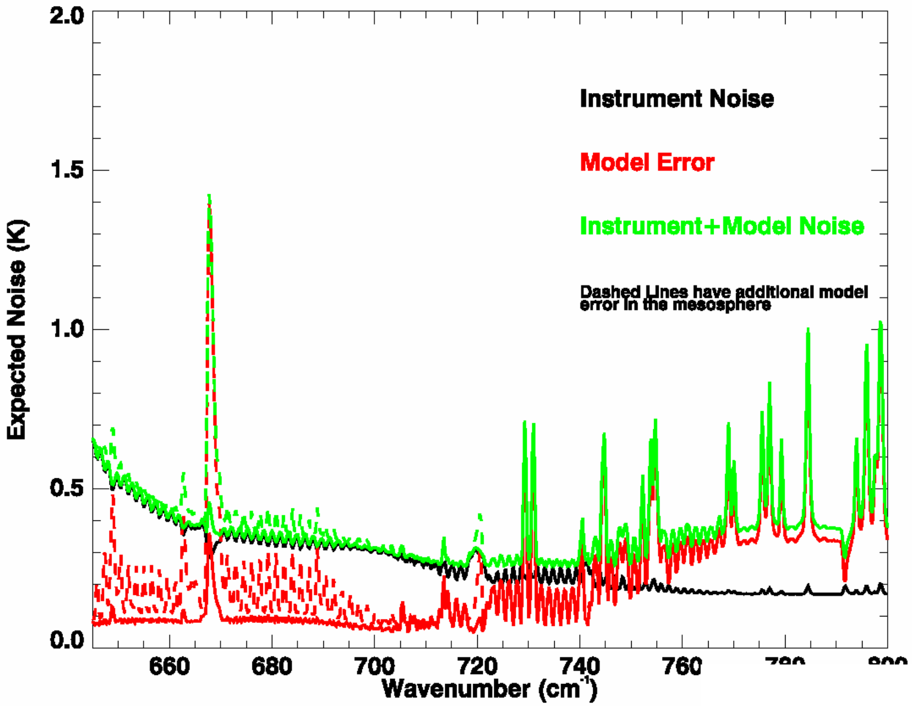
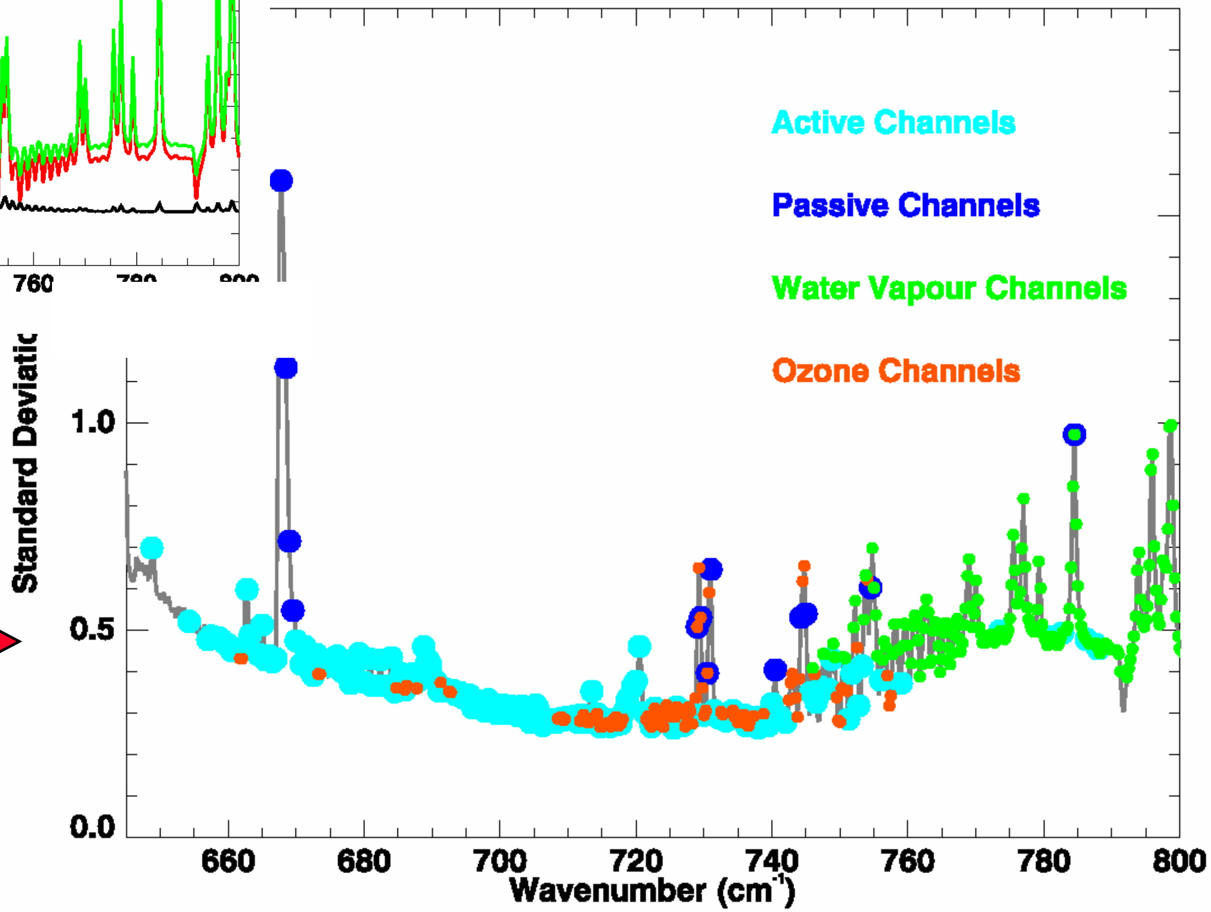
First –Guess Departure Standard Deviations in 15µm CO_2 Band



Calculated Std. Dev.



Observed Std. Dev.

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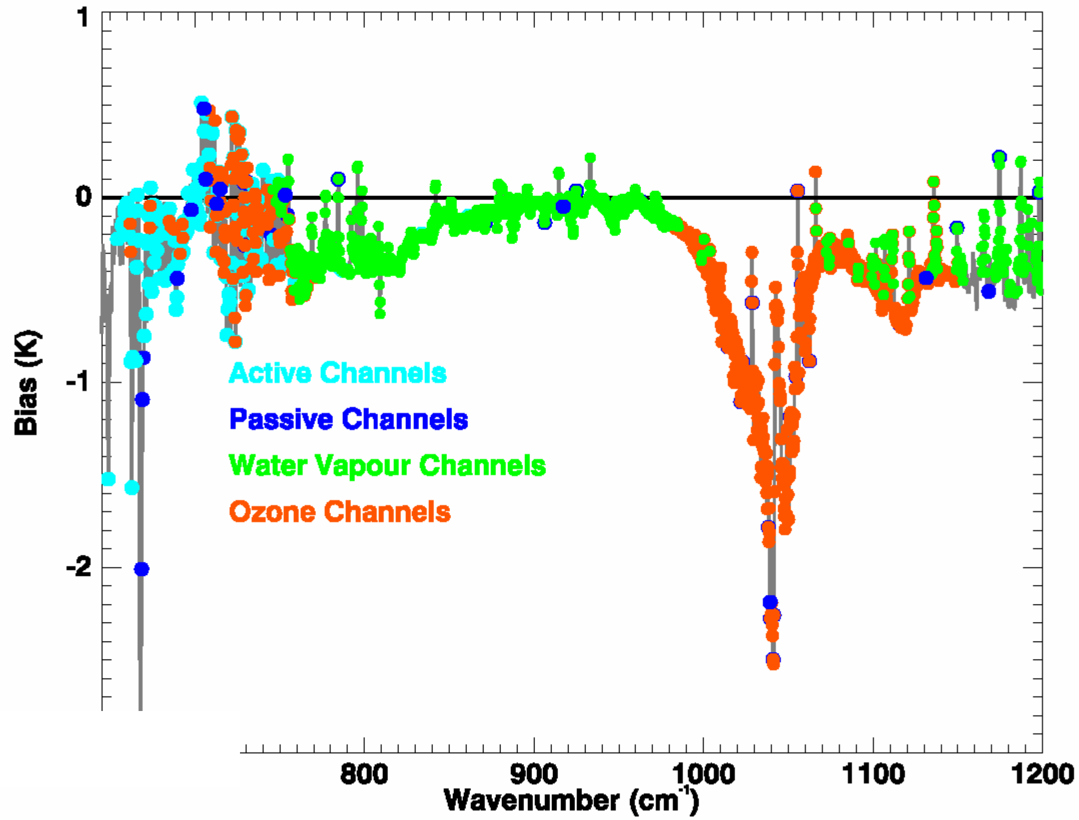
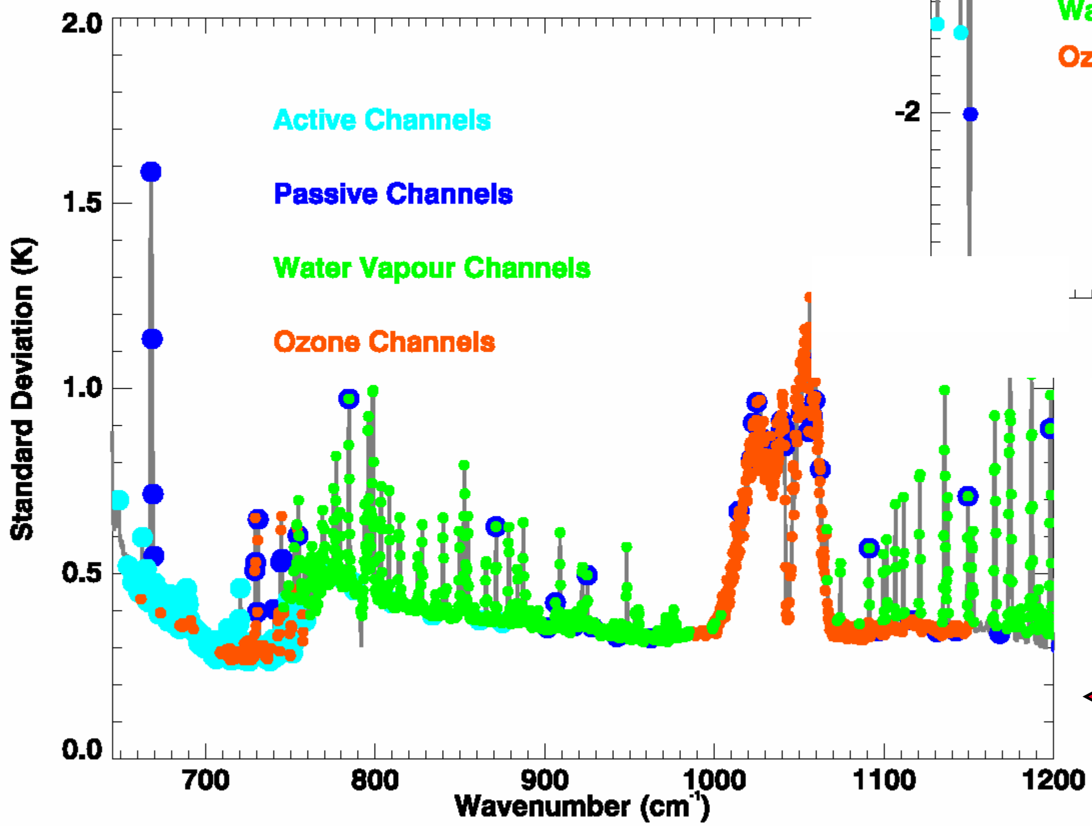
First Guess Departure Standard Deviations and Biases in the Longwave Window





Bias

Standard Deviation

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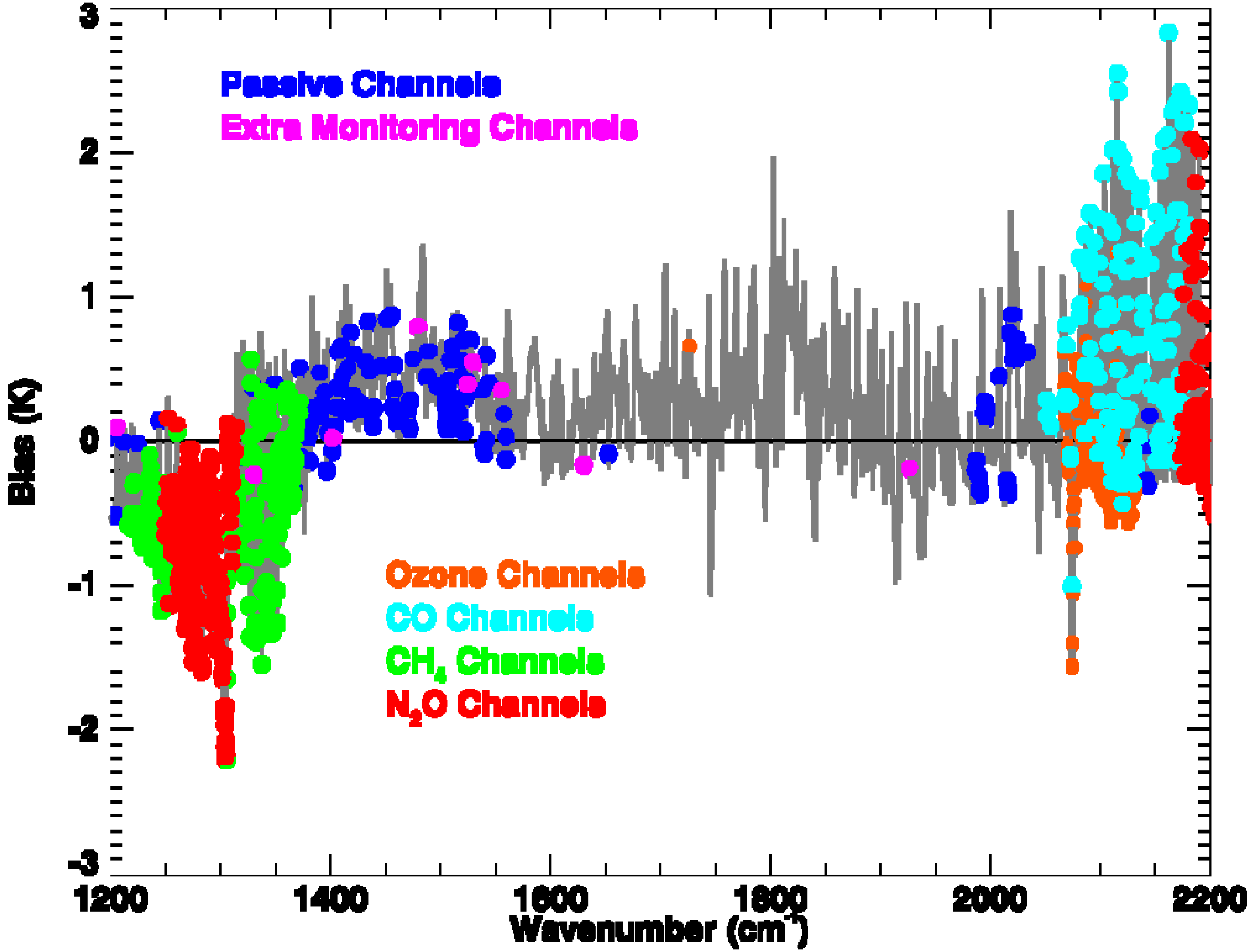
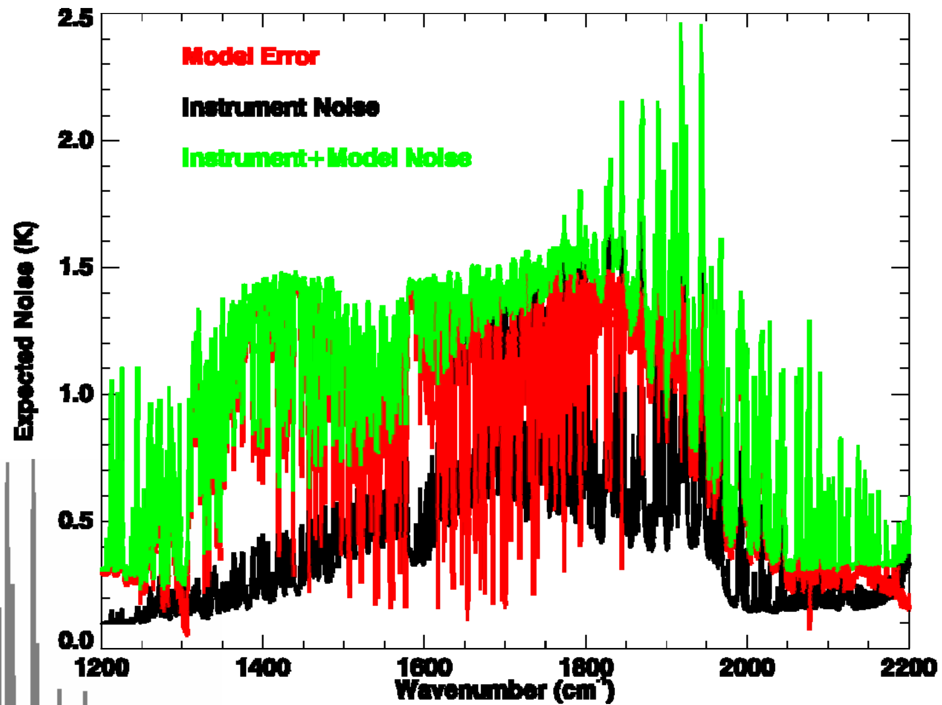
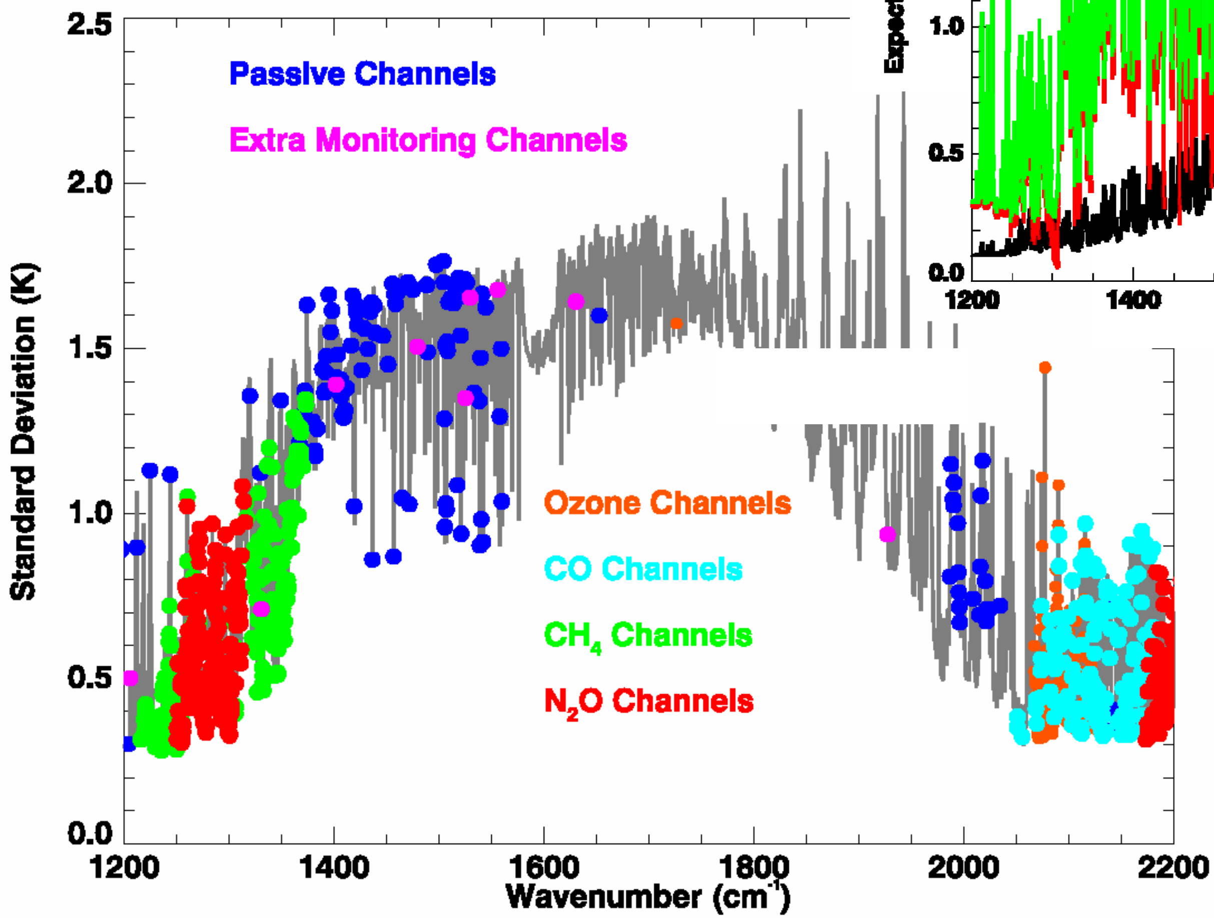
First-Guess Departure Biases in Water Band



First –Guess Departure Standard Deviations in Water Band





Calculated Std. Dev.

Observed Std. Dev.

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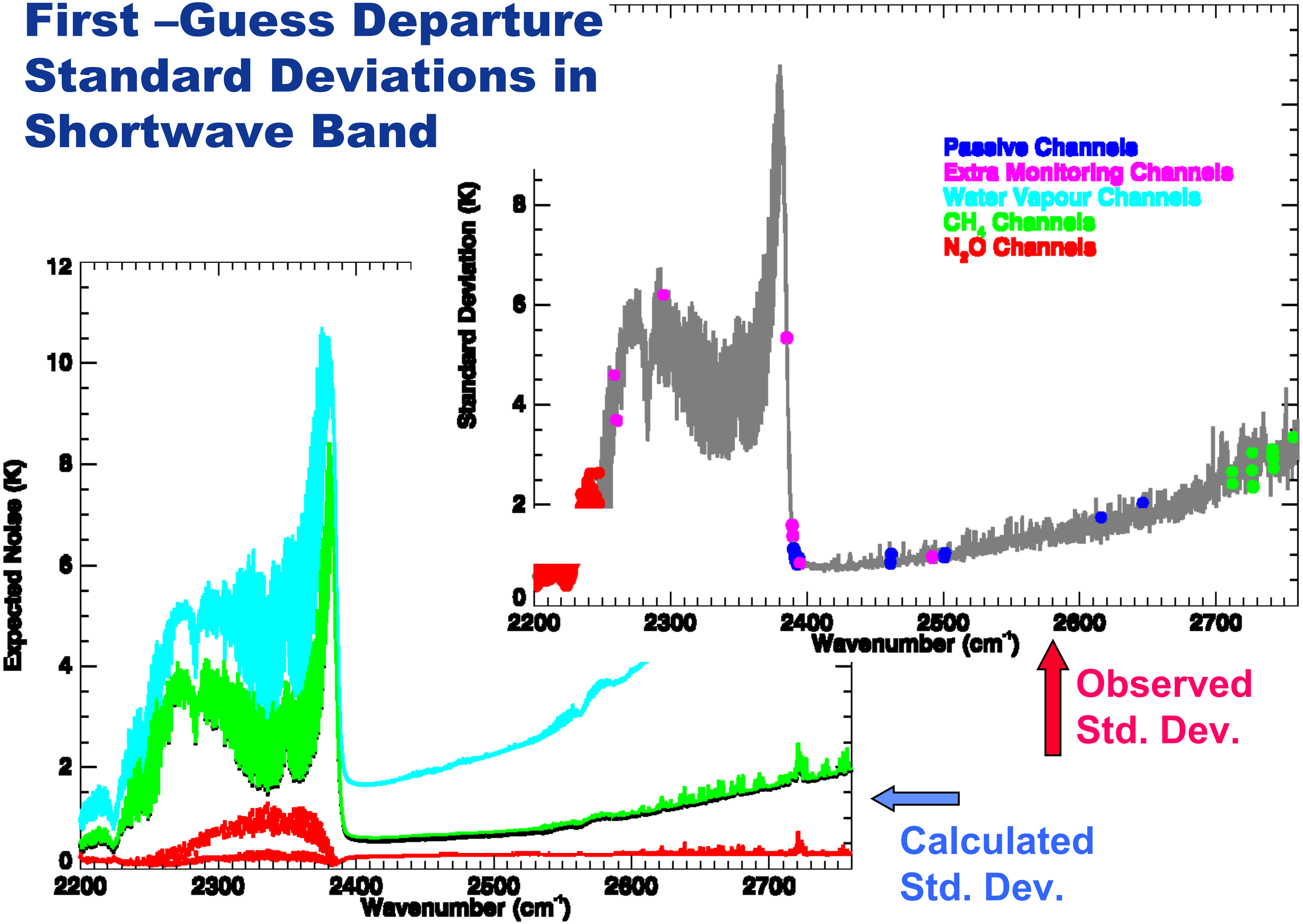
First –Guess Departure Standard Deviations in Shortwave Band



Observed Std. Dev.

Calculated Std. Dev.

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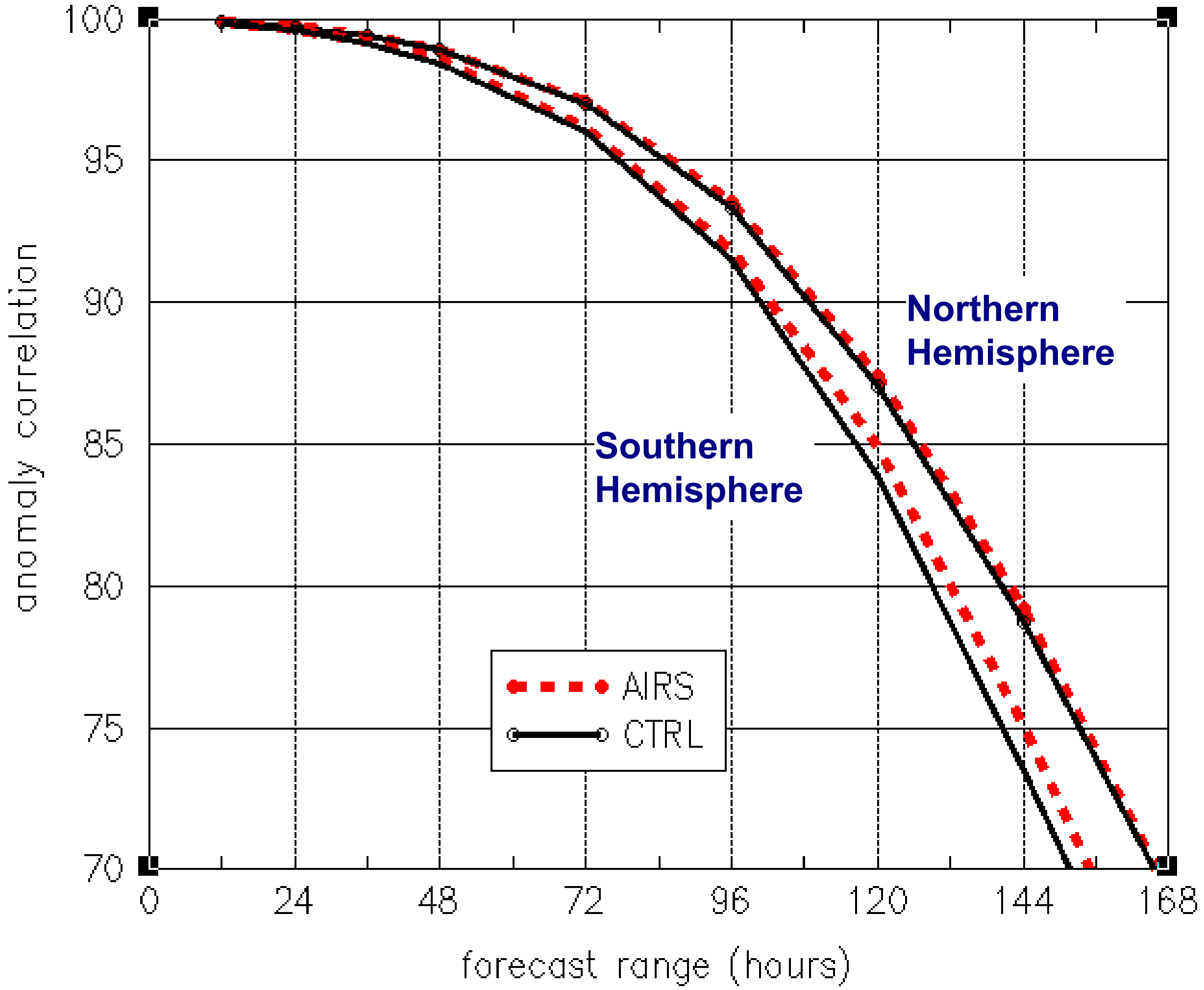
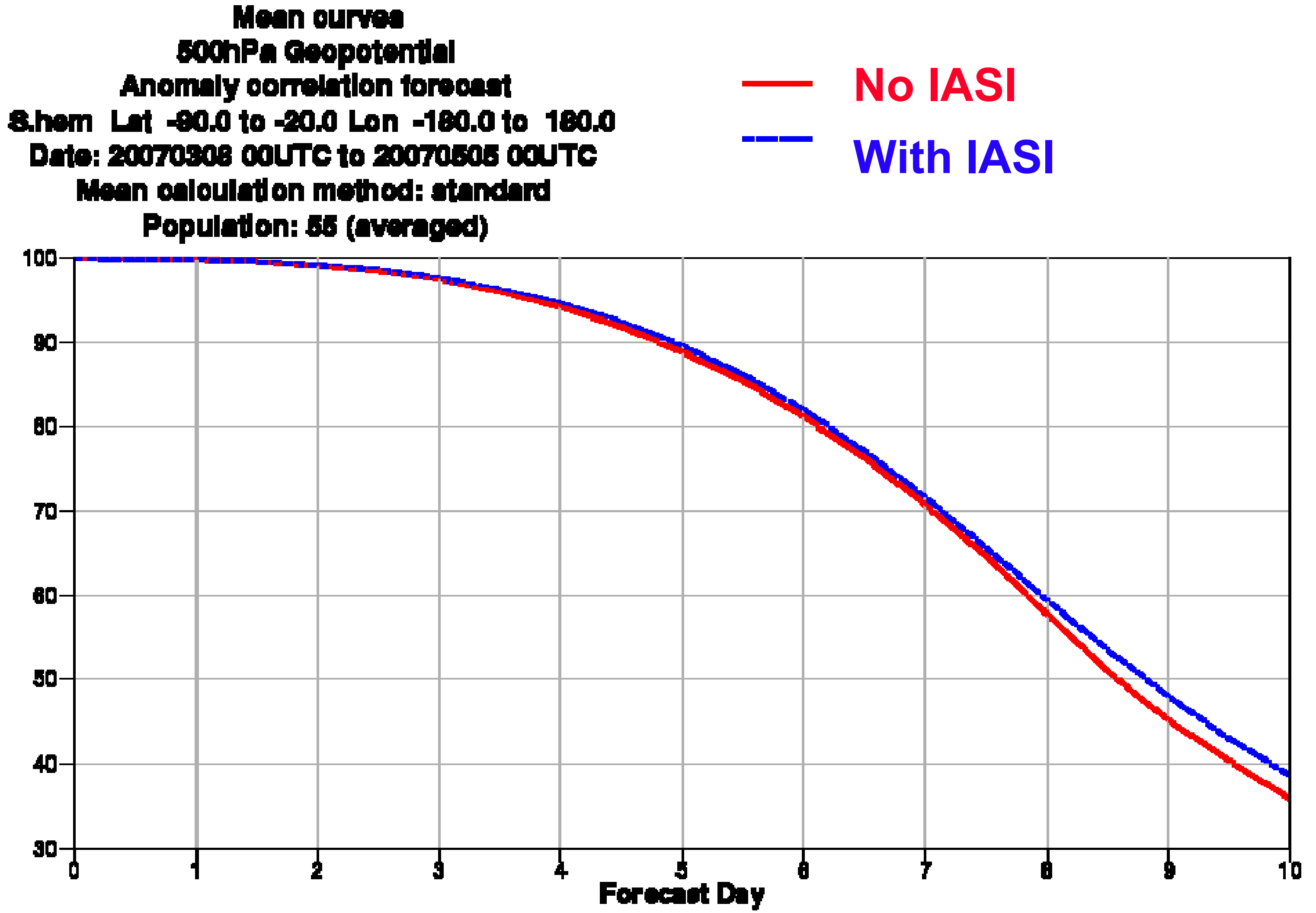
AIRS & IASI Forecast Impacts

AIRS Impact at ECMWF



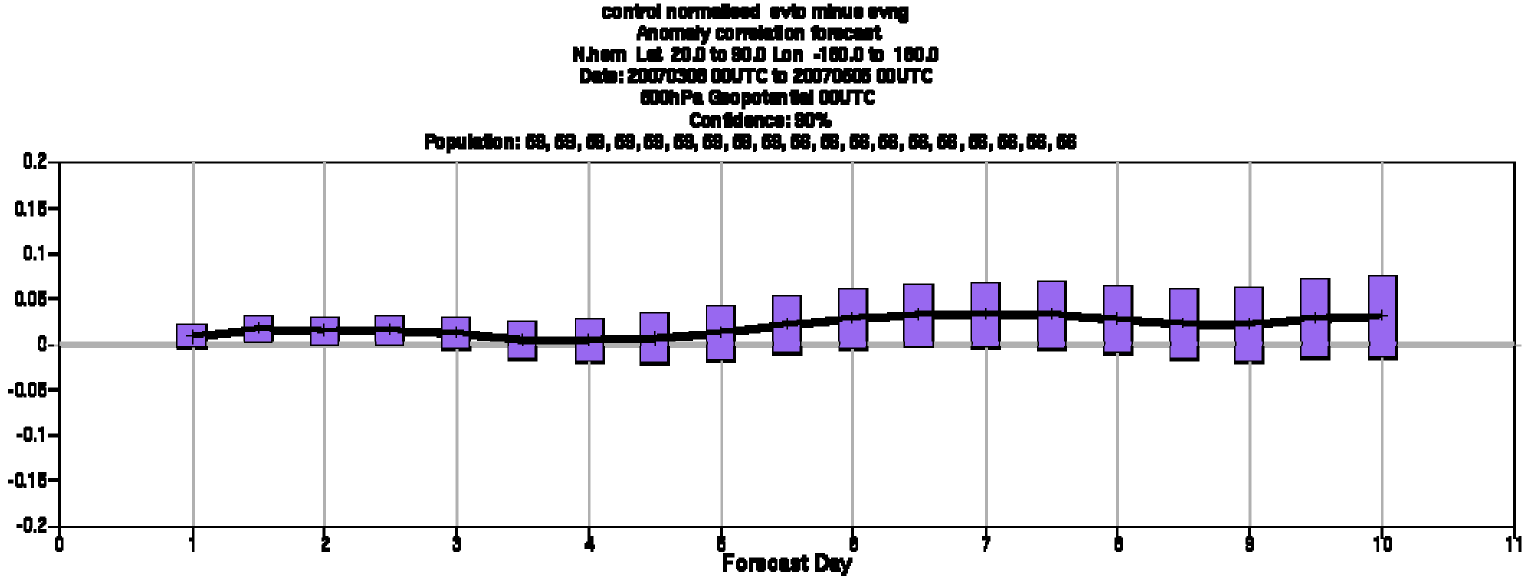
500hPa Geopotential Anomaly Correlation

IASI Impact on SH Geopot. AC



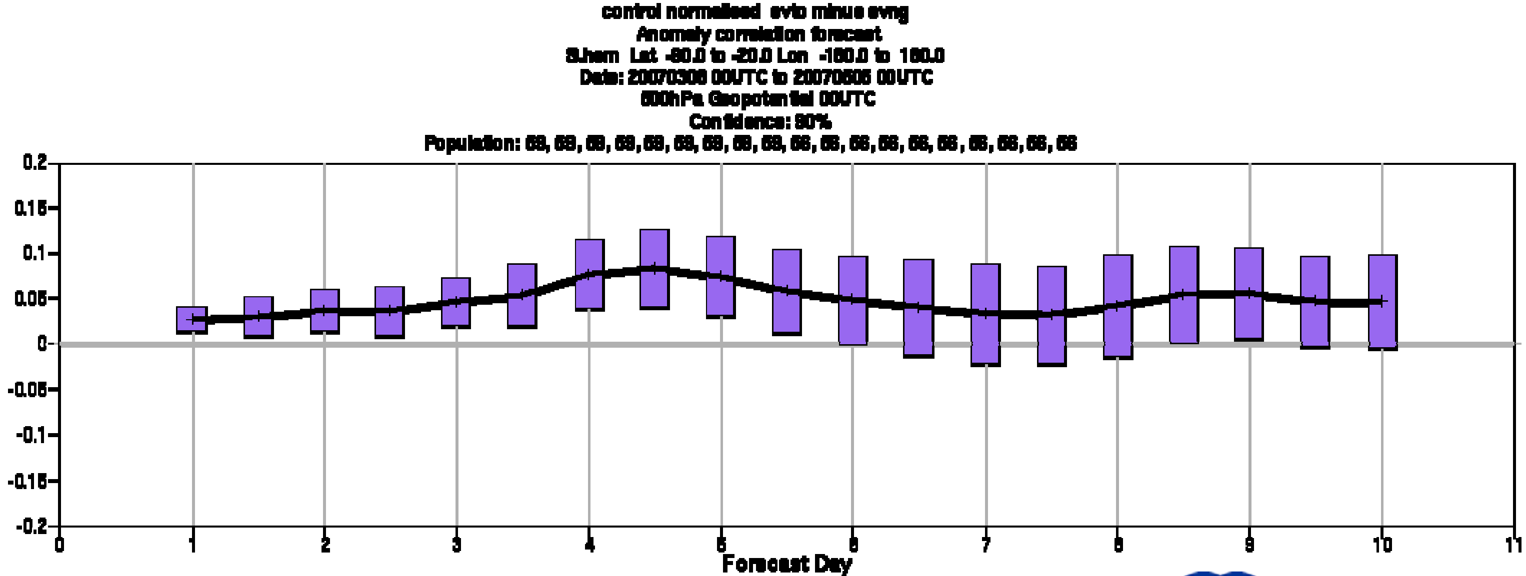
IASI Forecast Scores Again: 500hPa Geopot. AC

NH



IASI Better

SH



IASI Worse

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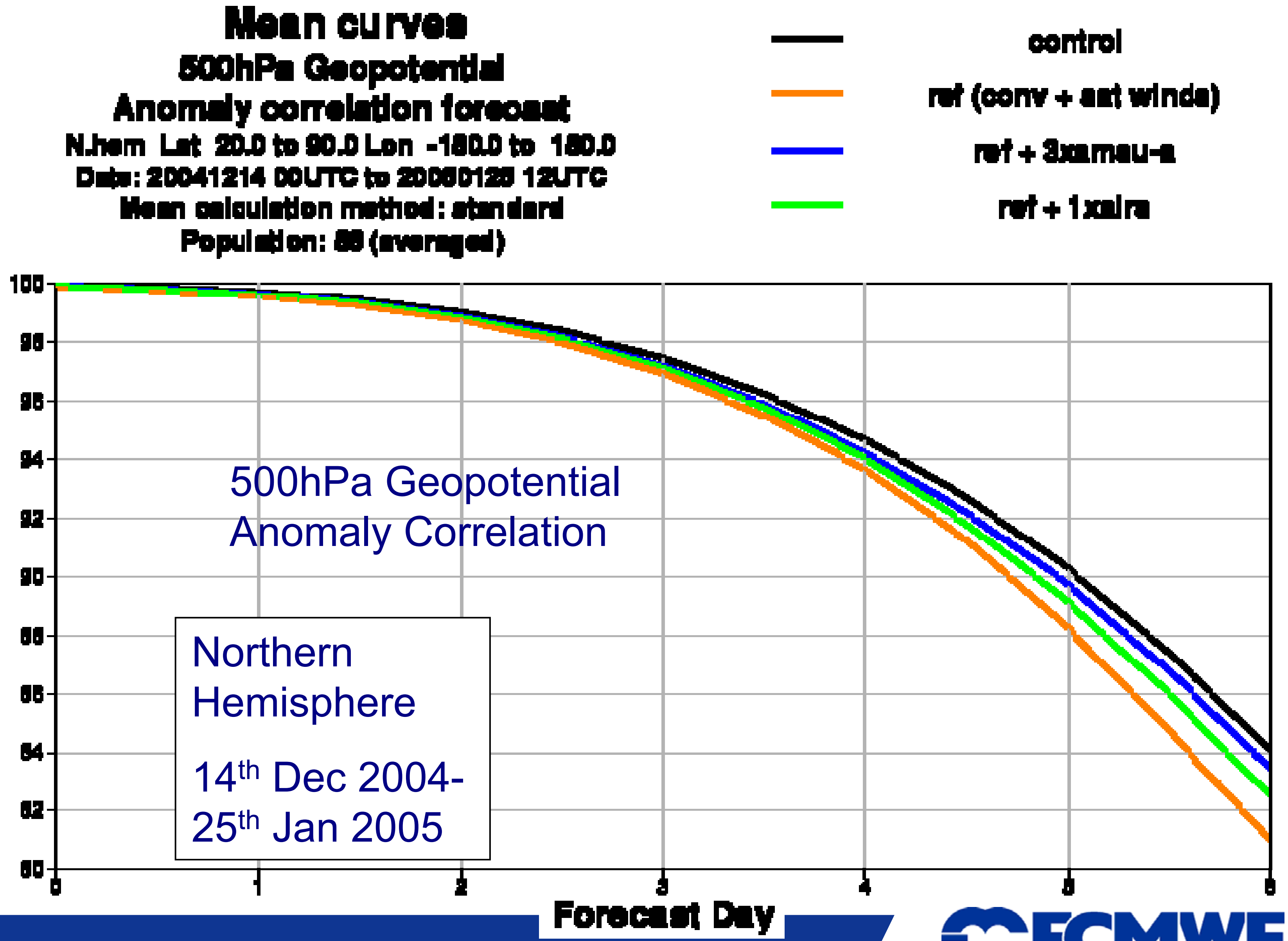
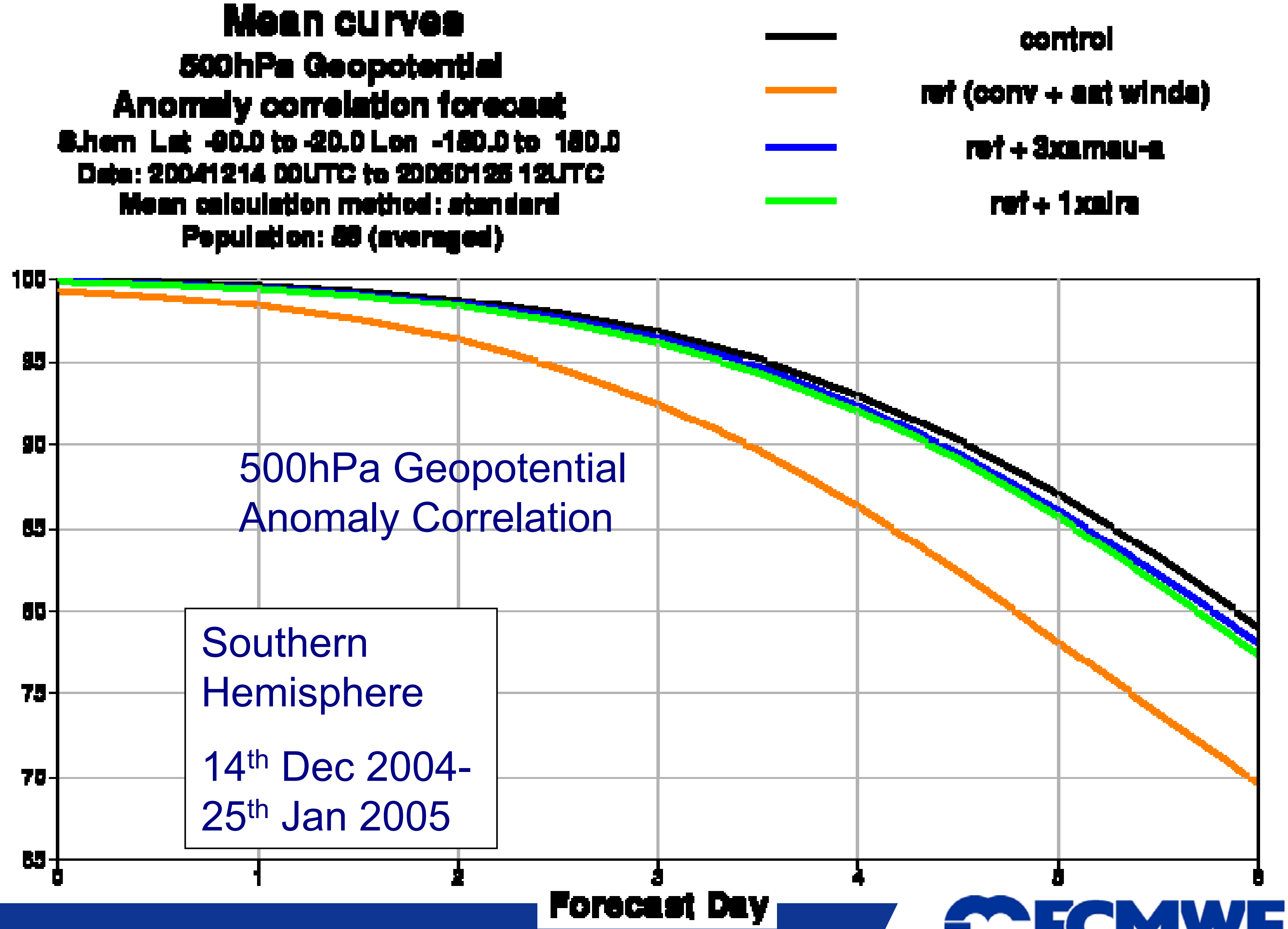
AIRS Impact at ECMWF in Context – N. Hemis.



AIRS Impact at ECMWF in Context – S. Hemis.



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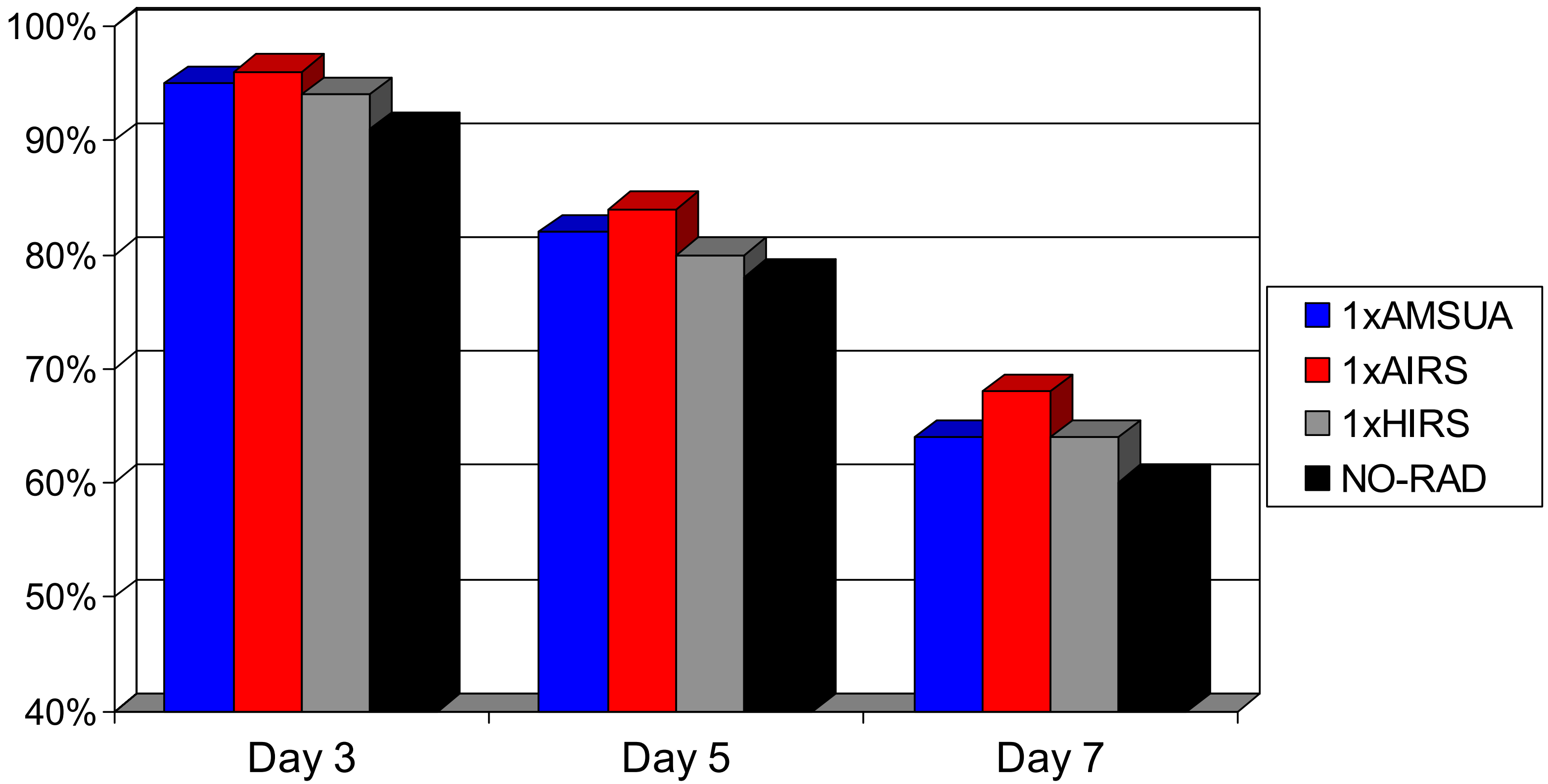
Single instrument experiments

Anomaly correlation of 500hPa height for the **Southern Hemisphere**
(average of 50 cases summer and winter 2003 verified with OPS analyses)



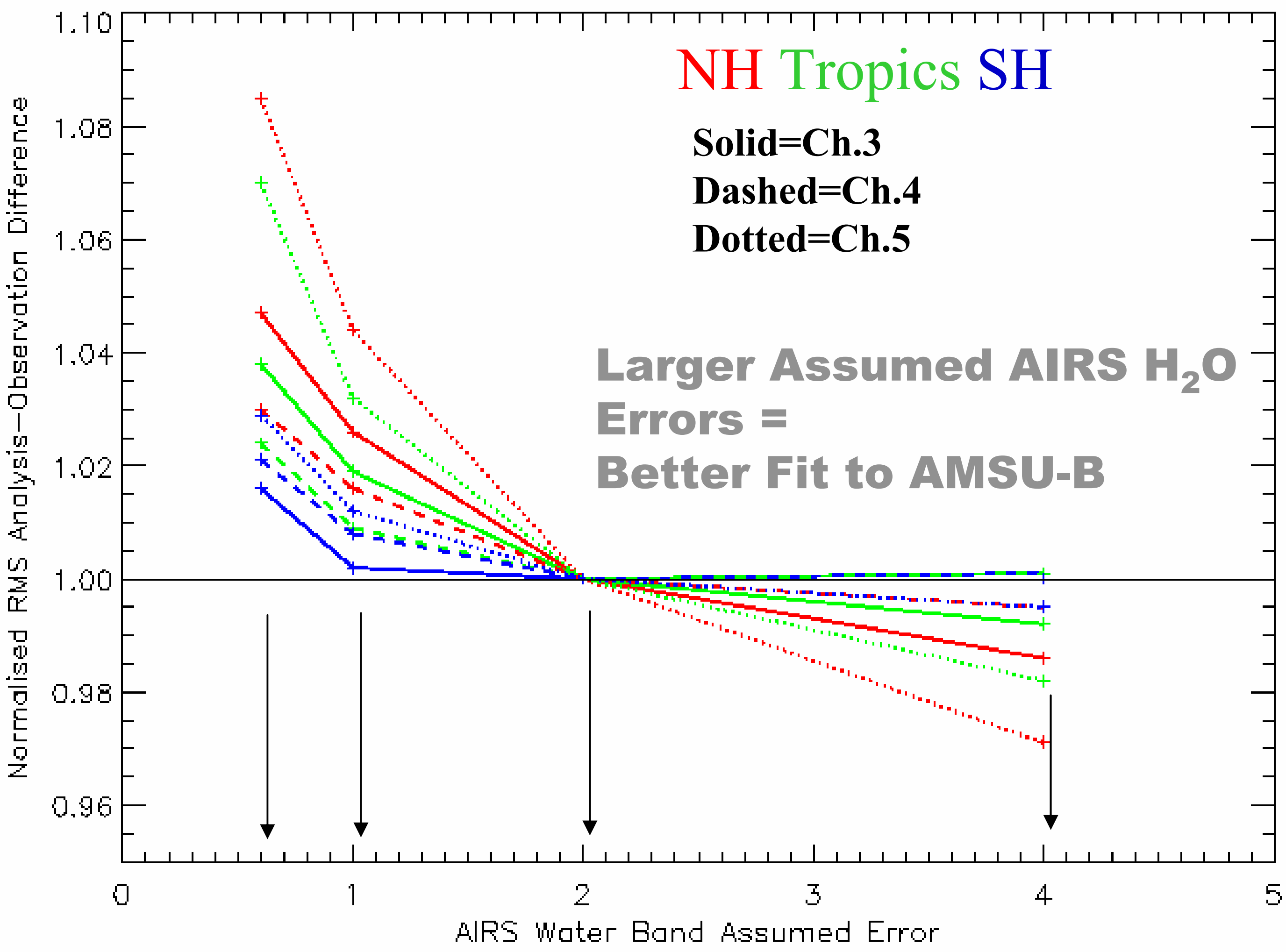
Challenges

Water Vapour

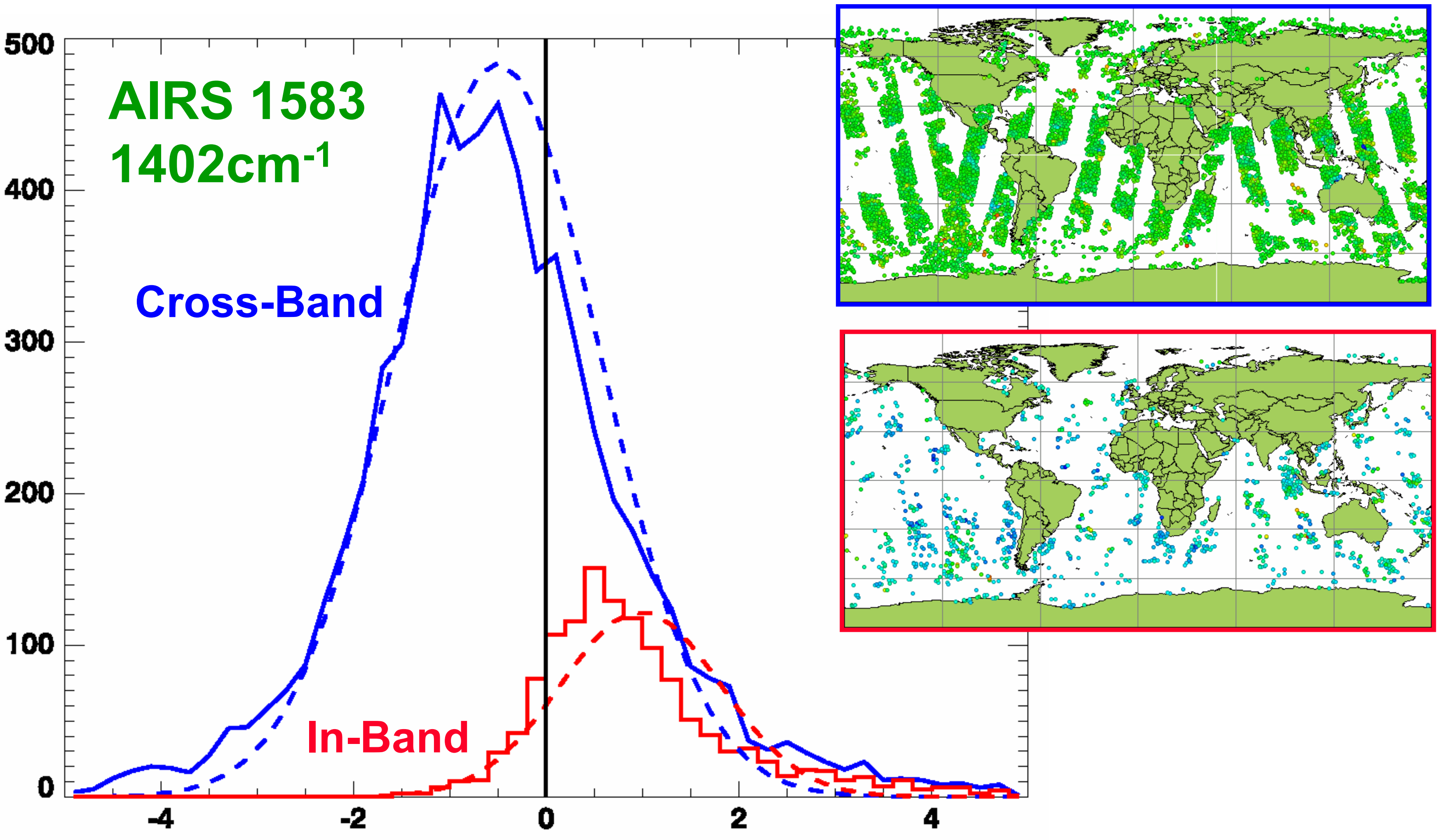
Use of Water Vapour Channels at ECMWF

- We get a small positive impact from using the water vapour channels
- We use a cloud detection scheme that uses the first guess departures in the water band itself
  - The signal from water vapour can mimic cloud
  - The resulting clear channels also tend to be those where water vapour departures are smallest
- We also assume 2K observation errors.

O-A Stats for NOAA-16 AMSU-B



In-band vs Cross-Band Cloud Detection



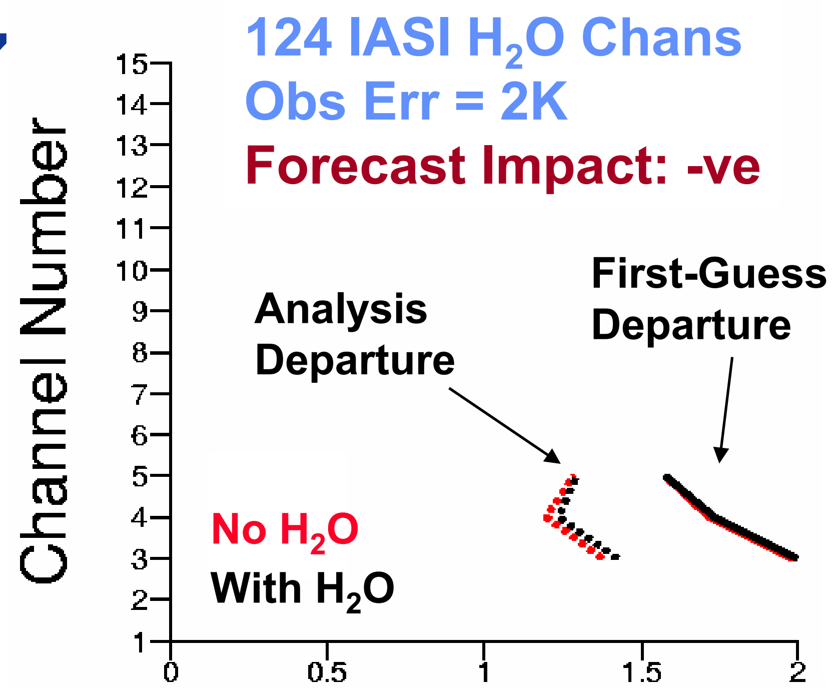
But....

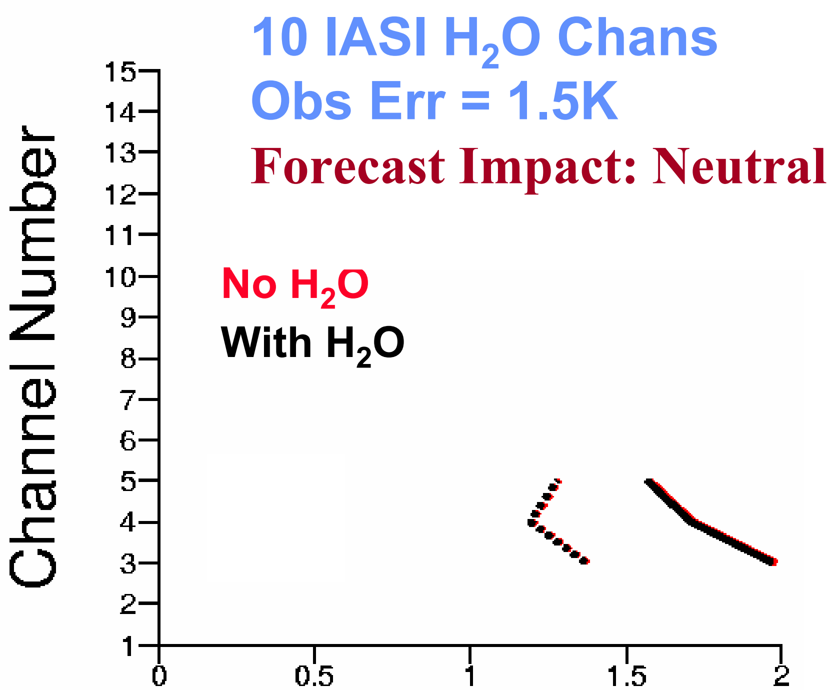
- In-band H_2O cloud detection with 2K assumed observation errors give small but positive impact
- Cross-band H_2O cloud detection gives worse impact than in-band unless assumed errors are > 6K!
- Water observation errors for AIRS are ~0.2K!

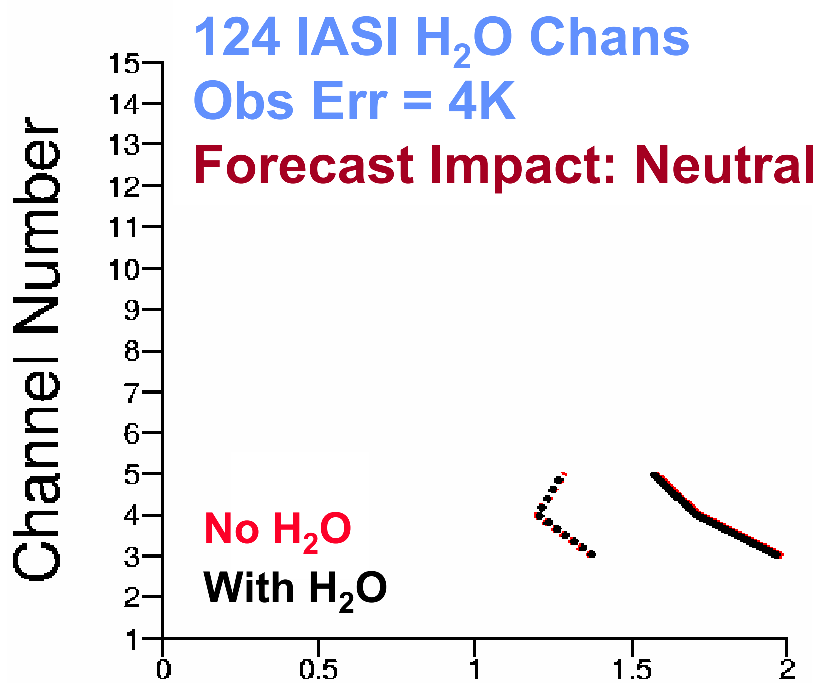
For IASI we have a similar story…

Std. Dev. of SH NOAA-17

With **IASI** using cross-band cloud detection, a 2K error will degrade fit to AMSU-B unless many fewer channels are used.







Some Water Discussion (1)

- The water vapour channels have temperature sensitivity which is highly dependent on the water vapour profile.
- It is possible that water vapour signal is causing erroneous temperature increments
- By removing the feedback of temperature information from the water vapour channels, it has been shown that this is not the case.

Some Water Discussion (2)

- We have to greatly inflate water vapour errors to avoid degrading the model
  - This is because of the large number of channels with error correlations between them (including bias)
- By assuming greatly increasing the water vapour observation errors we are negating the influence of inter-channel differences that allow us greater vertical resolution
  - Can we do a better job?

Cloud

Cloud

- Cloud in the field of view can greatly affect our ability to use IR radiances
- Studies have show that the most important areas to measure for accurate forecasts often have cloud
- We need to identify strategies to deal with cloud

Dealing with Cloud

- Use only clear fields of view
  - Low (~5%) yield
- Use only channels unaffected by cloud
  - Low yield in lower tropospheric channels
- Cloud clearing
  - Simulate a clear observation by using multiple fields of view and assume that only cloud fraction changes between them
- Simultaneous retrieval of cloud optical properties
  - These observations are rich in cloud information

Used now operationally

Under Investigation

Data Compression

Data Compression

- Advanced IR sounder radiances contain a lot of information (~30pieces) …
- …but there are two orders of magnitude more channels.
- Hence there is a large amount of redundancy
- How can we use these data more efficiently?

Why is data compression important?

- Very large data volumes need to be communicated in near-real time (e.g., EUMETSAT to NWP centres)
- Simulation of spectra (needed for assimilation) is costly
- Assimilation is costly
- Data storage

Efficient use of channels

- **All channels:**
  - 1000s of Channels
  - Not very efficient

- **Selected Channels:**
  - 50-1000 Channels
  - Simplest method
  - What we currently use
  - Throws away a lot of information

- **Selected Channels + Grouping (“Superchannels”):**
  - Reduced Number of Channels
  - Lower noise per channel used
  - Weighting Functions are Less Sharp?

Efficient use of channels (contd.)

- **Assimilating Retrievals:**
  - The old way
  - We can pass a smaller number of variables to the 3D/4DVar stage
  - No expensive RT modelling required at 3D/4DVar stage
  - Two main issues:
    - Inter-level correlations
    - *A priori* data

- **Principal Components and Reconstructed Radiances…**

Spectral data compression with PCA*

The complete AIRS spectrum can be compressed using a truncated principal component analysis (e.g. 200PCAs v 2300 rads)

Leading eigenvectors (200,say) of covariance of spectra from (large) training set

Mean spectrum

$$\mathbf{p} = \mathbf{V}^{T}(\mathbf{y} - \overline{\mathbf{y}})$$

Original Spectrum

- To use PCs in assimilation requires an efficient RT model to calculate PCs directly
- PCs are more difficult to interpret physically than radiances

N.B. This is usually performed in noise-normalised radiance space

This allows data to be transported efficiently

***Principal Component Analysis**

Spectral data compression and de-noising

The complete AIRS spectrum can be compressed using a truncated principal component analysis (e.g. 200PCAs v 2300 rads)

Leading eigenvectors (200,say) of covariance of spectra from (large) training set

Mean spectrum

Reconstructed spectrum

$$\mathbf{p} = \mathbf{V}^{\mathrm{T}}(\mathbf{y} - \overline{\mathbf{y}})$$

$$\mathbf{y}_{\mathbf{R}} = \overline{\mathbf{y}} + \mathbf{V}\mathbf{p}$$

Original Spectrum

N.B. This is usually performed in noise-normalised radiance space

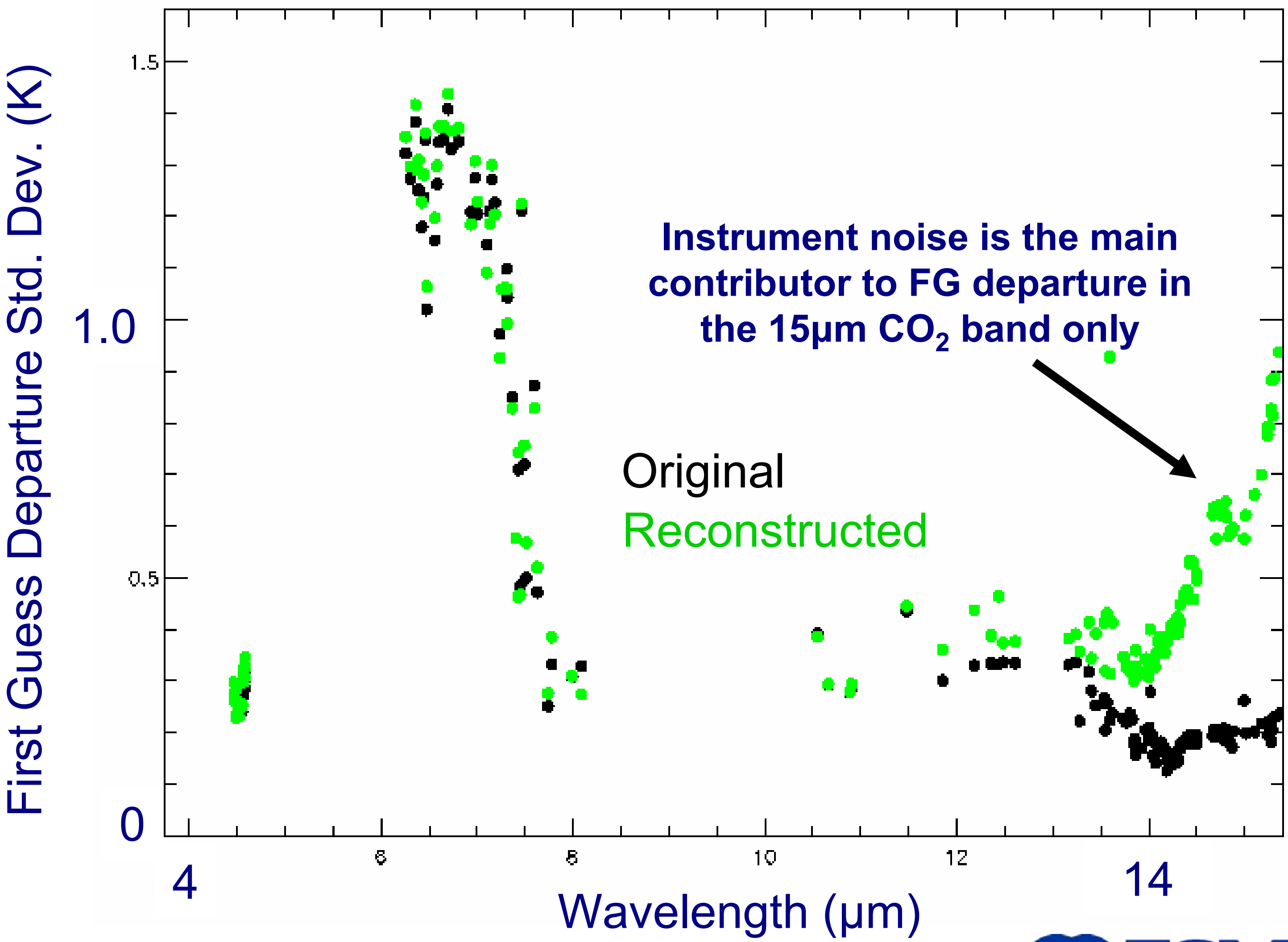
Each reconstructed channel is a linear combination of all the original channels and the data is significantly de-noised.

If *N* PCs are used all the information is contained in *N* reconstructed channels (theoretically)

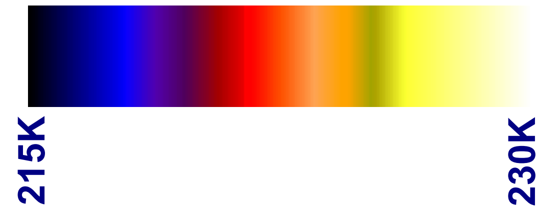
AIRS Reconstructed Radiances

- Data are supplied in near-real time by NOAA/NESDIS in the same format as the “real” radiances.
- The same channels are supplied, except some “popping” channels are missing
- Based on 200 PCs
- QC Flag supplied

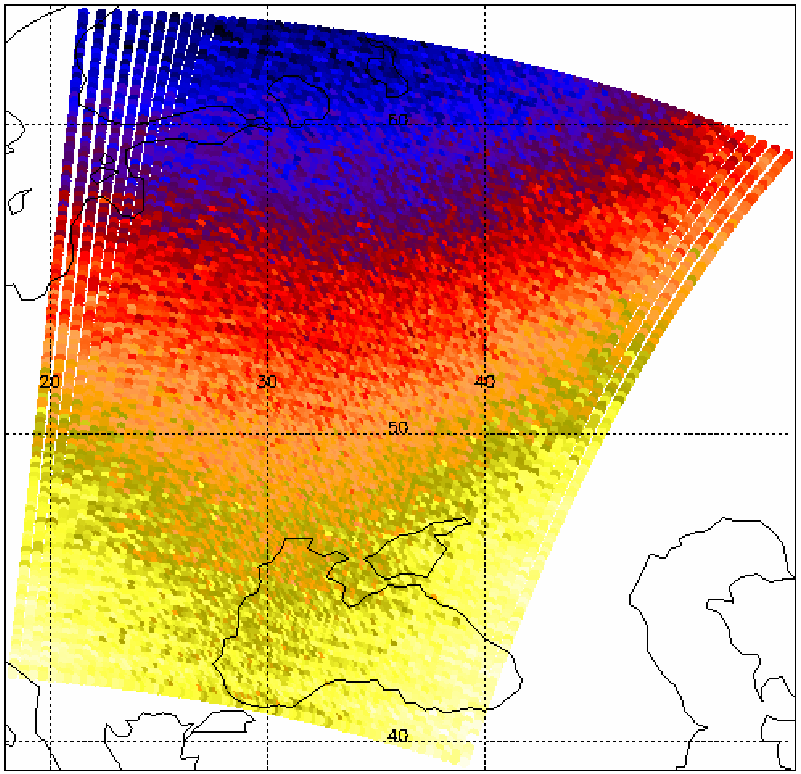
First Guess Departures for AIRS are Reduced



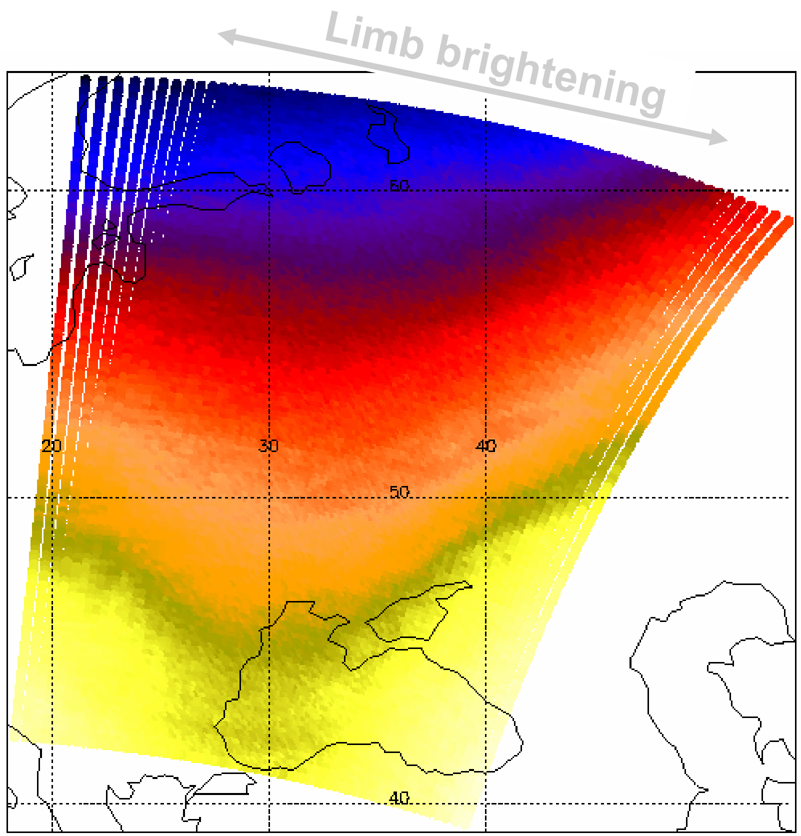
Spatial Denoising



Brightness Temperature (K)



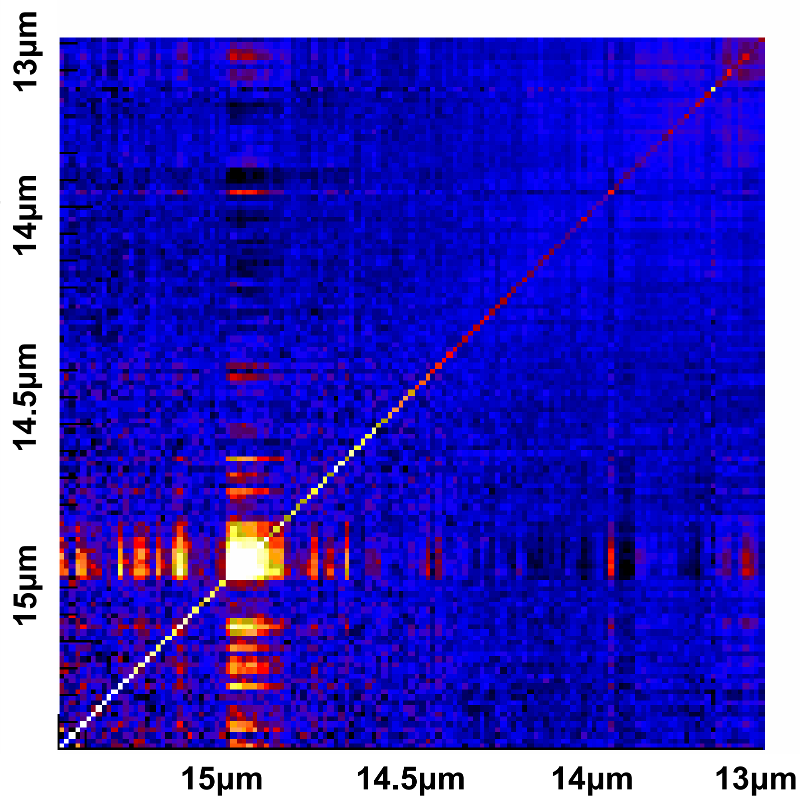
Original



"Denoised"

AIRS Channel 99
(674.4cm^{-1}, 14.83μm, ~15hPa)

A look at Reconstructed Radiances' Errors

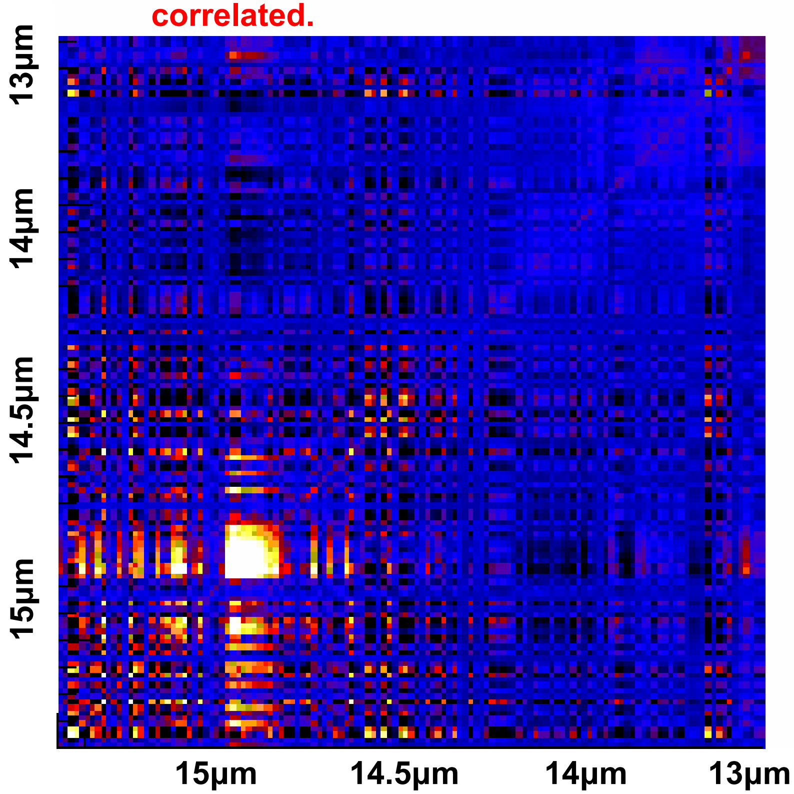


Original Radiances

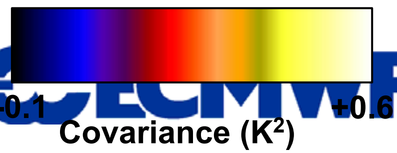
Instrument noise is dominant and diagonal. Correlated noise is from background error

Reconstructed Radiances

Instrument noise is reduced (std. dev. Is approximately halved) but has become correlated.

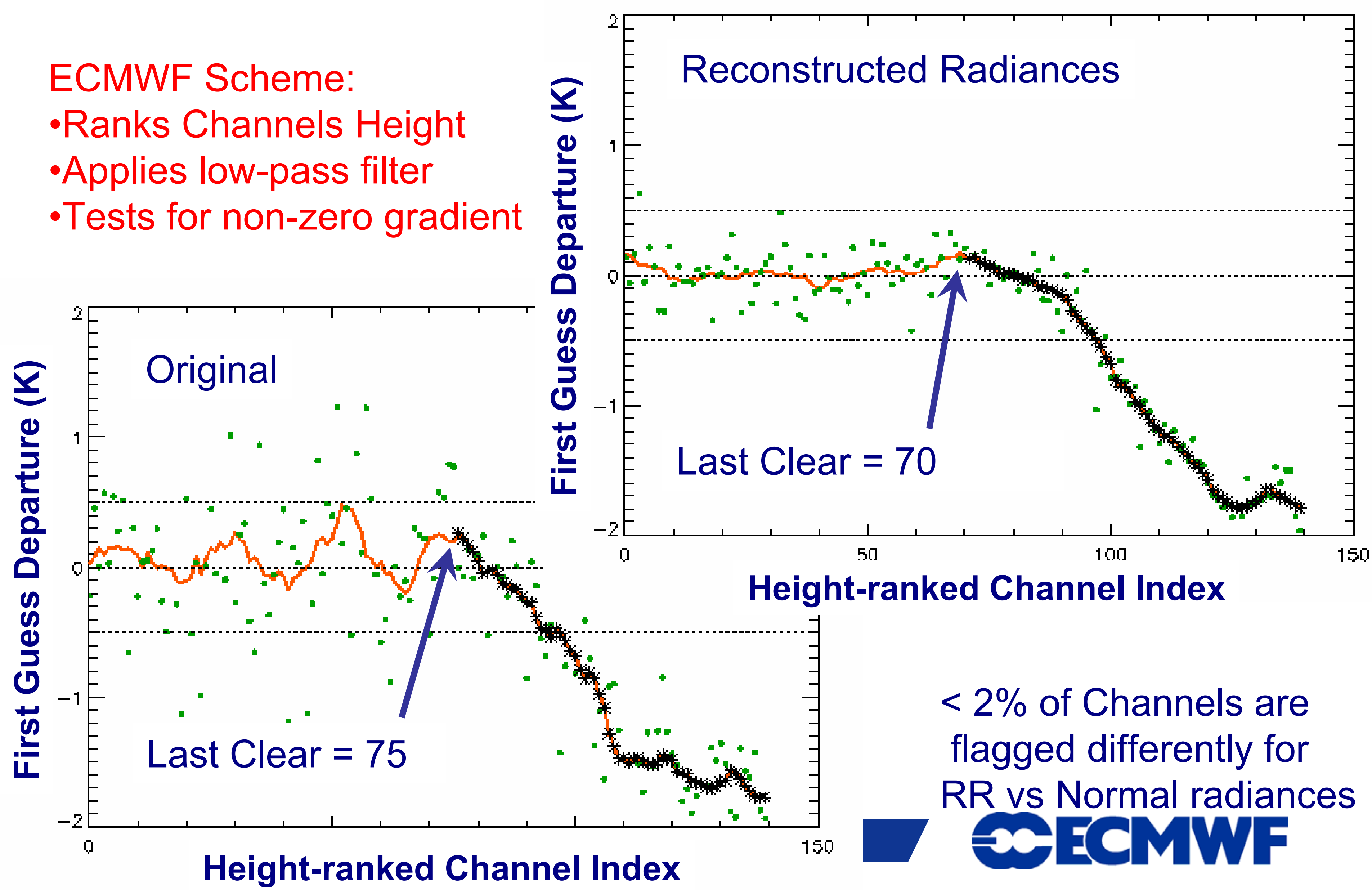


Covariances of background departures for clear observations in 15µm CO_2 band



Improvements in Cloud Detection

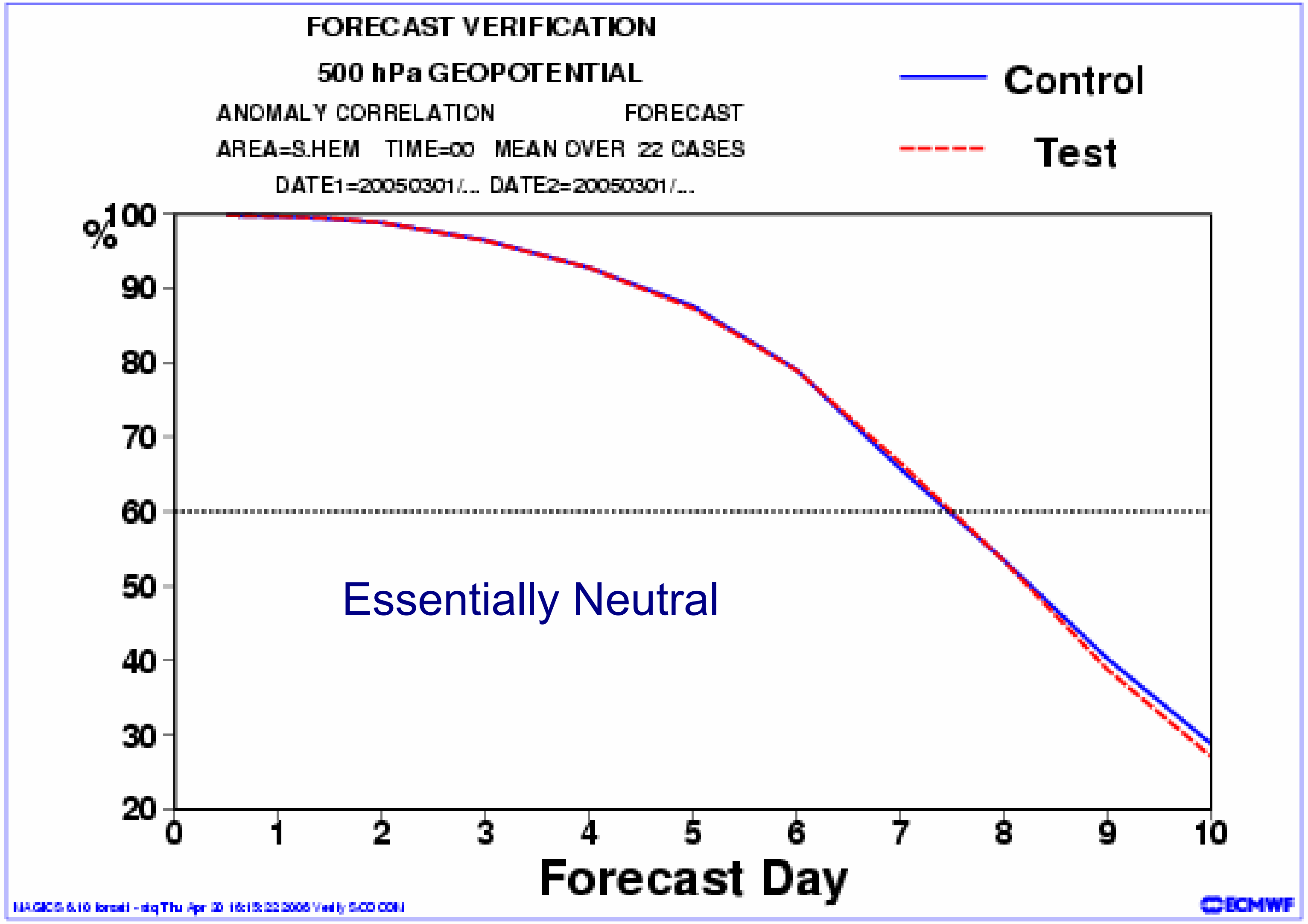
ECMWF Scheme:
- •Ranks Channels Height
- •Applies low-pass filter
- •Tests for non-zero gradient



< 2% of Channels are flagged differently for RR vs Normal radiances

ECMWF

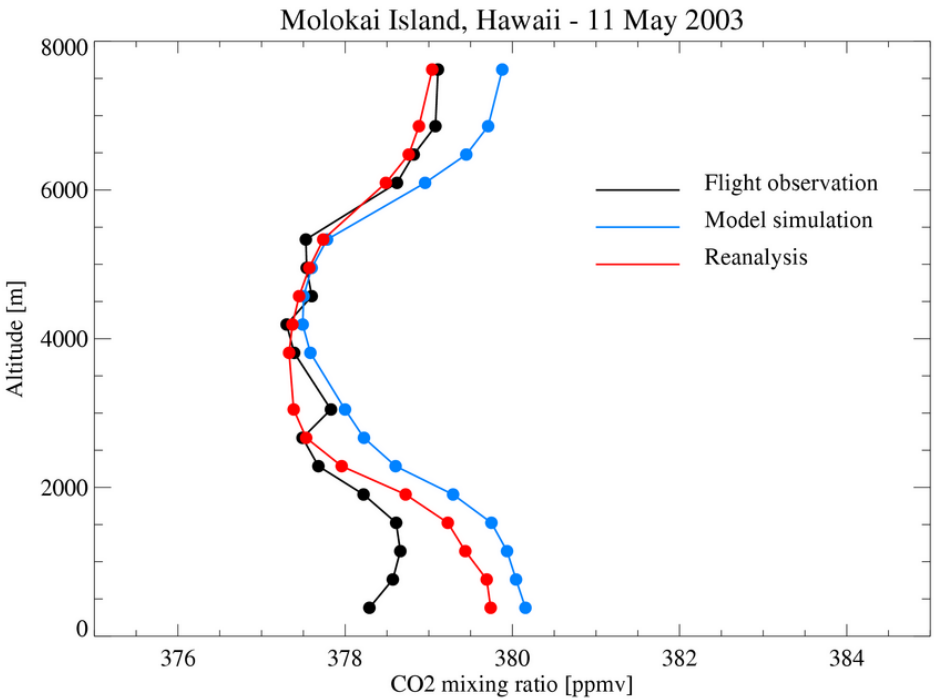
Forecast Impact of Reconstructed Radiances



“Trace” Gases

Using AIRS in CO_2 data assimilation

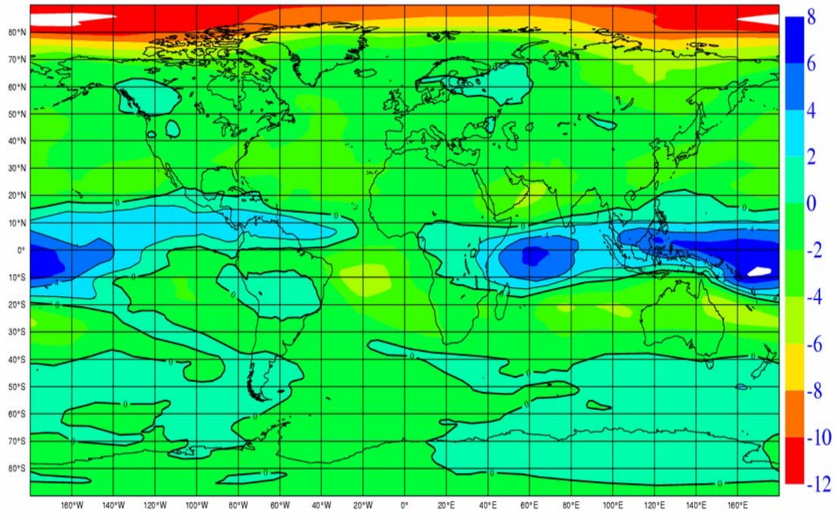
AIRS observations are used for CO_2 data assimilation within the GEMS project. Although the signal is small, it does improve the fit to independent aircraft observations as shown in the figure. In the next few months IASI will be implemented in the CO_2 assimilation as well.

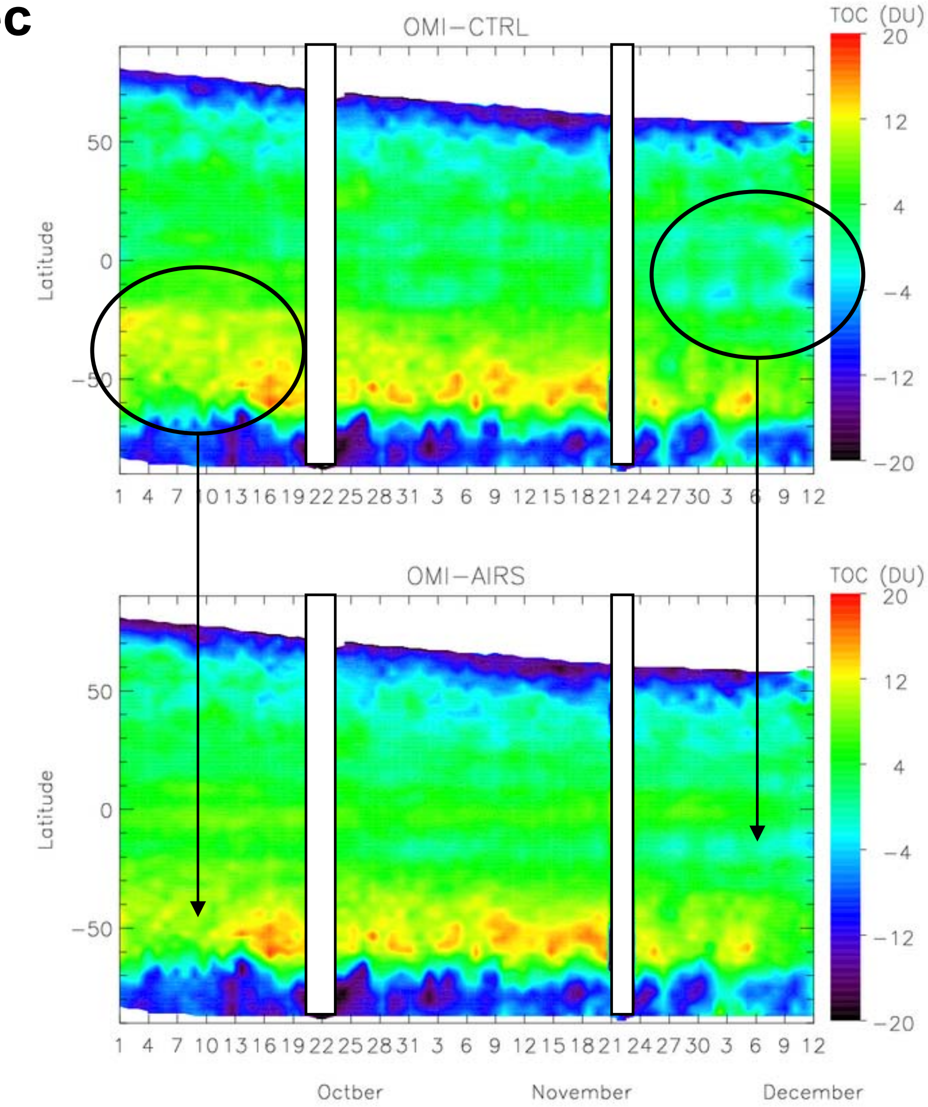


The flight data over Hawaii were provided by Pieter Tans, NOAA/ESRL.

Assimilation of AIRS O_3-sensitive IR channels

- **Two exp (T159L91), 15 Sep–14 Dec**
  - *CTRL*: Op. set up
  - *AIRS*: *CTRL* +36 ch. assimilated in [1003-1286] cm^{-1}
- **Radiances over land blacklisted.**
- **TCO is reduced in the tropics, increased at HL in the NH**





Courtesy Rossana Dragani

Conclusions

- AIRS and IASI have been operational at ECMWF since October 2003 and June 2007 respectively
- IASI and AIRS have demonstrated positive impacts on the ECMWF NWP model and form an important part of the assimilation system
- To make better use of the full dataset we need to address:
  - Water vapour assimilation
  - Assimilation in cloudy areas
  - Efficient use of more of the spectrum
  - Use over land

Coffee?

Time for ~~Lunch!!!!~~

ECMWF