Assimilation of IASI Principal Components

Andrew Collard

Acknowledgements to Tony McNally, Sean Healy, Fiona Hilton, Nigel Atkinson, Tim Hultberg, James Cameron, Marco Matricardi, Richard Engelen

Overview

- Introduction
- Why are we interested?
- Basic Concepts
- Strategies
- Experience with AIRS
- Discussion
- Questions

Introduction

The Aim of this Talk

To suggest questions that should be addressed if we are to use principal components to make more efficient use of IASI observations

Why are we interested?

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 full spectra (needed for assimilation) is costly
- Assimilation of the full spectrum is costly and inefficient
- Data storage

Why is data compression important?

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- **Assimilation of the full spectrum is costly and inefficient**
- Data storage

Basic Concepts

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

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

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

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

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

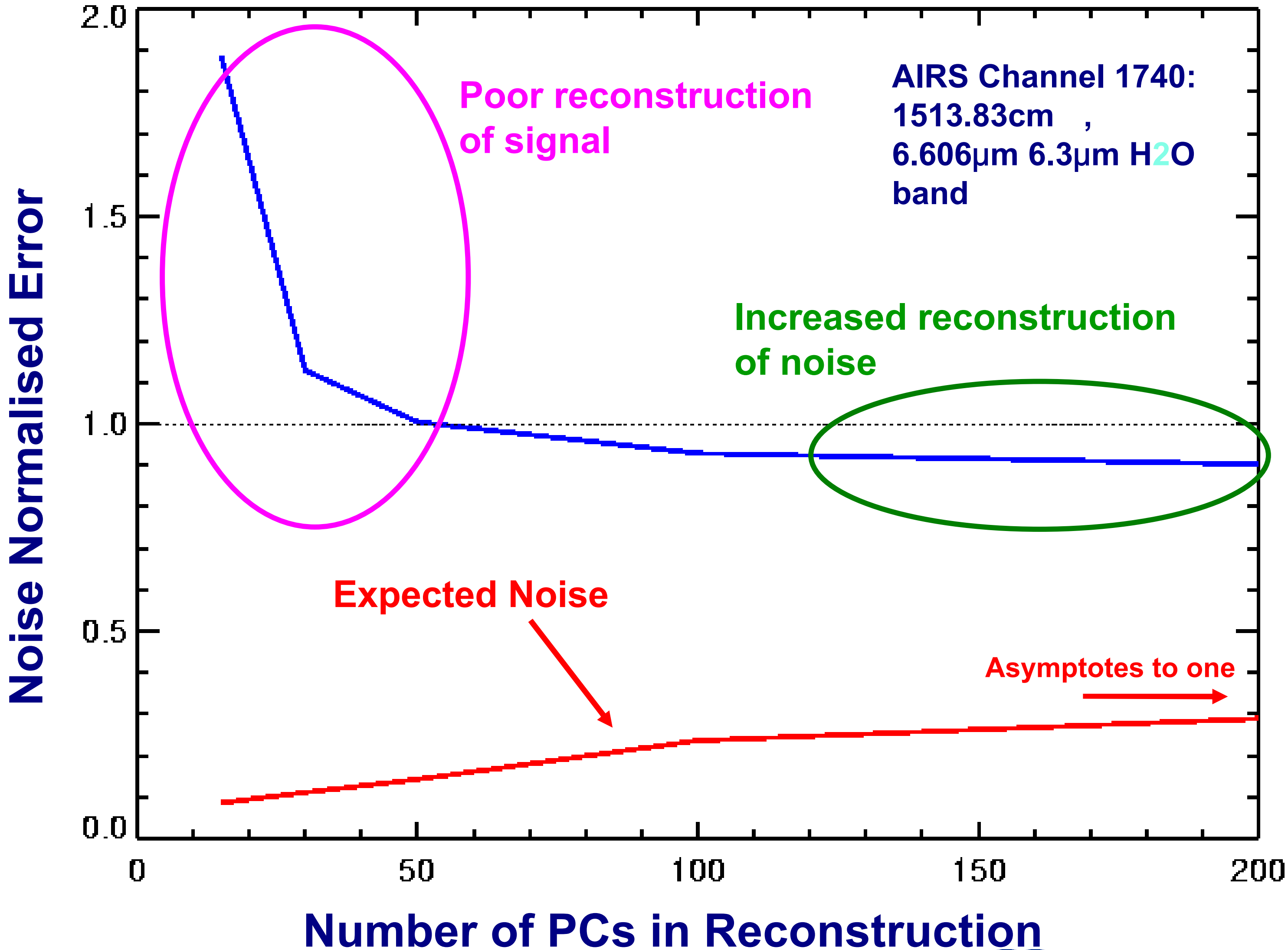
Original Spectrum

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)

Reconstruction Errors



Transformation of Instrument Noise

Error in observation, ε_y, is transformed by:

$$\boldsymbol{\varepsilon}_{\mathbf{y}_R} = \mathbf{V}\mathbf{V}^{\mathrm{T}}\boldsymbol{\varepsilon}_{\mathbf{y}} + \boldsymbol{\varepsilon}_{\mathbf{R}}$$

Where ε_R is the reconstruction error (the difference between the noise-free reconstructed and true radiances).

∴ Observation error covariance , E_R, of reconstructed radiances:

$$\mathbf{E}_{\mathbf{R}} = \mathbf{V}\mathbf{V}^{\mathrm{T}}\mathbf{E}\mathbf{V}^{\mathrm{T}}\mathbf{V} + \mathbf{F}_{\mathbf{R}}$$

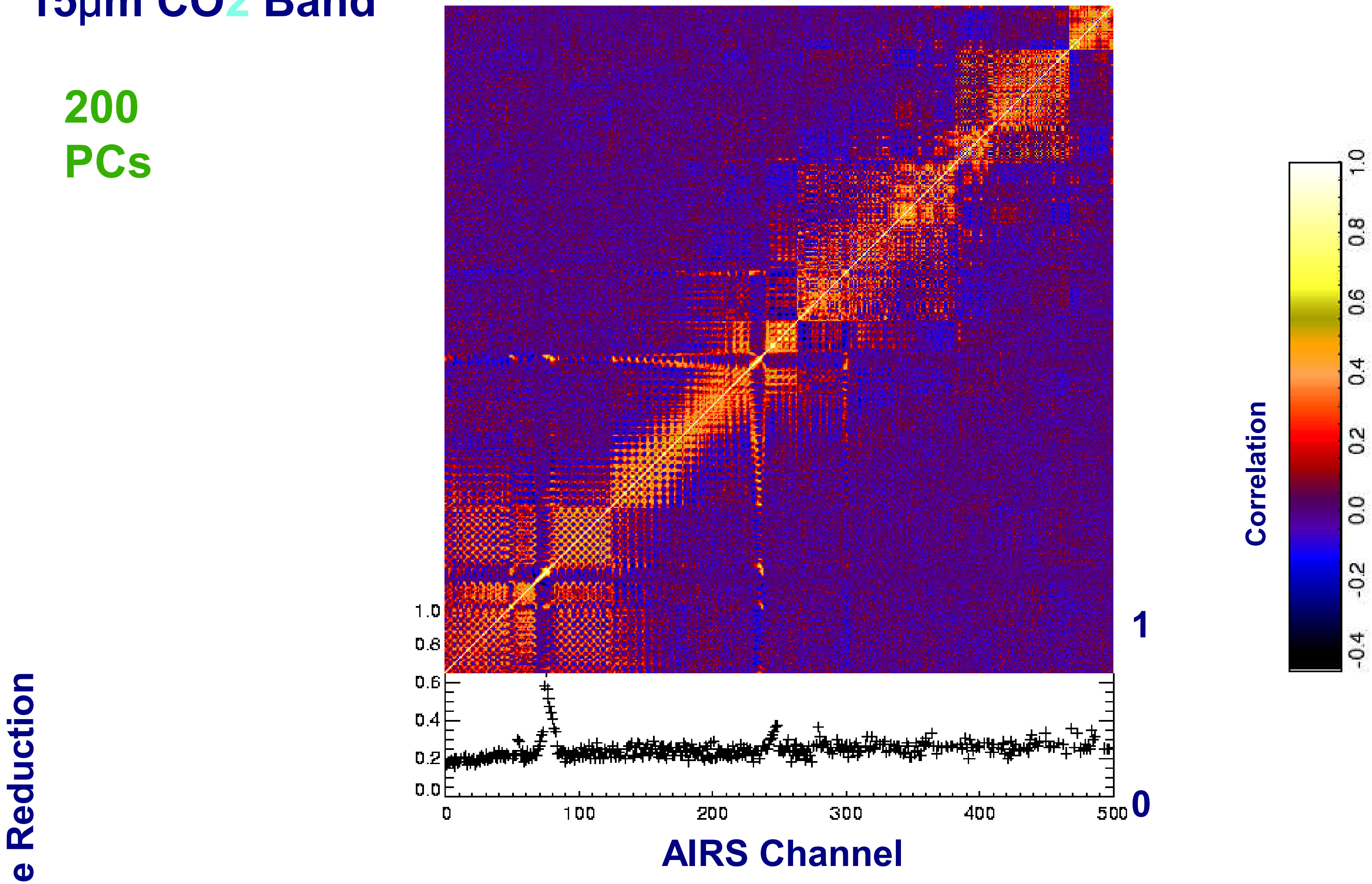
If we have assumed the correct E for noise normalisation E=I above

In addition, the ***forward model term*** **is not modified by reconstruction.**

Noise Reduction and Correlations

15µm CO_2 Band

200
PCs



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Strategies and Choices

Choices for production of PCs (1)

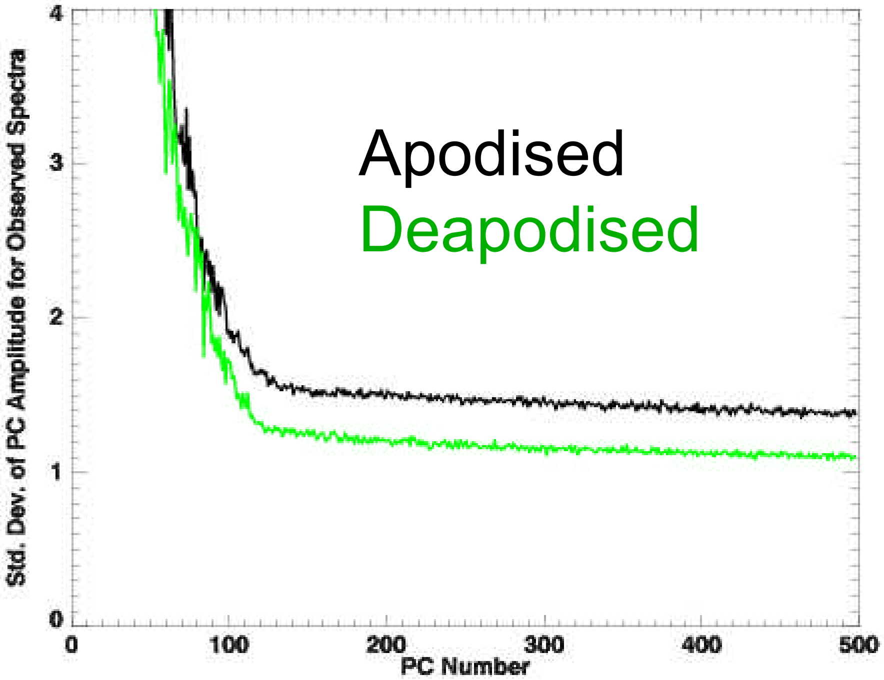
- PCs from simulated data vs PCs from observed data
  - Simulated data may contain the signal from atmospheric structures that may not be well represented in an observed dataset.
  - Conversely, simulated data may not fully reflect reality, especially clouds
  - For data distribution, observational fidelity is paramount and observation based PCs should be used (possibly with residuals)
  - For assimilation purposes more research needs to be done.

Choices for production of PCs (2)

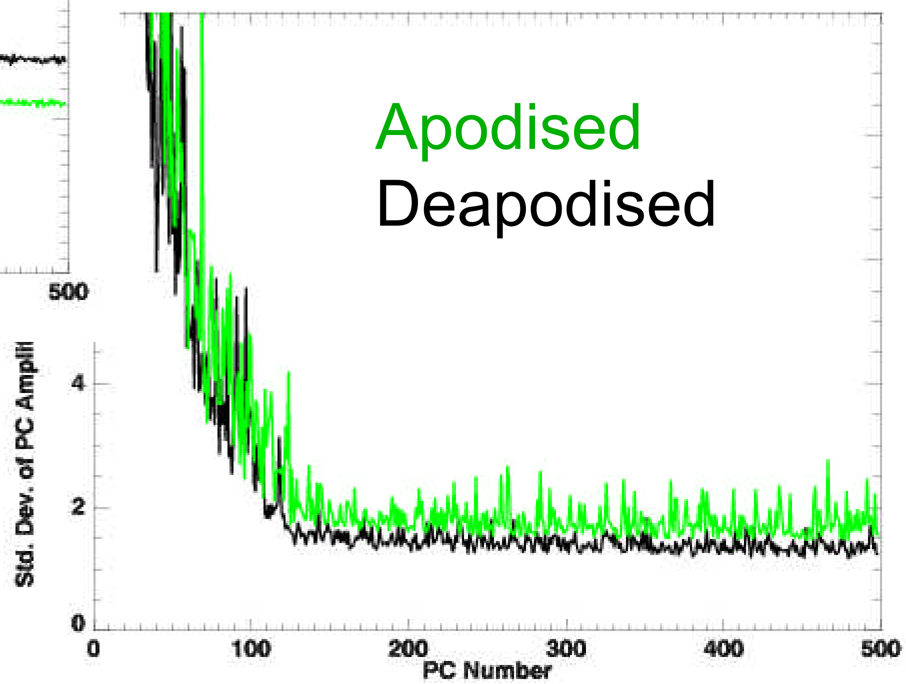
- Noise normalise with diagonal error covariance or with covariance appropriate to apodised spectrum
  - This is equivalent to deapodising and normalising with diagonal error covariance – this option is available in AAPP
  - Whether this confers any advantage is not clear

PC amplitudes: Apodised vs Deapodised

EOFs from Nigel Atkinson



Std.Dev. of PC amplitudes for real observations



Std.Dev. of Difference in PC amplitudes for real observations and calculations

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Choices for production of PCs (3)

- Global vs “Granular”
  - Granular PCs are produced by taking a, say, six minute period of observed data (c.f. an AIRS granule) and calculating a set of PCs specific to those data.
  - Ensures that EOFs are truly representative of spectra being compressed and that compression is therefore more efficient.
  - Calculation of these PCs will be computationally more intensive and, if used for data communication, will have to be communicated themselves.
  - A constantly varying set of EOFs

Strategies for Assimilation of PCs

- Direct Assimilation of Principal Components
- Assimilation of reconstructed radiances as proxy for real radiances
- Assimilation of reconstructed radiances directly (i.e., forward-modelling the reconstructed radiances themselves)

Loop of Jacobians of PCs

Issues with direct assimilation of PC amplitudes

- Jacobians of principal components are more non-localised than raw channels
  - Signals are less separable (in the vertical and between temperature and humidity etc.)
  - It is harder to have a cloud detection scheme where only “channels” above the cloud/surface are used.
  - We are therefore limited to “hole hunting” or to doing assimilation of cloudy radiances
- It is possible that the degree of non-locality can be reduced with the appropriate selection of sub-bands for the PC calculation
- Requires new RT models. These have been developed but have not been tested in assimilation systems. E.g., PCRTM (Liu); PCRTTOV (Matricardi); Havemann-Taylor.
- Principal components need to be fixed and will generally be independent of any PCs used for communication (which in general will change with time). Therefore, ideally data communication will be lossless.

Strategies for Assimilation of PCs

- Direct Assimilation of Principal Components
- **Assimilation of reconstructed radiances as proxy for real radiances**
- Assimilation of reconstructed radiances directly (i.e., forward-modelling the reconstructed radiances themselves)

Reconstructed Radiances as "Denoised" Observations

- Treat reconstructed radiances as real radiances with lower (but correlated) noise.
- There is an additional error term due to the signals in the true spectrum that are not represented in the principal components.
- No special RT model is required beyond that already used to calculate the original radiances.
- The principal components from the data provider can be used as long as error characteristics do not evolve significantly.

Strategies for Assimilation of PCs

- Direct Assimilation of Principal Components
- Assimilation of reconstructed radiances as proxy for real radiances
- **Assimilation of reconstructed radiances directly (i.e., forward-modelling the reconstructed radiances themselves)**

Issues with direct assimilation of PC amplitudes

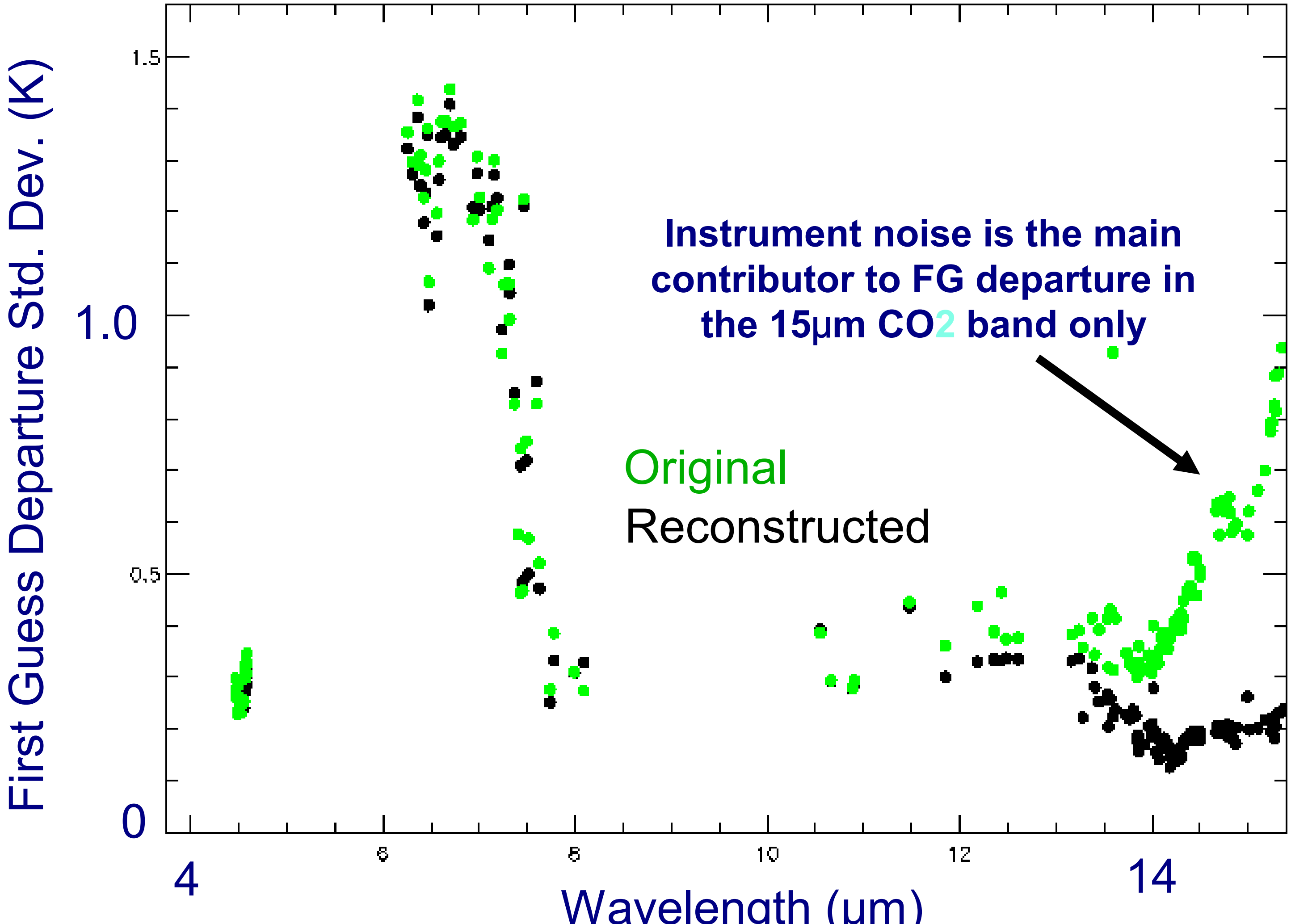
- Model reconstructed radiances directly (i.e., each channel is a linear combination of the entire original spectrum).
- No additional error term due to missing components in PCs: it will be missing in both the observation and the RT calculation.
- As with assimilation of principal components: Requires new RT models. These have been developed but have not been tested in assimilation systems. E.g., PCRTM (Liu); PCRTTOV (Matricardi); Havemann-Taylor.
- As with assimilation of principal components: Principal components need to be fixed and will generally be independent of any PCs used for communication (which in general will change with time). Therefore, ideally data communication will be lossless.

Experience with Assimilating Reconstructed Radiances

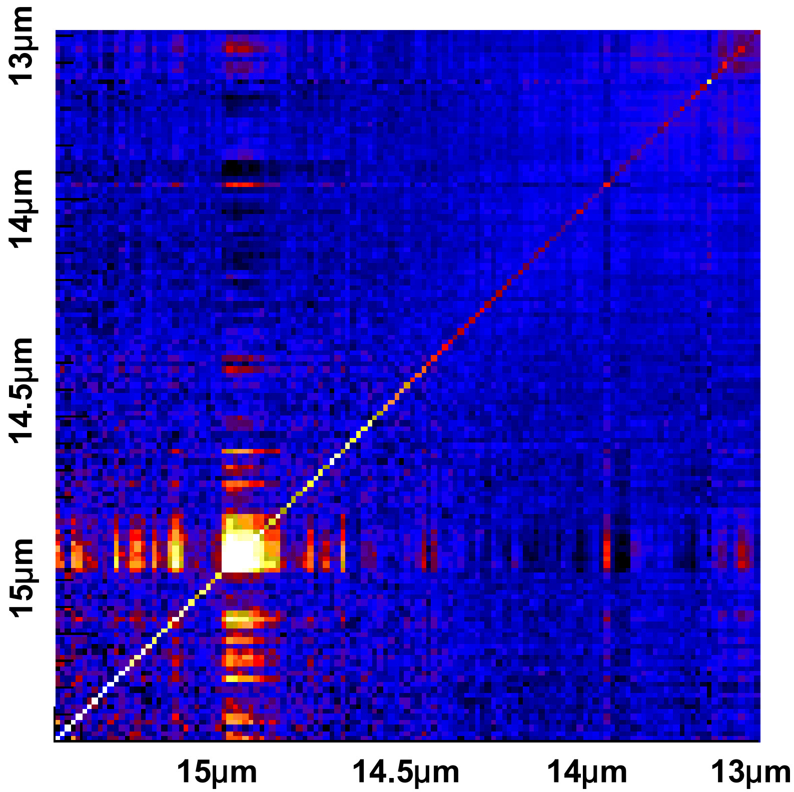
AIRS Reconstructed Radiances

- 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
- We treat reconstructed radiances as a proxy for real radiances

First Guess Departures for AIRS are Reduced



A look at Reconstructed Radiances' Errors

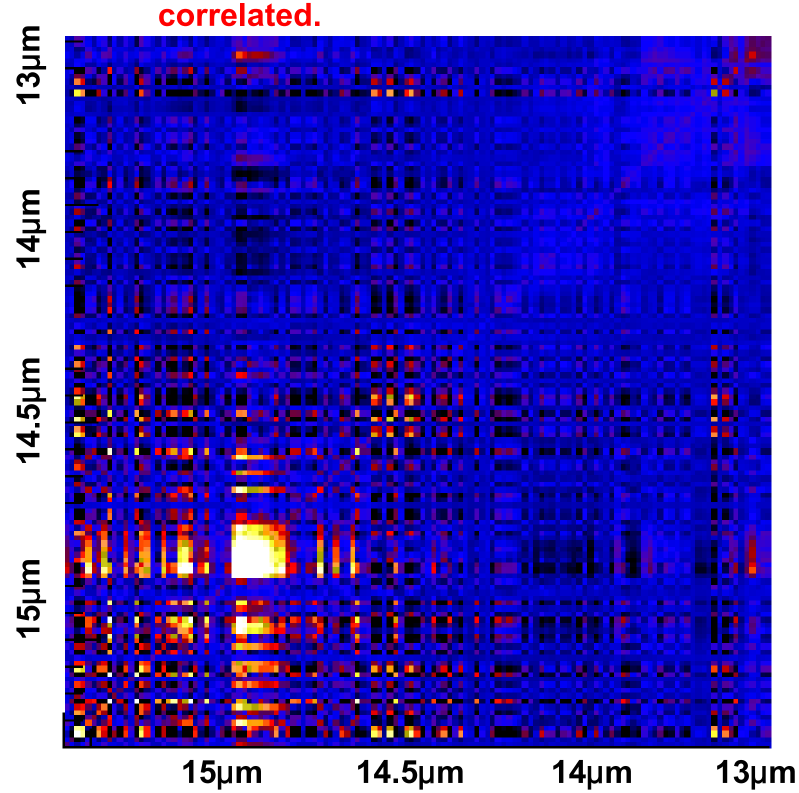


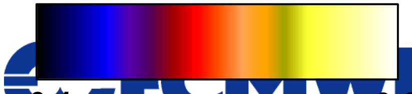
Original Radiances

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.

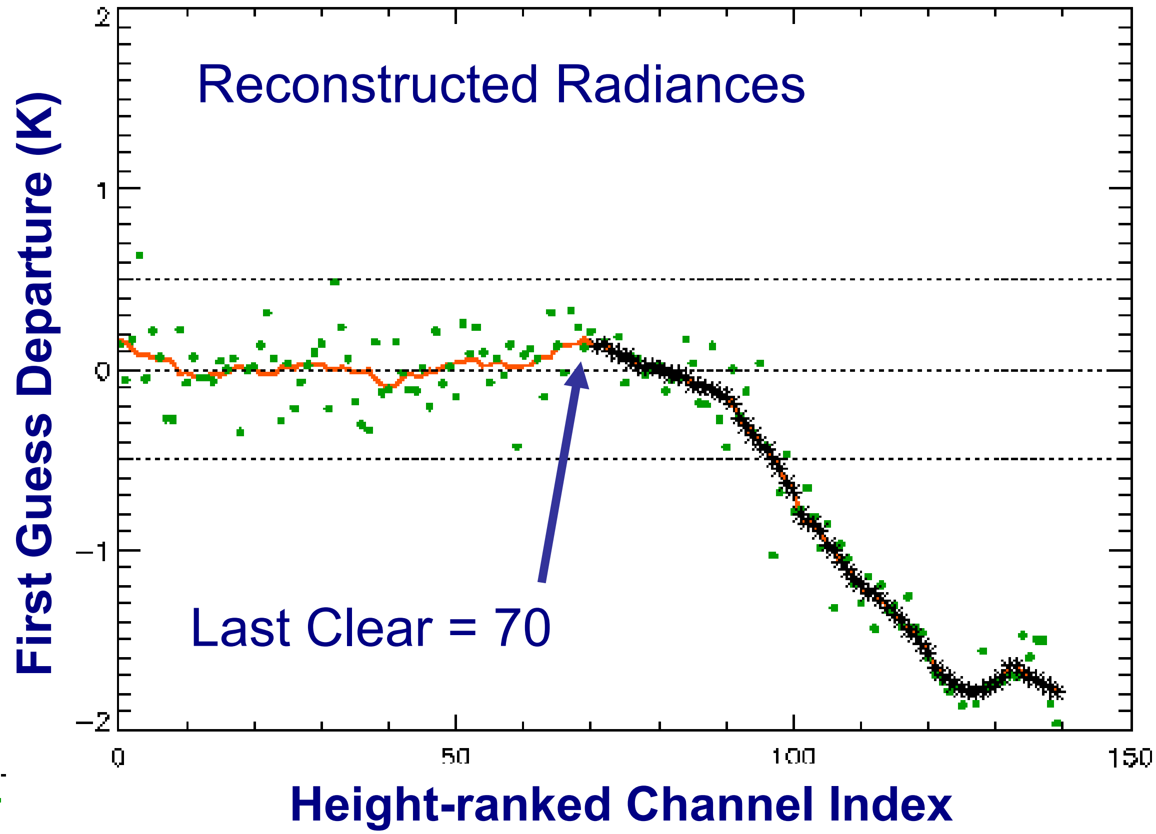


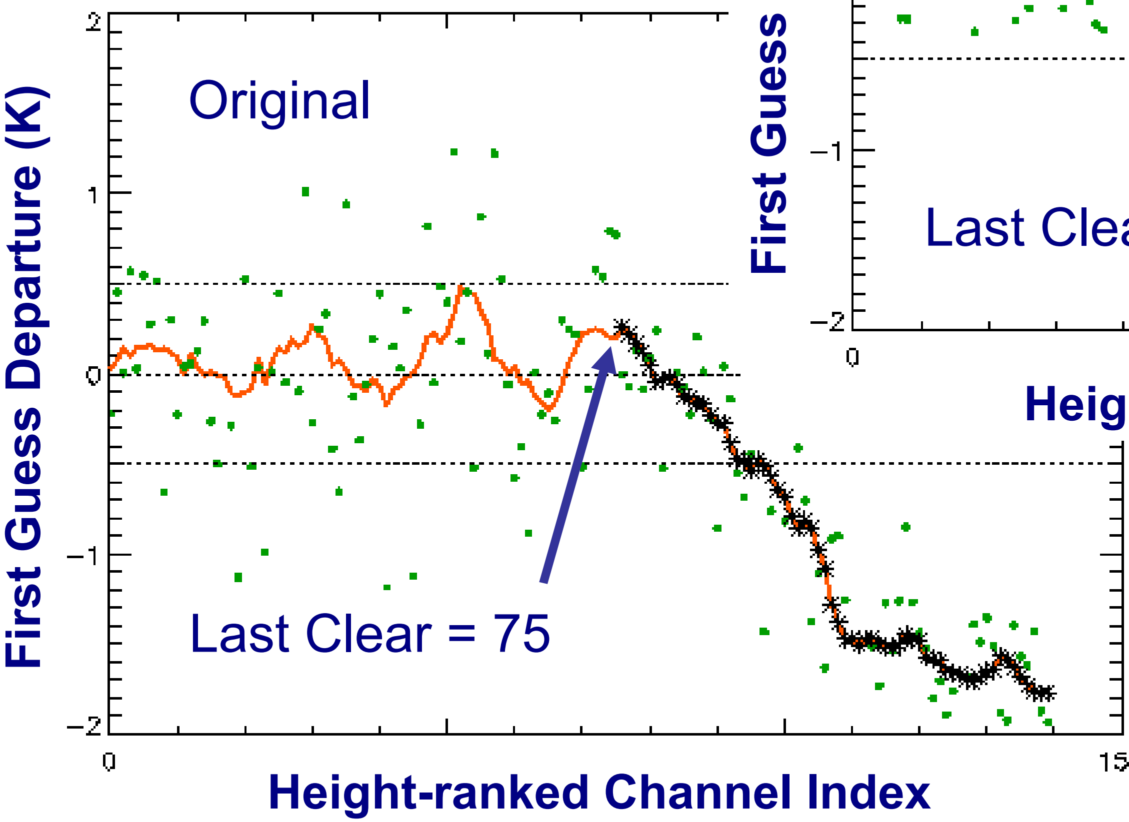


Covariances of background departures for clear observations in 15µm CO_2 band

Improvements in Cloud Detection

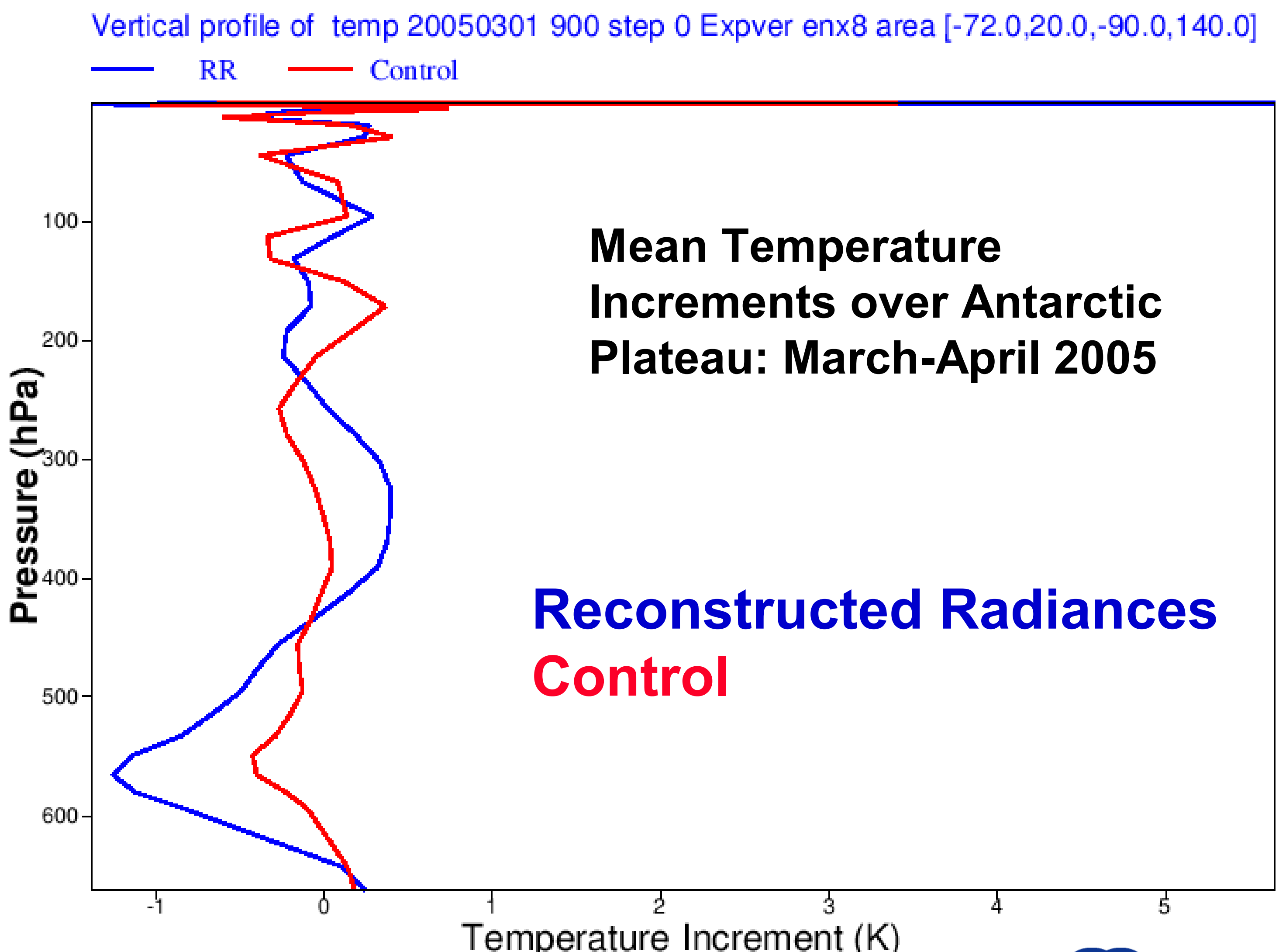
ECMWF Scheme:
- Ranks Channels Height
- Applies low-pass filter
- Tests for non-zero gradient



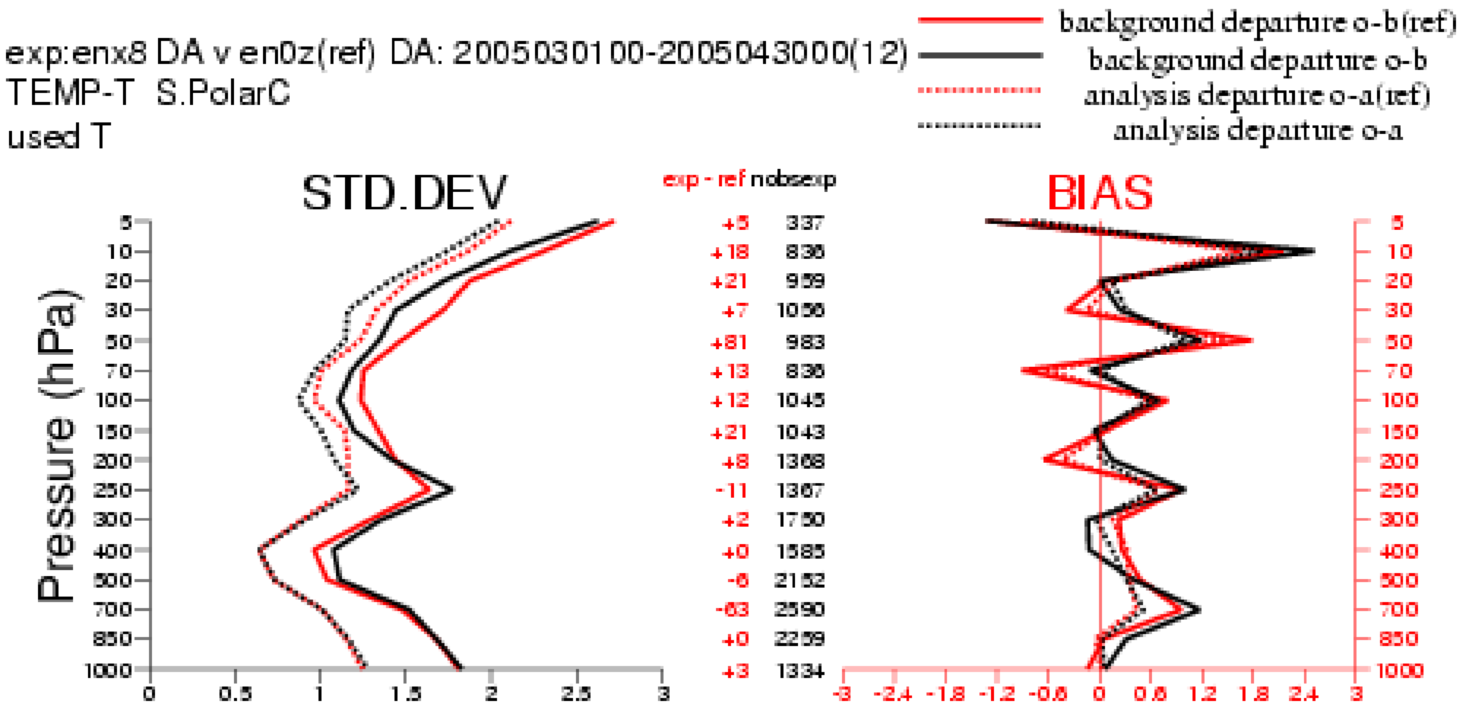


< 2% of Channels are flagged differently for RR vs Normal radiances

Reconstructed Radiances Result in Different Increments…



Improvements to Antarctic Stratosphere



"Stratospheric Oscillation" in comparison
to Antarctic radiosondes is greatly reduced
on moving to reconstructed radiances

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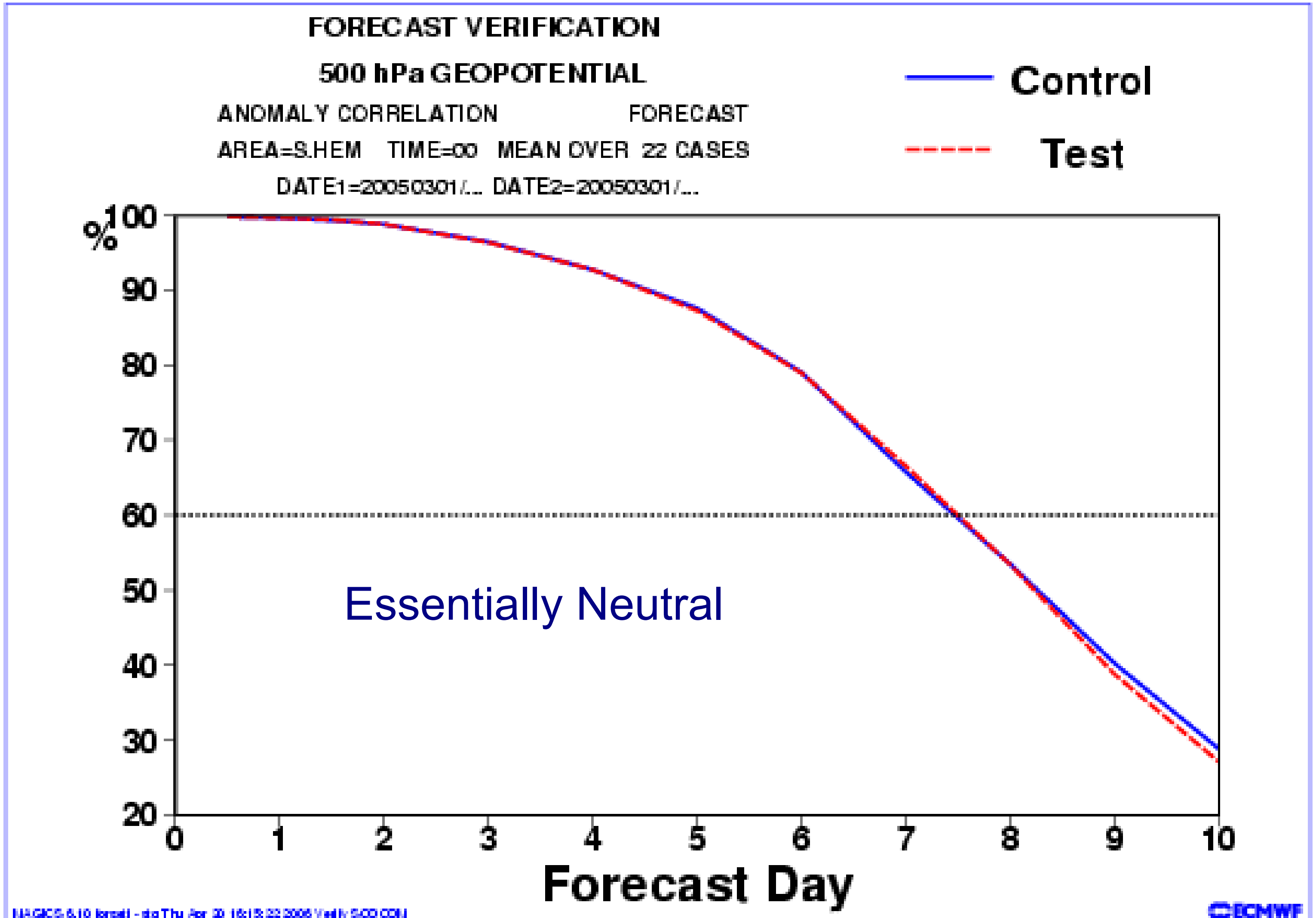
Forecast Impact of Reconstructed Radiances



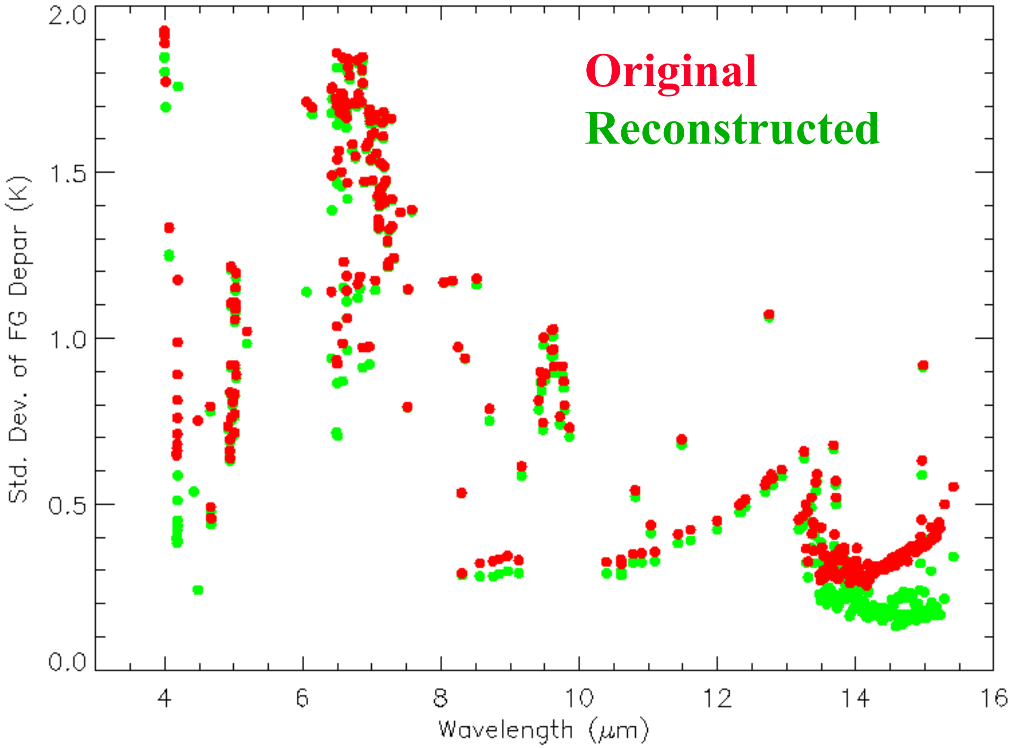
So why not use the RR data more aggressively?

- More aggressive errors have been tried:
  - Reduction of existing diagonal errors
  - “Bottom up” construction of full covariances
  - Hollingsworth-Lönnberg approach

- Results have been neutral or negative with respect to:
  - Fit to other observations
  - Performance of short/medium range forecasts

IASI Reconstructed Radiances

- We have developed a package under the NWPSAF to produce reconstructed radiances from the full IASI spectrum
- This includes derivation of the principal components from climatology
- Available from the NWPSAF



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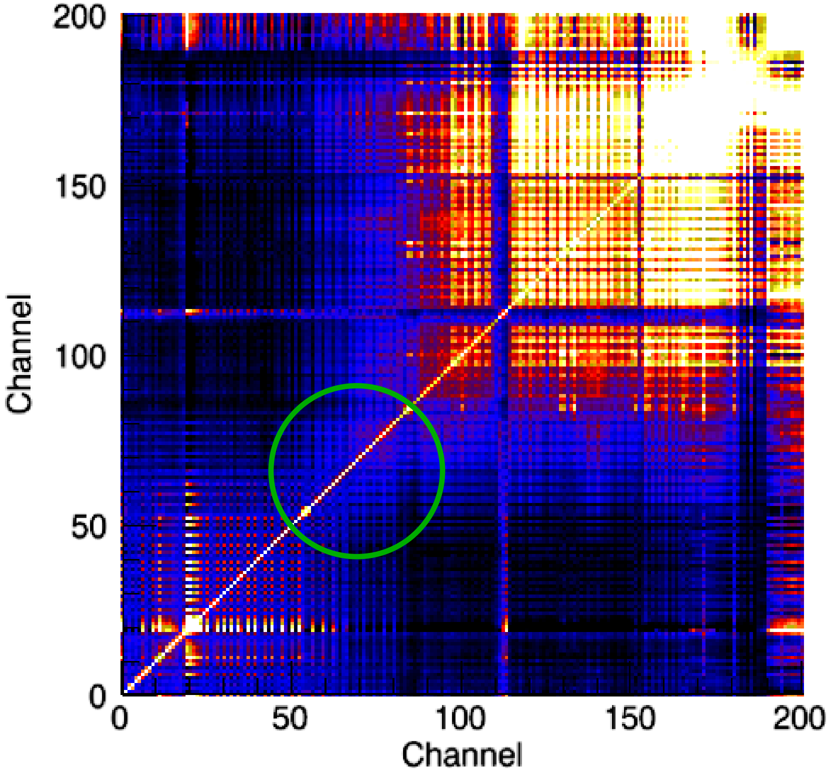
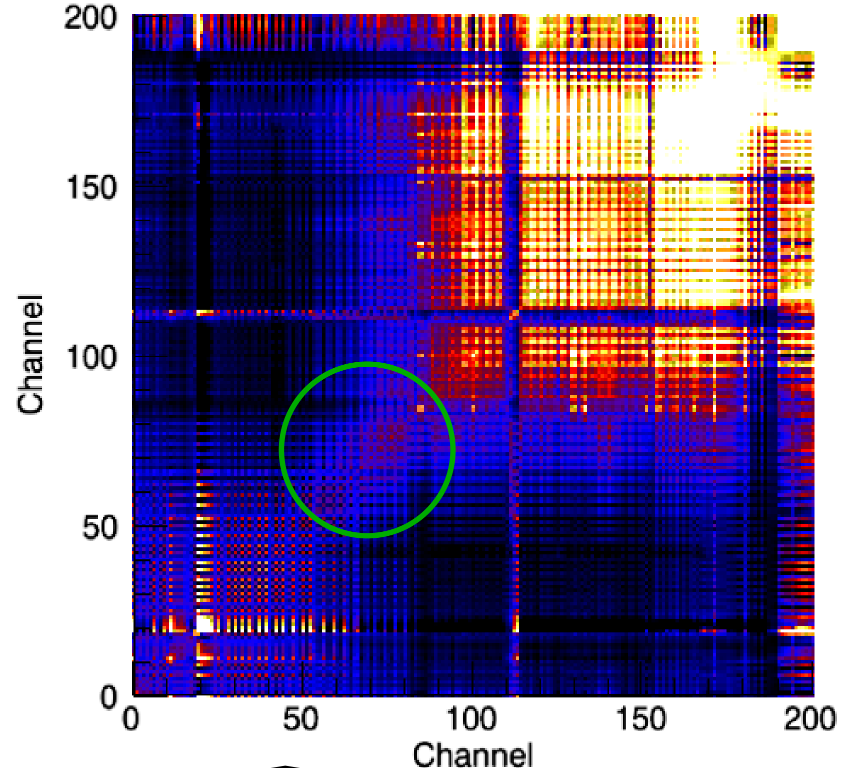
Correlation Structure of FG Departures

Original Data
Strong Diagonal from instrument noise
Most correlation from model error



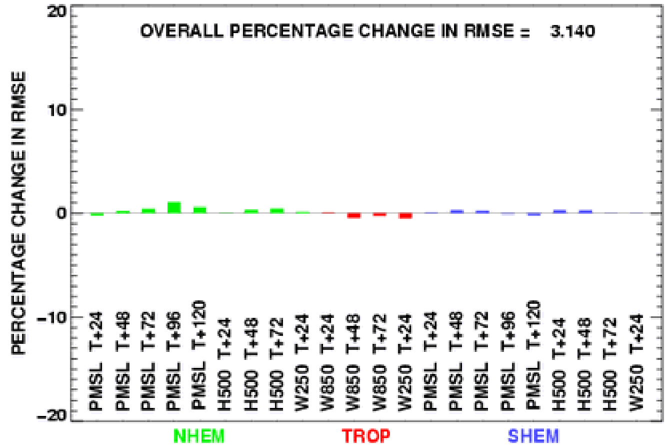


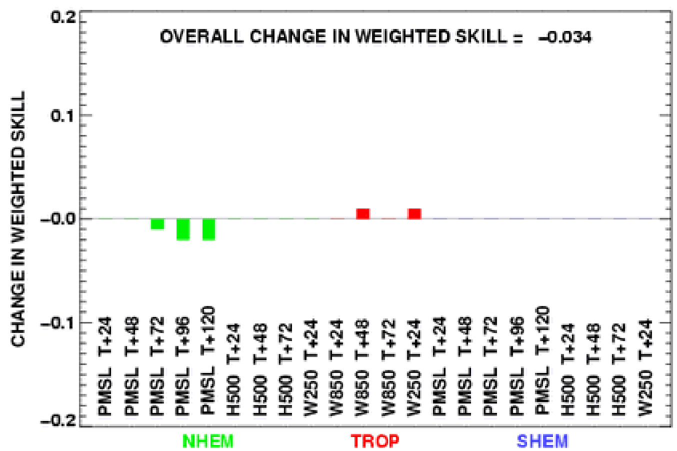
Reconstructed Radiances
Diagonal is greatly reduced
Additional correlations from measurements

Met Office Assimilation of RRs

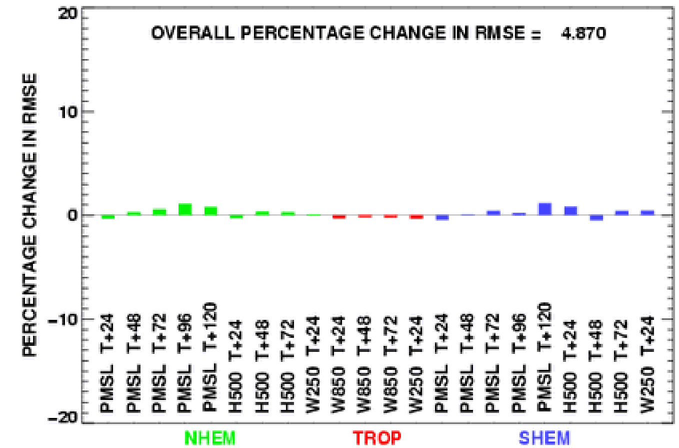
From Fiona Hilton

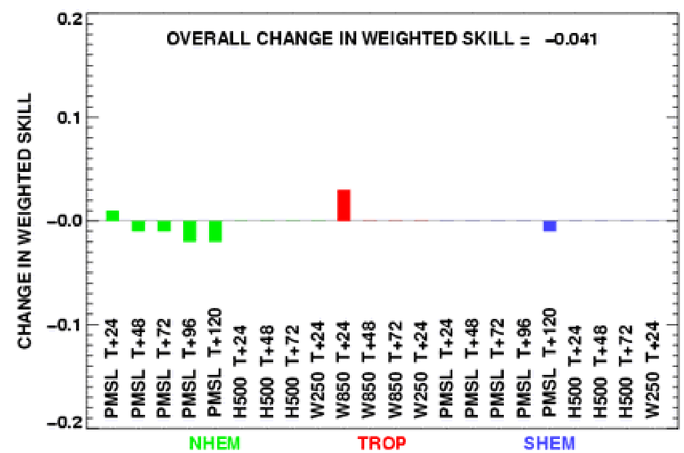
RECONSTRUCTED RADIANCES VS CONTROL (JUN2008)
VERIFICATION VS ANALYSIS
OVERALL CHANGE IN NWP INDEX = –0.172





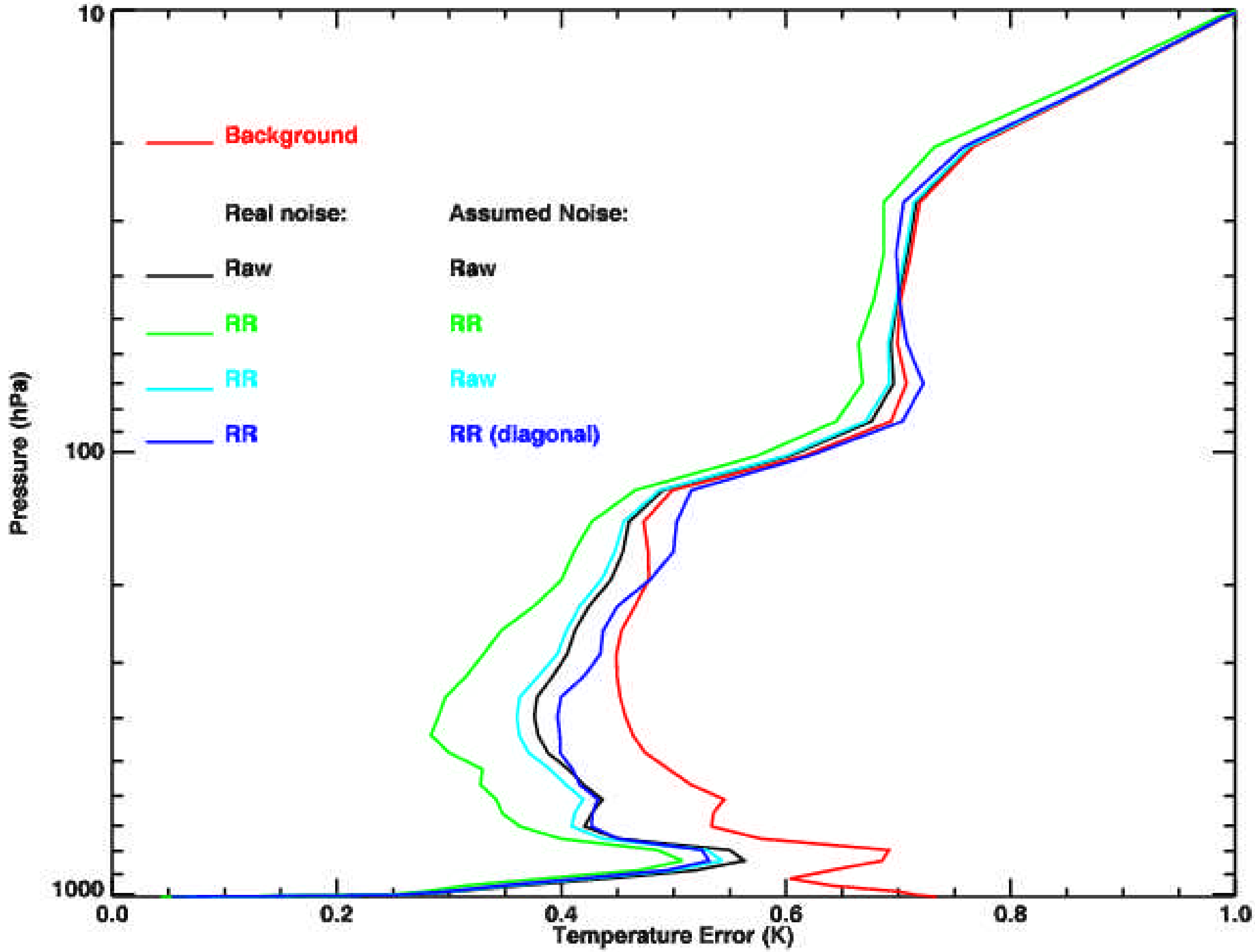
RECONSTRUCTED RADIANCES VS CONTROL (JUN2008)
VERIFICATION VS OBSERVATIONS
OVERALL CHANGE IN NWP INDEX = –0.122



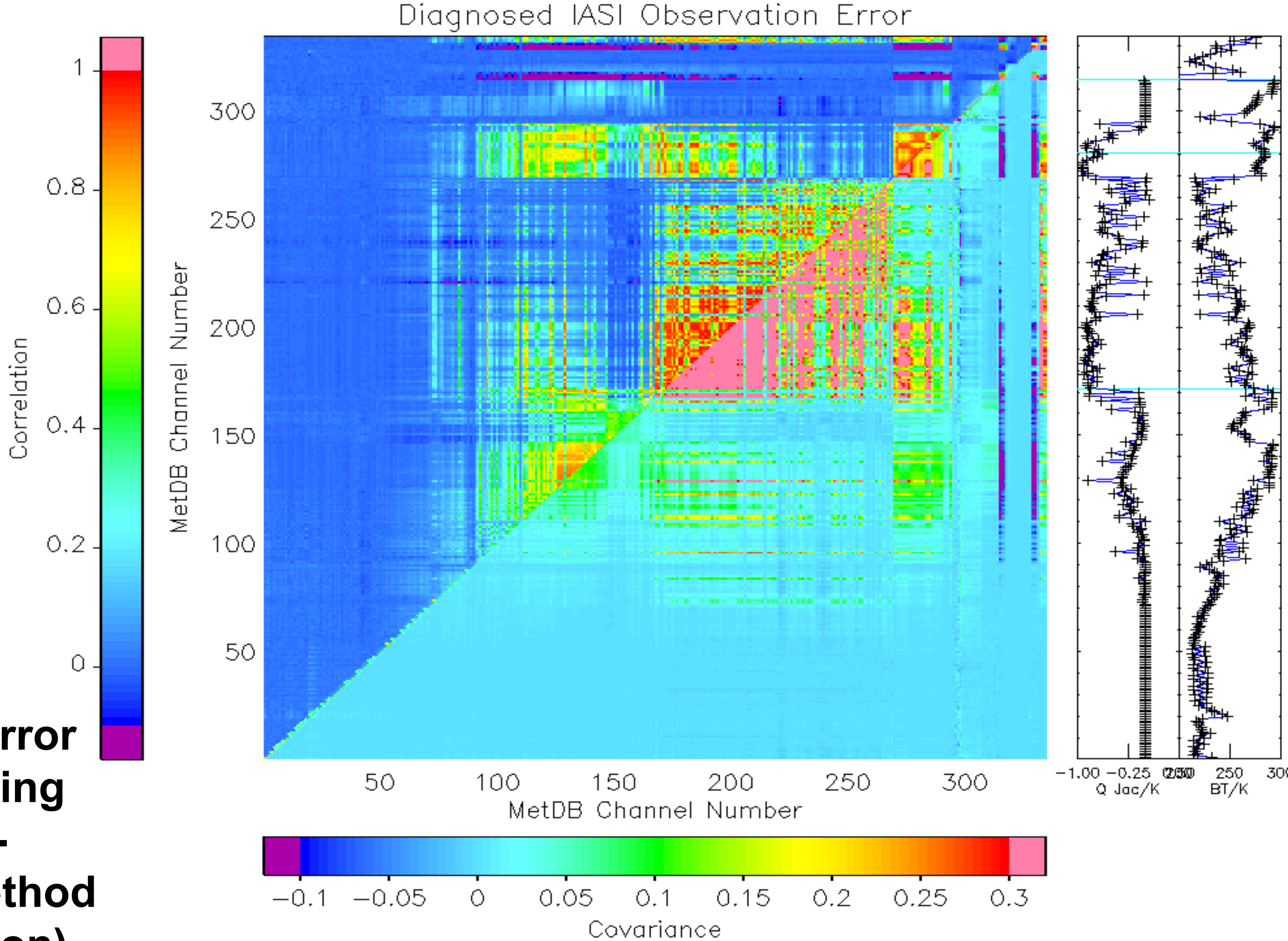


Discussion

Assimilating Reconstructed Radiances – Linear Theory



Error covariance of IASI spectrum may be highly correlated



Derived IASI Error Covariance using Hollingsworth-Lonneberg method (James Cameron)

Should we expect greater impact from IASI/AIRS RR assimilation and how do we achieve this?

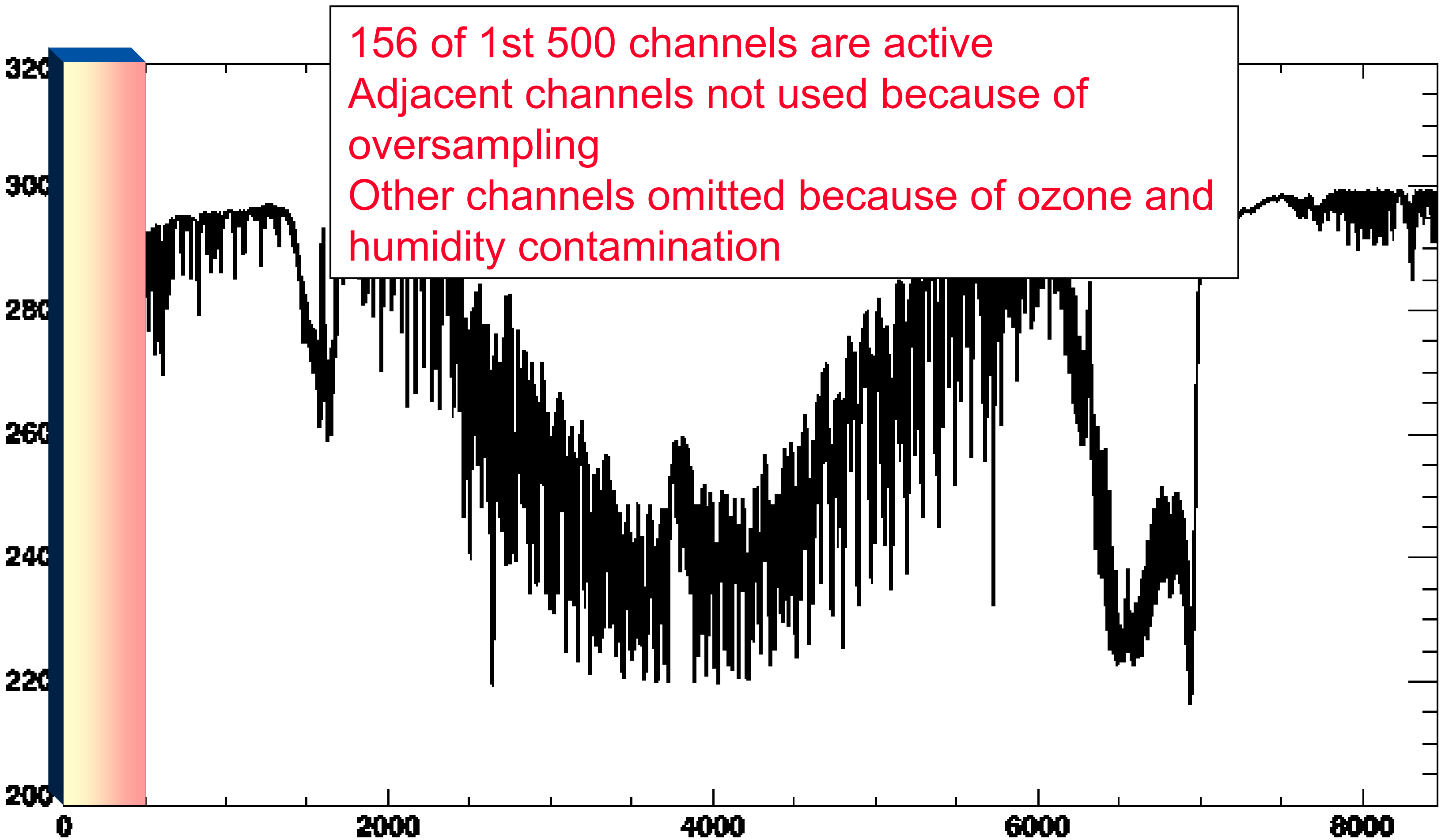
- We already make very good use of the available channels in the 15 micron band
- Greatest smoothing seen in stratospheric channels
- Using noise filtered radiances in IASI band 3 is promising and will be investigated
- In other bands, it is not clear that the limiting factor on forecast impact is instrument noise
- Idealised calculations indicate that a more correct error covariance matrix should help us obtain greater impact
    - But obtaining this matrix is not straightforward – even the matrix used for normal observations may be inadequate
    - We also need to ensure that bias correction, cloud detection and other QC issues are properly addressed.

Questions

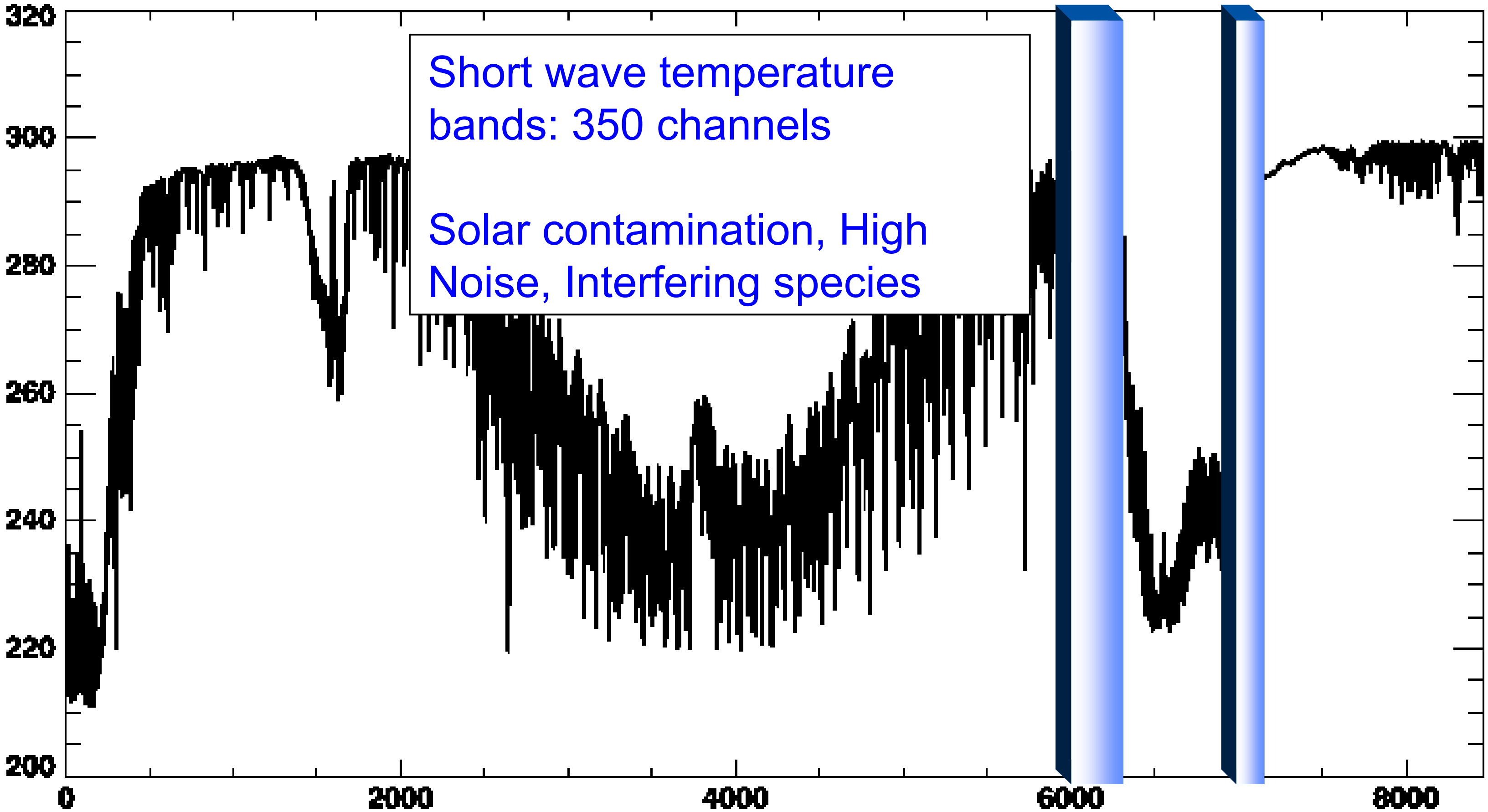
- **What do we want from data providers?**
  - Full data (or compressed losslessly, e.g., using predictor-corrector method of Tony Lee)?
  - Or is a the distribution of principal components adequate
- **What is the optimal way of using compressed data?**
  - Reconstructed radiances as a proxy for real radiances
  - Reconstructed radiances as its own datatype
  - Direct assimilation of principal components
  - Something else? Retrievals? ☺
- **Strategies for making better use of these datatypes?**
- **Should we be expecting significant improvement through the use of these datatypes?**
- **Are there applications in trace gas and climate studies?**

Thank you

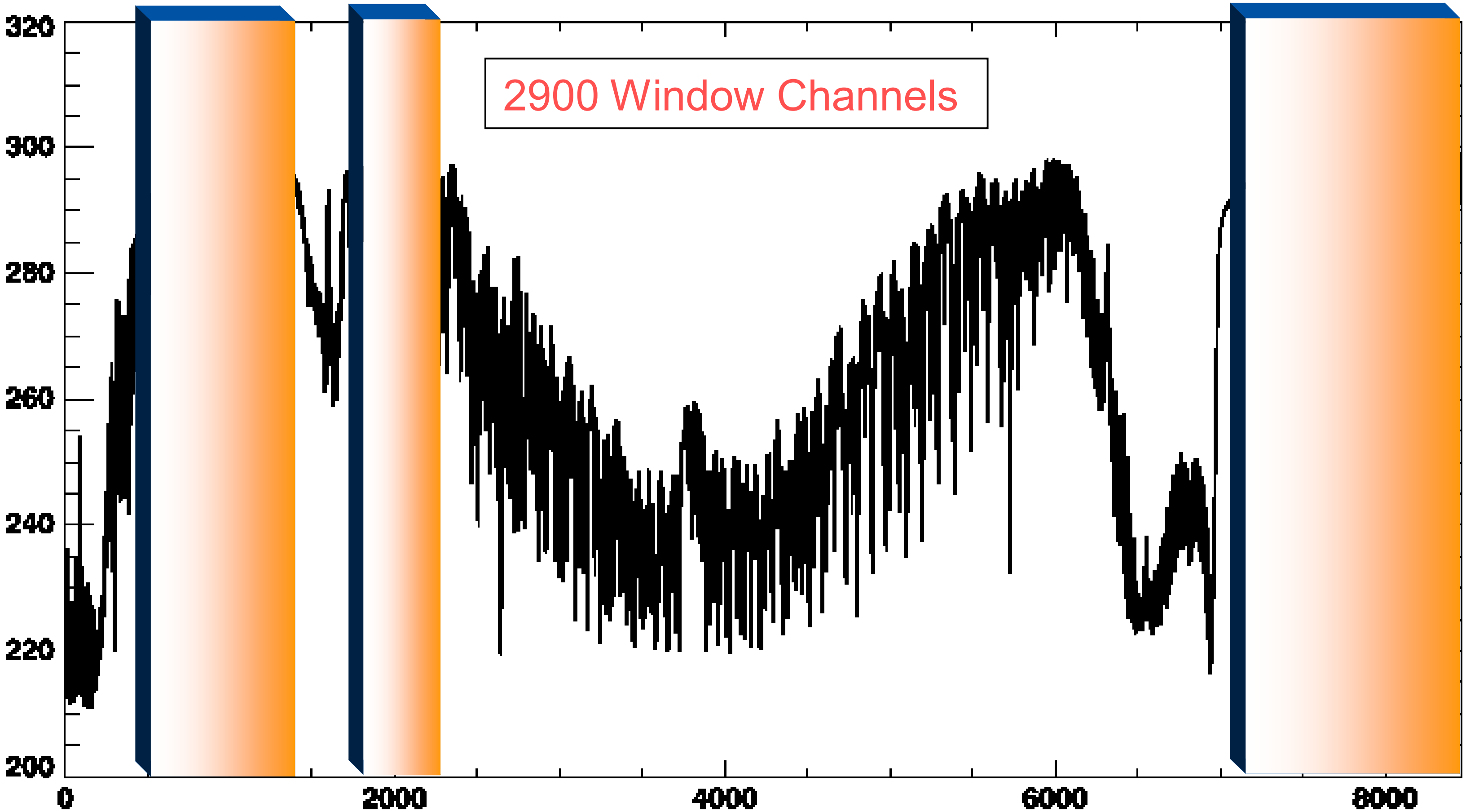
Using the IASI Spectrum
Longwave CO_2 Band



Using the IASI Spectrum
Shortwave CO_2 Band



Using the IASI Spectrum
Channels Primarily Sensitive to the Surface



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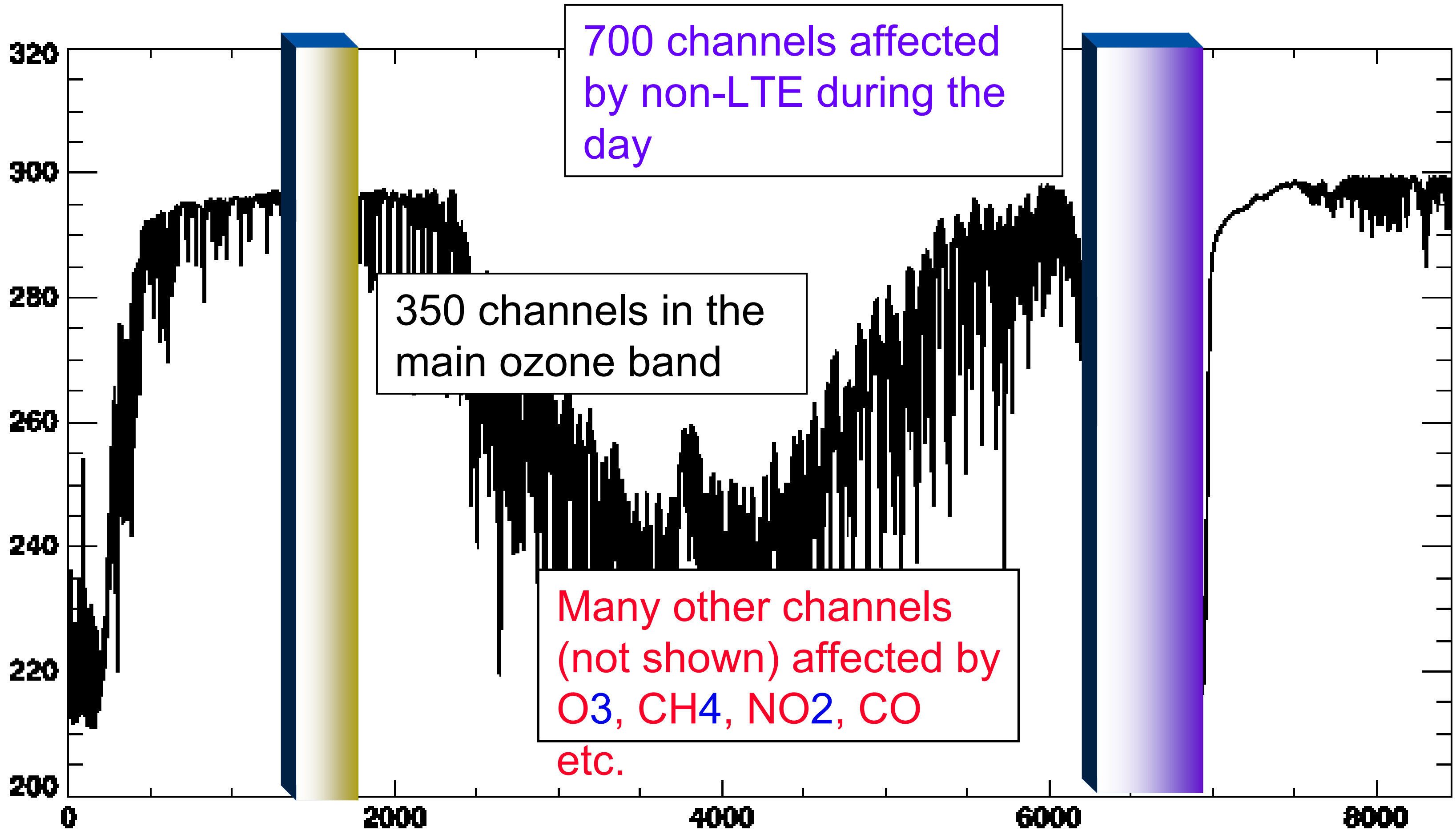
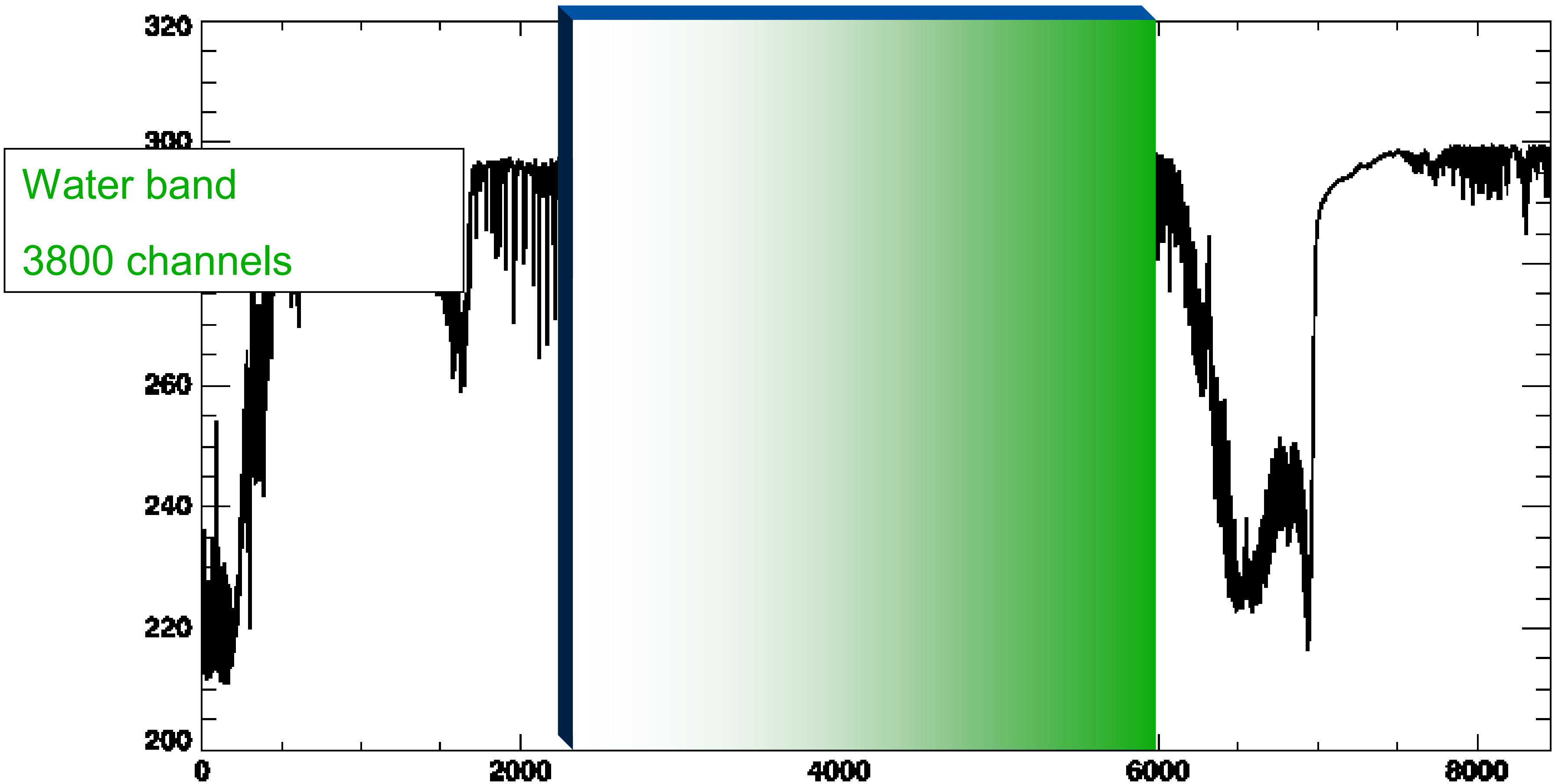
Using the IASI Spectrum
Trace Gases and RT Challenges



Using the IASI Spectrum

The 6.3μm Water Band



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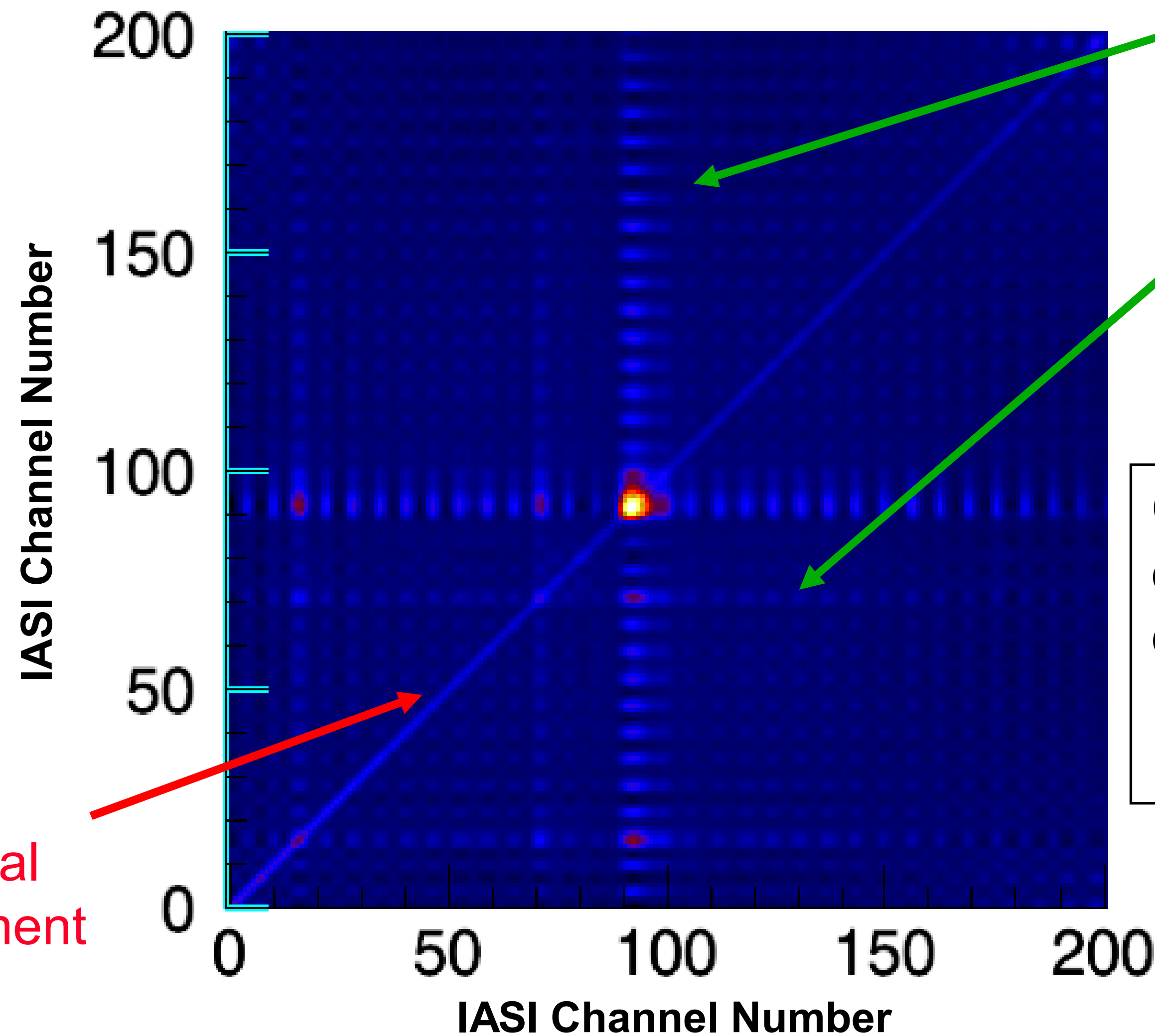
IASI Spectral Correlation



Correlations from forecast model

Covariance of first-guess departures

1st 200 channels

Nearly diagonal instrument noise

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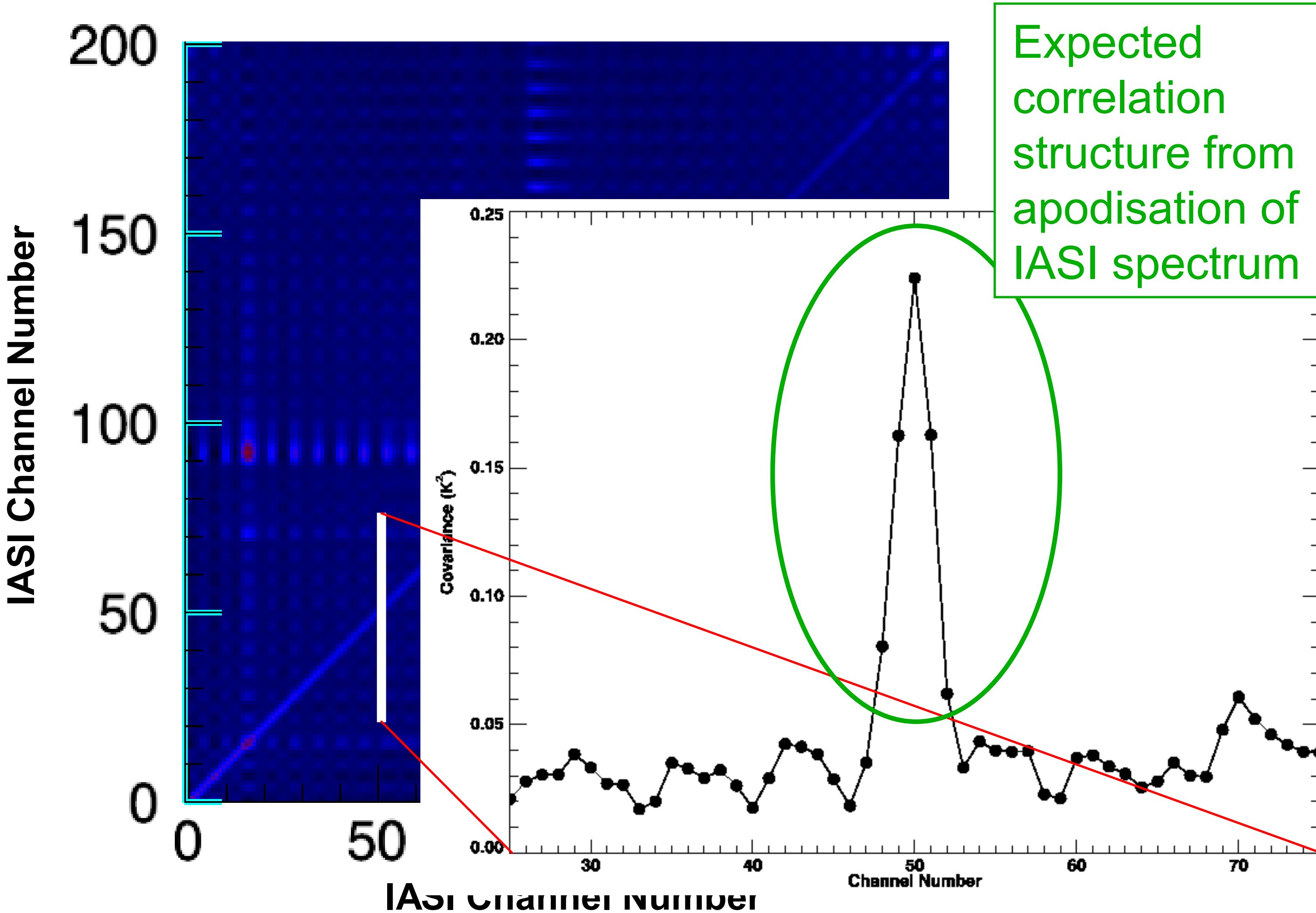
IASI Spectral Correlation



Expected correlation structure from apodisation of IASI spectrum

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