Improved Assimilation of Reconstructed Radiances for NWP

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- Sean Healy (ECMWF)
- Andrew Collard (NCEP)
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- Steve English (ECMWF)
- Stephan Havemann (Met Office)

Outline

- Why reconstructed radiances?
- Choosing a channel selection for reconstructed radiances
  - Constraints
  - Method
- 1D-Var results with RR channel selection
- What about PC Scores?

Why reconstructed radiances?

Why reconstructed radiances?

- The baseline dissemination for MTG-IRS is PC Scores
  - We will all have to prepare for using these data in the future
- Should provide benefit over raw radiances:
  - PC scores contain almost all the signal in each spectrum but in ~300 quantities instead of ~8000, and what is thrown away is mostly random instrument noise
  - It is theoretically possible to reconstruct ~300 radiances with the same information content as the PC scores.
  - In other words, reconstructed radiances should allow us to access more of the spectral information with reduced noise.

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Linear analysis and Degrees of Freedom for Signal

- x is a model state vector
- x_b is the background state – the a priori estimate of x_{true}
- y_o is the observation vector
- H is the observation operator (inc radiative transfer code)
- **H** is the linearised observation operator
- **B** is the background error covariance matrix
- **R** is the observation error covariance matrix

- The analysis, x_a is given by

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{K}[\mathbf{y}_o - H(\mathbf{x}_b)] \qquad \mathbf{K} = (\mathbf{B}^{-1} + \mathbf{H}^T\mathbf{R}^{-1}\mathbf{H})^{-1}\mathbf{H}^T\mathbf{R}^{-1}$$

- And the analysis error is given by

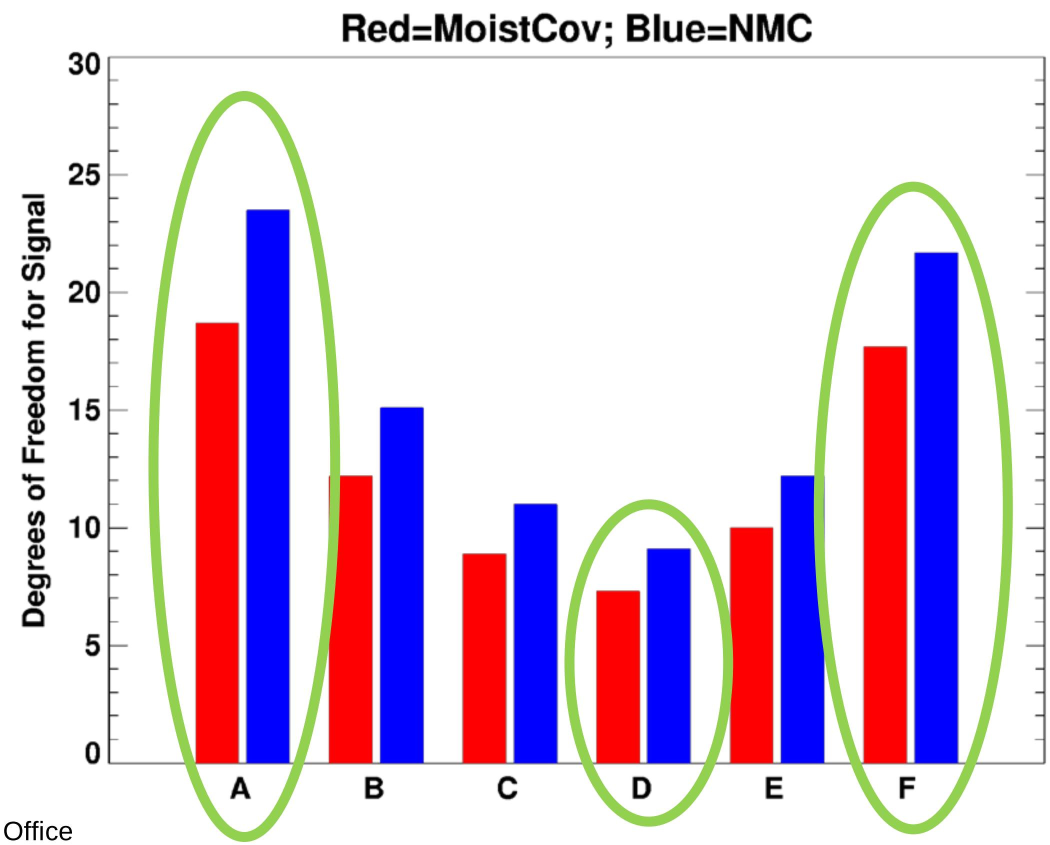
$$\mathbf{A} = (\,\mathbf{I} - \mathbf{KH}\,)\,\mathbf{B}$$

DFS is given by

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

DFS for optimal analysis Varying the channel selection

- R = Instrument noise
- A=Full Spec B=314 Chans C=OPS D=VAR E=Band 1 F= 290 PCS from EUMETSAT

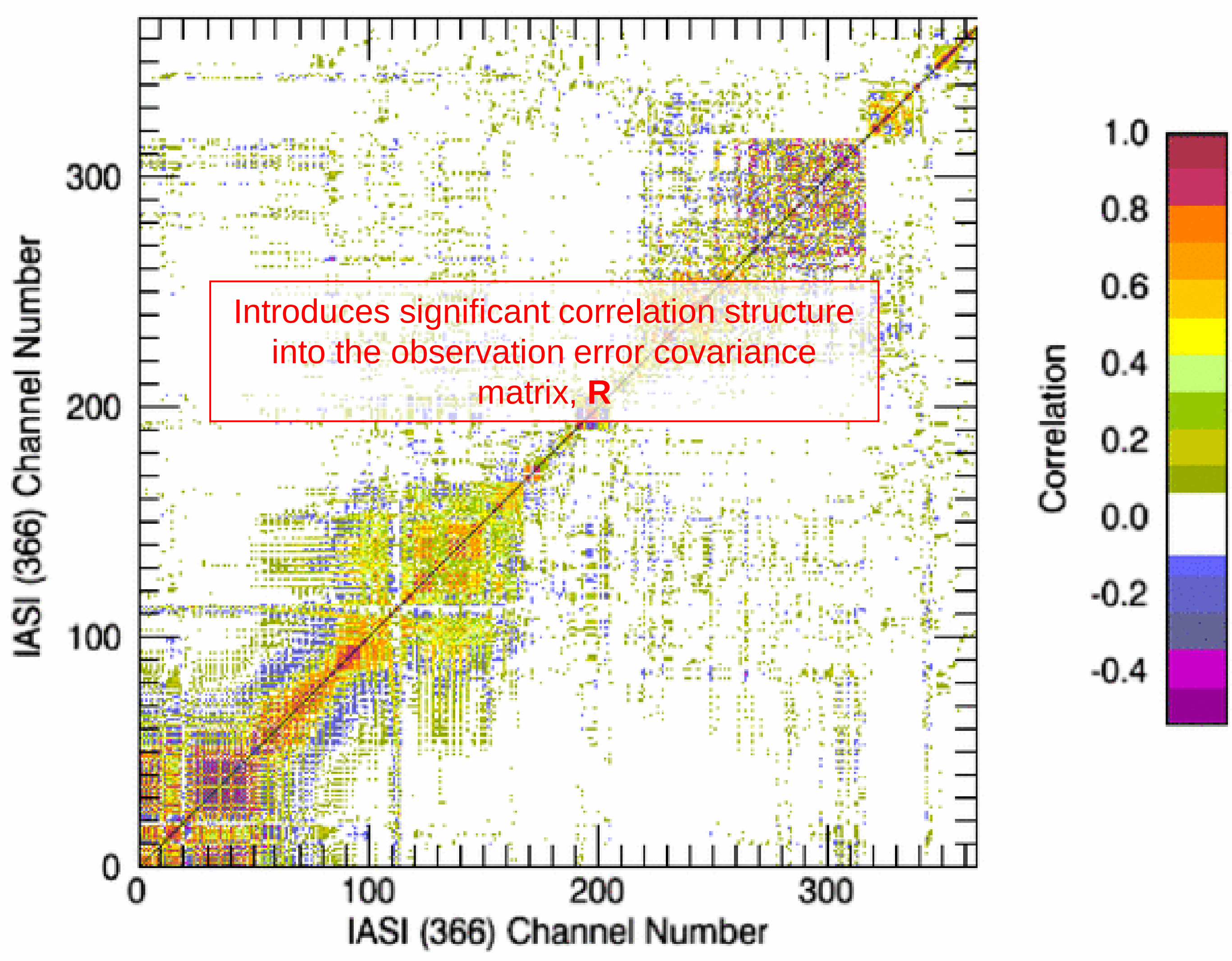


Red and Blue columns are calculated using different estimates of the Background Error

Choosing a channel selection for reconstructed radiances

Constraints

Transformation matrix from raw radiances to reconstructed



If you remember nothing else, remember this!

The Rank of The **R** matrix is determined by the number of independent components. In this case, *npc*

You can't assimilate more than *npc* channels or your **R** matrix will not invert!

290 PCs = 290 channels?

- Why can't we use 290 channels from Collard (2007)?
  - The channels are not selected optimally taking account of inter-channel error correlations
  - The killer is that there are too many channels in Band 1
    - 136 channels but only 90 PC scores
- But you assimilated those channels in 2009/2010!
  - Yes, but only assuming a diagonal error covariance matrix – no issues with matrix rank there
  - You can do anything with a diagonal matrix, but it doesn't mean it's right!

Choosing a channel selection for reconstructed radiances

Method

Channel Selection Method

- Like Collard (2007), I choose successive channels based on DFS
  - Choose next channel which adds most information on top of the channels already chosen
- Two major differences:
  - Calculate the Analysis Error and DFS in full for each candidate channel using full covariance matrix for **R**
  - Prevent selection of channels that raise the condition number of the resultant R-matrix too high

Condition Number

- Condition number is the ratio of the largest to smallest eigenvalues, and affects the stability of the solution
  - If it is too high, there is not enough independence between rows of the matrix
  - If there are negative eigenvectors, the matrix will not invert
- What is “too high”?
  - A factor of 1.3 times the lowest condition number
- It turns out that the channel selection is quite highly tuned to the observation errors used in the DFS calculation

Linear analysis results

- Compare channel selections using DFS calculated over 8 atmospheric profiles from different Lat/Lon zones on 70 Model Levels, and including US Standard atmosphere
- Linear analysis profile results and averaging kernels are presented for the US Standard atmosphere

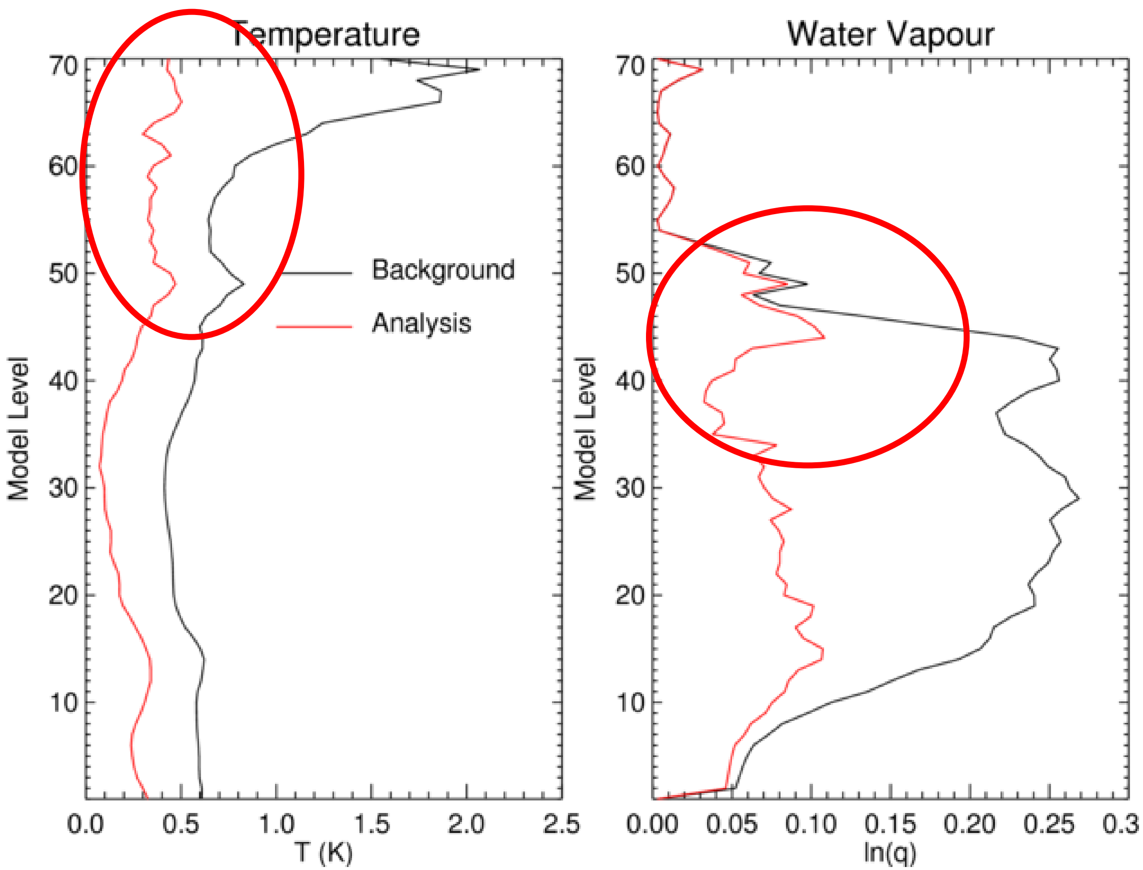
DFS over 8 atmospheres
No forward model error
Channel Selections for Bands 1 and 2 only

Channel Selection	DFS Calculation		DFS
	Noise matrix	Jacobians	
4D-VAR	$\mathbf{E}$	$\mathbf{H}(x)$	65
Collard	$\mathbf{E}$	$\mathbf{H}(x)$	106
Full Spec	$\mathbf{E}$	$\mathbf{H}(x)$	**161**
210 PC Scores			152
New RR Selection	$\mathbf{E}$	$\mathbf{H}(x)$	100
New RR Selection	$\mathbf{L}_{rr}\mathbf{L}_p{}^T\mathbf{E}\mathbf{L}_p\mathbf{L}_{rr}{}^T$	$\mathbf{H}(x)$	291
New RR Selection	$\mathbf{L}_{rr}\mathbf{L}_p{}^T\mathbf{E}\mathbf{L}_p\mathbf{L}_{rr}{}^T$	$\mathbf{L}_{rr}\mathbf{L}_p{}^T\mathbf{H}(x)$	151

RR Channel Selection
Analysis Errors: Raw Jacobians, RR Noise

DFS over 8 profiles: 291

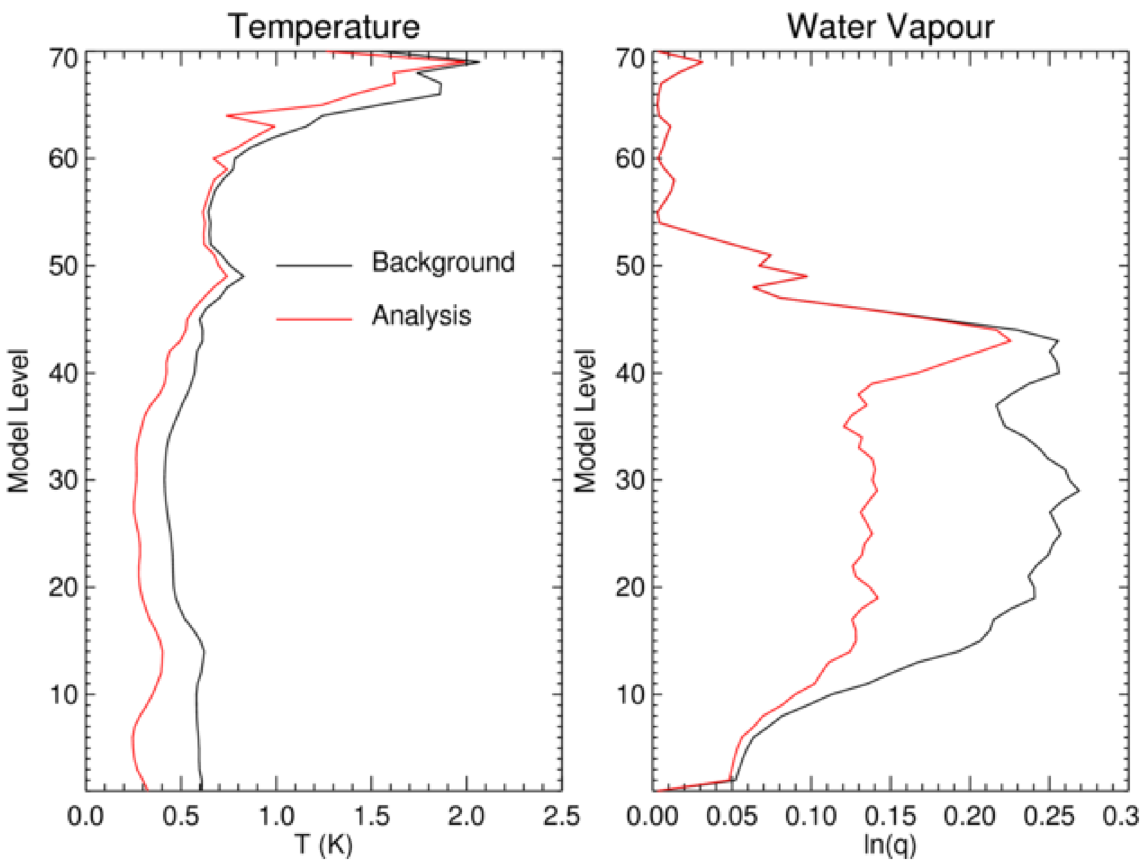
Condition Number of R: 2.6×10^8



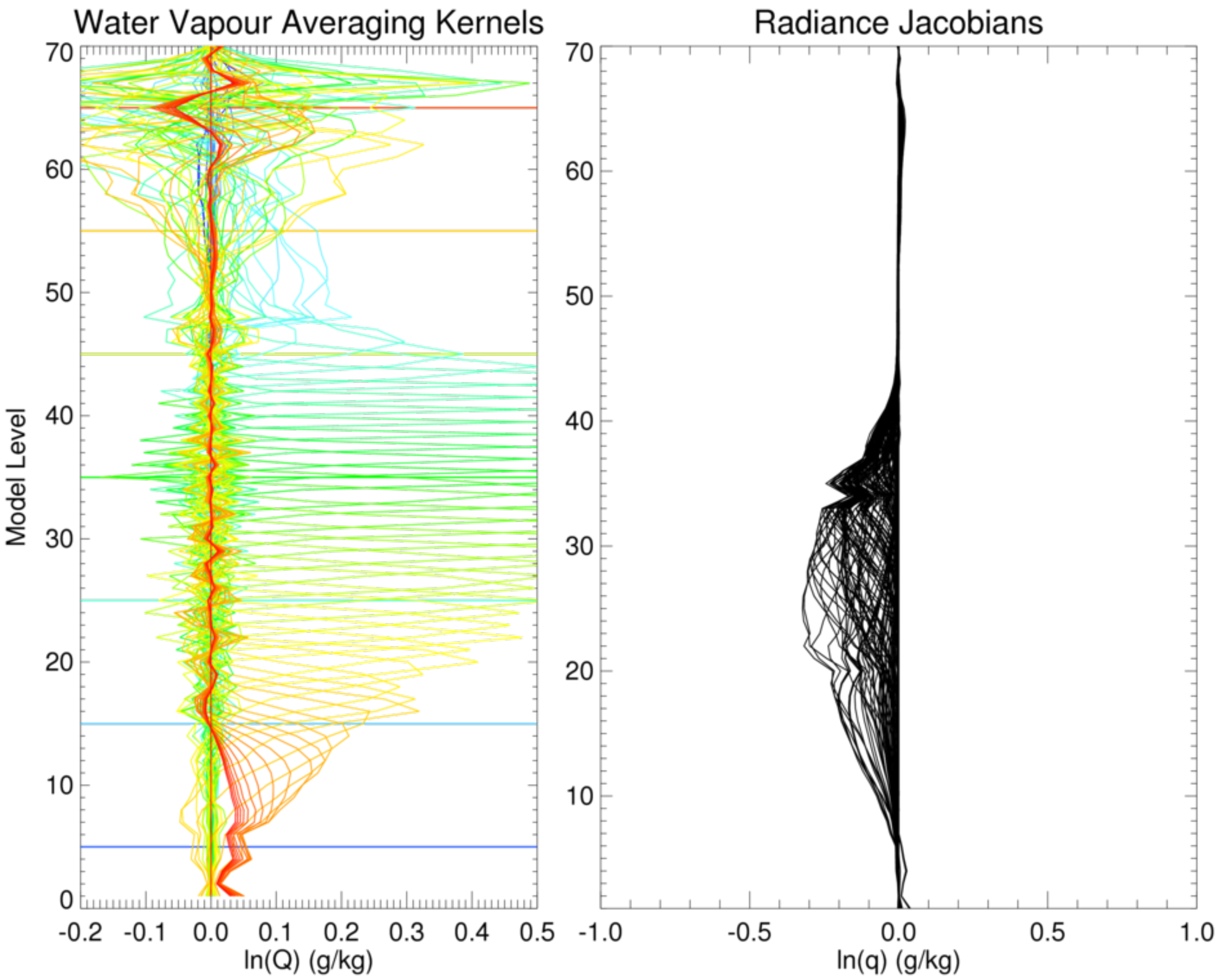
RR channel selection
Analysis Errors: RR Jacobians, RR Noise

DFS over 8 profiles: 162

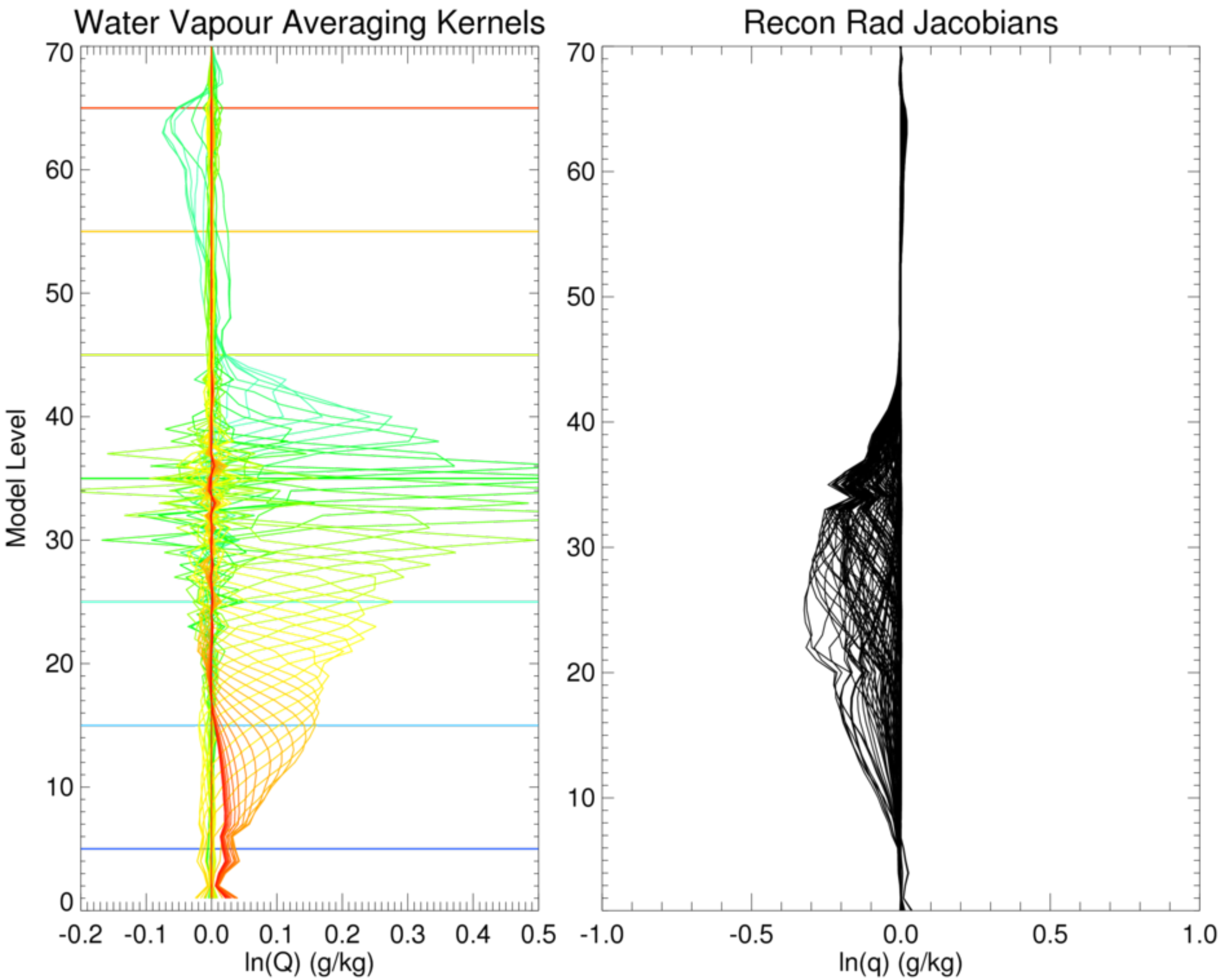
Condition Number of R: 2.6×10^8



AKs with Radiance Jacobians and RR Errors – Water Vapour



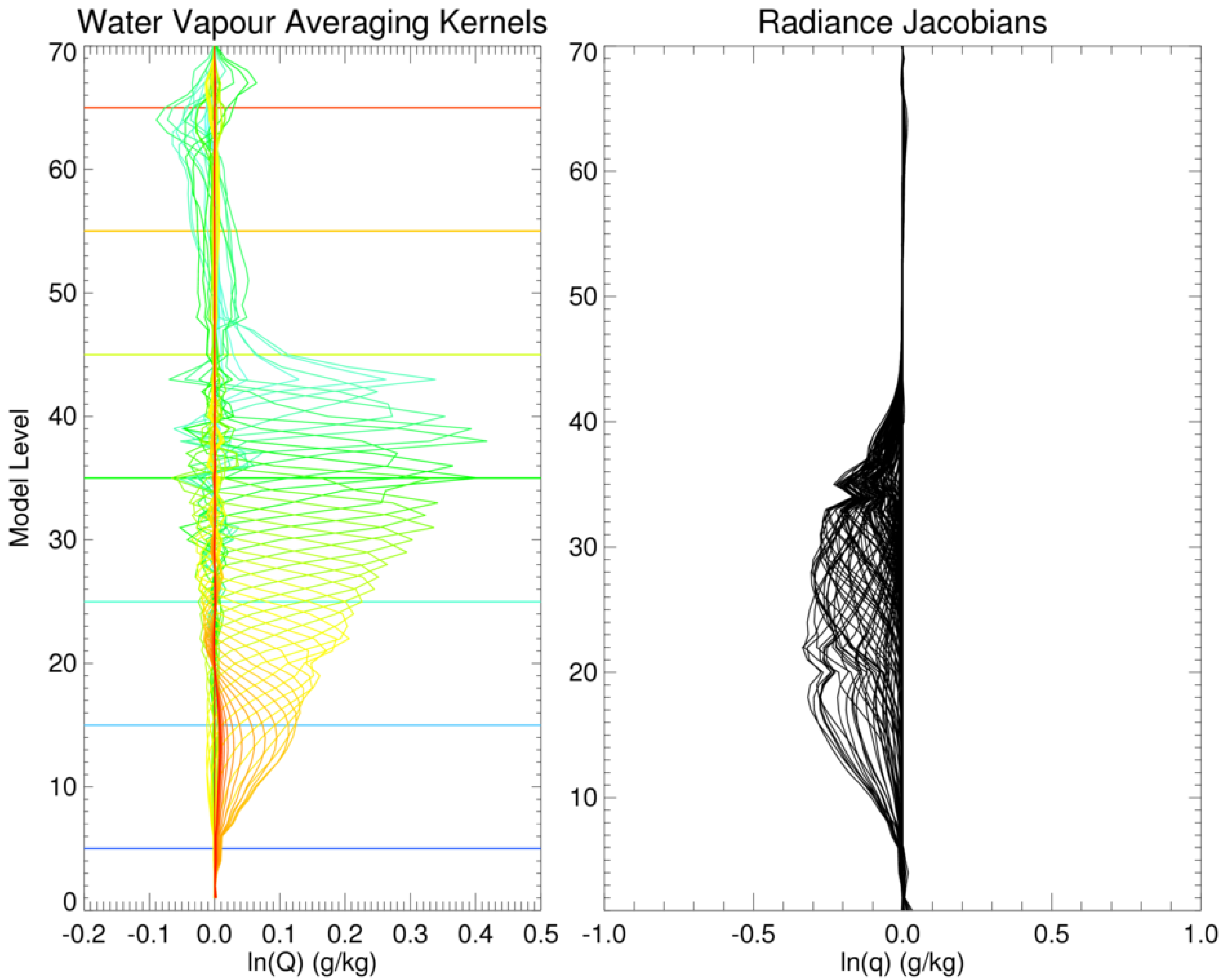
AKs with RR Jacobians and RR Errors – Water Vapour



We can’t afford to forward model RRs!

- In reality, forward modelling the full spectrum to create a properly forward-modelled reconstructed radiance is too slow
- We can only forward model and calculate Jacobians for the raw radiance
- Calculating the extra forward model error term this creates is very hard
- This means we are stuck with the crazy averaging kernels...
  - Unless we can ‘tame’ them by empirically adjusting the **R** matrix to increase values on the diagonal relative to the off-diagonal

AKs with Raw Jacobians and RR Errors ‘Tamed’ – Water Vapour



What do we learn from this?

- There is no more information in the observation than is contained in the full raw radiance spectrum.
- It is possible to get almost all of this information out using RRs, but:
  - If you use the wrong error covariances, you introduce spurious features that look like information but aren't.
  - If you use raw radiance jacobians with reconstructed radiance error covariances your answer can be very wrong indeed.
  - You can to some extent mitigate against this by making the **R** matrix more diagonal and increasing the errors
- So, can we actually use these reconstructed radiance observations?

1D-Var Simulation results

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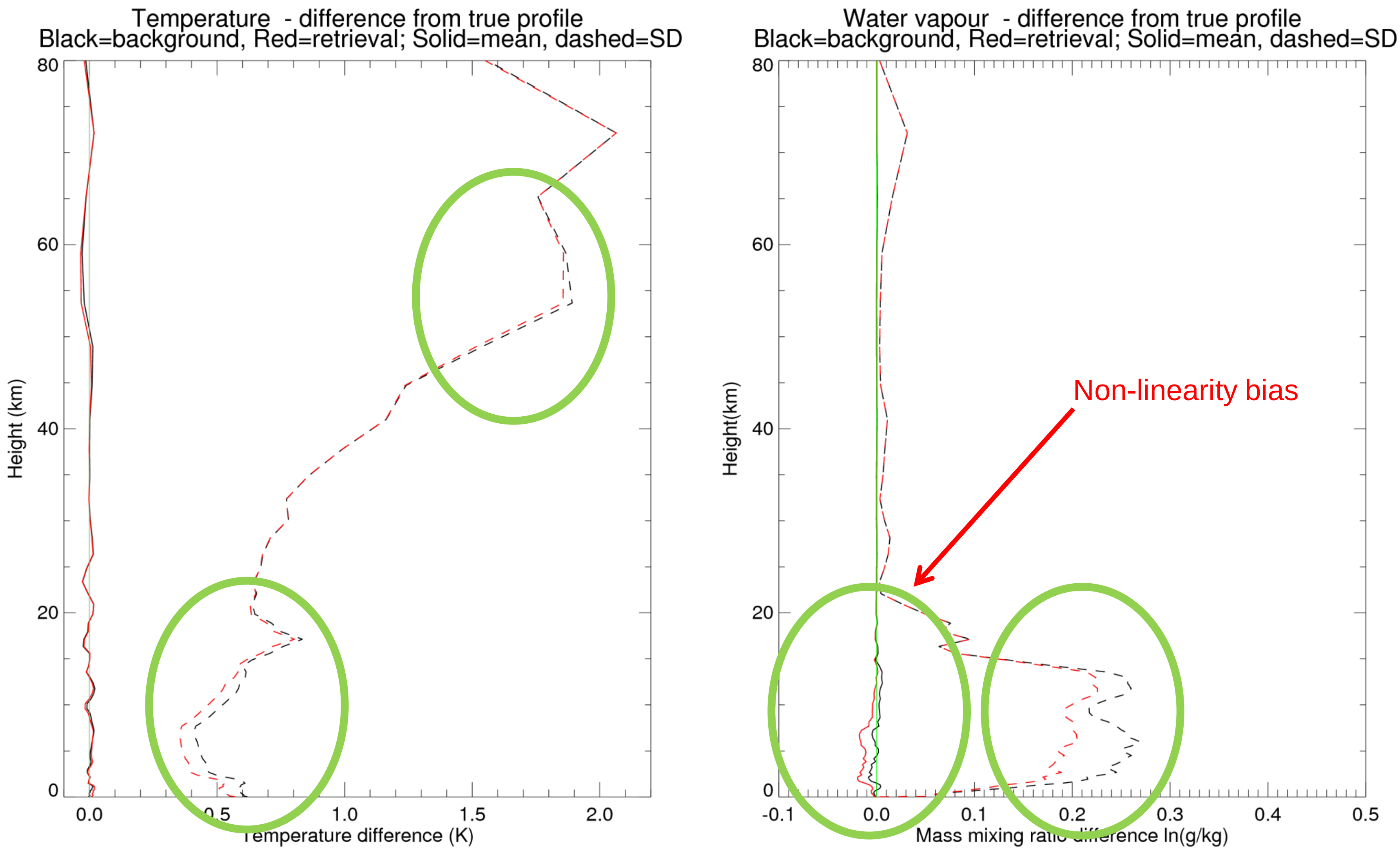
1D-Var Simulation Setup

- 4348 profiles on 70 vertical levels from the Met Office UM
- Observations simulated using RTTOV-10
- Noise added according to diagonal L1c IASI instrument noise
- Observations converted to PC Scores with EUMETSAT PCs, then back into reconstructed radiances
- **R** matrix converted to reconstructed radiances
  - Missing Error Term! – No forward model reconstruction error
- New channel selection assimilated

4D-Var Channels – Inst Noise



RR Channels – RR Inst Noise ‘Untamed’

- Did not work! Minimisation failed for almost every observation

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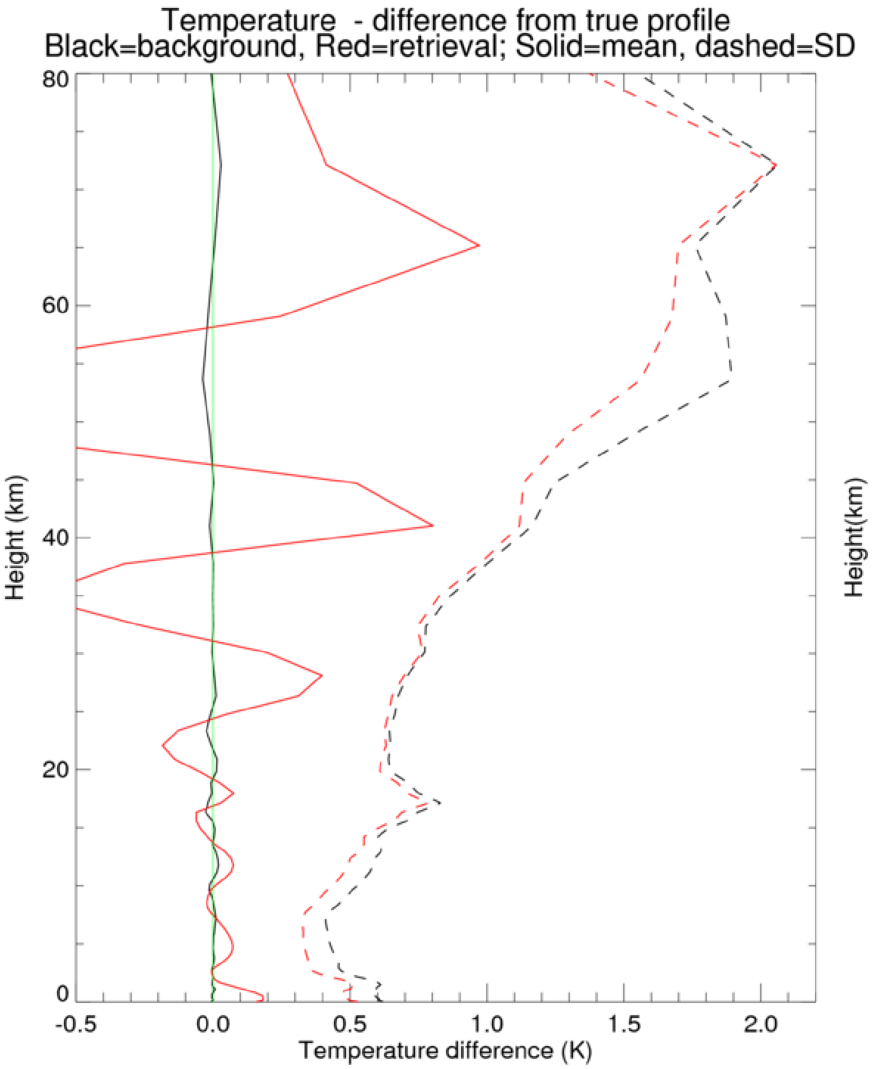
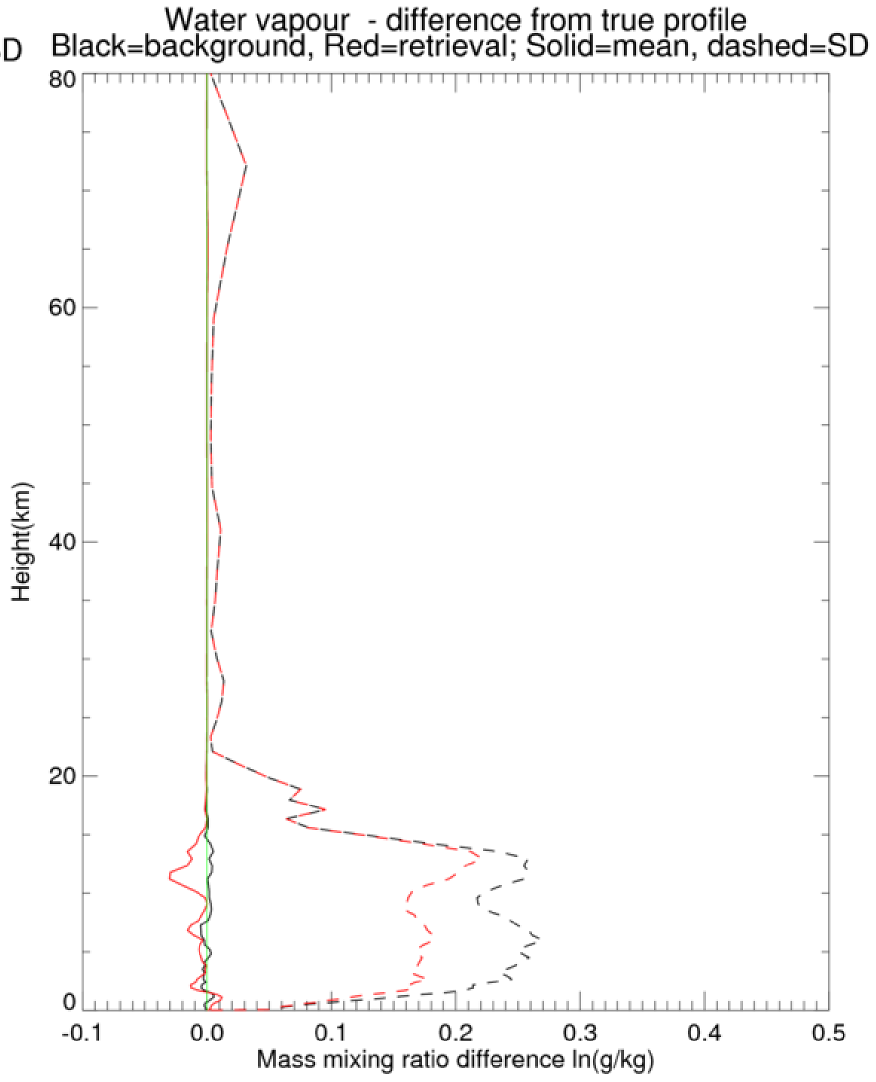
RR Channels –
RR Inst Noise 'Tamed'





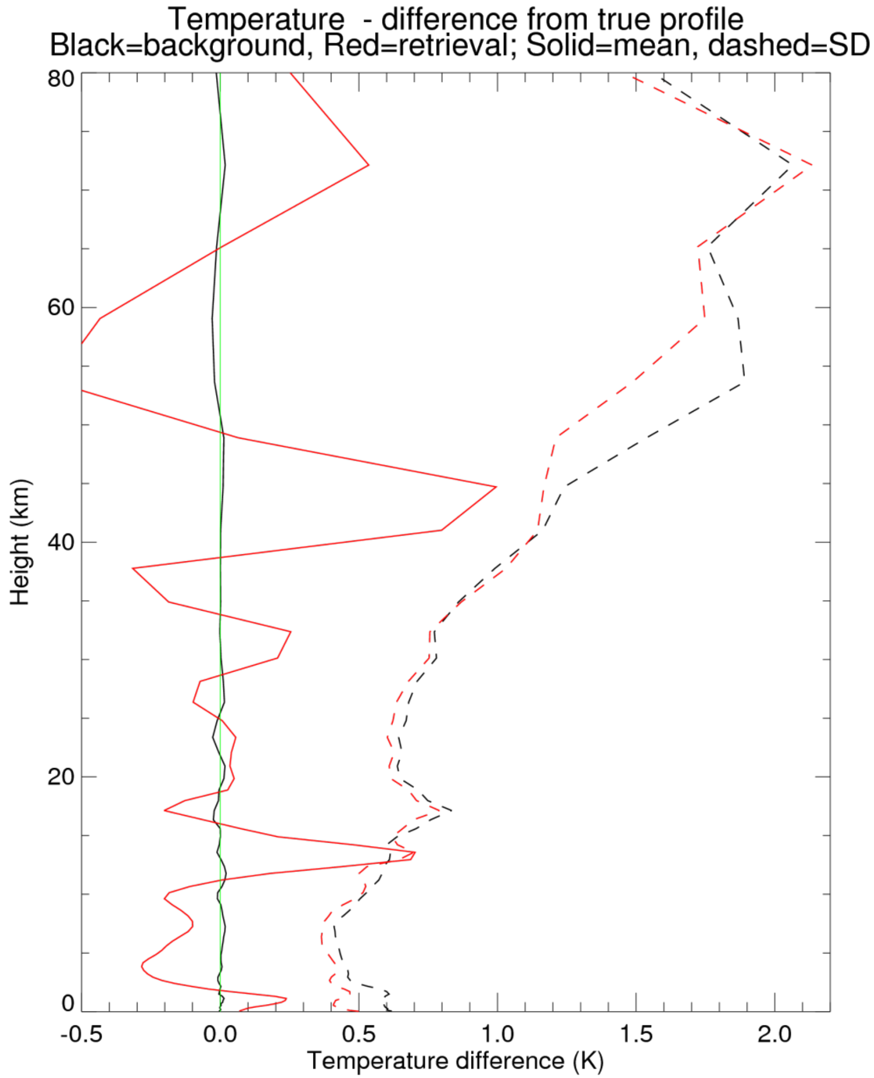
What about PC scores?

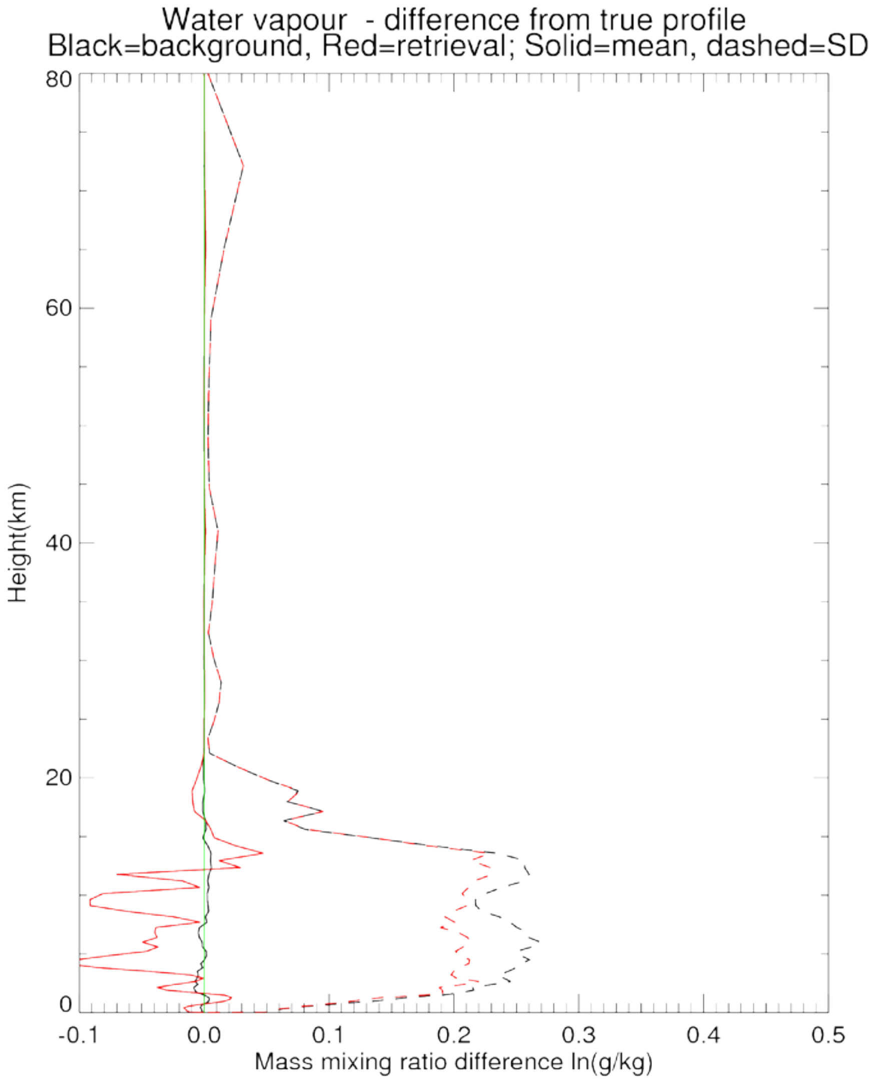
PC-RTTOV 1D-Var experiments

- I couldn't assimilate EUMETSAT PCs because no forward model so I use PC-RTTOV PCs to compress the spectrum instead

- Note this differs from Marco Matricardi's work because the PC Scores assimilated here are based on the full spectrum, not the 366 channel subset.
- The aim of this work is to increase the quantity of spectral information assimilated

PC-RTTOV PC Scores from RTTOV10 Radiances

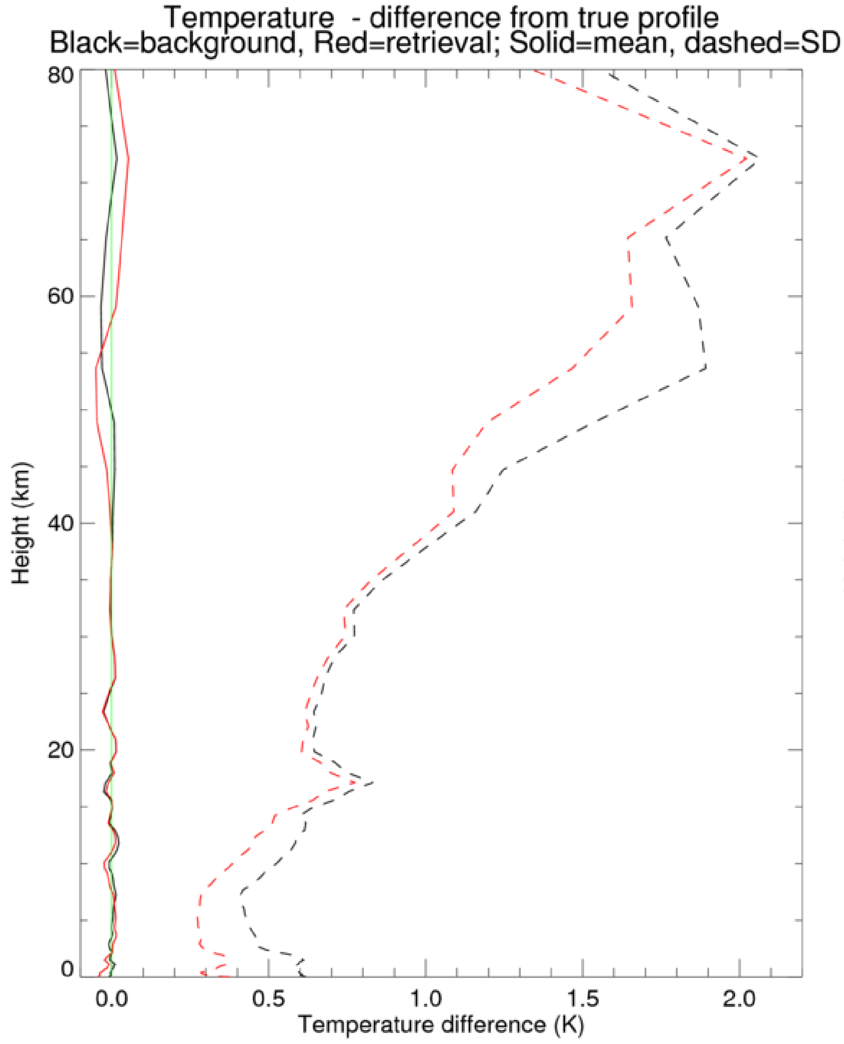


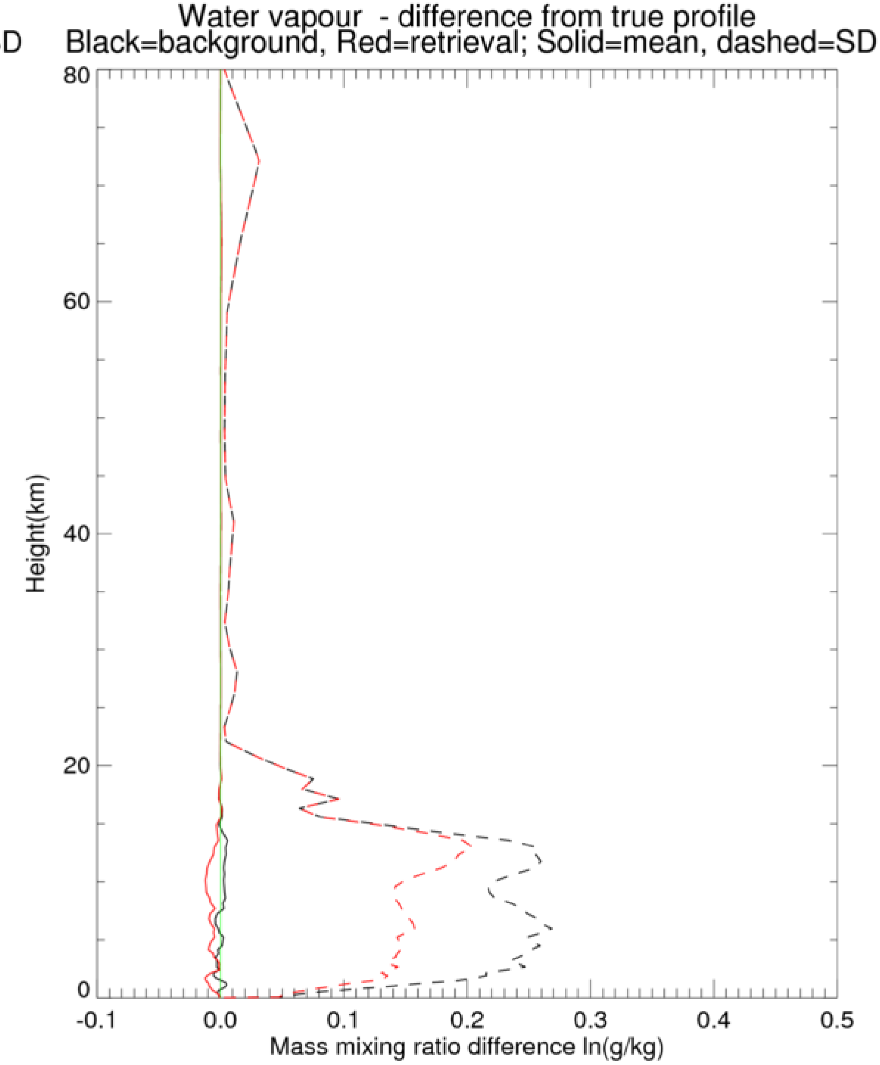


What is going on in that retrieval?

- It turns out there is a missing error term:
  - The observations were simulated using RTTOV then converted to PC-RTTOV PC scores
  - This effectively adds a forward-model error
- Now try again using PC-RTTOV to simulate the observations

PC-RTTOV PC Scores from PC-RTTOV Radiances





What have we learned from 1D-Var simulation studies?

- PC assimilation and RR assimilation behave similarly when error terms are neglected in the **R** matrix with large osciallatory biases in the retrieval
  - Hopefully, in the real world with additional sources of error, the effects on the retrieval will be less dramatic!
- We can’t calculate all the error terms.
  - We will have to rely on diagnostic techniques such as Desroziers and Hollingsworth-Loennberg
  - It is quite likely that the diagnosed matrices will need empirical stabilisation to reduce the condition number

Summary

Why do this?

- Theoretically, should be able to access full information content from PC scores, whilst maintaining the processing in radiance space
  - PC scores are difficult to use in cloudy scenes
  - Not so intuitive for monitoring / physical understanding etc
- We are likely to have to use reconstructed radiances in the future if bandwidth precludes the dissemination of raw spectra from e.g. IASI-NG, MTG-IRS

Where do we go from here?

- A channel selection for the Met Office 4D-Var based on a full **R** matrix derived using the Hollingsworth-Lönnberg method has been attempted
- Need to try this channel selection in operational 1D-Var pre-processor and 4D-Var
  - Will need iterations on the observation error term using Desroziers diagnostics.
- It is a promising technique, but the devil is in the details

Thanks for listening! Any questions?

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Principal Component Compression
based on EUMETSAT L1 PC Scores

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$$y_{pc} = \mathbf{L}^T \mathbf{E}^{-1/2} (y_{chan} - y_{mean})$$

- y_{chan} is the observation in channel space
- y_{mean} is the climatological mean spectrum
- y_{pc} is the observation in PC space
- *npc* is the numper of retained PCs (290)
- **L** is the PC eigenvector matrix (size *nchan* x *npc*)
- **E** is the noise covariance matrix

- Note that here, the observation is noise-normalised but other norms are used when PCs are designed for assimilation rather than dissemination

Radiance Reconstruction
based on EUMETSAT L1 PC Scores

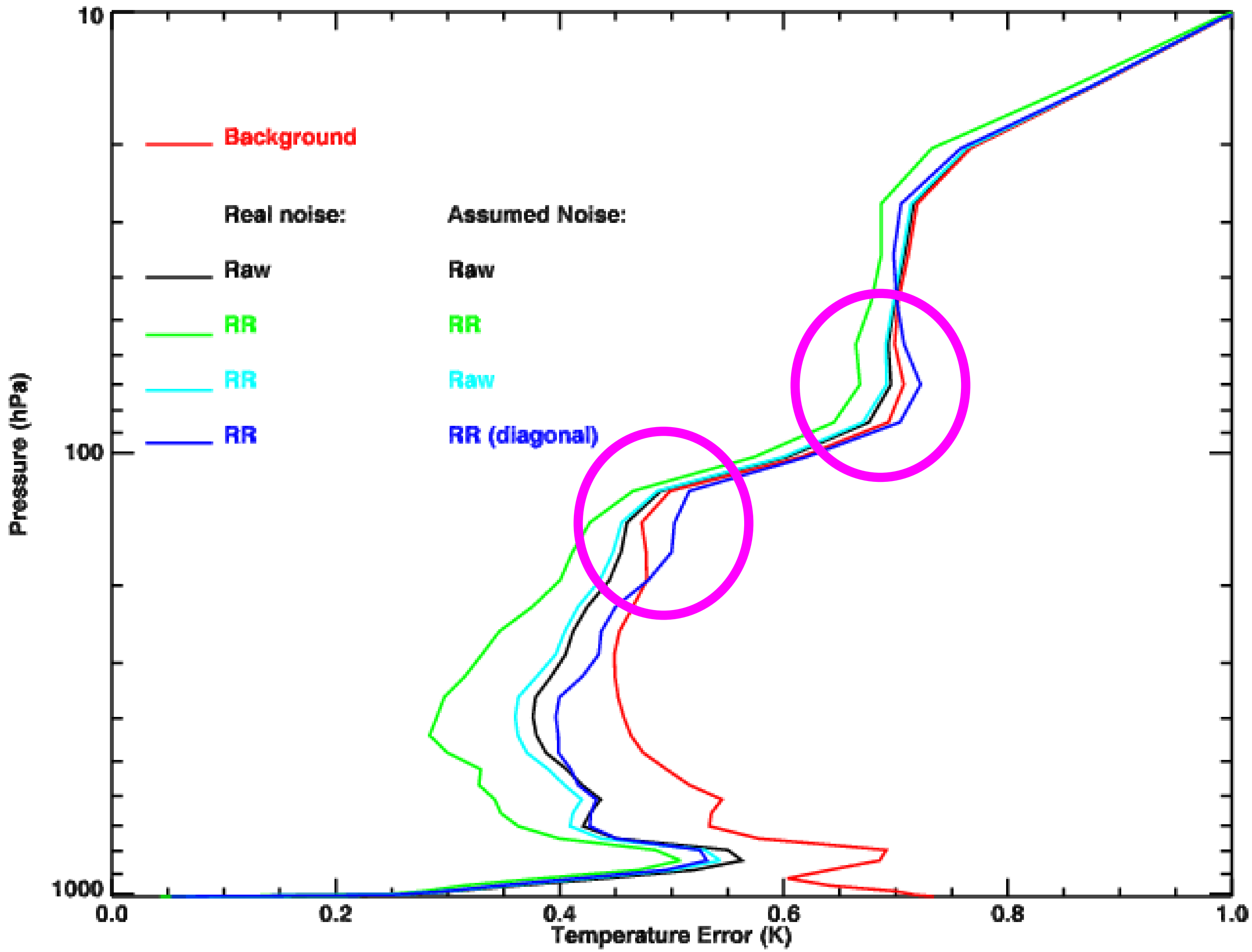
$$y_{rr} = \mathbf{E}^{1/2}\,\mathbf{L}_{rr}\,y_{pc} + y_{mean}$$

$$= \mathbf{E}^{1/2}\,\mathbf{L}_{rr}\,\mathbf{L}^{T}_{pc}\,\mathbf{E}^{-1/2}\,y_{chan} + y_{mean}$$

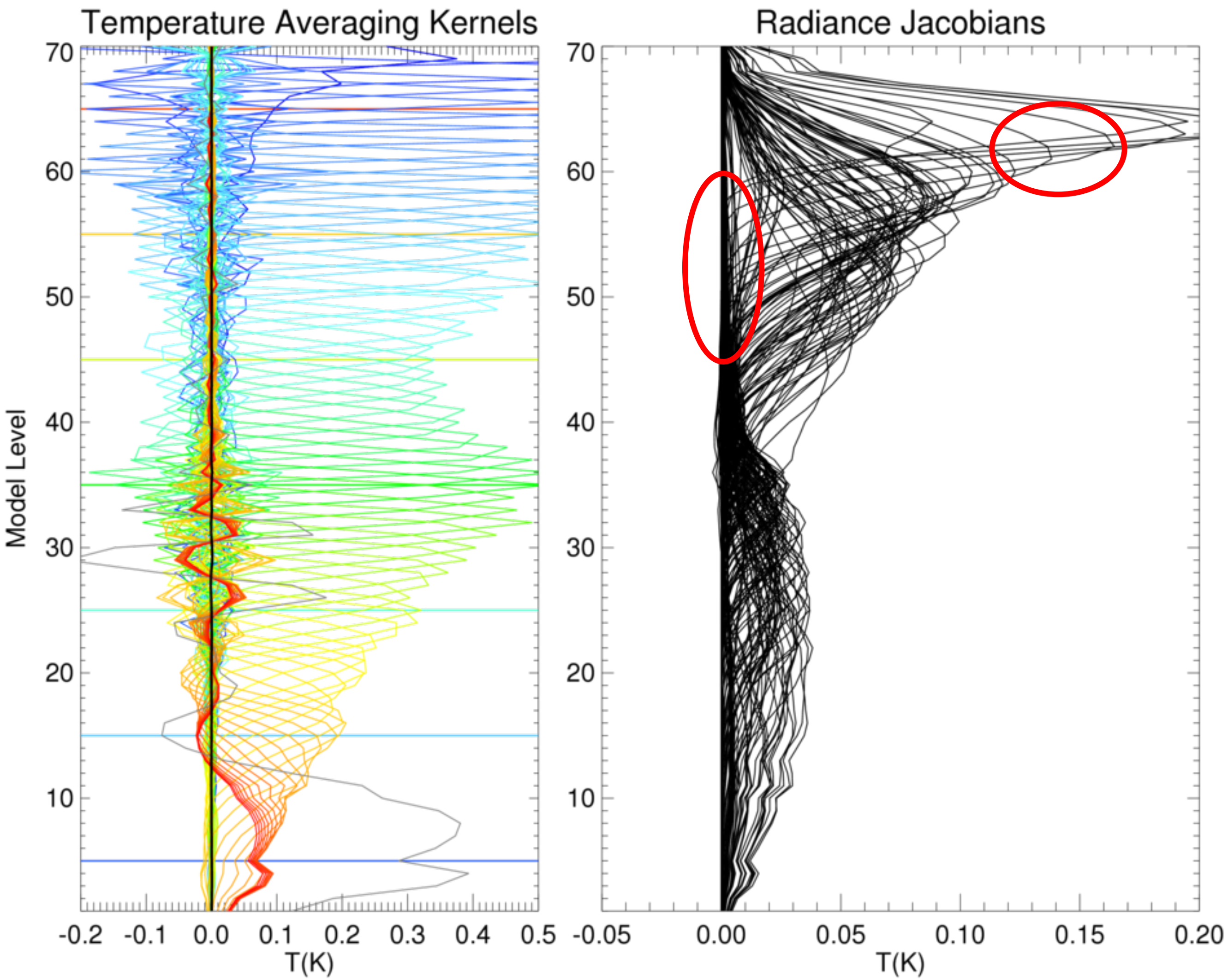
- **The critical point is this:**
- $\mathbf{L}_{pc}$ is size (*nchan* x *npc*), $\mathbf{L}_{rr}$ is size (*nrr* x *npc*)
- *nrr* <= *npc*

- The same matrix transform applies to the **R** matrix and introduces significant inter-channel correlations

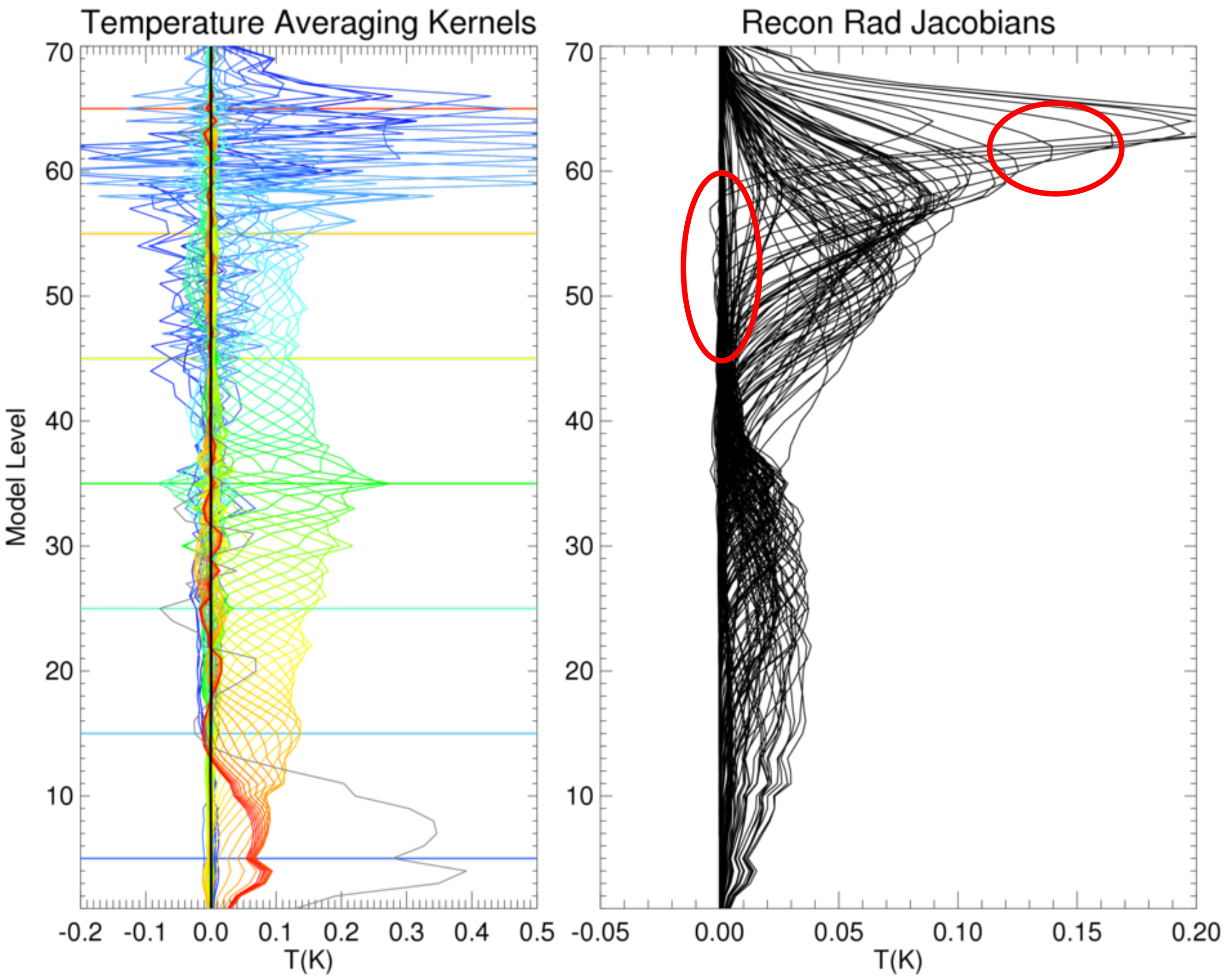
What happens when you use the wrong errors? (plot from A. Collard)



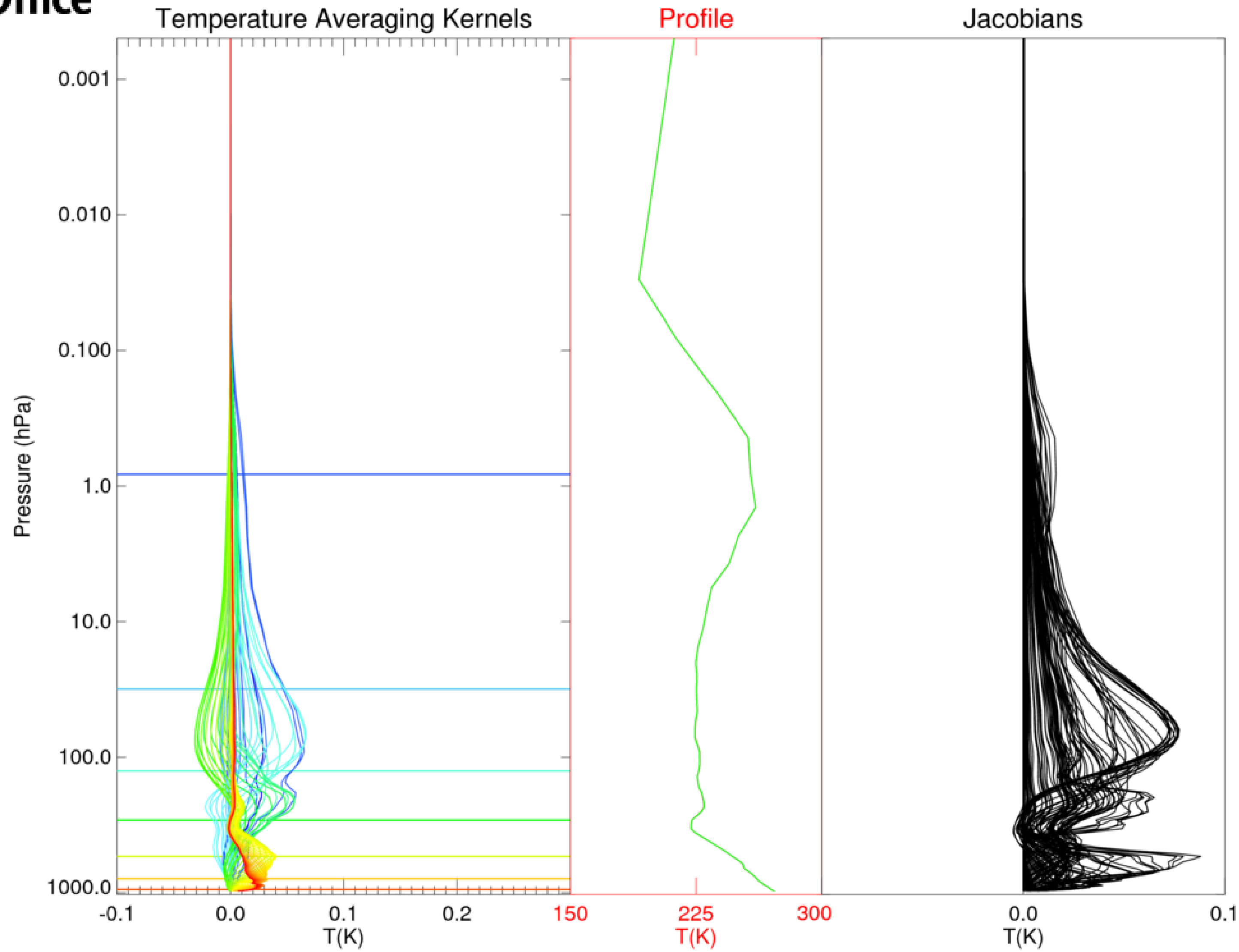
AKs with Radiance Jacobians and RR Errors - Temperature



AKs with RR Jacobians and RR Errors - Temperature

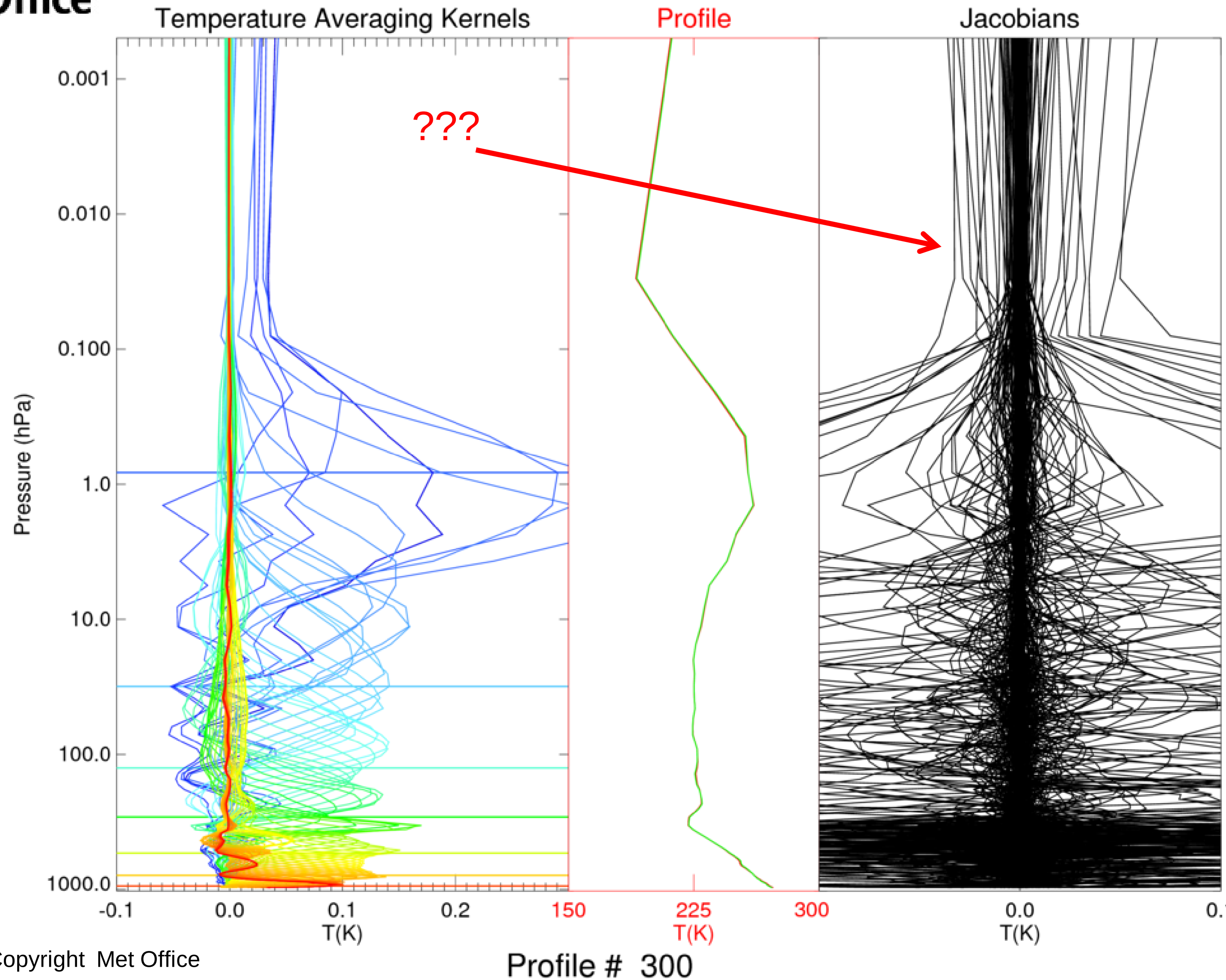


Jacobians and Averaging Kernels 4D-Var Channels - Temperature

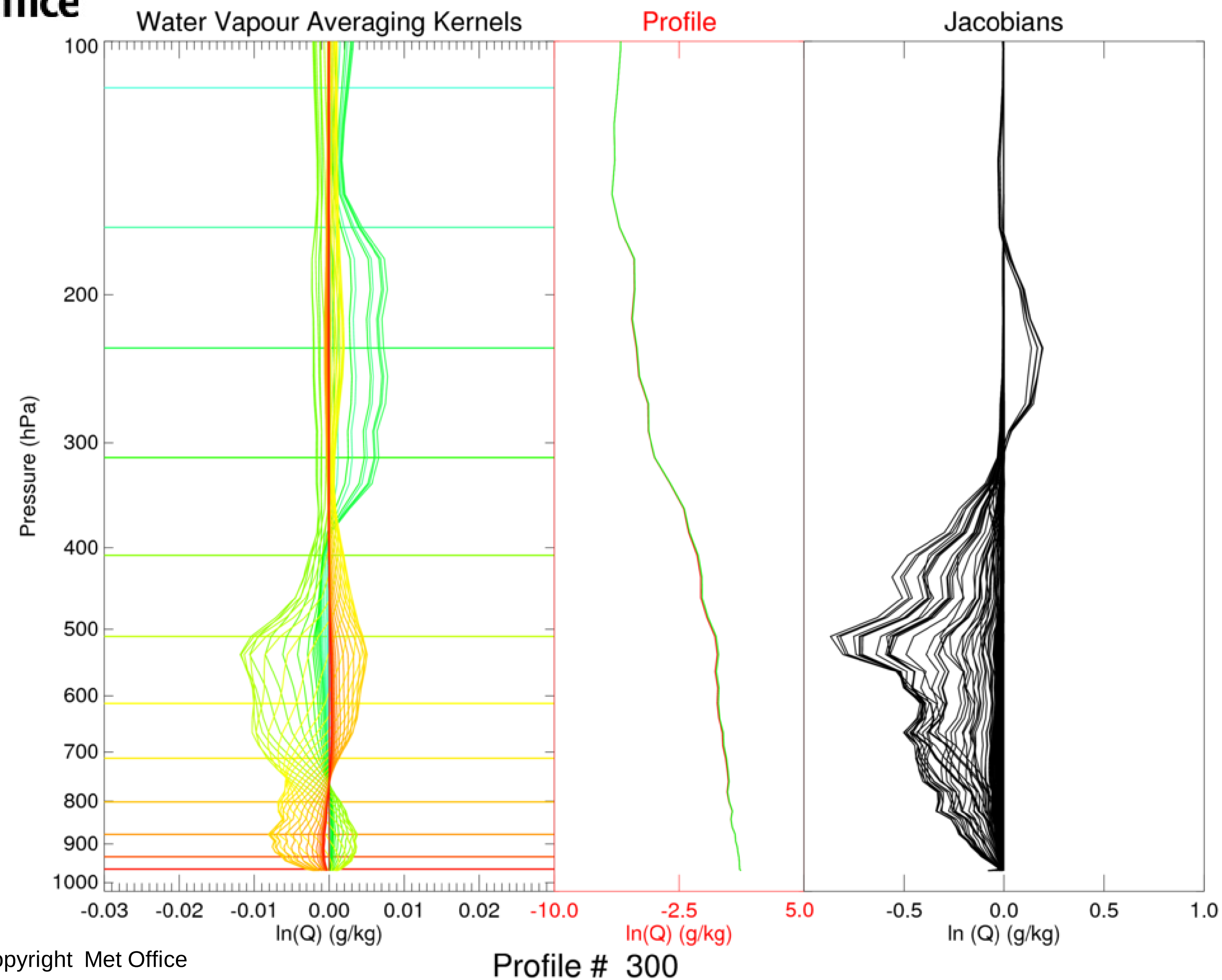


Profile # 300

Jacobians and Averaging Kernels PC-RTTOV PC Scores - Temperature



Jacobians and Averaging Kernels 4D-Var Channels – Water Vapour



Jacobians and Averaging Kernels PC-RTTOV PC Scores – Water Vapour

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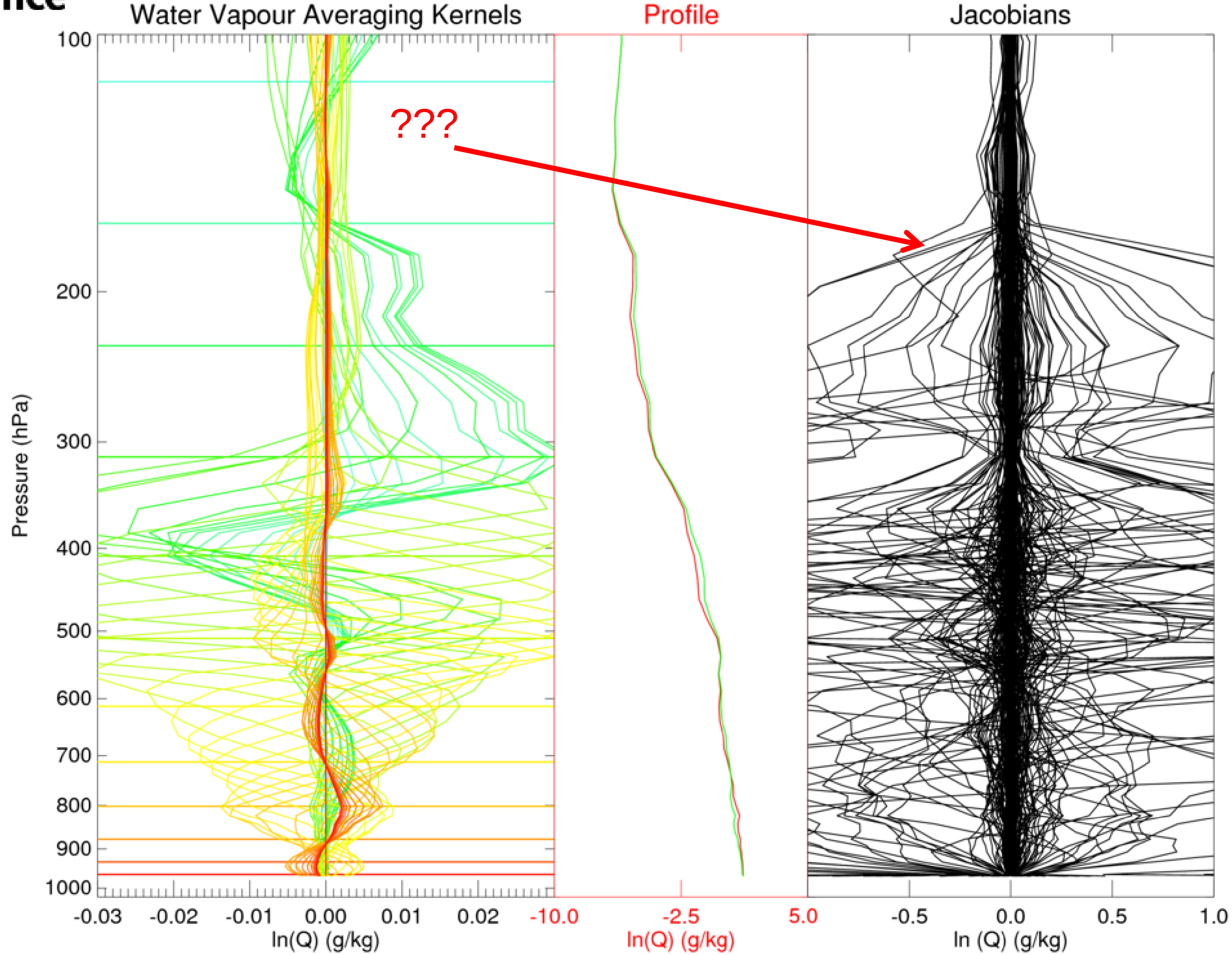
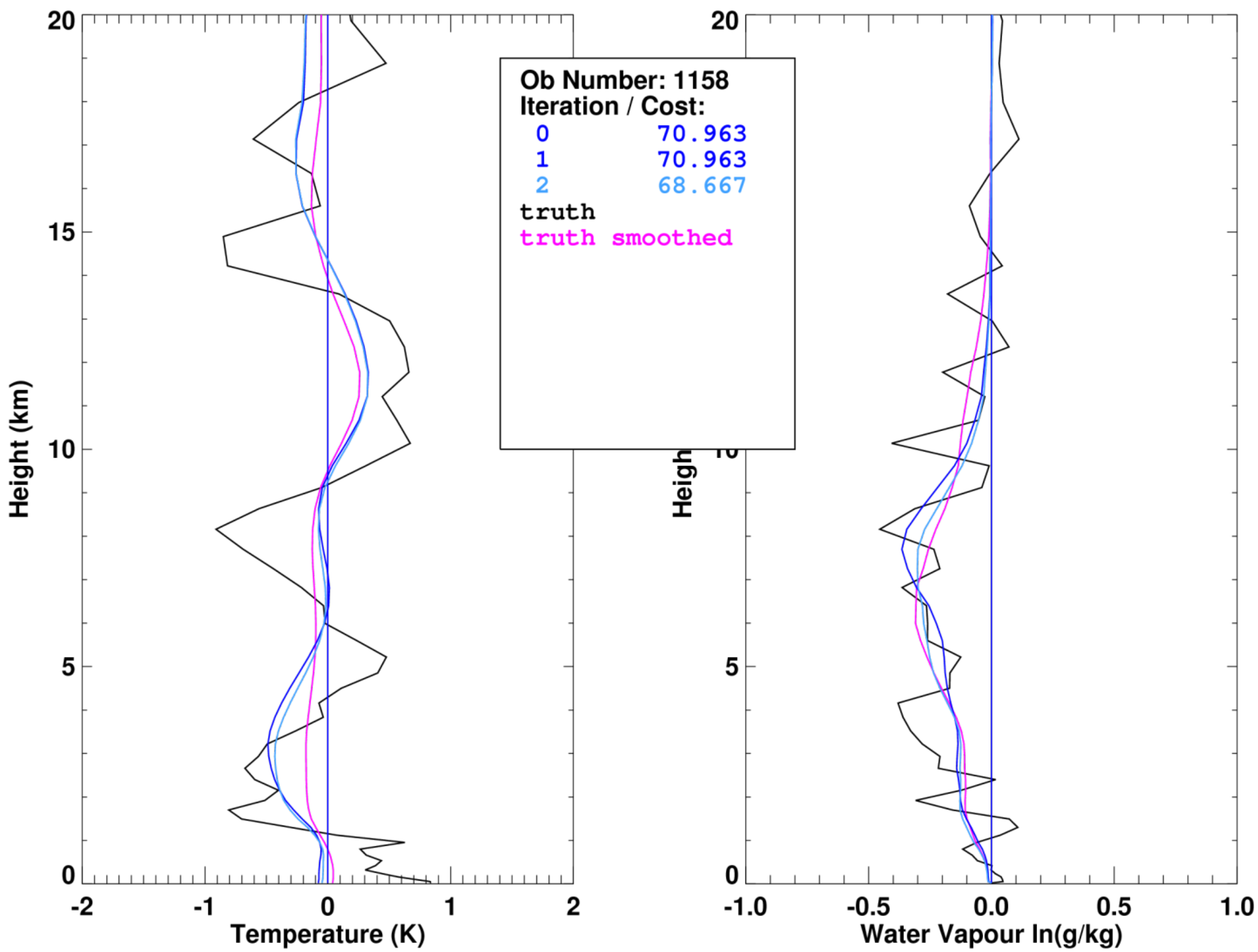
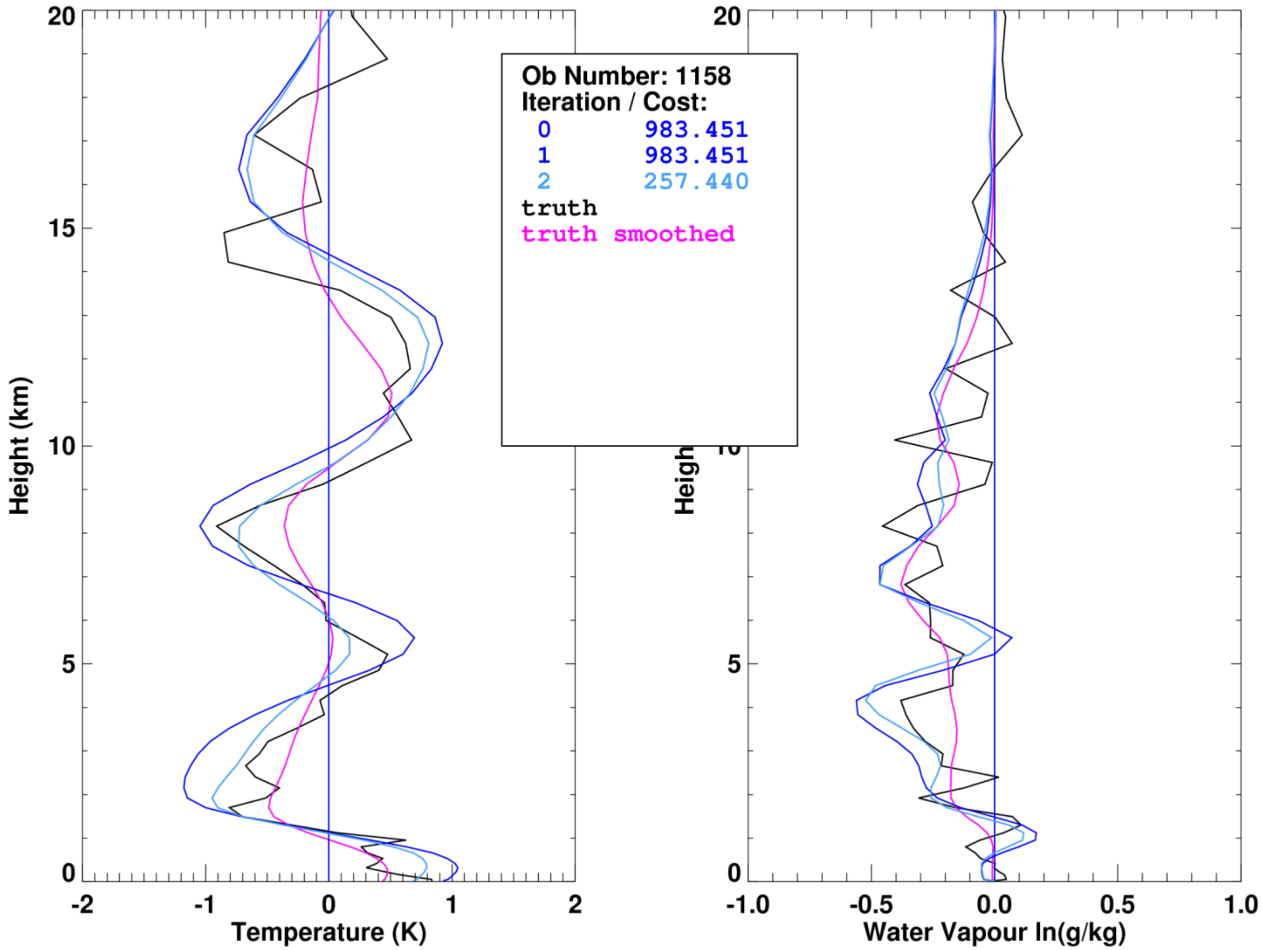


Profile # 300

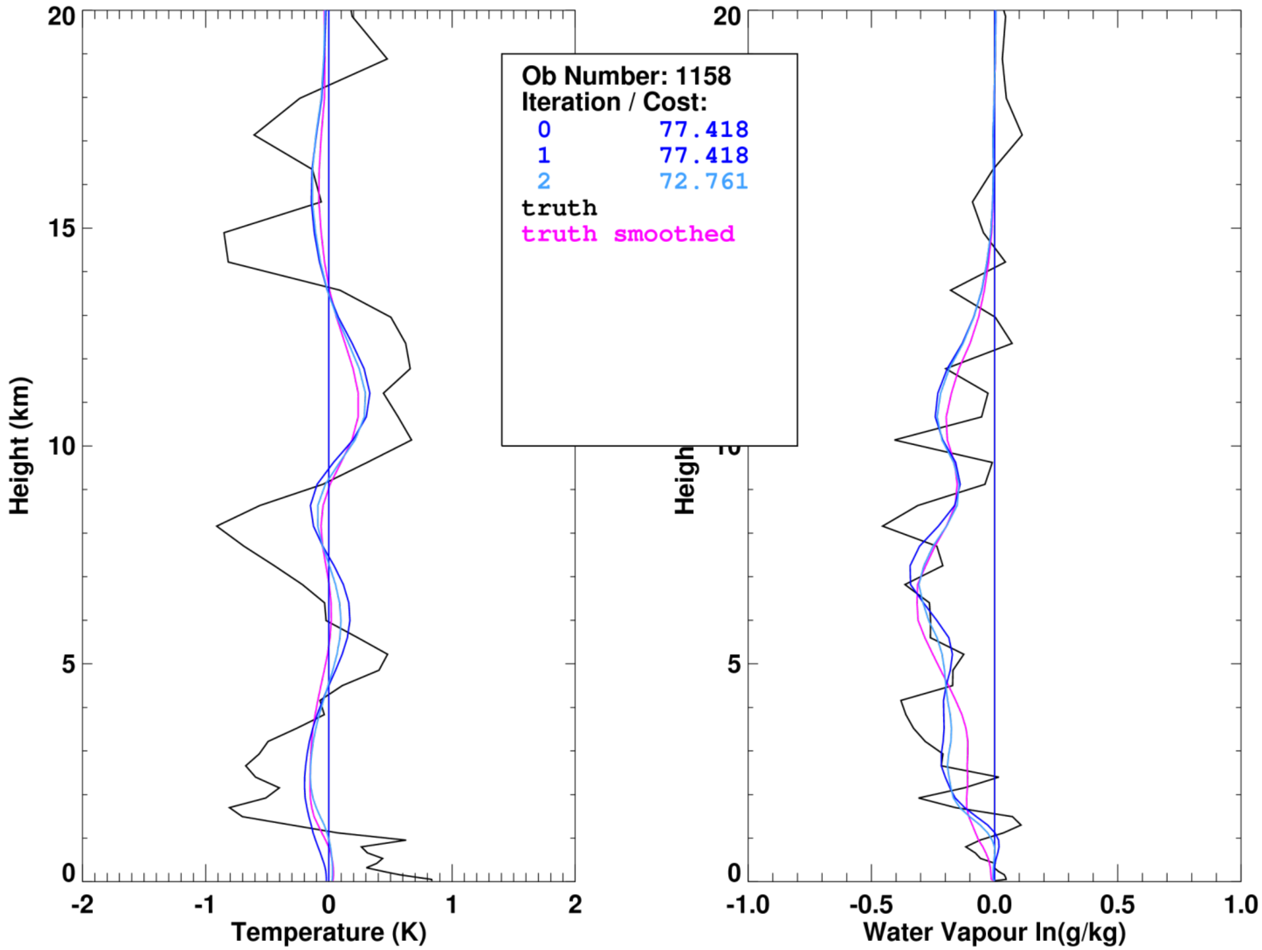
Minimisation – 4D-Var channels Instrument noise



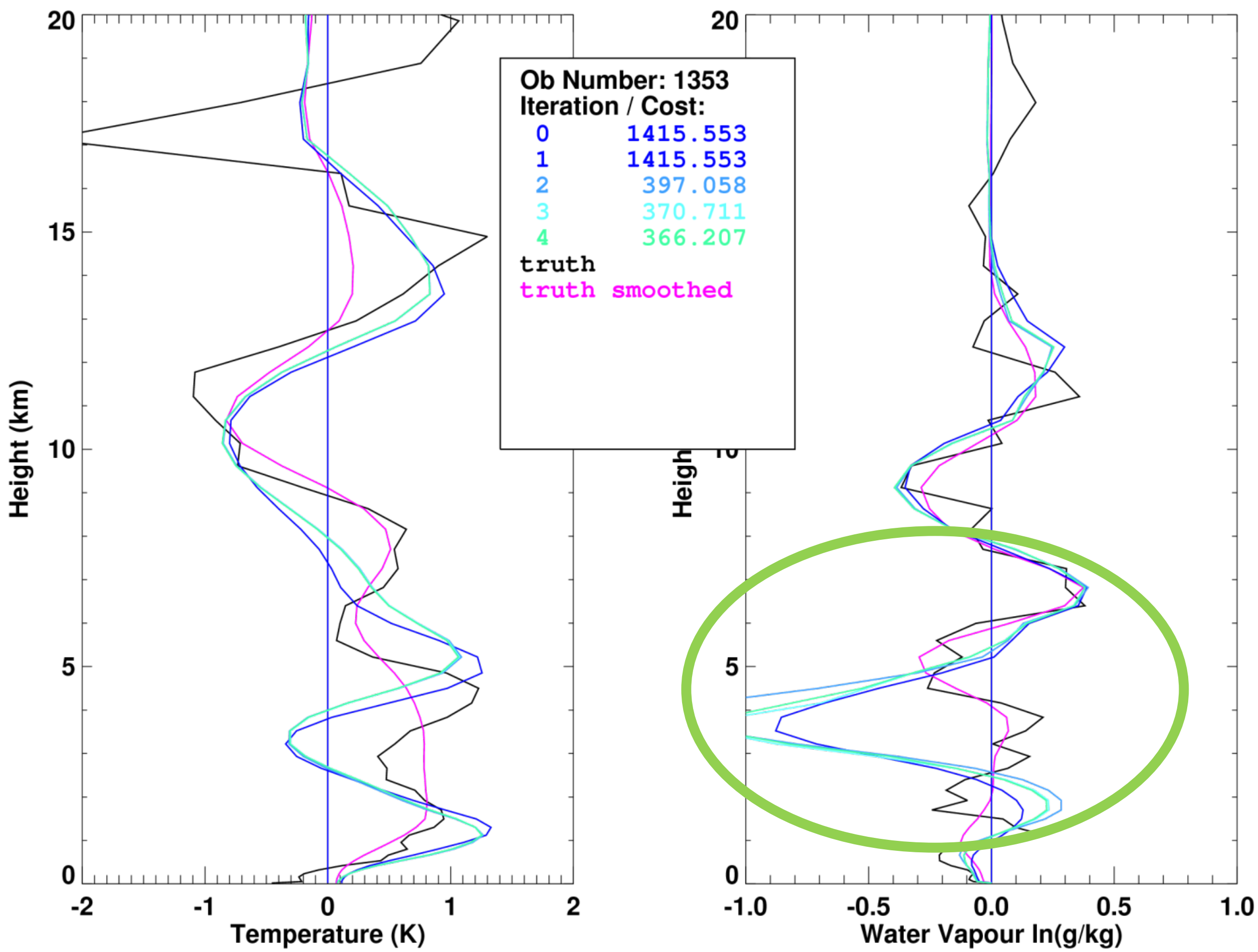
Minimisation – PC Scores Instrument noise



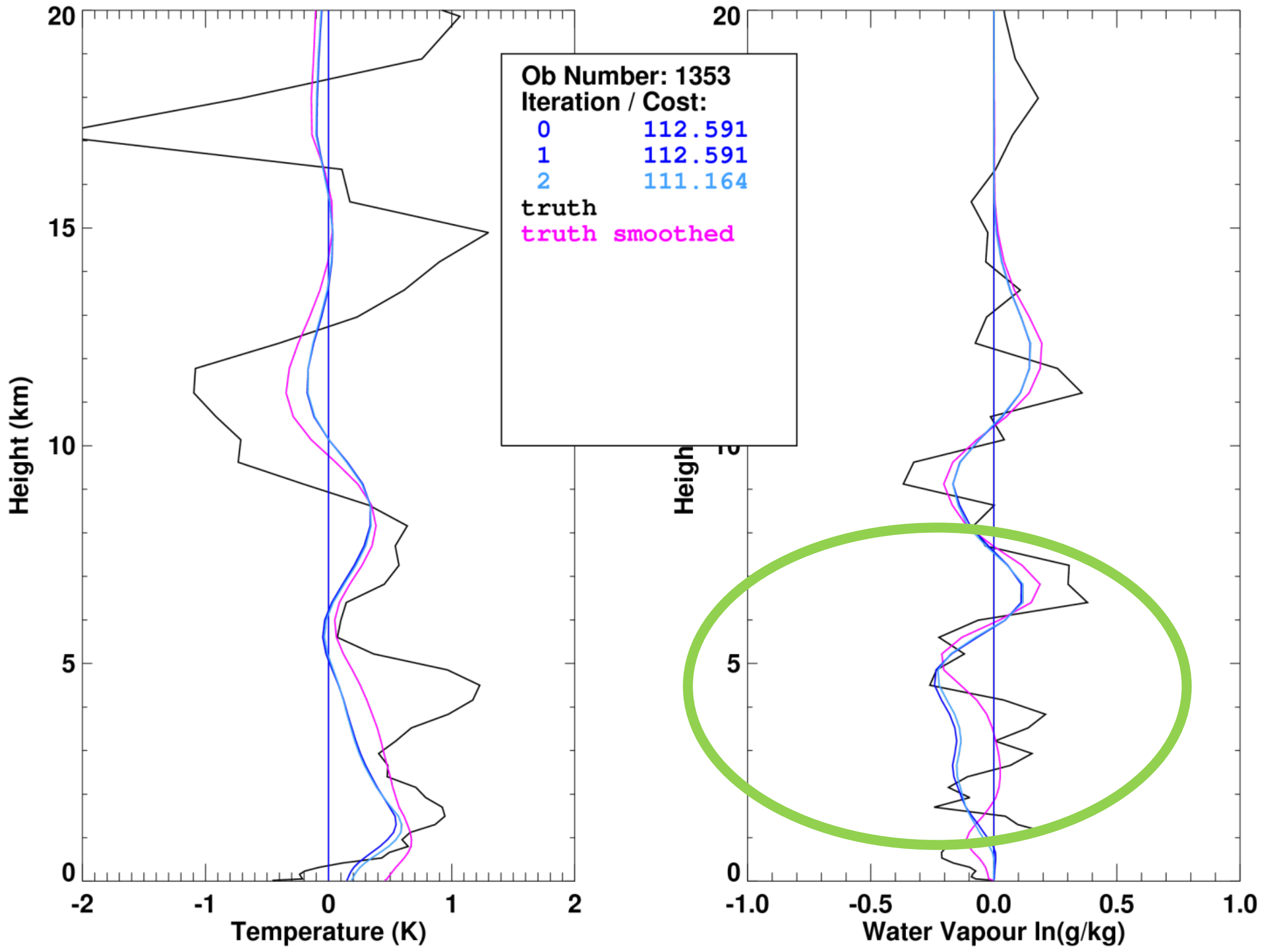
Minimisation – PC scores
Instrument noise + RT error



Minimisation – PC Scores
Instrument noise



Minimisation – PC scores
Instrument noise + RT error



Raw Radiance Forward Modelling

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- The matrix $\mathbf{L}_{rr}\mathbf{L}_{p}^{T}$ also affects the Jacobian
- We should be using: $\tilde{H}(\mathbf{x}) = \mathbf{L}_{rr} H_{pc}(\mathbf{x})$

$$
\begin{aligned}
\delta\tilde{\mathbf{y}} &= (\tilde{\mathbf{y}} - \tilde{\mathbf{y}}_t) - (\tilde{H}(\mathbf{x}) - \tilde{\mathbf{y}}_t) \\
&= \mathbf{L}_{rr}\mathbf{L}_p^{\mathrm{T}}((\mathbf{y} - \mathbf{y}_t) - (H(\mathbf{x}) - \mathbf{y}_t))
\end{aligned}
$$

- But in reality that is far too inefficient, so we just use

$$
\begin{aligned}
\delta\tilde{\mathbf{y}}' &= (\tilde{\mathbf{y}} - \tilde{\mathbf{y}}_t) - (H(\mathbf{x}) - \tilde{\mathbf{y}}_t) \\
&= \mathbf{L}_{rr}\mathbf{L}_p^{\mathrm{T}}(\mathbf{y} - \mathbf{y}_t) - (H(\mathbf{x}) - \mathbf{L}_{rr}\mathbf{L}_p^{\mathrm{T}}\mathbf{y}_t))
\end{aligned}
$$

- That leads to additional forward model error (or you could call it “reconstruction error”)…

Additional forward model error

- Instead of:

$$\begin{aligned}\tilde{\mathbf{R}} = & \ \mathbf{L}_{rr}\mathbf{L}_p^{\mathrm{T}}\mathbf{E}\mathbf{L}_p\mathbf{L}_{rr}^{\mathrm{T}} \quad + \quad \mathbf{L}_{rr}\mathbf{L}_p^{\mathrm{T}}\mathbf{F}\mathbf{L}_p\mathbf{L}_{rr}^{\mathrm{T}} \\ = & \ \mathbf{L}_{rr}\mathbf{L}_p^{\mathrm{T}}\mathbf{R}\mathbf{L}_p\mathbf{L}_{rr}^{\mathrm{T}}\end{aligned}$$

- We now have:

$$\tilde{\mathbf{R}}' = \mathbf{L}_p\mathbf{L}_p^{\mathrm{T}}\mathbf{E}\mathbf{L}_p\mathbf{L}_p^{\mathrm{T}} \quad + \quad \mathbf{F}'$$

$$\begin{aligned}\delta\tilde{\mathbf{y}}_{fm} = & \ H(\mathbf{x}) - \mathbf{L}_{rr}\mathbf{L}_p^{\mathrm{T}}\mathbf{y}_t \\ = & \ \mathbf{y}_t + \epsilon_{fm} - \mathbf{L}_{rr}\mathbf{L}_p^{\mathrm{T}}\mathbf{y}_t \\ = & \ (\mathbf{I} - \mathbf{L}_{rr}\mathbf{L}_p^{\mathrm{T}})\mathbf{y}_t + \epsilon_{fm}\end{aligned}$$

$$\begin{aligned}\mathbf{F}' = & \ < \delta\tilde{\mathbf{y}}_{fm}\delta\tilde{\mathbf{y}}_{fm}^{\mathrm{T}} > \\ = & \ (\mathbf{I} - \mathbf{L}_{rr}\mathbf{L}_p^{\mathrm{T}}) < \mathbf{y}_t\mathbf{y}_t^{\mathrm{T}} > (\mathbf{I} - \mathbf{L}_{rr}\mathbf{L}_p^{\mathrm{T}})^{\mathrm{T}} \quad + \quad \mathbf{F} \\ = & \ \mathbf{\Phi} \quad + \quad \mathbf{F}\end{aligned}$$

Additional forward model error

- $\mathbf{\Phi}$ results from (small) atmospheric signal in the discarded PCs
- Also, **F** does not get filtered by $\mathbf{L}_{rr}\mathbf{L}_{p}^{T}$

- It is REALLY important to get this right
- I will demonstrate this later… but first we need a channel selection!