Situation dependent inter-channel observation error correlations for all-sky data assimilation

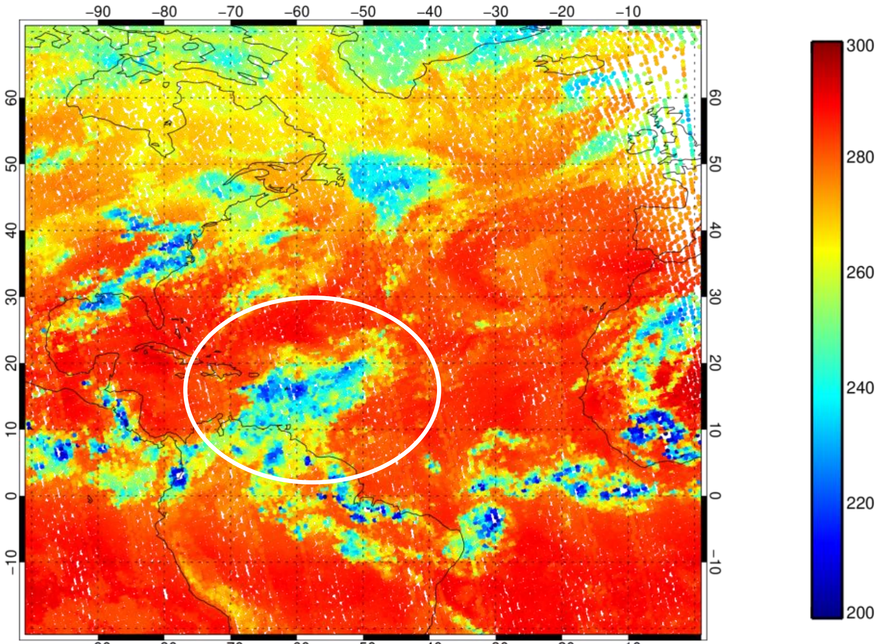
Alan Geer

Thanks to: Katrin Lonitz, Stefano Migliorini, Marco Matricardi, Niels Bormann, Peter Weston

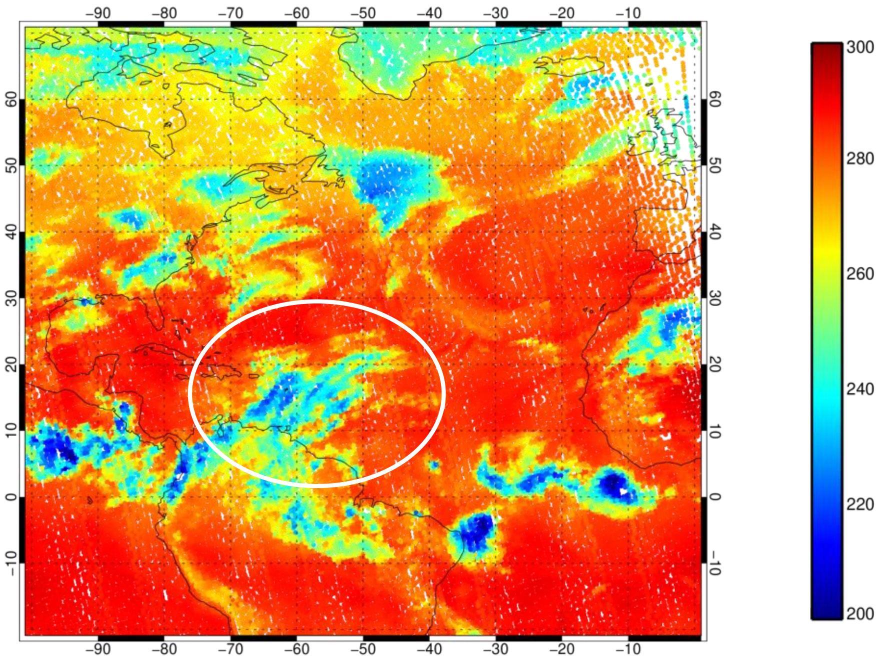
Recap all-sky situation-dependent observation errors

All-sky IASI (hyperspectral IR) channel 906

Obs

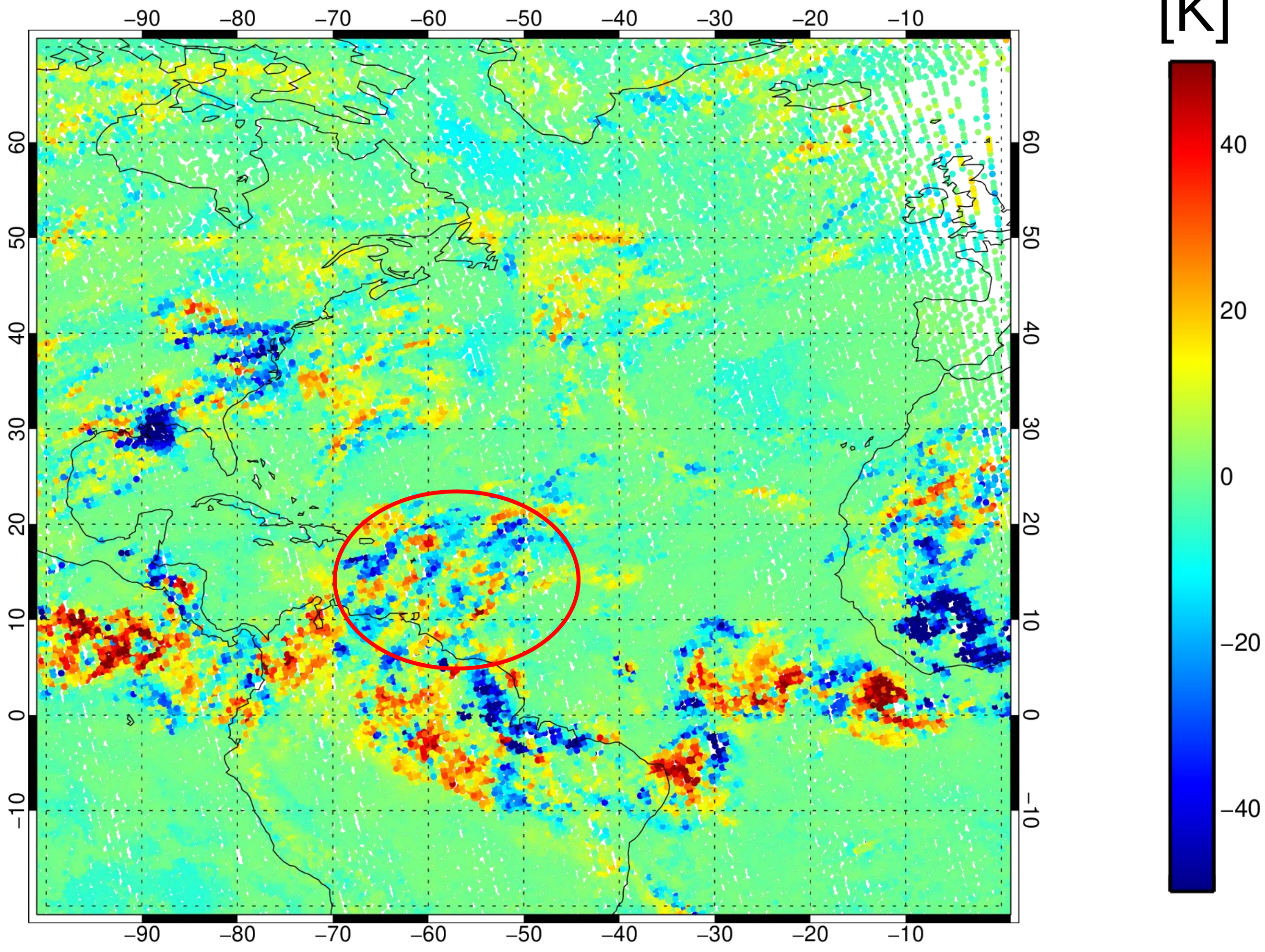


Model
(12h
forecast)



Obs - model (O-B)

[K]

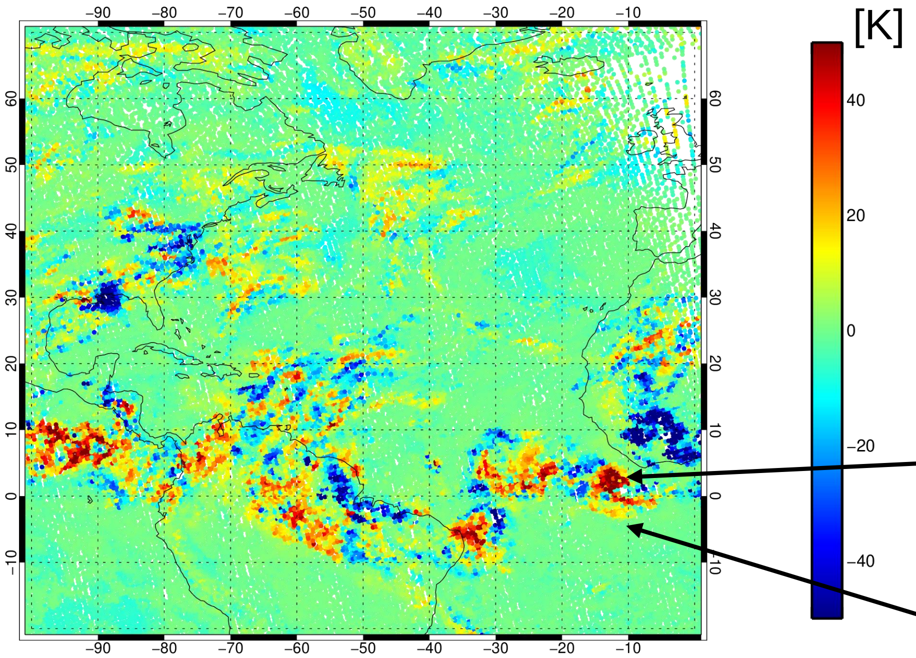


Properties of all-sky background departures

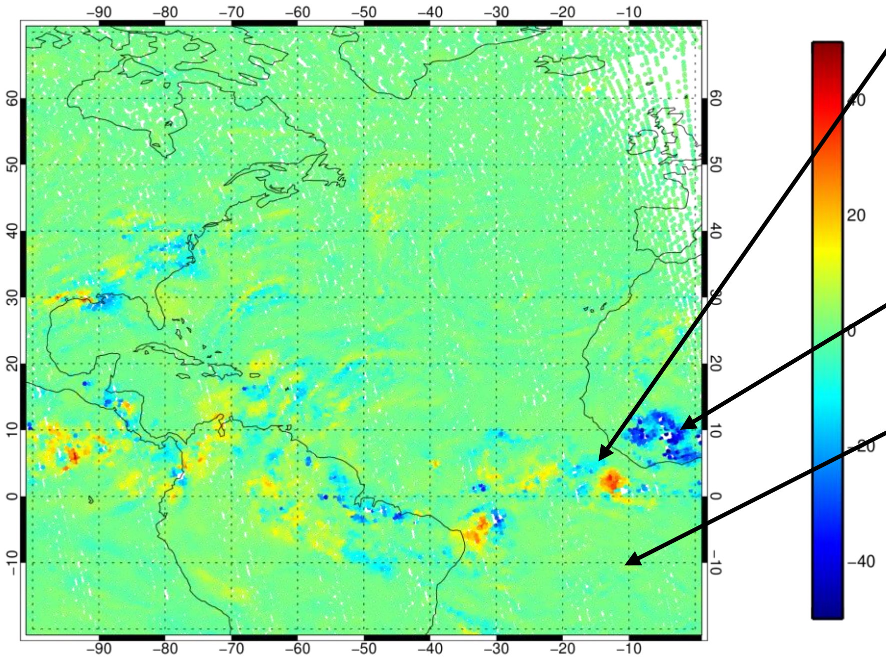
Obs - model

$$d_i = y_i - H_i(\mathrm{x})$$

IASI Ch. 906
(lower troposphere)



IASI Ch. 3002
(upper tropospherehumidity /cloud)



Spatially correlated

Interchannel correlated

Much bigger in the presence of cloud than in clear skies

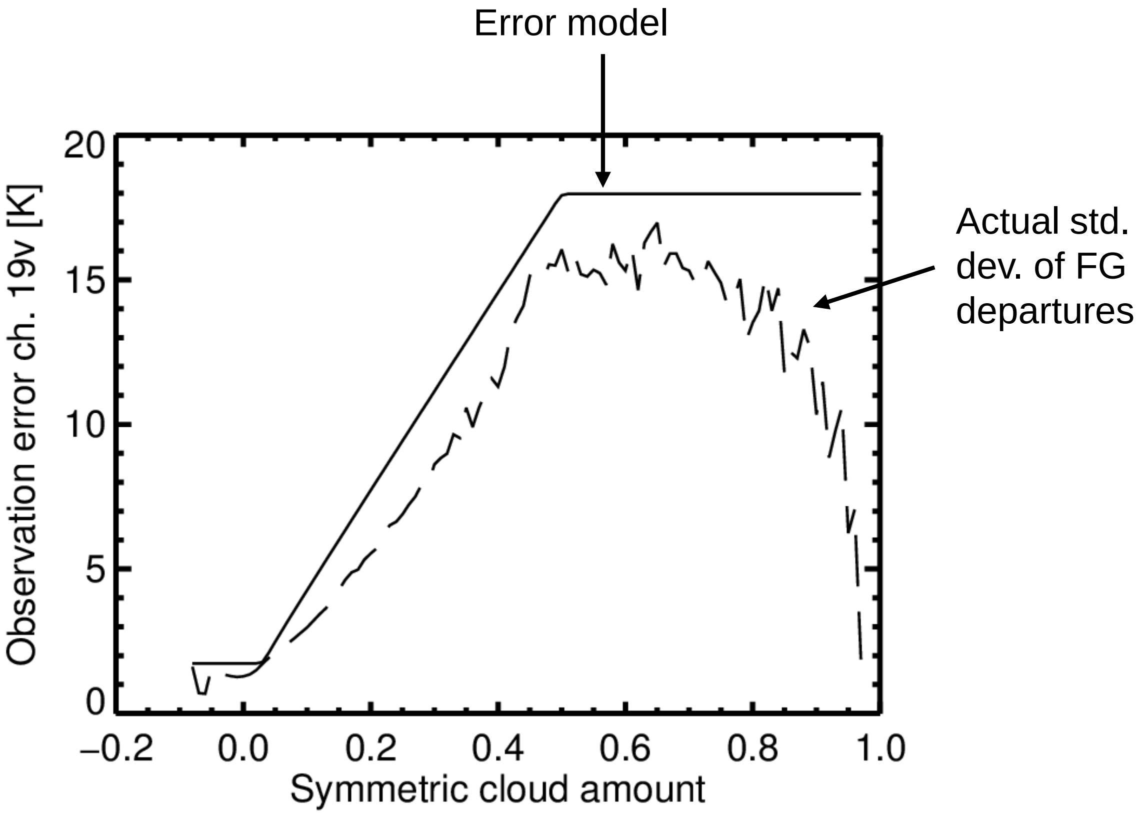
Moisture and temperature errors: O(0.1 – 5 K)
Cloud errors: O(10 – 100 K)

Current all-sky microwave model (no interchannel error correlations)

$$
\mathbf{R}_i = \begin{matrix} \sigma^2_{19V} & 0 & 0 & \dots & 0 \\ 0 & \sigma^2_{19H} & 0 & \dots & 0 \\ 0 & 0 & \sigma^2_{22V} & \dots & 0 \\ \dots & \dots & \dots & \dots & 0 \\ 0 & 0 & 0 & 0 & \sigma^2_{183\pm 7} \end{matrix}
$$

Observation error covariance matrix tailored to one SSMIS observation (i)

19v, 19h, 22v… = channel names

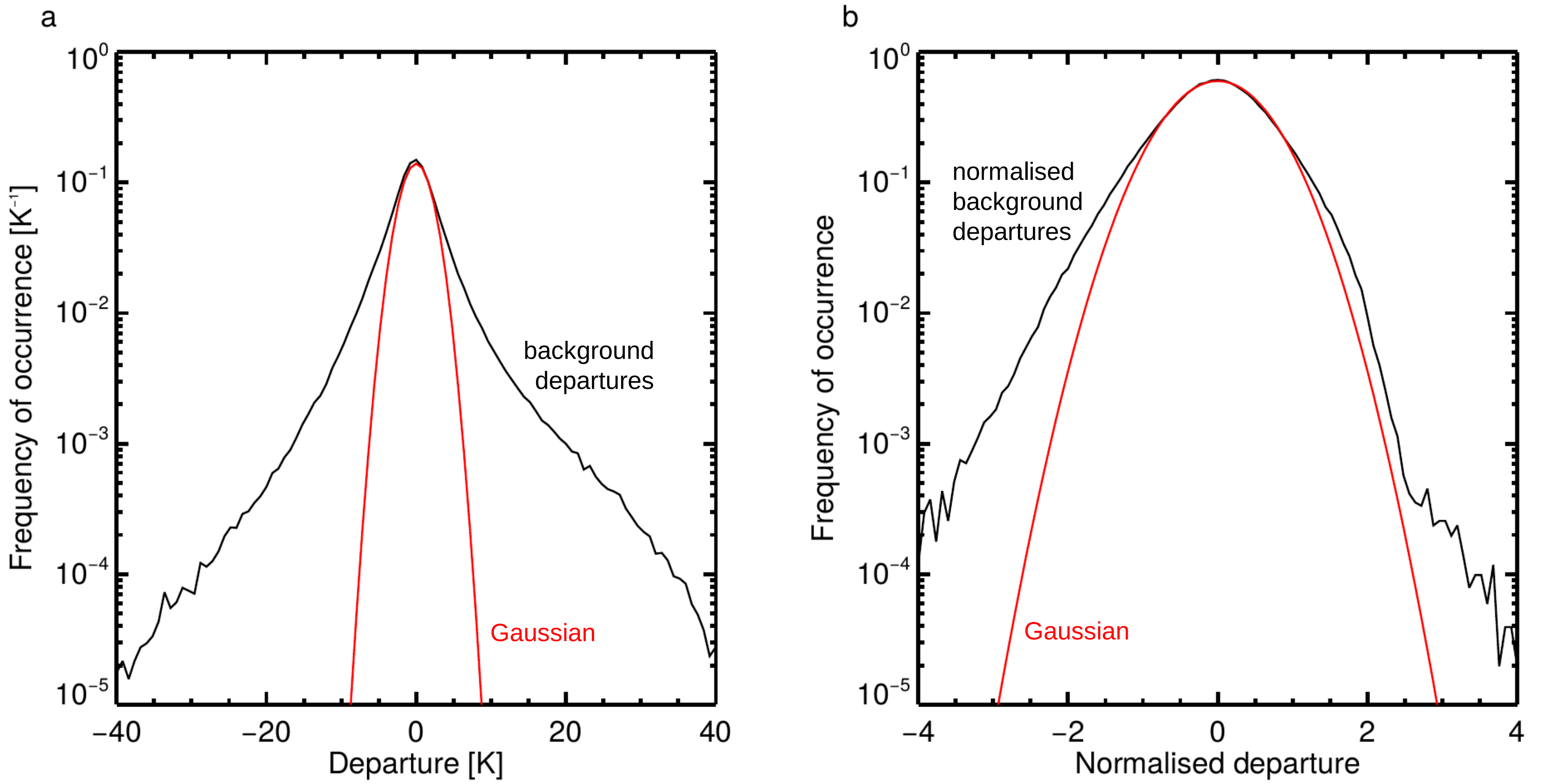


(C37 = average amount of “cloud” from observation and first guess)

Clear → Cloudy

Situation-dependent observation error

All-sky microwave departures look a lot more Gaussian



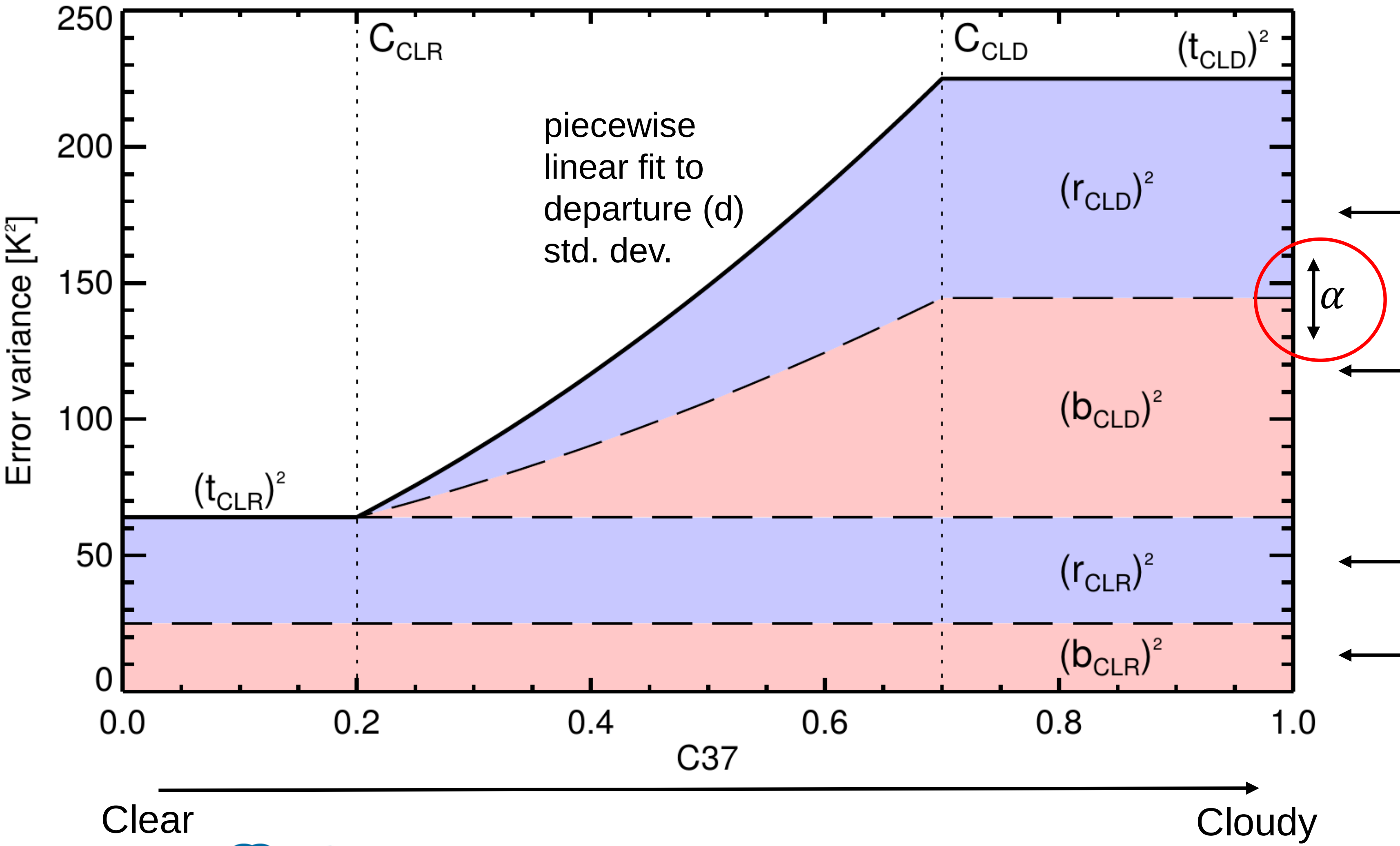
Geer and Bauer (2010,2011)

Various cloud proxy variables, e.g for all-sky IR Okamoto et al. (2014)

Normalised by the symmetric observation error model (symmetric = binned by mean of observed and simulated cloud amount)

Er, what about background error?

$$E(\mathrm{dd}^T) = \underbrace{\mathrm{HBH}^T}_{\text{Background error}} + \underbrace{\mathrm{R}}_{\text{Observation error}}$$



Original error model was tuneable

Obs error

Background error

Cloudy

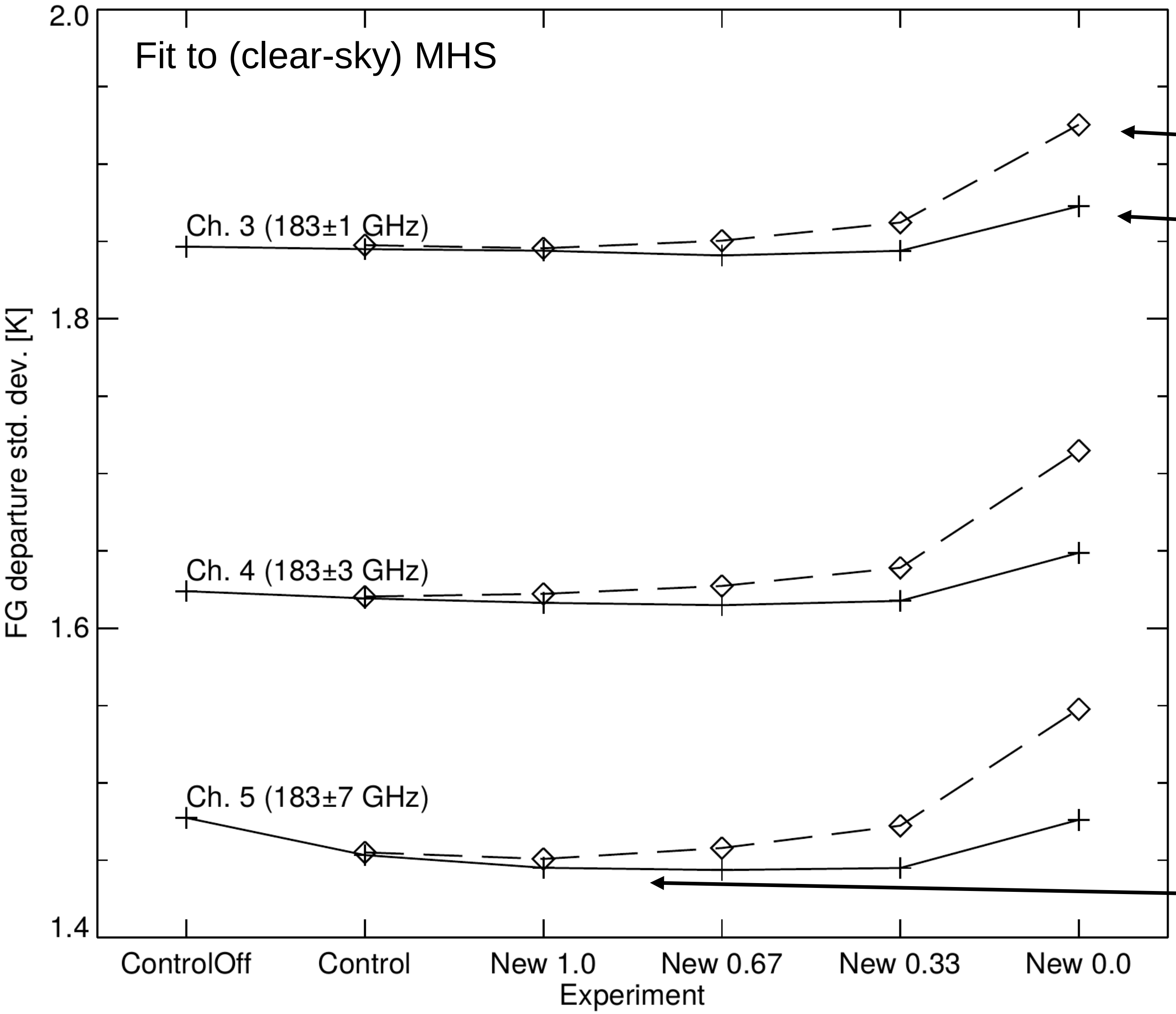
Obs error

Background error

Clear

Er, what about background error?

Tune observation error model for all-sky microwave imagers



Without VarQC

With VarQC

α = 1 means all departure error is observation error!

Best α between 1.0 and 0.67

A big approximation – ignore background error in all-sky observation error modelling

$$E(\mathrm{dd}^T) = \mathrm{HBH}^T + \mathrm{R}$$

All-sky applications: observation error (representation error) is dominant

$$E(\mathrm{dd}^T) \approx \widetilde{\mathrm{R}}$$

Try to subtract background error properly:

- Desroziers (2005) statistics
- Ensemble HBHT estimates

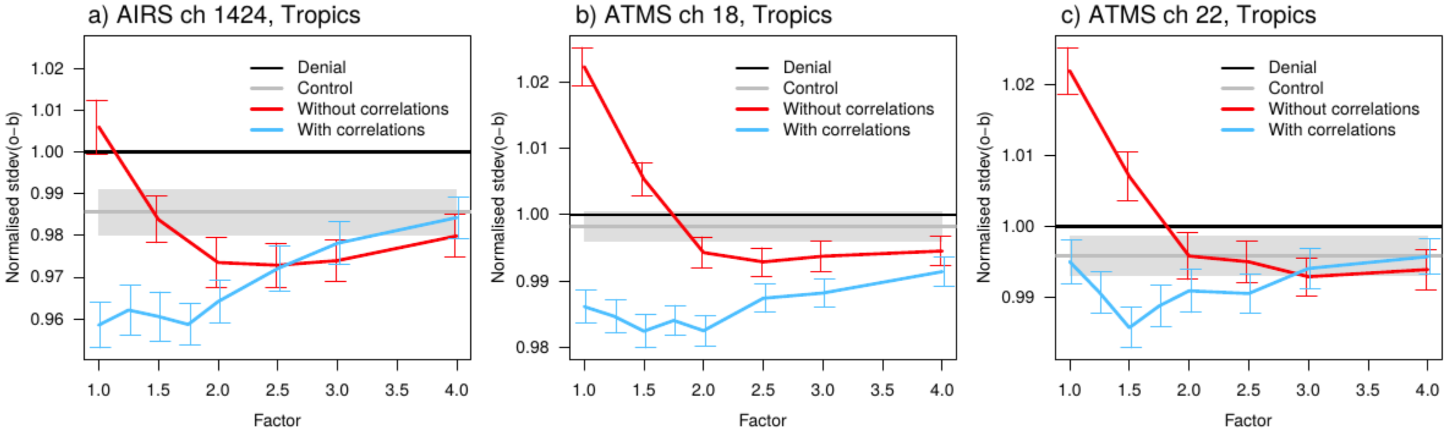
Interchannel correlated observation errors for all-sky assimilation of IASI water vapour channels

Aim: move from clear-sky to all-sky assimilation for IASI

ECMWF

Bormann et al. (2015,2016) – correlated observation error for clear-sky assimilation

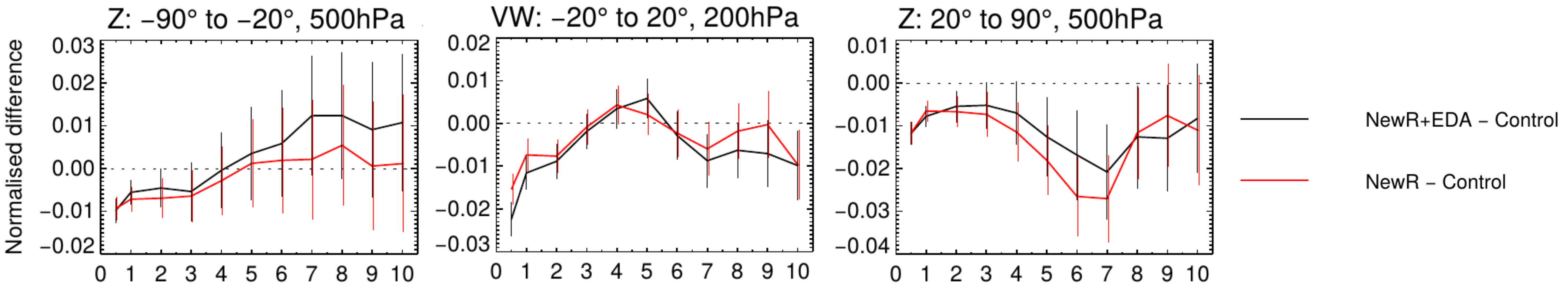
- Desroziers-estimated observation error matrix plus scaling:



- With a floor on eigenvalues to improve conditioning
- Improves forecast scores:

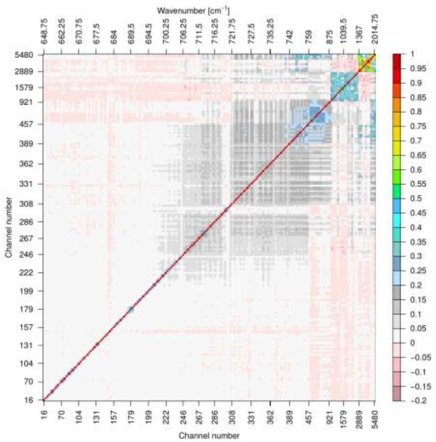
IASI diagonal errors better

IASI correlated errors better



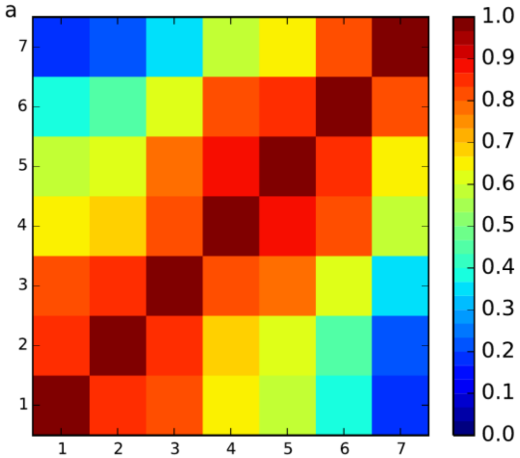
All-sky IR error model aim: correlated, situation dependent

Geer (2019, AMT, https://doi.org/10.5194/amt-12-3629-2019)

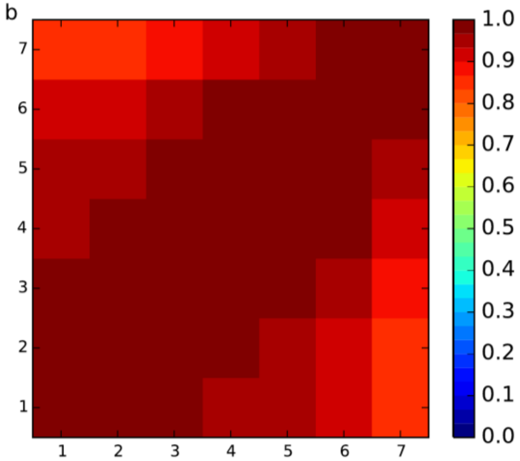


7 WV channels ordered by peak of weighting function (from lowest)

Full correlation matrix for clear-sky situations (Bormann et al., 2016)



WV channel part of correlation matrix for clear-sky situations (Bormann et al., 2016)



Global constant correlation matrix of global all-sky IR departures

Eigenvector decomposition of the error covariance matrices

All-sky and clear-sky eigenvectors are very similar

$$\widetilde{\mathbf{R}} = \mathbf{E}\boldsymbol{\Lambda}^{-1}\mathbf{E}^{\mathbf{T}}$$

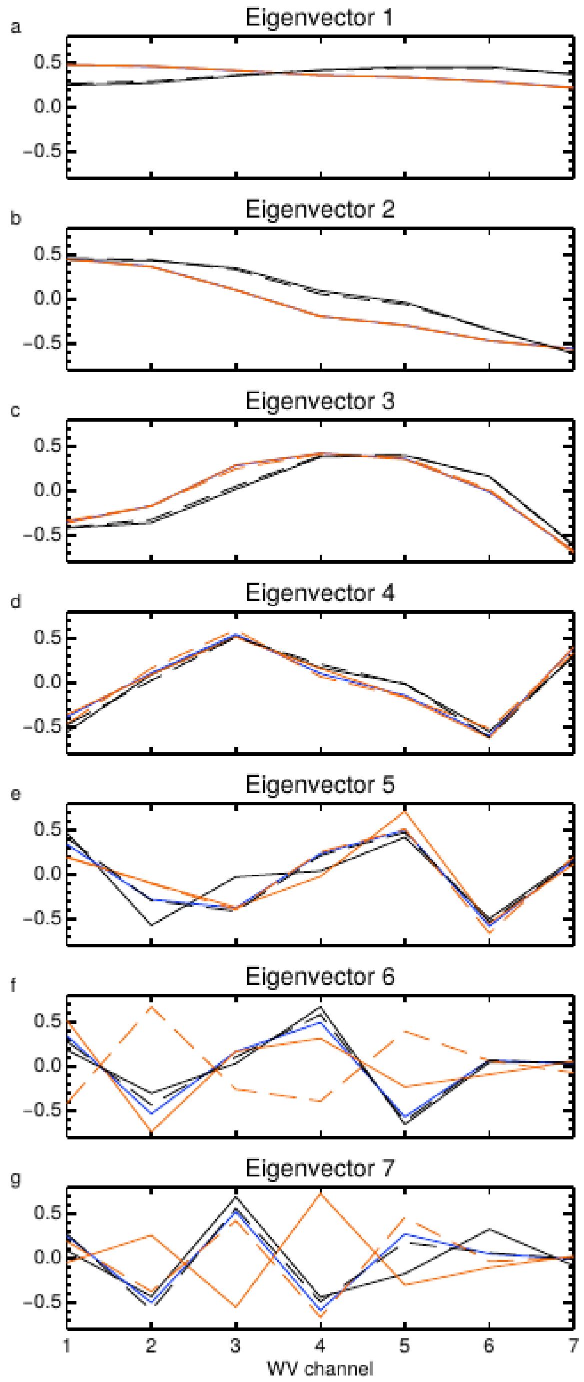
Eigenvectors

Bormann et al.
(Desroziers + tuning)

Clear-sky
All-sky

Operational clear-sky
45r1 clear-sky
43r1 all-sky
45r1 all-sky land/ocean
45r1 all-sky ocean only

$$\widetilde{\mathrm{R}} \approx E(\mathrm{dd}^T)$$



Clear-sky
All-sky

ECMWF

Eigenvector decomposition of the error covariance matrices

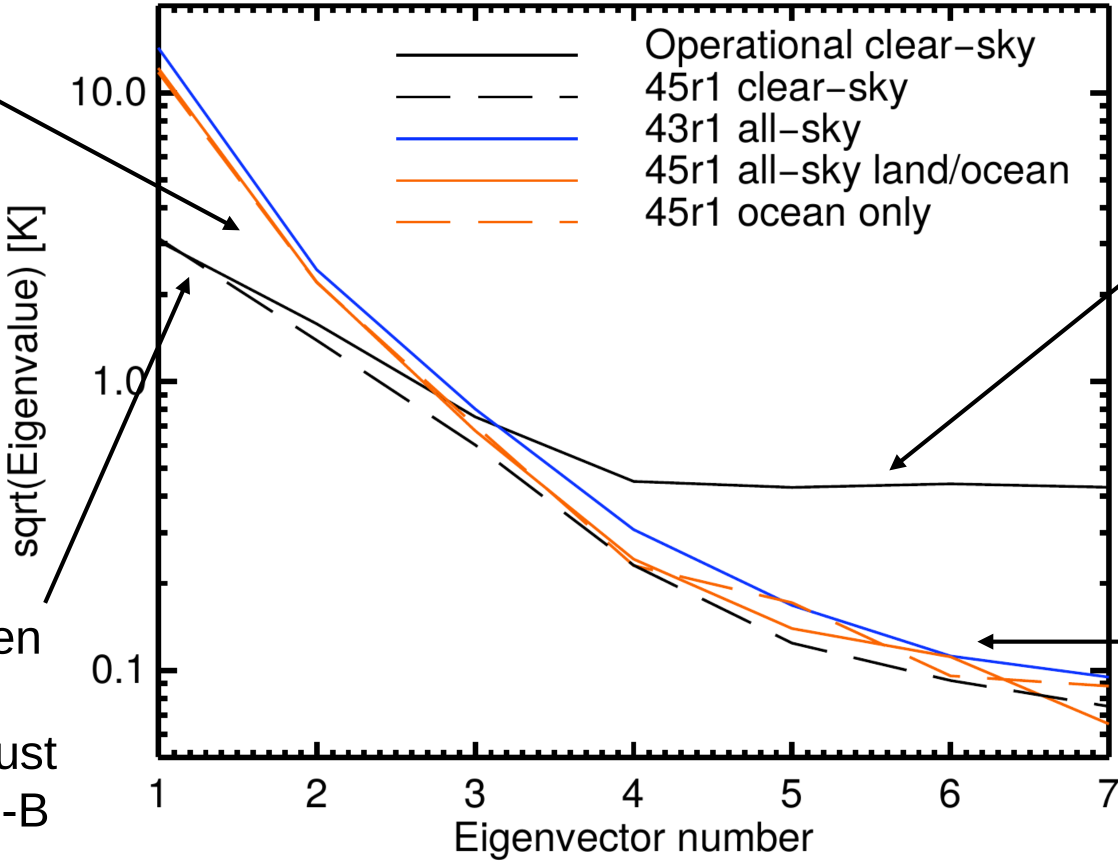
All-sky and clear-sky eigenvectors are very similar

Main differences are in the eigenvalues

$$\tilde{\mathbf{R}} = \mathbf{E}\mathbf{\Lambda}^{-1}\mathbf{E}^{\mathrm{T}}$$

Eigenvalues

Primary all-sky / clear-sky difference is in the 2 leading eigenvalues



Bormann et al. operational clear-sky eigenvalues after “floor” retuning. Stated aim: improve conditioning

Little difference between careful Bormann et al. (2016) approach and just taking covariance of O-B

Clear-sky and all-sky eigenvalues before any tuning

One way to think about obs error covariance matrices

λ_j eigenvalue and e_j eigenvector *j*

Departure – one channel (*i*)

$$d_i = y_i - H_i(\mathrm{x})$$

	Uncorrelated error	Correlated error represented by an eigendecomposition
Cost function	$J^O(\mathrm{x}) = \frac{1}{2}\mathrm{d}^\mathrm{T}\widetilde{\mathbf{R}}^{-1}\mathrm{d} = \frac{1}{2}\sum_{i=1}^{n}\left(\frac{d_i}{\sigma_i^o}\right)^2$	$J^O(\mathrm{x}) = \frac{1}{2}\mathrm{d}^\mathrm{T}\mathbf{E}\boldsymbol{\Lambda}^{-1}\mathbf{E}^\mathrm{T}\mathrm{d} = \frac{1}{2}\sum_{j=1}^{n}\left(\frac{\mathrm{e}_j^\mathrm{T}\mathrm{d}}{\lambda_j^{0.5}}\right)^2$
Cost function gradient	$J^{O\prime}(\mathrm{x}) = -\mathbf{H}^\mathrm{T}\widetilde{\mathbf{R}}^{-1}\mathrm{d} = \frac{1}{2}\sum_{i=1}^{n}\mathrm{h}_i\frac{d_i}{(\sigma_i^o)^2}$	$J^{O\prime}(\mathrm{x}) = -\mathbf{H}^\mathrm{T}\mathbf{E}\boldsymbol{\Lambda}^{-1}\mathbf{E}^\mathrm{T}\mathrm{d} = \frac{1}{2}\sum_{i=1}^{n}\mathbf{H}^\mathrm{T}\mathrm{e}_j\frac{\mathrm{e}_j^\mathrm{T}\mathrm{d}}{\lambda_j}$

Jacobian – one obs

"Eigendeparture *j*"

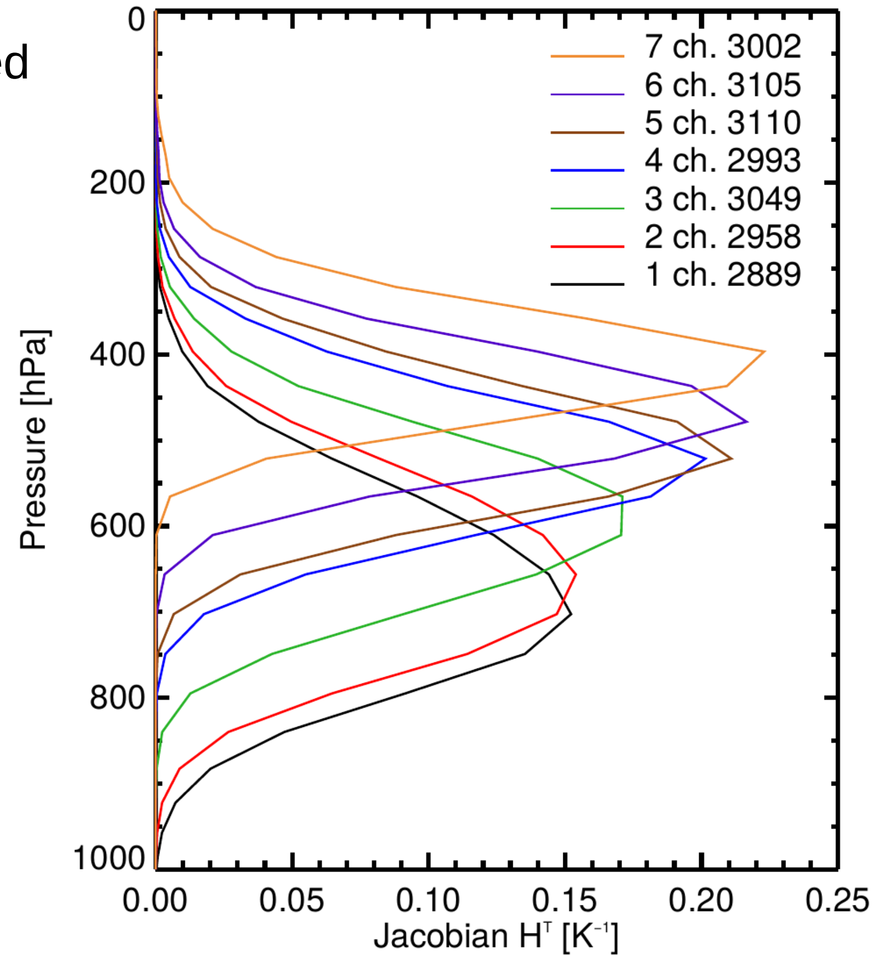
its observation error is its eigenvalue^0.5

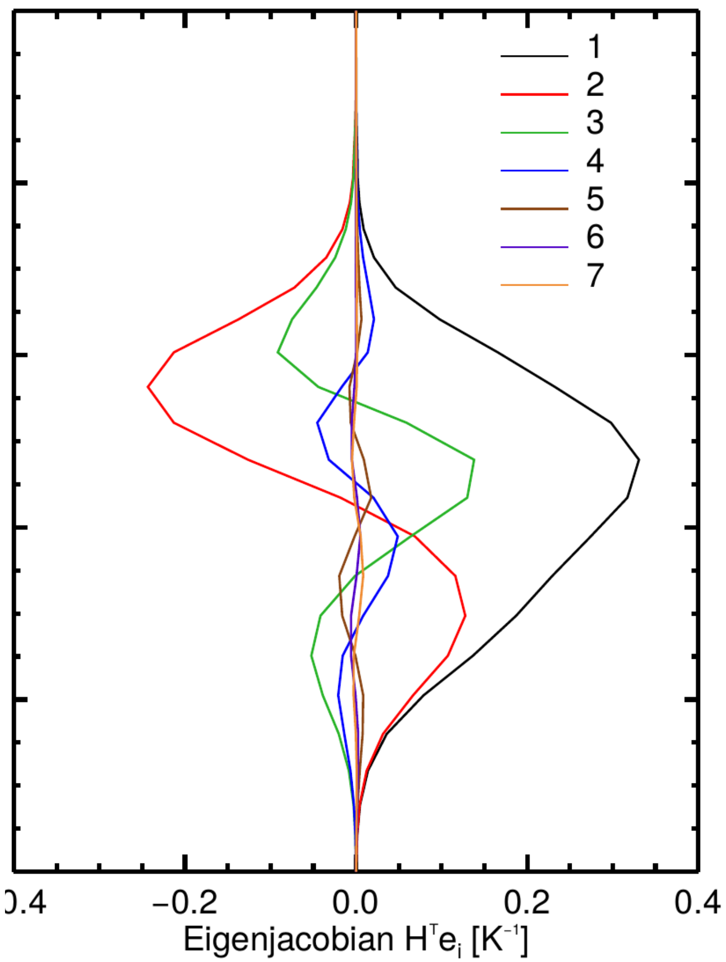
"Eigenjacobian"

IASI temperature sensitivities, clear sky (7 all-sky WV channels)

Jacobians (uncorrelated obs. error)

h_i





Eigenjacobians (correlated obs. error)

$\mathbf{H}^{\mathrm{T}}\mathrm{e}_j$

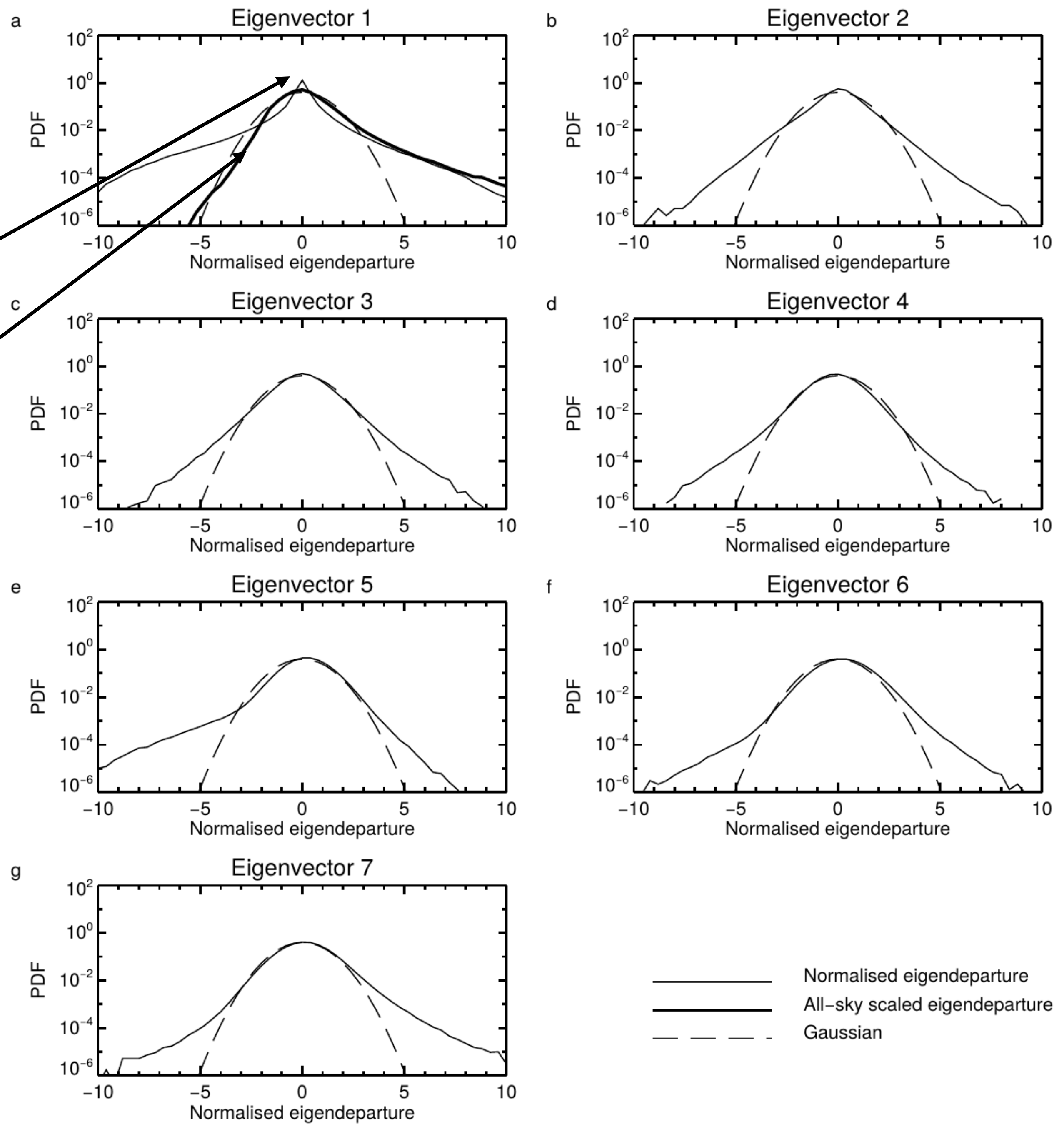
Normalised eigendepartures

With global constant leading eigenvalue

When scaled by all-sky error model

Near-Gaussianity of normalised background departures achieved within +/-3 range across all 7 eigenvectors

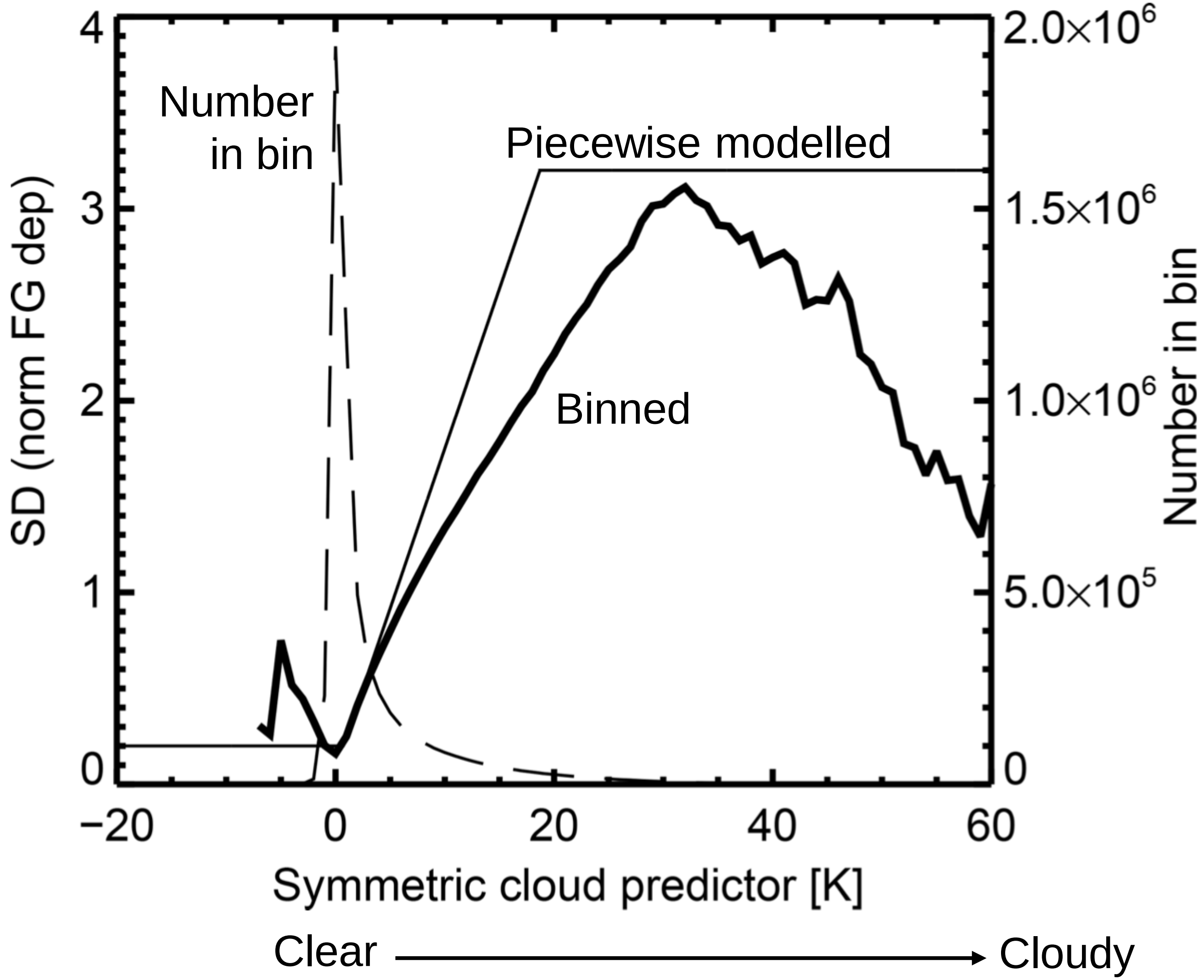
How to apply VarQC? Also define VarQC on the eigenprojected observations



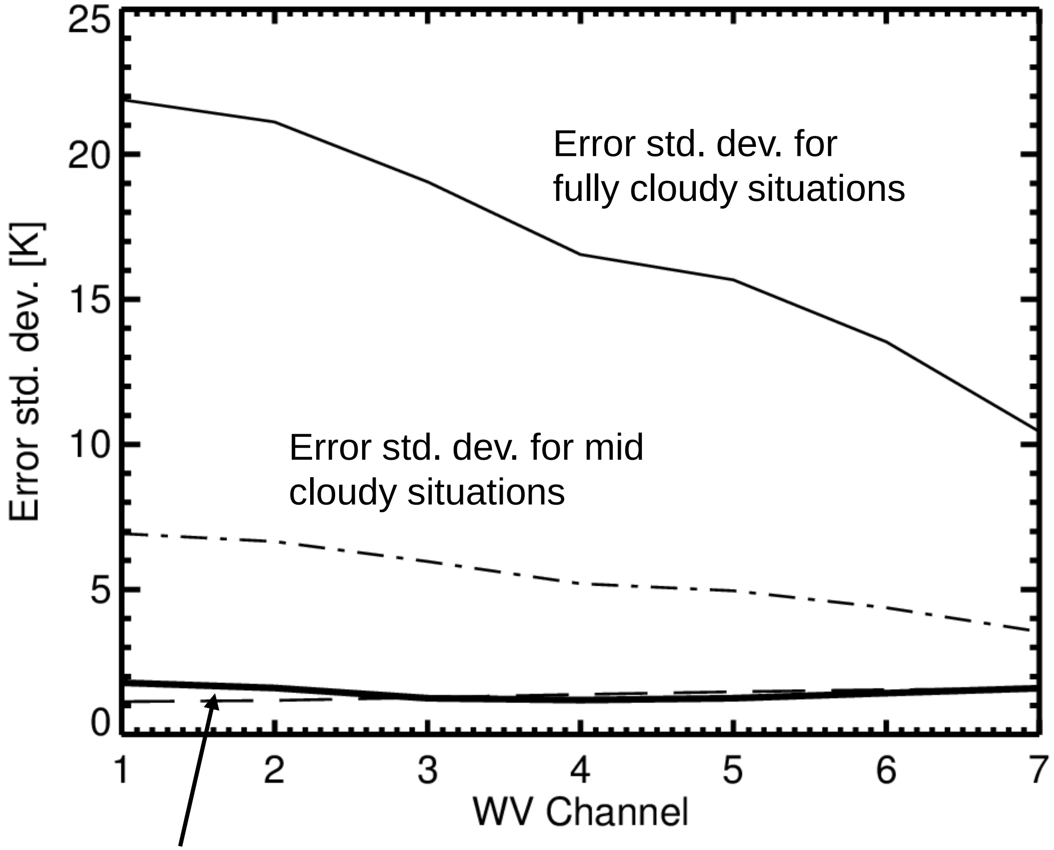
ECMWF

Standard all-sky observation error model – just applied to “eigenchannels”

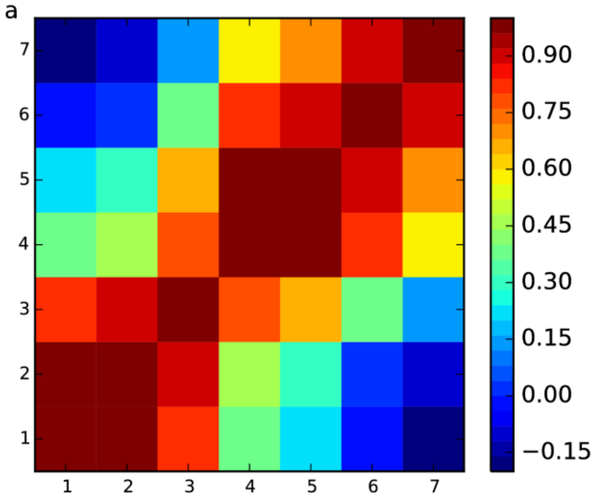
Standard deviation of normalised eigenvector 1 departures, as a function of cloud amount



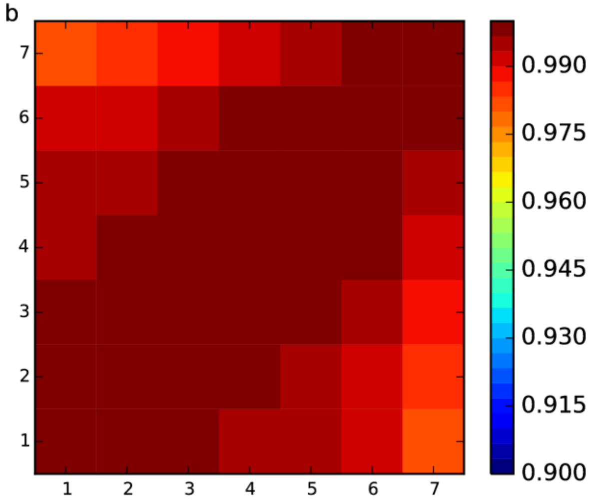
All-sky IR error model: one error covariance matrix with **eigenvalue scaling** as function of symmetric cloud amount -> adaptive covariance matrix



Similar error std. dev. in clear-sky situations from new model and existing clear-sky error model

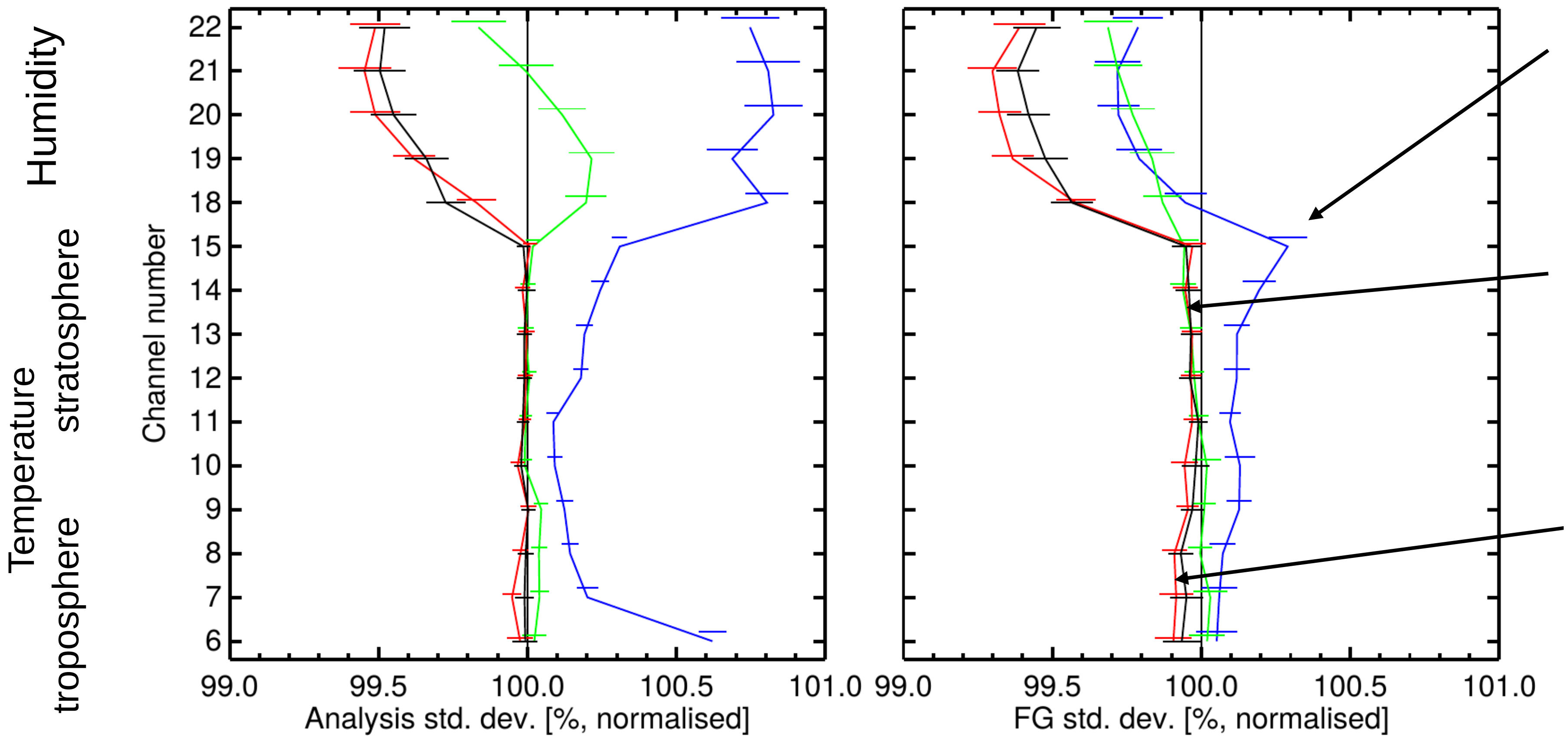


Correlation matrix for clear-sky situations



Correlation matrix for fully cloudy situations

Analysis fit and T+12 forecast verification: fit to ATMS

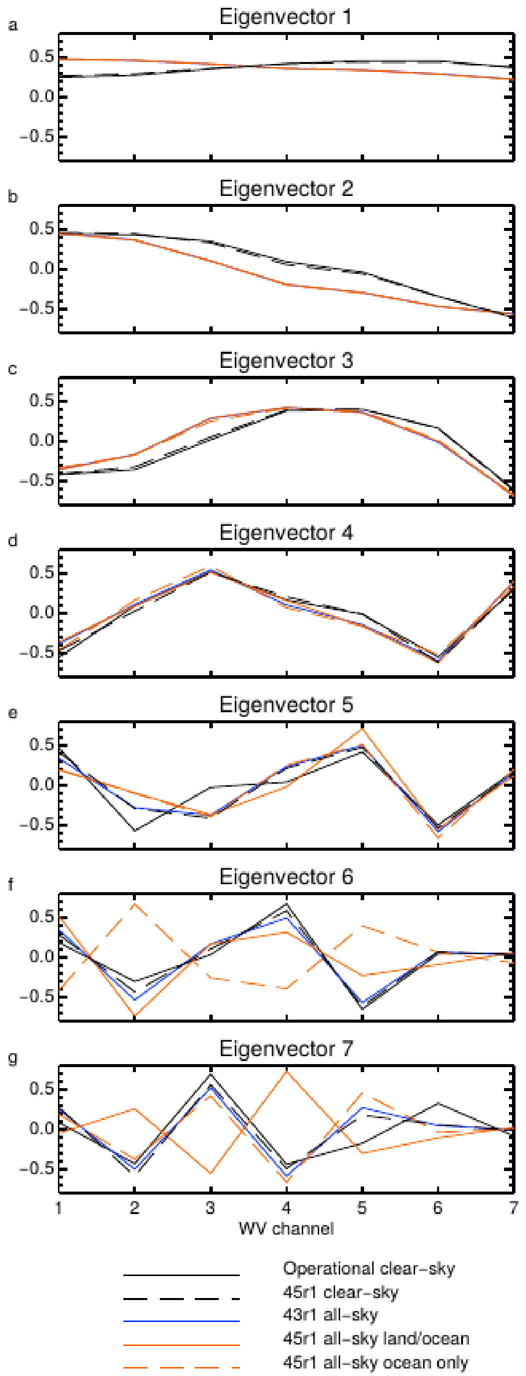


Raw situation-dependent all-sky error model degrades forecasts (particularly stratosphere)

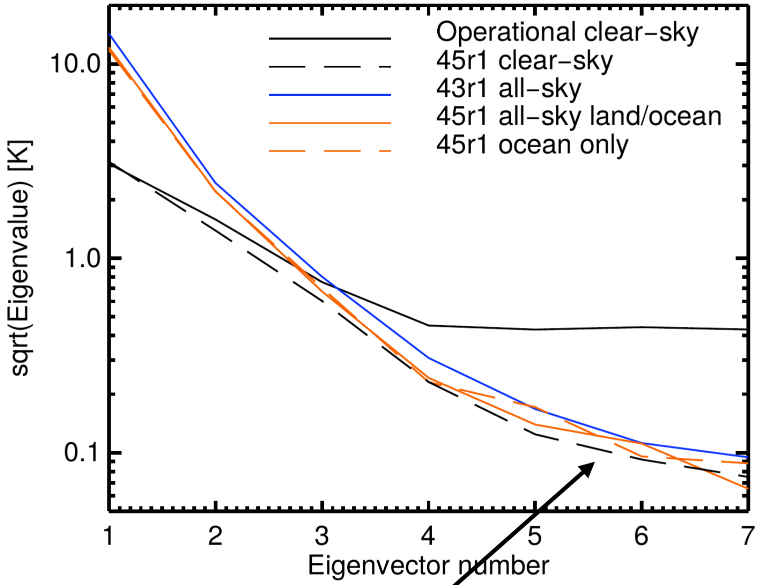
A diagonal model does not degrade (neither does it improve much)

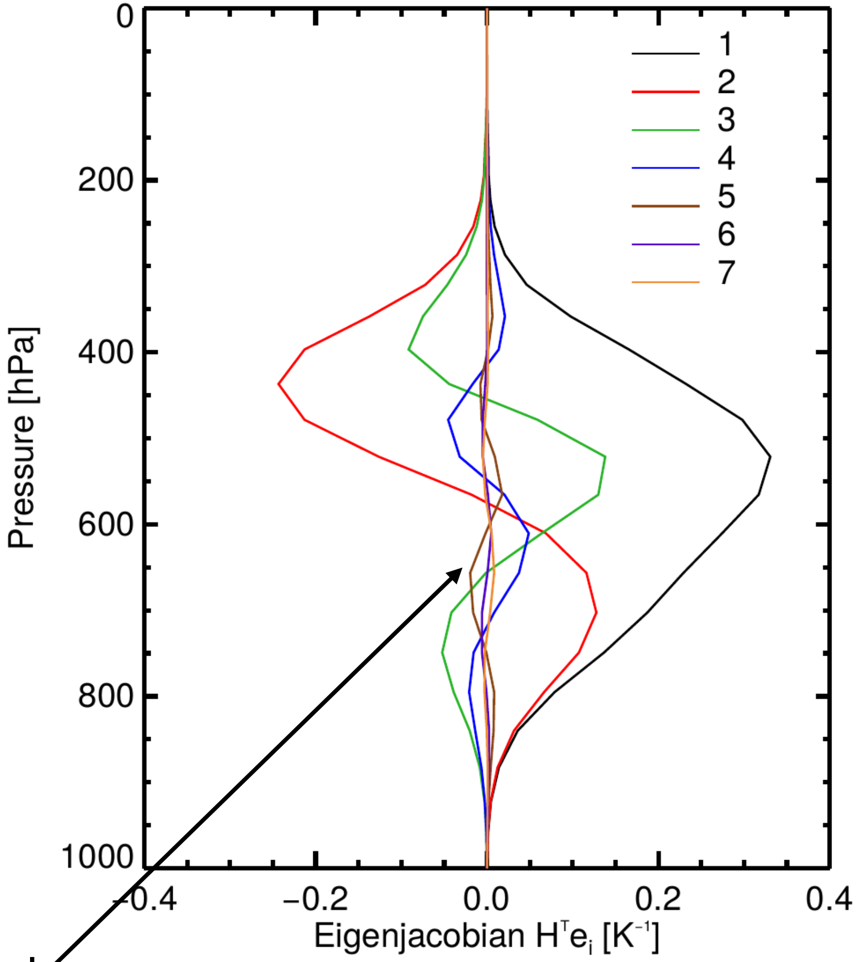
Eigenvalue floor situation-dependent all-sky error model improves forecasts

100% = Control: full system minus 7 IASI WV channels



What's the difficulty with the trailing eigenvectors?



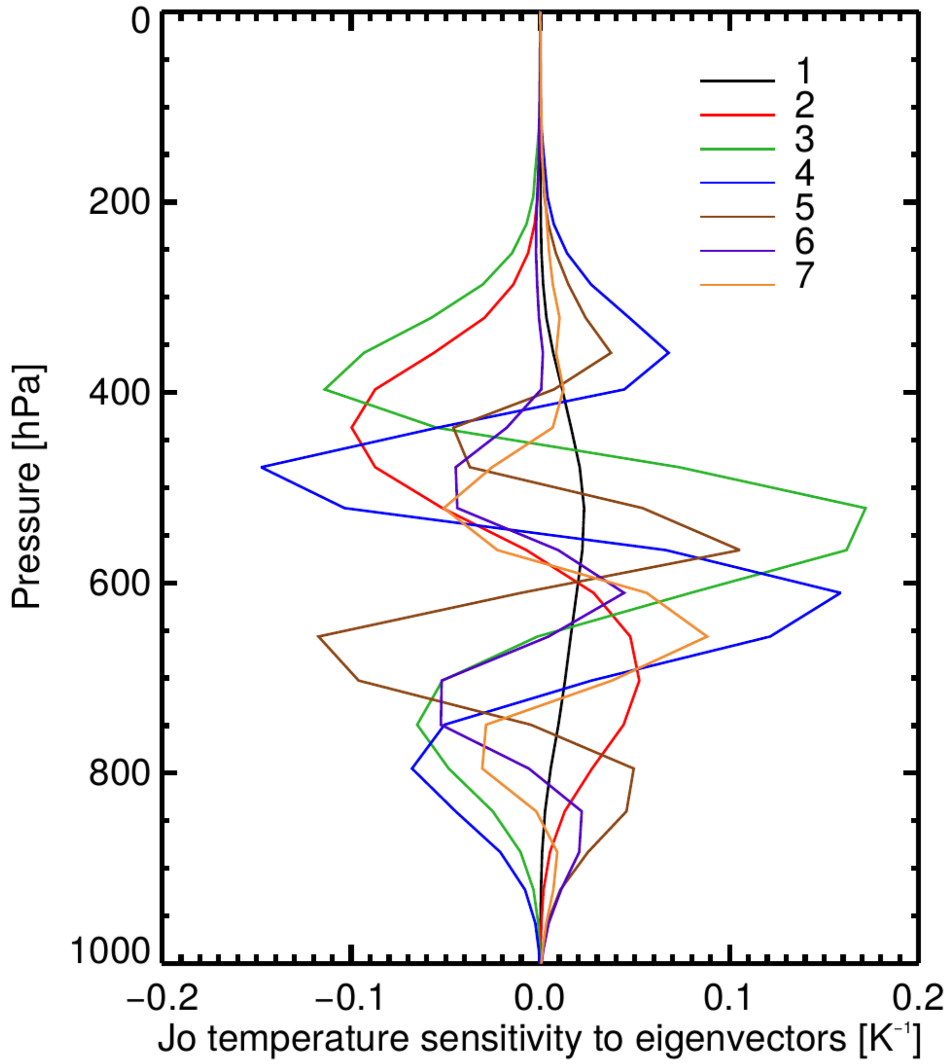


Strong amplification of: high-order combinations of channels

non-localised oscillatory T features

T sensitivity by eigenchannel
(clear-sky $\mathbf{H}$)

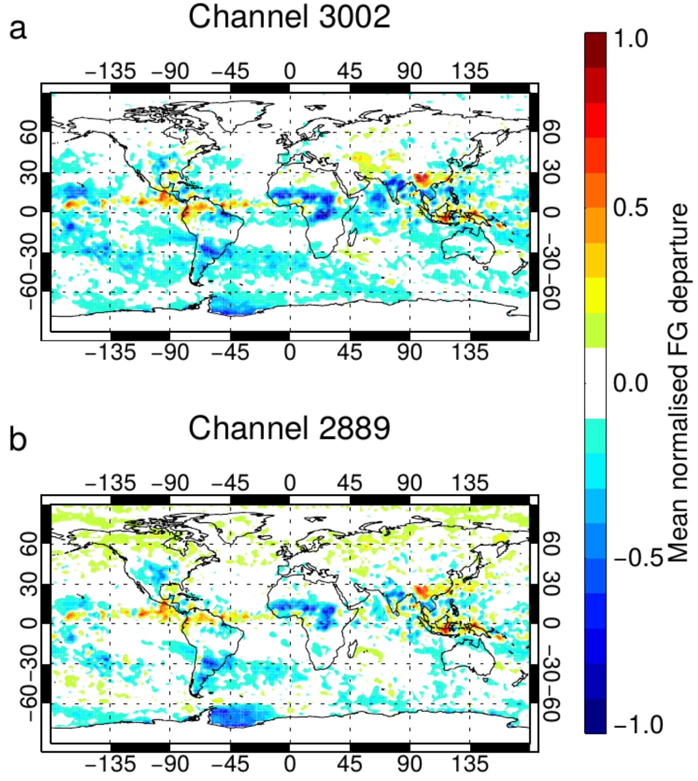
$$\mathbf{H}^{\mathrm{T}} \mathrm{e}_j \frac{1}{\lambda_j^{0.5}}$$



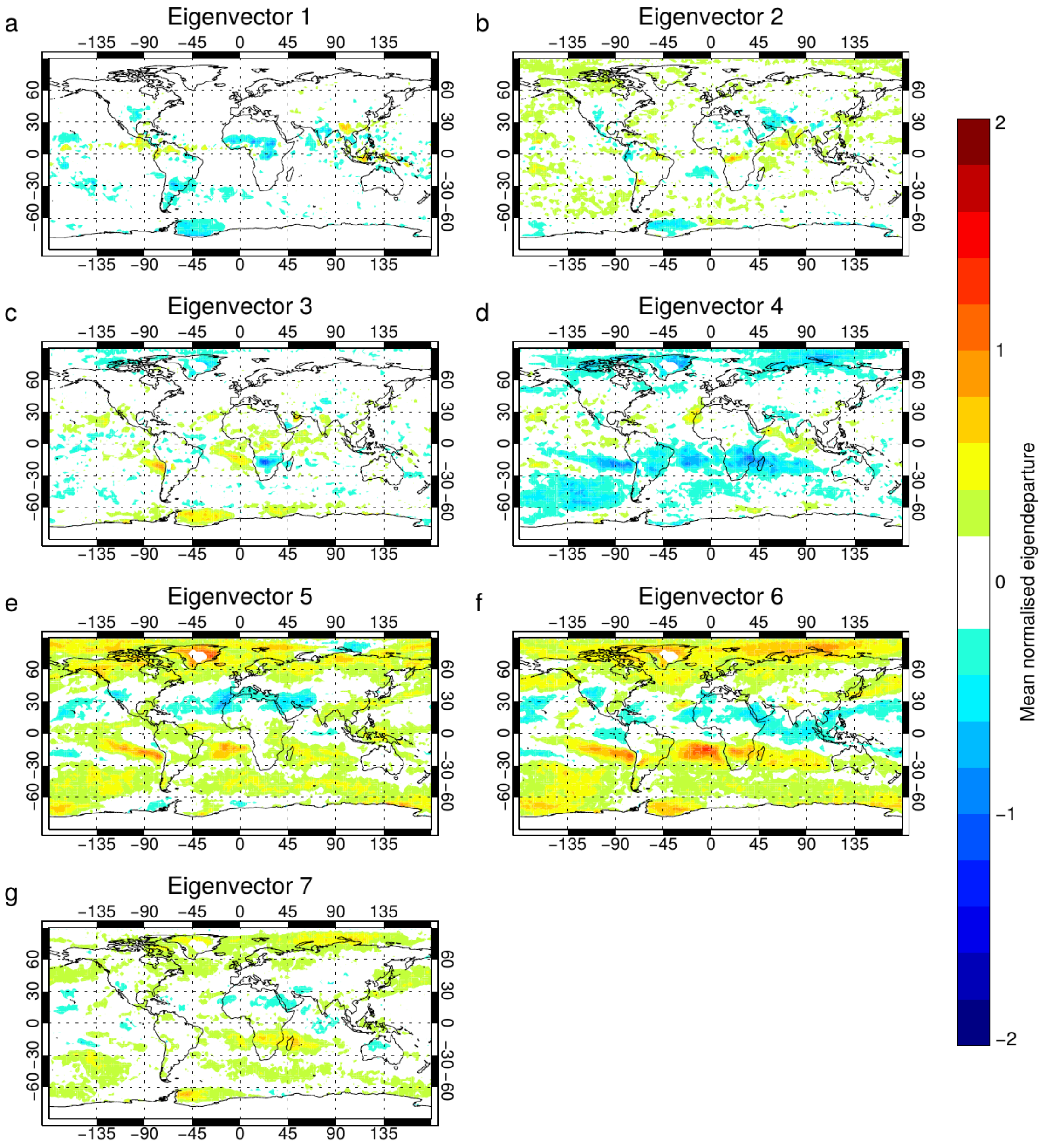
Why eigenvalue floor is important

1. Bias looks very different with correlated error

Departures normalised by diagonal observation error $\dfrac{d_i}{\sigma_i^o}$

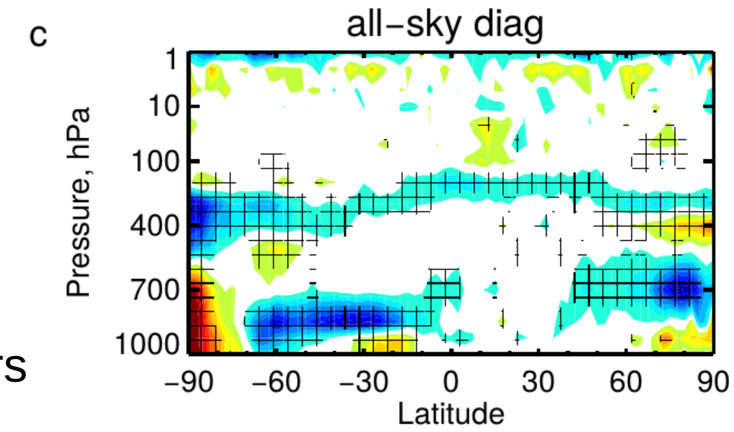


Eigendepartures normalised by square root of eigenvalue $\dfrac{e_j^T d}{\lambda_j^{0.5}}$



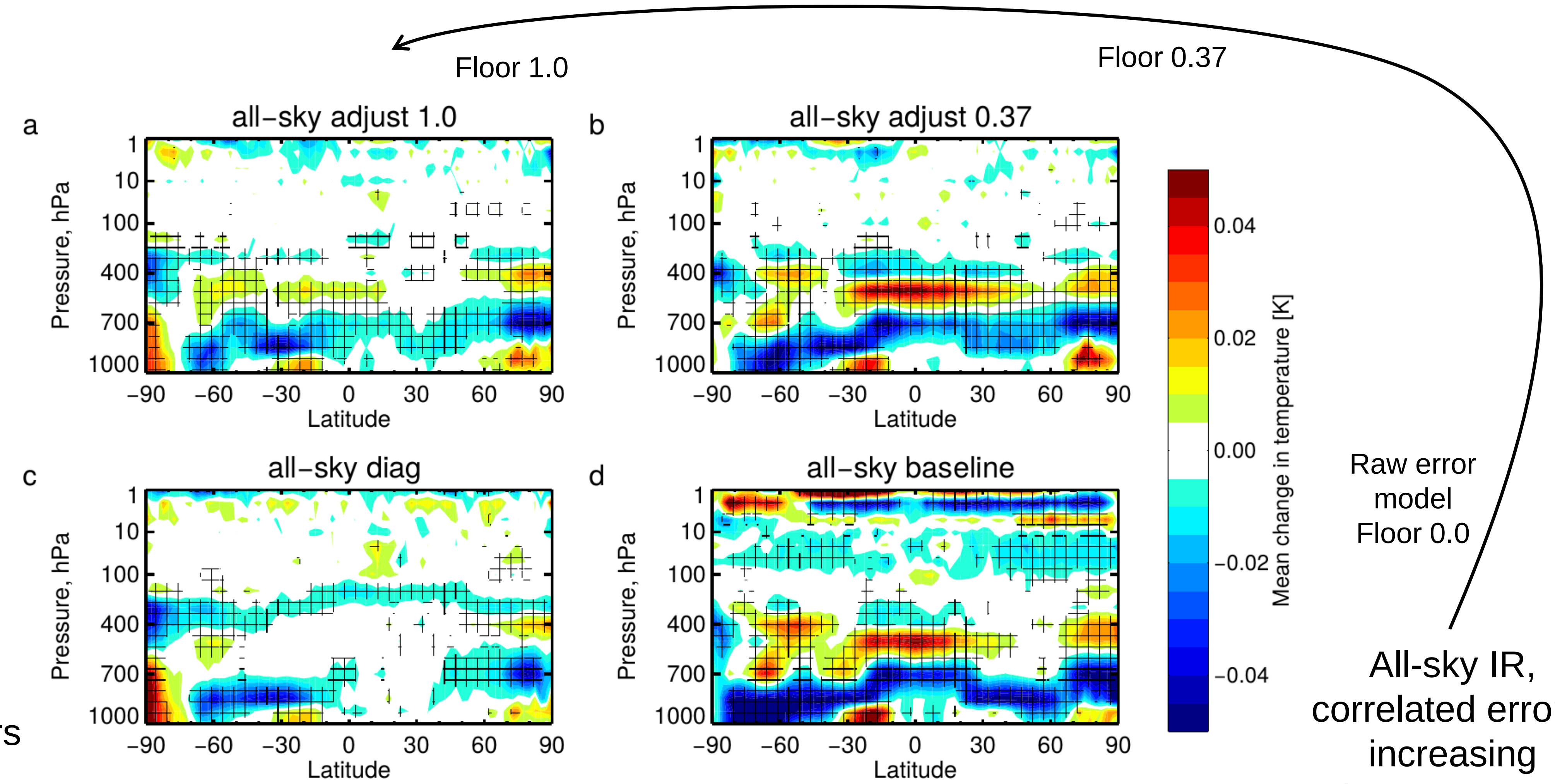
Mean change in zonal temperature analysis versus no-WV7 control

All-sky IR,
diagonal errors



Eigenbiases map onto vertically oscillating bias in T

Mean change in zonal temperature analysis versus no-WV7 control



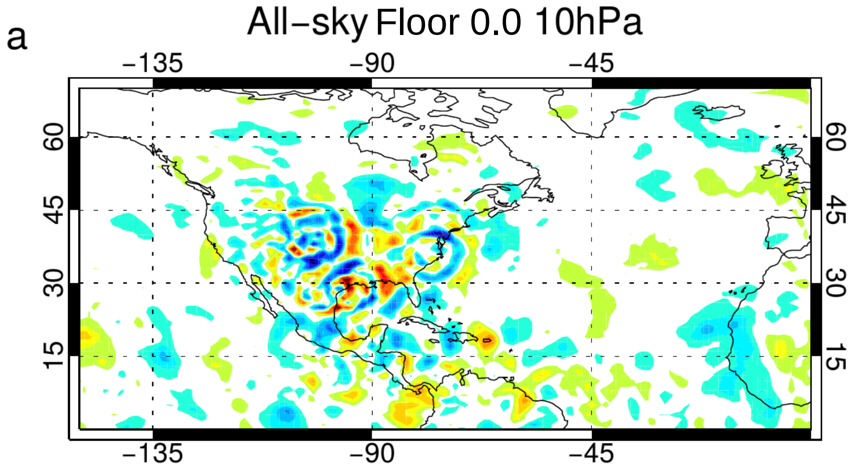
All-sky IR, diagonal errors

All-sky IR, correlated errors, increasing eigenvalue floor

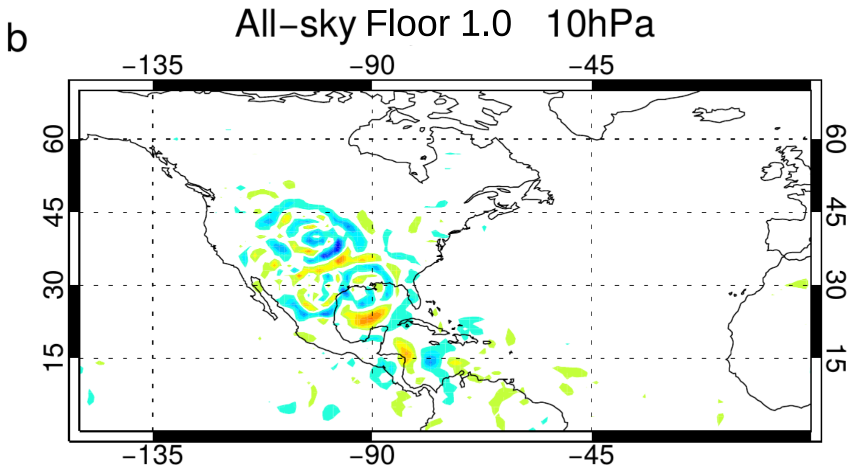
Why eigenvalue floor is important

2. Stratospheric temperature increments generated by all-sky IR WV channels

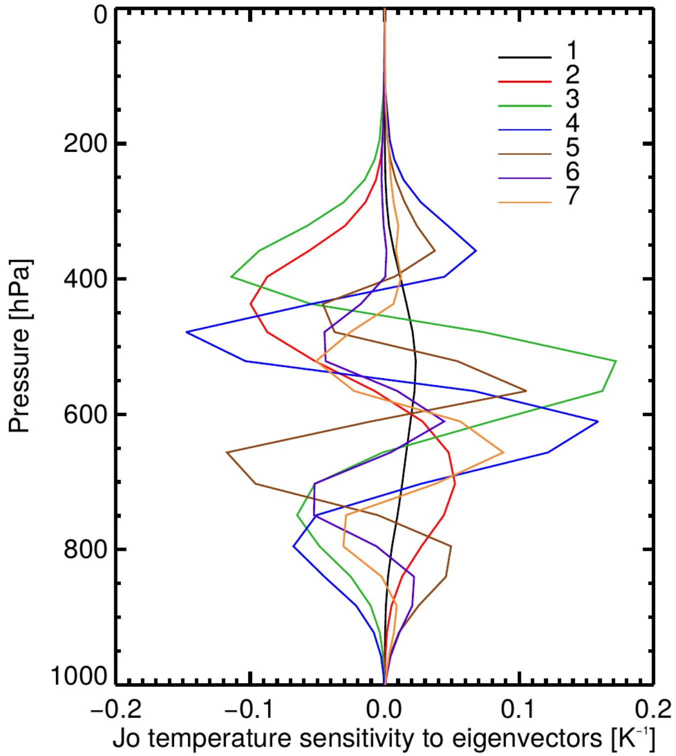
Raw situation-dependent all-sky error model



Situation-dependent all-sky error model with 1.0 eigenvalue floor



Clear-sky T sensitivity by eigenchannel



$$\mathbf{H}^{\mathrm{T}} e_j \frac{1}{\lambda_j^{0.5}}$$

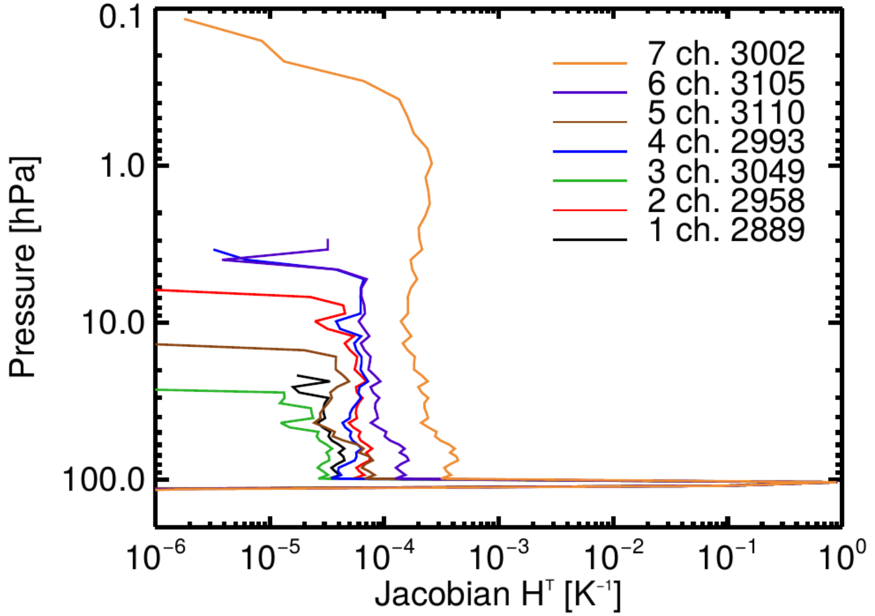
Why eigenvalue floor is important

3. Stratospheric temperature sensitivity is large in trailing eigenvectors

% of jacobian / eigenjacobian above 100 hPa

Chan. / Eigen.	Clr TB	Clr Eigen	Cld TB	Cld Eigen
1	0.00	0.01	0.08	0.25
2	0.00	0.04	0.20	1.42
3	0.00	0.10	0.05	6.20
4	0.04	0.10	0.20	7.04
5	0.01	0.06	0.132	13.1
6	0.01	0.59	0.367	10.3
7	0.11	0.53	$\boxed{1.23}$	$\boxed{59.5}$

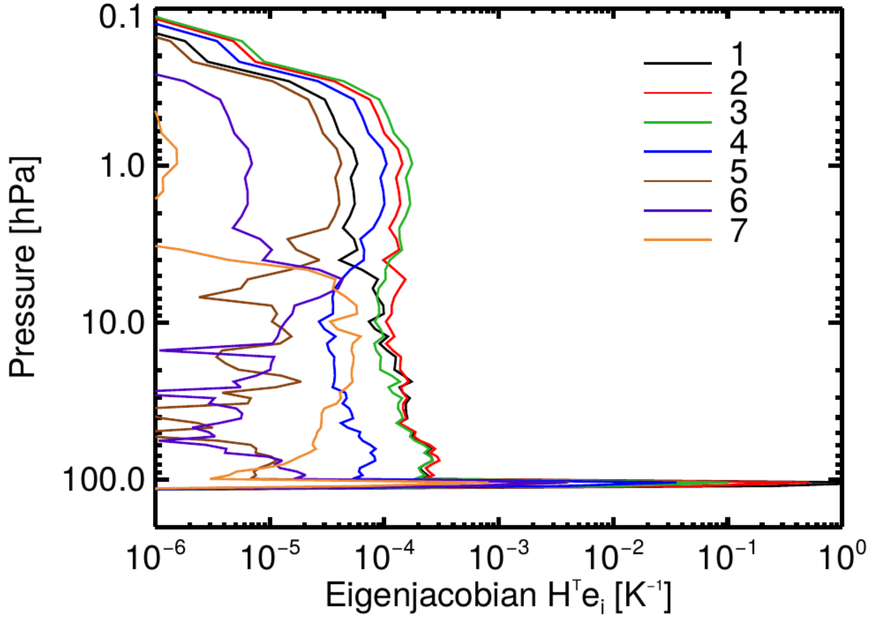
a



jacobian $\mathbf{H}^{\mathrm{T}}$

100% opaque cloud at tropopause

b



eigenjacobian $\mathbf{H}^{\mathrm{T}}e_j$

Using observation error covariance matrices is not just about conditioning

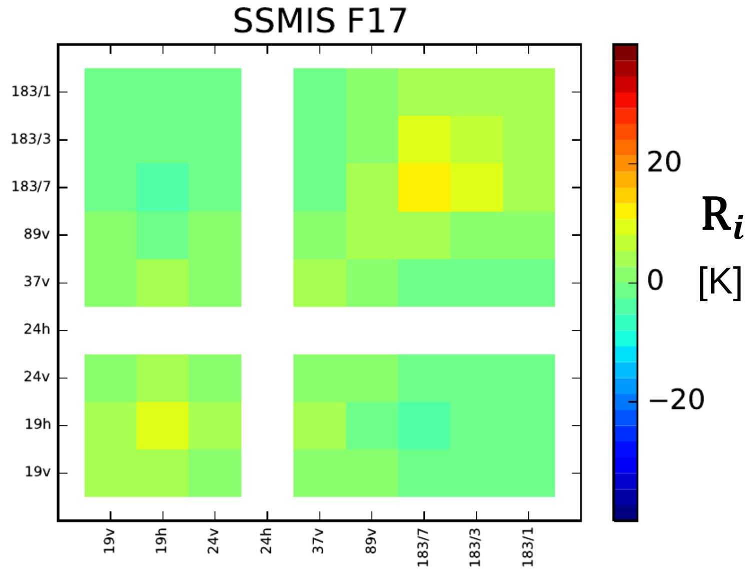
- Small trailing eigenvalues in the observation error covariance matrix amplify sensitivity to high-order combinations of channels
- Issues
  1. Trailing eigenvalues amplify some odd bias patterns seen in the eigendepartures
  2. Eigenjacobians of trailing eigenvectors map onto high-order vertical T oscillations: gravity waves
  3. Unexpected sensitivities: Trailing eigenjacobian (j=7) over very high clouds has 60% of its temperature sensitivity in the stratosphere
- By increasing the trailing eigenvalues
  - are we protecting the analysis?
  - are we losing real information?
- Are the trailing eigenstructures reliable? (sampling errors?)

Correlated all-sky microwave observation errors

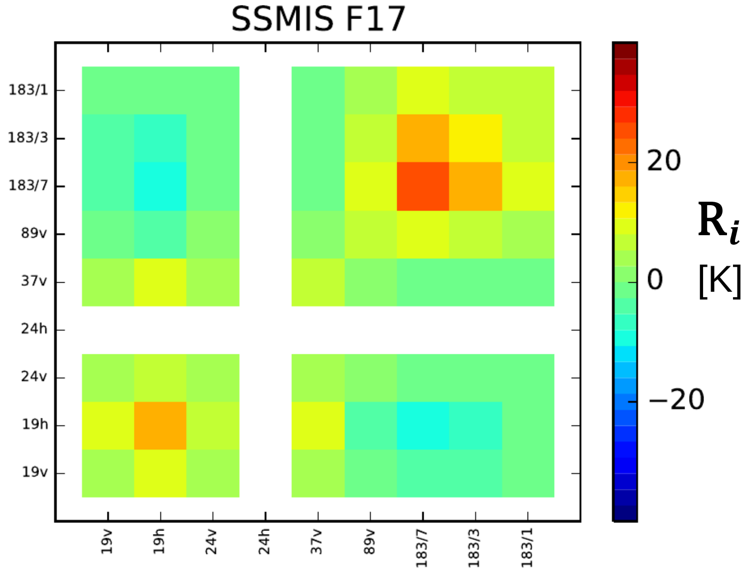
New error model for all-sky microwave – one fully specified interchannel covariance matrix per symmetric cloud & TWCV bin (-> 164 error covariance matrices)

Increasing amount of cloud at observation location

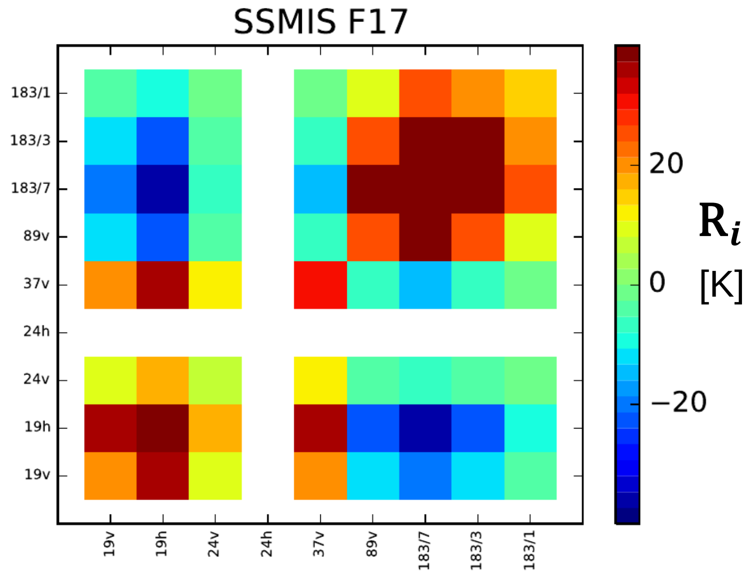
C37 bin: -1.00 to 0.02



C37 bin: 0.04 to 0.05



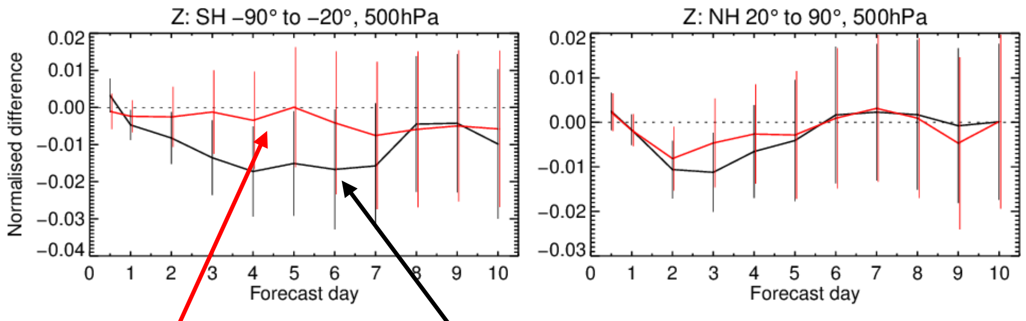
C37 bin: 0.12 to 0.13



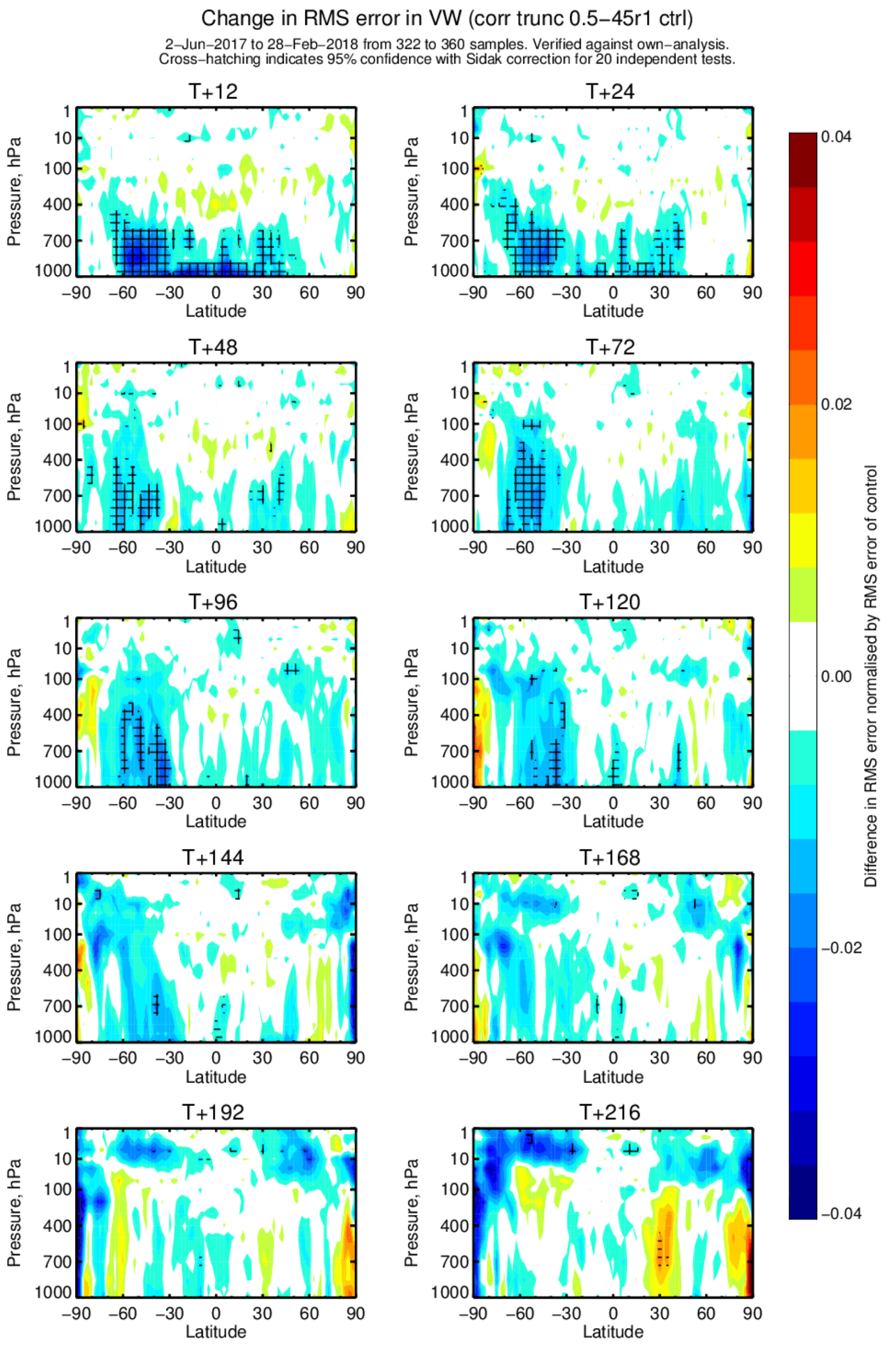
All-sky microwave error covariances

Impact: reduction in forecast error

Total impact of microwave imagers versus no imager control



Impact of implementing observation error covariances for GMI, AMSR2, SSMIS F17 (versus control)



- Results: all-sky microwave imager impact increased, particularly at 500hPa and below

- Essential to good results:
  - VarQC
  - Eigenvalue truncation at 0.5

These "details" were the difficult part. And it got more difficult again when the system changed at next model cycle…

ECMWF

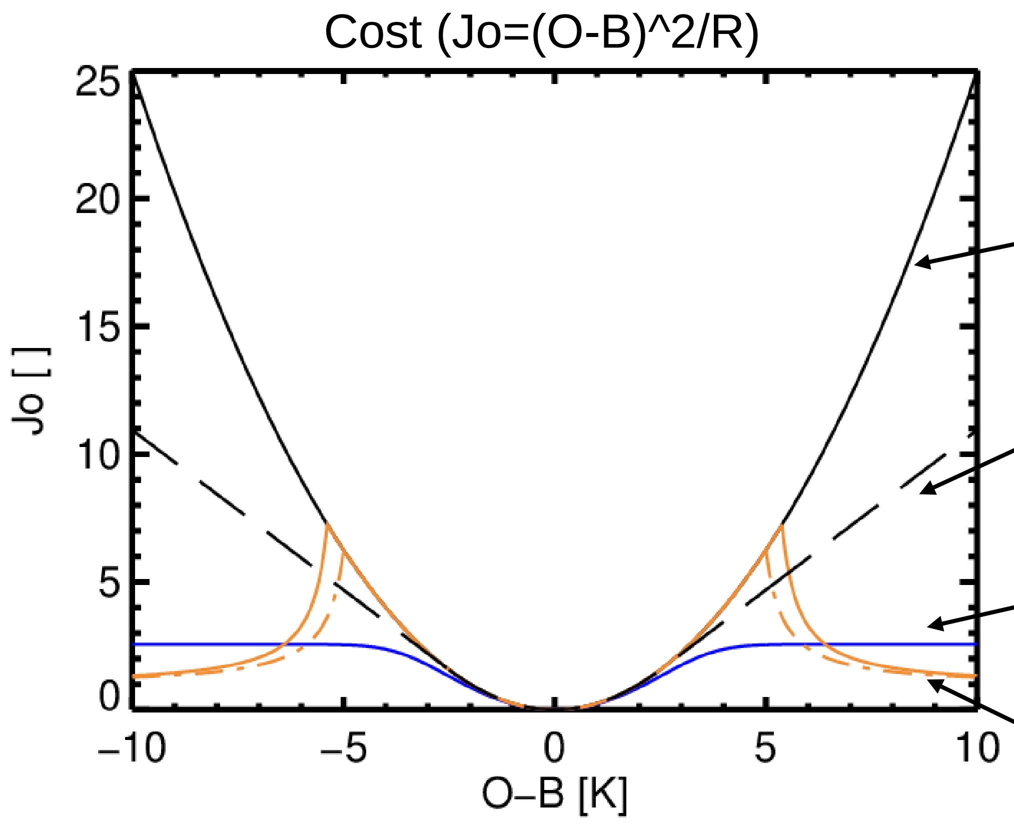
Summary

- Two different strategies for all-sky adaptive observation error interchannel covariance matrices:
  - Binned Gaussian populations -> 164 error covariance matrices in lookup table function of (TCWV, symmetric cloud amount)
    - Cycle 45r1 for all-sky microwave imagers (SSMIS, AMSR2, GMI) with 1% boost to forecast scores.
    - Cycle 46r1 experimentation not good, subsequently **abandoned** – addition of 150 GHz?
  - Eigenvalue scaling using symmetric error model approach (Geer, 2019, AMT, https://doi.org/10.5194/amt-12-3629-2019)
    - For the first time, all-sky IR is giving good results in the ECMWF system
      - All-sky IR similar to clear-sky in midlatitudes; better forecasts than clear-sky in tropics
    - Aim to progress to operational all-sky IR but **paused**, awaiting finalisation of new clear-sky hyperspectral IR developments (move to reconstructed radiances framework?)

- Issues with observation error covariances can be understood **physically** by studying eigenjacobians and eigendepartures

Spare slides

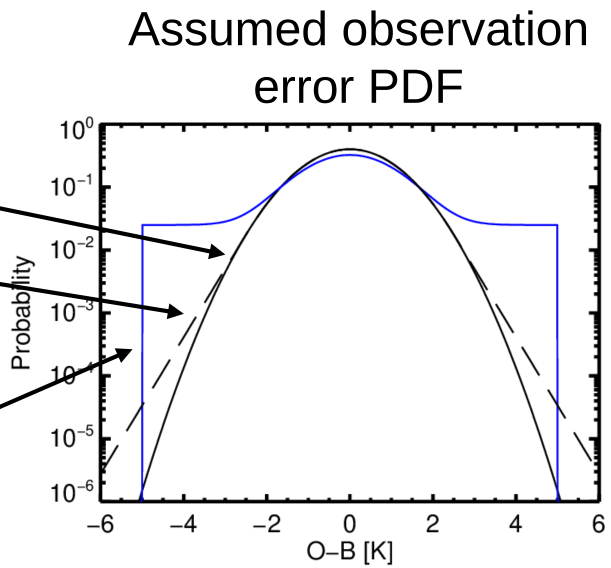
Overlap between VarQC and observation error



Gaussian errors
5K error std. dev.

Huber norm "VarQC" errors
5K error std. dev., changeover at +/- 2.5K - Tavolato and Isaksen (2014)

Classic "VarQC" errors (Gaussian plus top-hat)
5K error std. dev.; PGE=0.25, l=5
Ingleby and Lorenc (1993), Andersson and Jarvinen (1998)



Error is function of (O-B)^2 minus estimated B error:
Obs errors of 5K, changeover at 5K
Minamide and Zhang (2017), Bonavita et al. (2017)

Source of background departure errors (observation space)

	Instrument noise (e.g. 0.3K)	**Observation operator**	**Error of representation / model error**	**Background (forecast) error**
Clear areas	May dominate	Usually minor	Treated as minor, not actually	Small (0.1K)
Cloudy areas	Irrelevant	Secondary (5K?)	Dominant (20K?)	Secondary (5K?)

“Representation spectrum”