Biases in radiative transfer models for high resolution sounders

Roger Saunders,
Met Office, Exeter, U.K

Acknowledgements

Stuart Newman and James Cameron

(Met Office, U.K.)

Marco Matricardi, Graeme Kelly and

Erik Andersson (ECMWF)

Phil Watts (EUMETSAT)

George Aumann (JPL)

Hong Zhang (CIMSS)

Louis Garand (MSC)

+

AIRS RT modellers

Talk overview

- RT models – the basics
- Possible sources of bias in RT models
- Examples of RT model bias
  - Forward model
  - Jacobians
- How can we reduce biases?

Fast RT models

Given an atmospheric state ***X*** *(T,q,T_s, …)* a fast RT model ***H*** allows one to compute the top of atmosphere radiance for a radiometer channel within a few *msecs*. This allows *Observed minus Calculated* radiance values to be computed "on the fly" in an NWP model

In addition for assimilation and retrievals the gradient of the RT model with respect to the atmospheric state variables is also required. This is called the Jacobian.

Biases are possible in both the forward model and Jacobian calculations

Fast RT model: Terminology

$$y = H(X)$$

Where:

y **is vector of radiance channels**

ATOVS is 20, AIRS can be 2378, IASI can be 8461

X **is state vector:**

Profile: T(p), q(p), oz(p), etc on 40-100 levels

Surface: $T_s, q_s, P_s,$

Cloud: LWC(p), IWC(p)

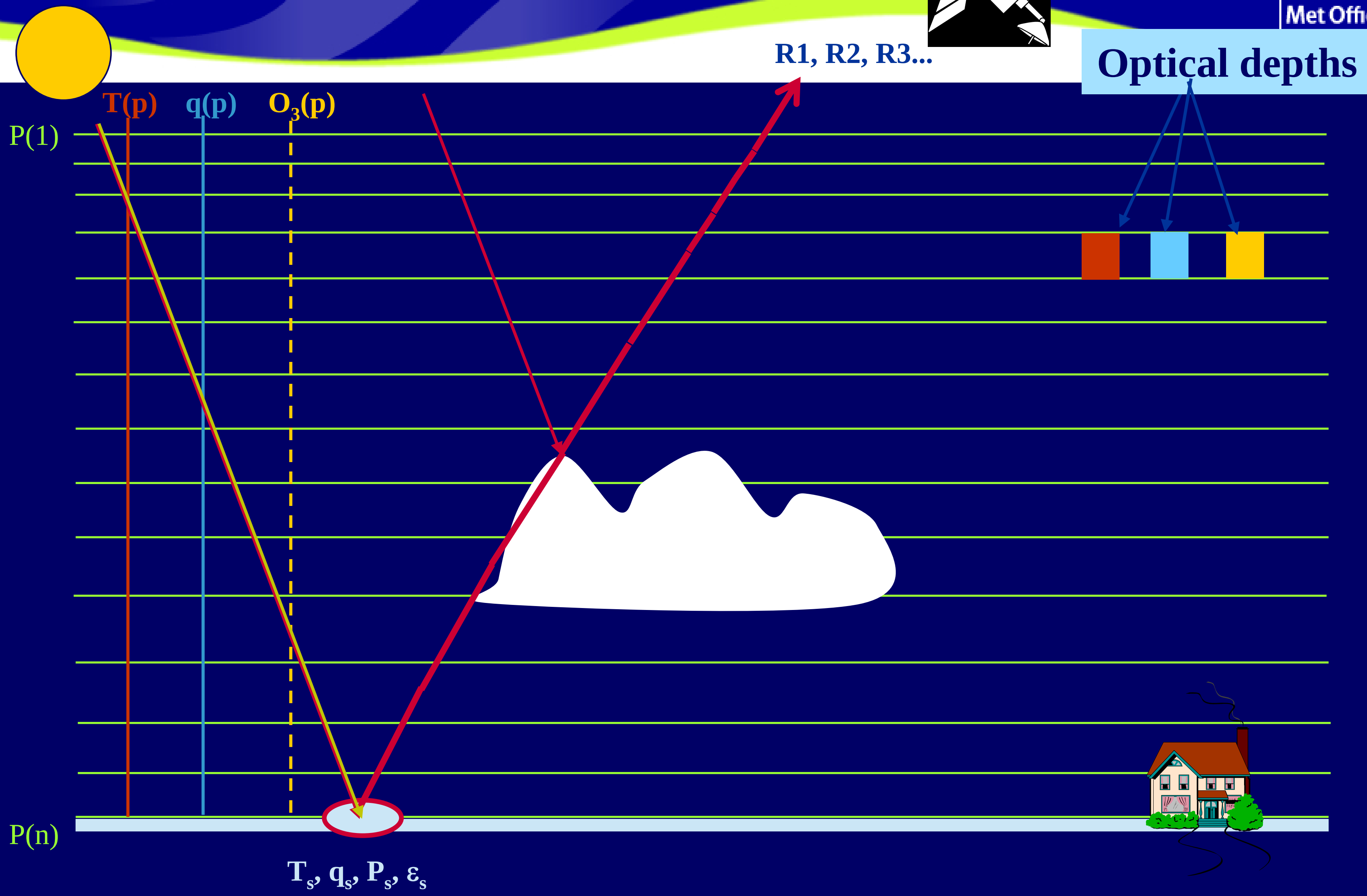
Precip: Hydrometeor profile

H **is observation operator for radiance measurements and comprises:**

Interpolation of model fields to observations

Fast radiative transfer model

Fast model process



Radiative Transfer Equation

$$R_\nu \cong \varepsilon_\nu B_\nu(\Theta_s) T_{s,\nu} + \int_{p_s}^{0} B_\nu(\Theta(p)) \frac{\partial T_\nu(p,\theta_u)}{\partial p} dp$$

$$+ (1-\varepsilon_\nu) T_{s,\nu} \int_{0}^{p_s} B_\nu(\Theta(p)) \frac{\partial T_\nu^*(p,\theta_d)}{\partial p} dp + \rho_\nu T_{s,\nu} T_\nu(p_s,\theta_{sun}) F_{0,\nu} \cos\theta_{sun}$$

- The first term is the surface emission
- The second term is the upwelling thermal emssion
- The third term is the reflected downwelling radiation
- The last term is the reflected solar radiation

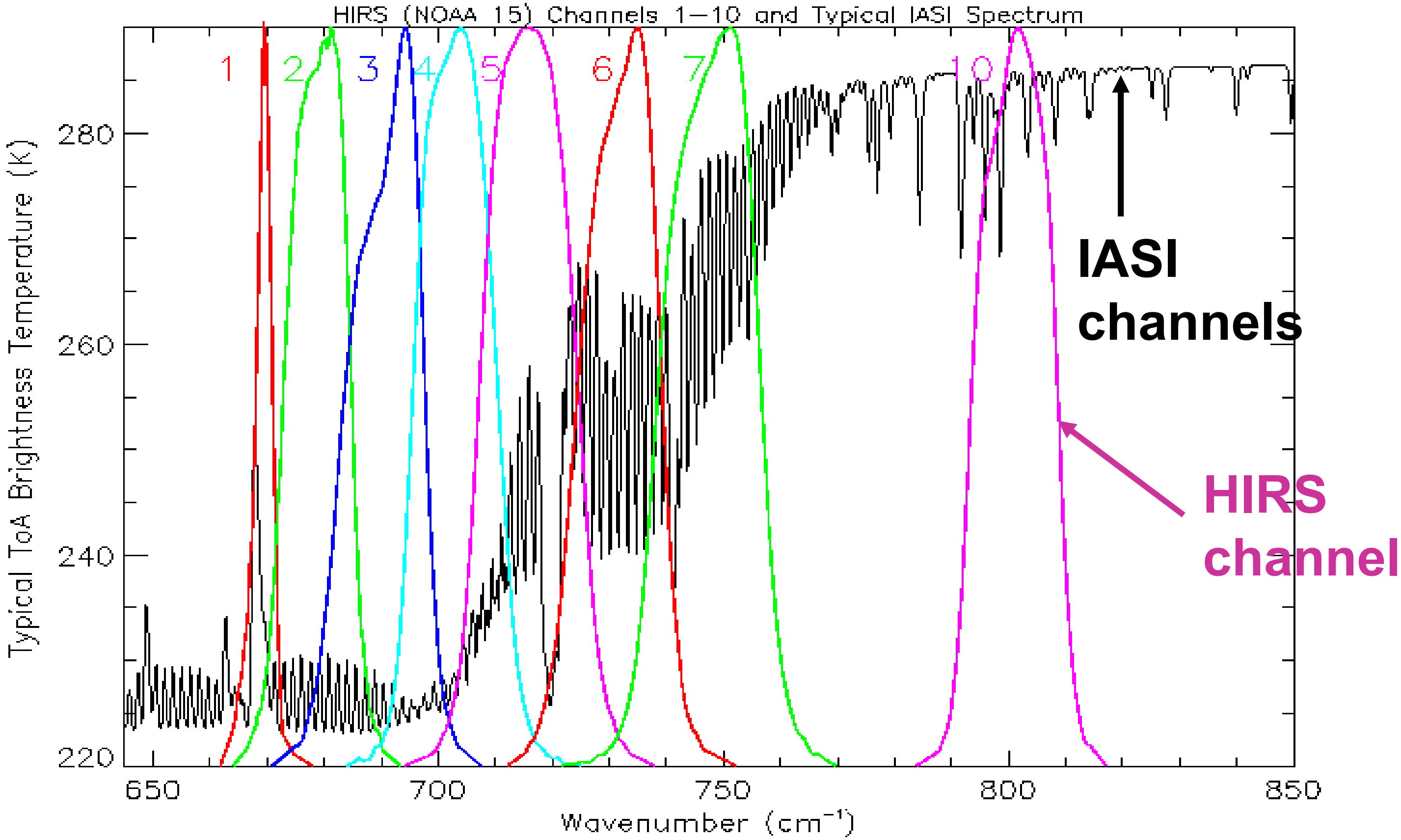
Jacobian/Tangent Linear/Adjoint

- Operators to compute gradient of model $\boldsymbol{y}=\boldsymbol{H}(\mathbf{X})$ about initial state **X**. The full Jacobian matrix **H** is

$$\mathbf{H} \equiv \frac{\partial \mathbf{y}}{\partial \mathbf{X}}$$

- *y* has dimension of number of channels and **X** the number of state vector variables
- **H** can be a large matrix if more than 1 profile at a time is operated on (hence the TL/AD operators) but for 1 profile it is *chans x (levels x ngases + surface)* so is used in 1DVar applications.

Infrared channels in 15µm CO_2 band



Spectrum of infrared radiation from atmosphere

HIRS 19 channels vs IASI 8461 channels

Fast Model Approaches

- Linear regression (profile $\Rightarrow$ optical depth)
  - On fixed pressure levels (RTTOV, PLOD, SARTA)
  - On fixed absorber overburden layers (OPTRAN)
- Physical method (MSCFAST)
- Correlated K distribution (Synsatrad)
- Optimal Spectral Sampling (OSS see Jean-Luc's talk)
- Neural nets (LMD)
- PCA approach for advanced IR sounders (see Xu Liu)

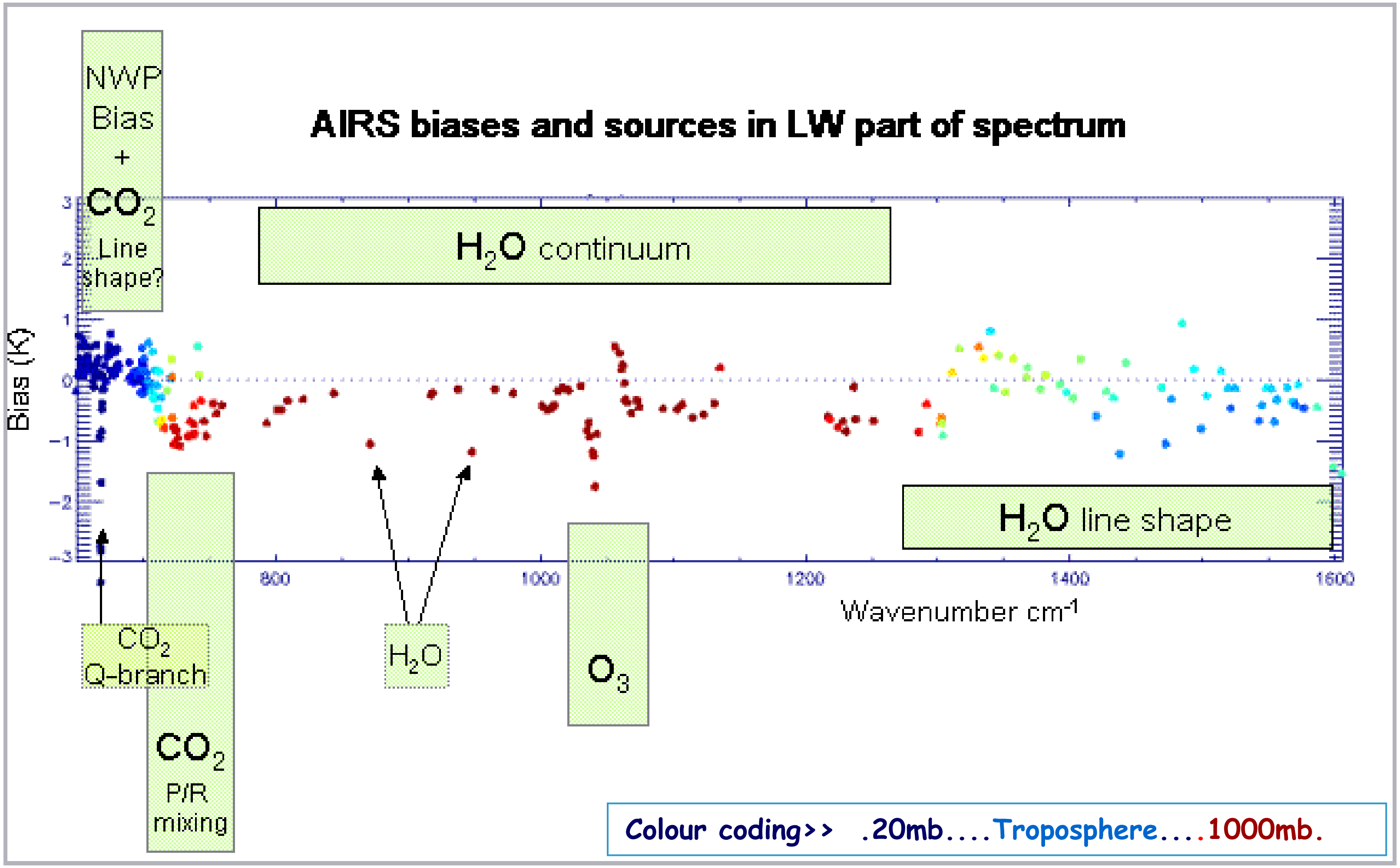
Talk overview

- RT models – the basics
- Possible sources of bias in RT models
- Examples of RT model bias
  - Forward model
  - Jacobians
- How can we reduce biases

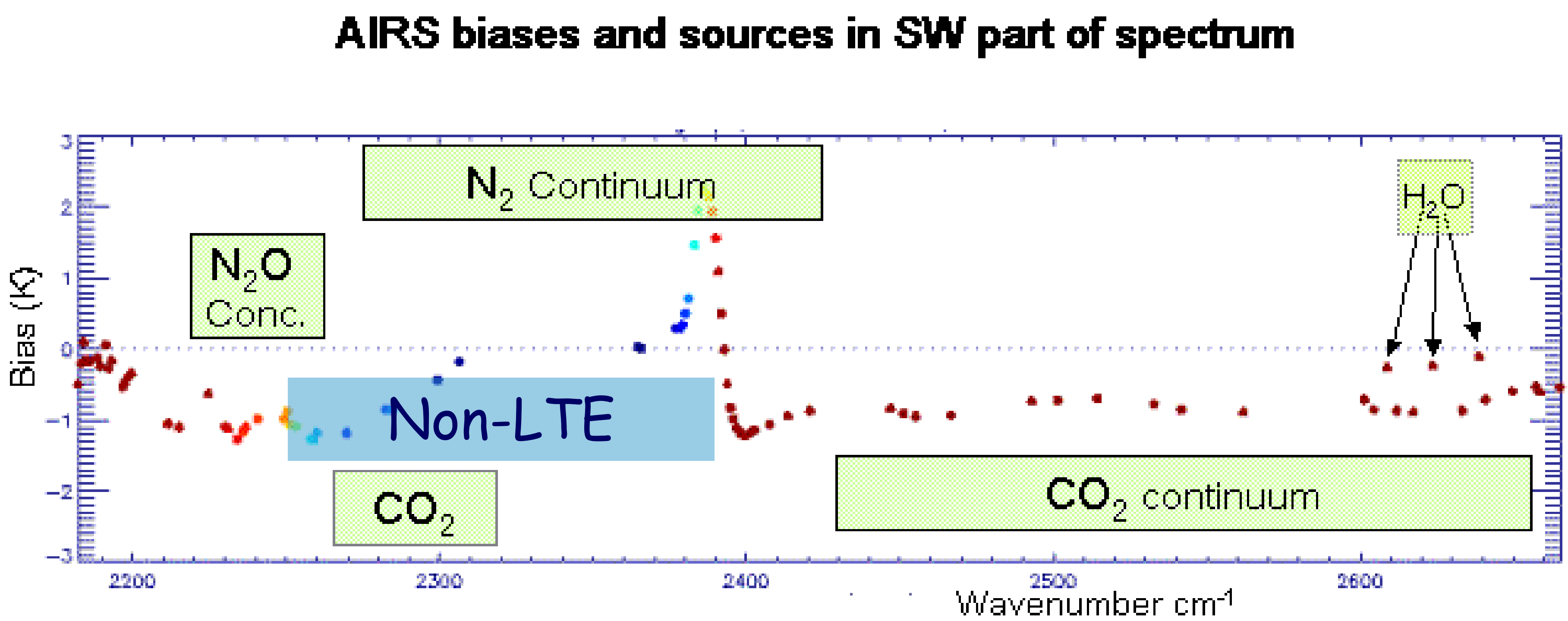
Sources of bias in RT models (1)

- Underlying spectroscopy:
  - Line parameters (frequency, strength, width, temp dep., line mixing….)
  - Water vapour continuum parameterisation
  - Non-LTE for SWIR channels
  - Zeeman splitting for high peaking channels
  - CFC absorption
- Assumptions made in Line-by-Line model
  - Quantisation (levels, spectral)
  - Line shape formulation
  - Combination of line and continuum absorption

Bias Overview 650-1600 cm^{-1}

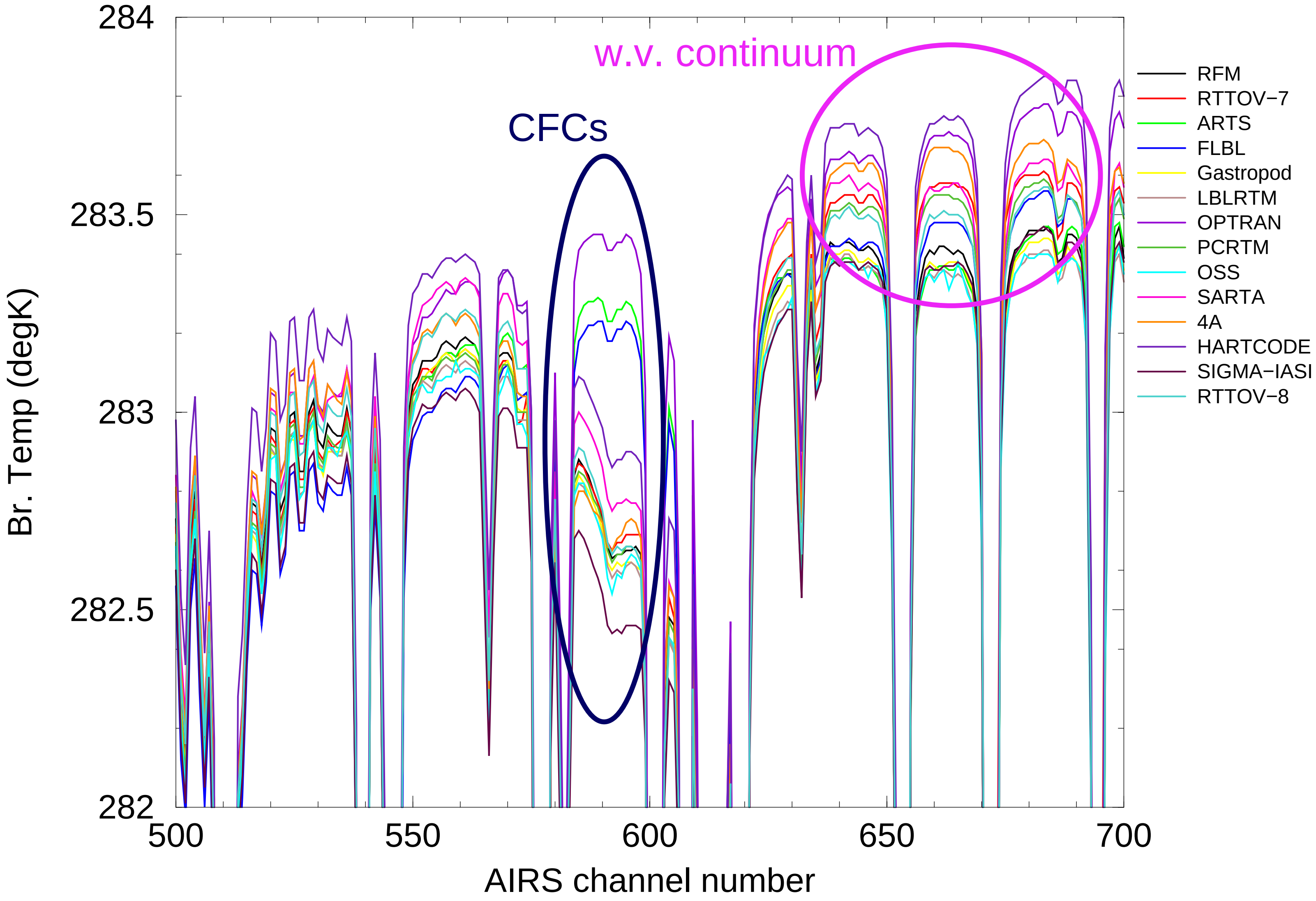


Bias Overview 2180-2670 cm^{-1}

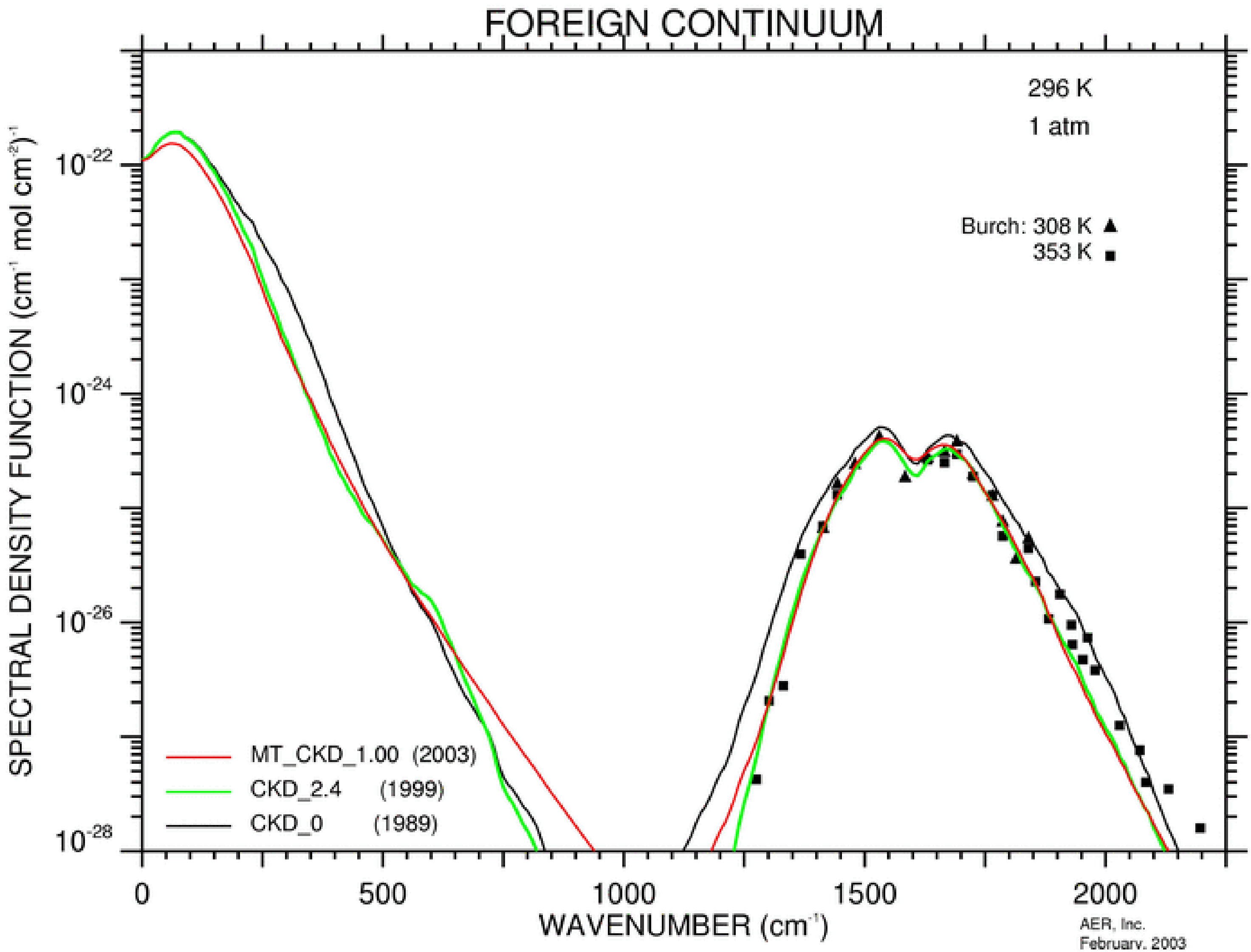


Colour coding>> .20mb....Troposphere....1000mb.

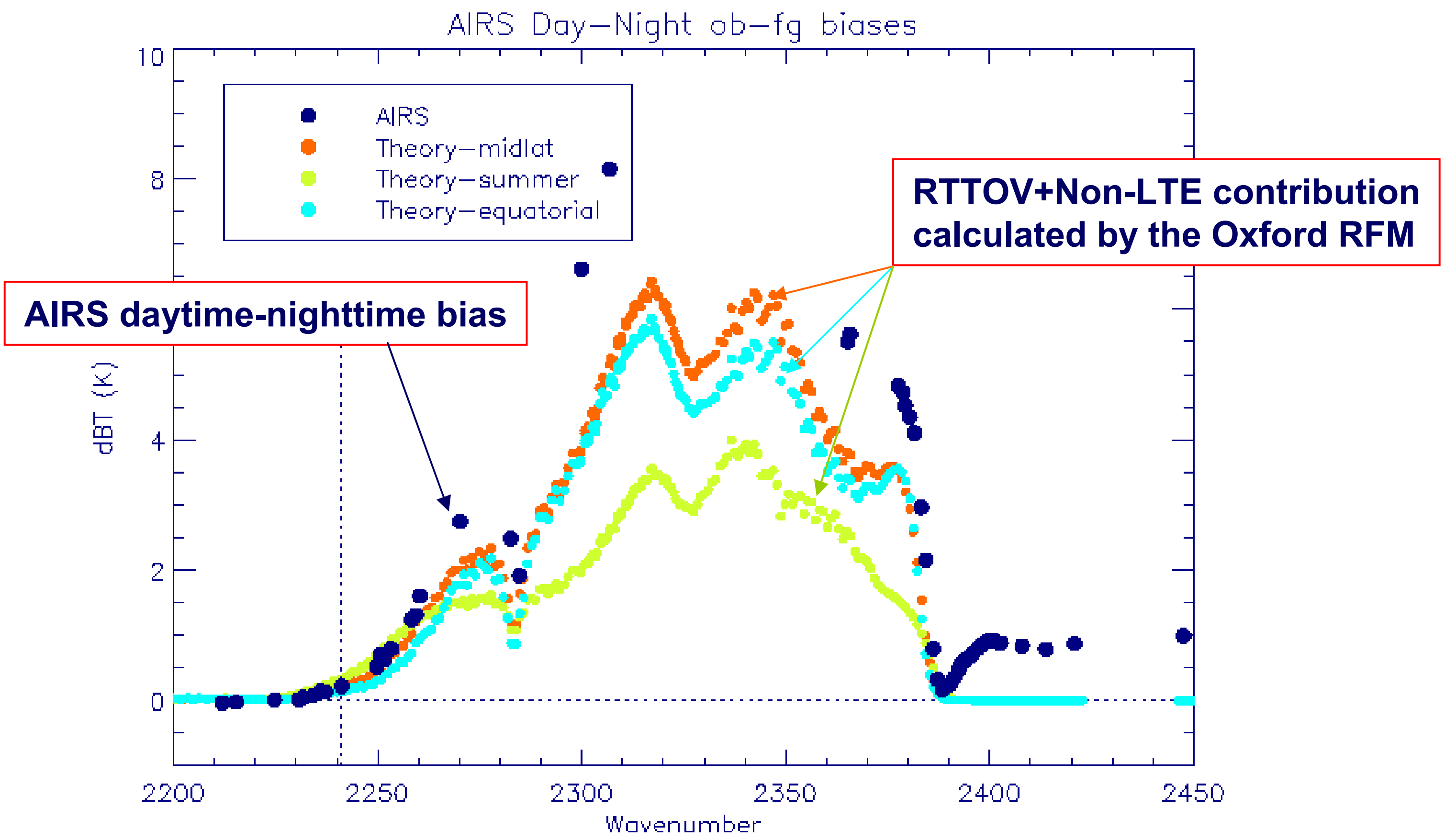
Comparison of AIRS forward models



Water vapour continuum



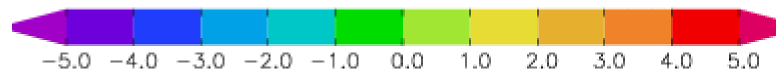
Non-LTE 2240-2390 cm^{-1}

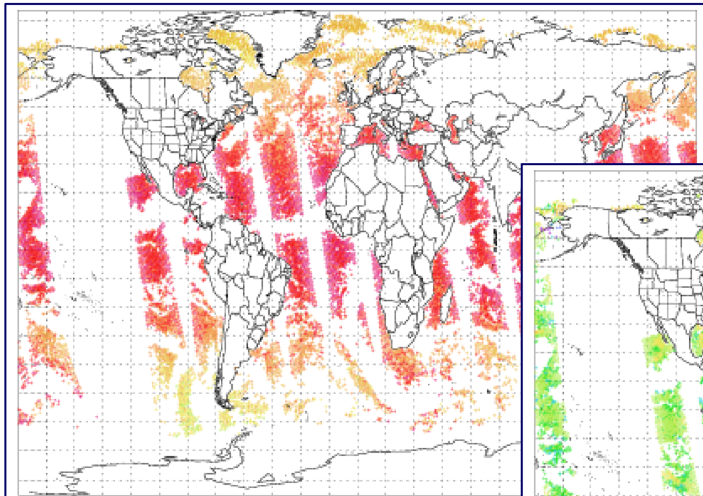


Thanks: Niels Bormann, Anu Dudhia, Phil Watts

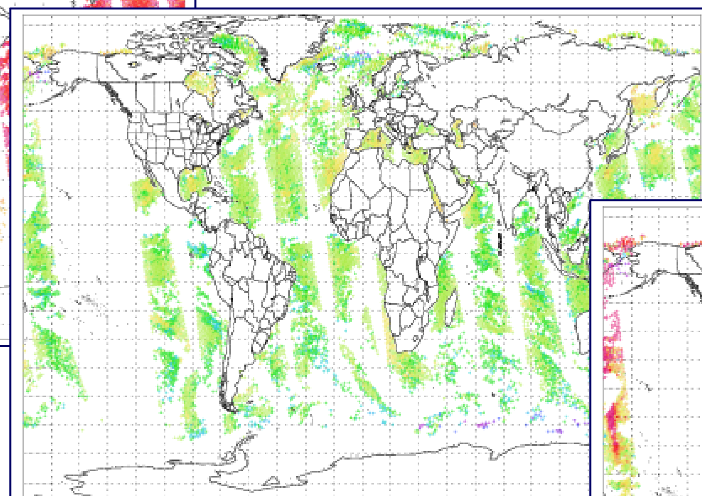
O-B difference

- **Large positive bias in the SW-IR in the day-time**
  due to Non LTE effect in upper sounding chs and sunglint in window

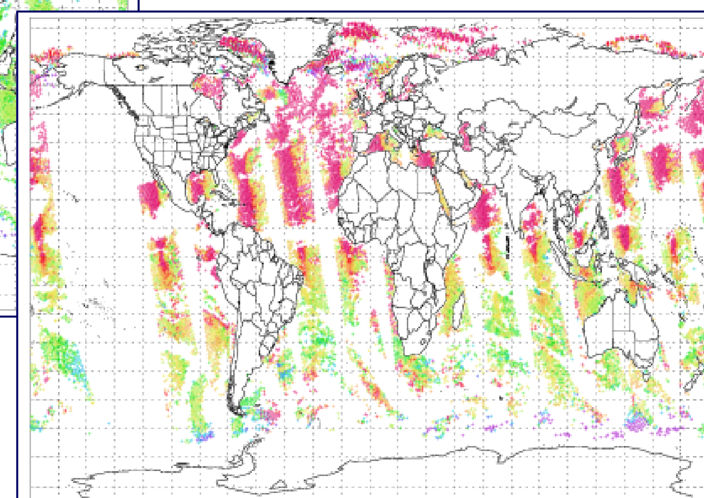




2387cm^{-1} (4.19micron) Non-LTE



2392cm^{-1} (4.18micron)

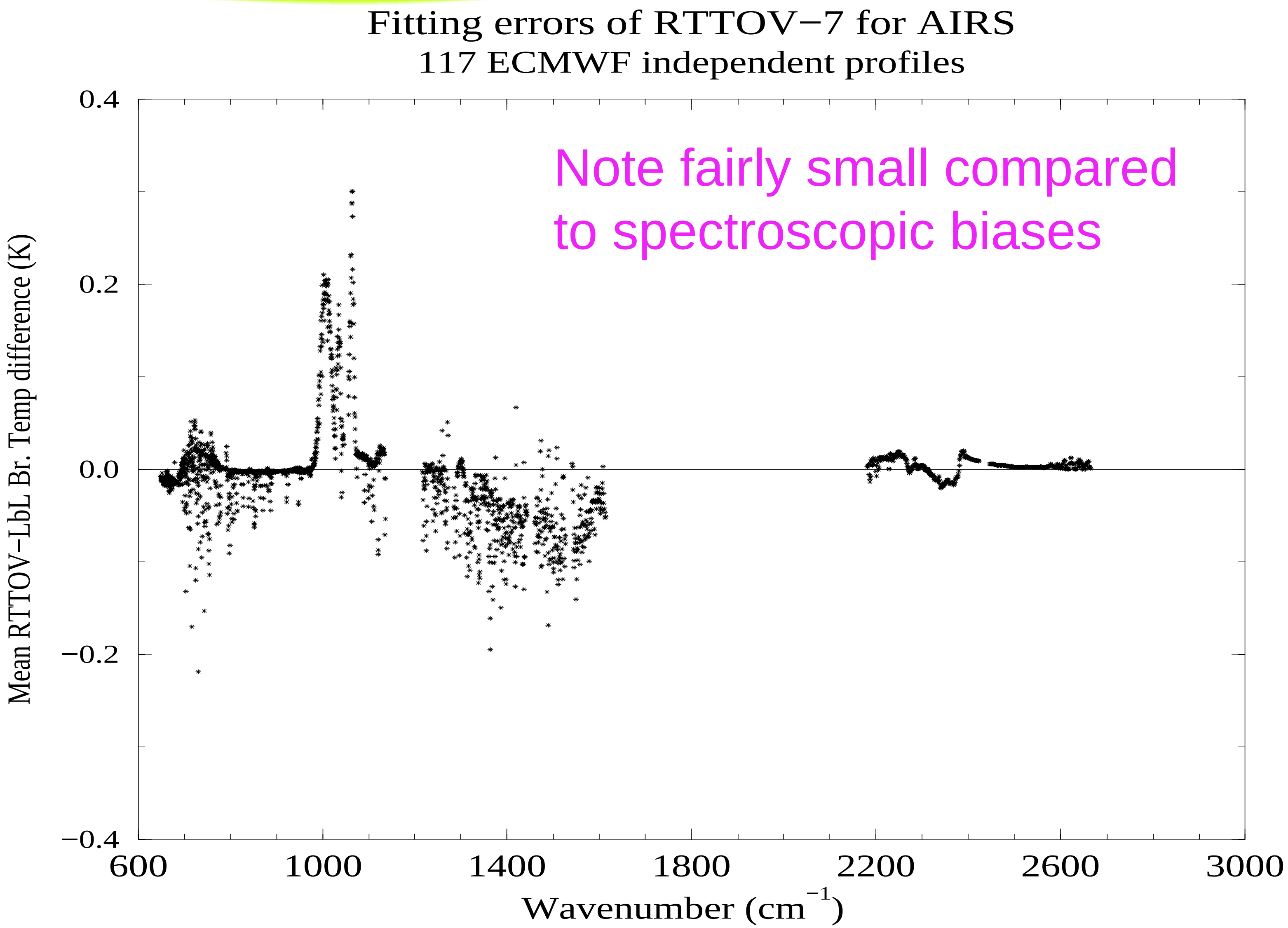


2618cm^{-1} (3.82micron) sunglint

Sources of bias in RT models (2)

- Fast model parameterisation:
  - Regression or look up table technique
  - Unrepresentative profile training set
  - Level quantisation, plane parallel assumption
  - Omission of reflected solar term
- Surface emissivity parametrisation
  - Smaller biases over ocean larger over land
- Incorrect instrument spectral response function
  - Problem for some IR radiometers
  - Not an issue for microwave and HiRes IR
- Errors in cloud or precipitation radiative properties
  - Water vapour clouds reasonable
  - Ice crystals more difficult

RTTOV fast model errors



Note fairly small compared to spectroscopic biases

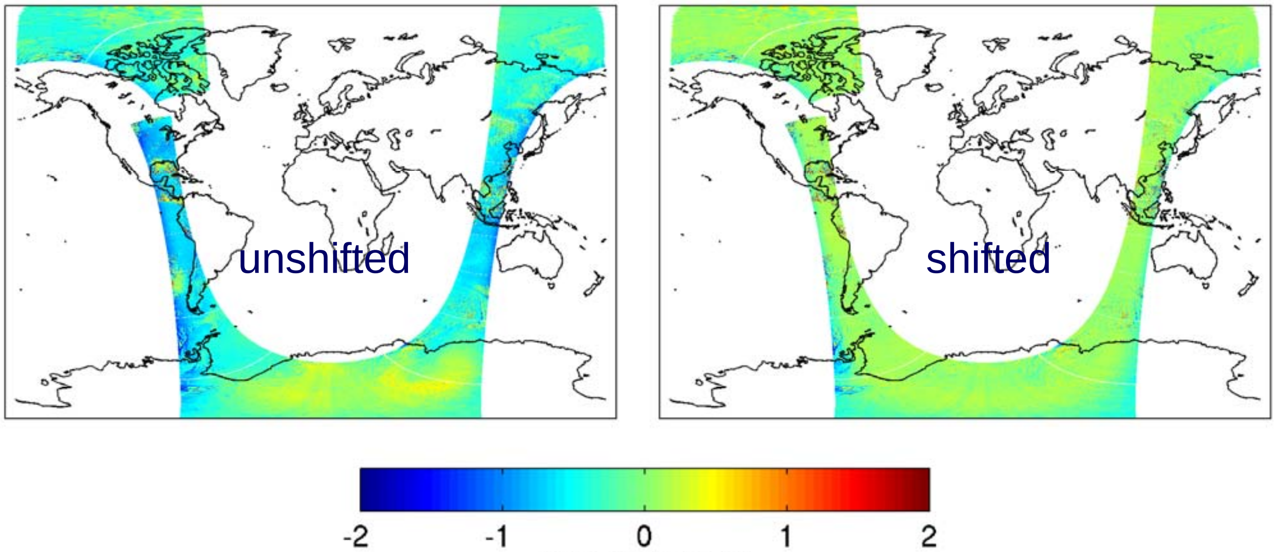
Errors in MODIS spectral response functions

courtesy of Hong Zhang (CIMSS)

MODIS minus AIRS convolved over MODIS SRF

MODIS band 35 (13.9 µm) brightness temperature differences using original SRF (black) and using MODIS SRF shifted +0.8 cm^{-1} (red)

From Tobin et al 2005



SRF shifted for CO_2 channels

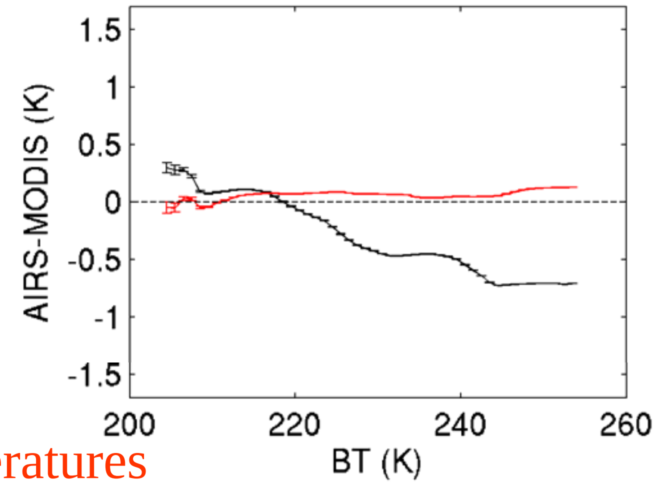
band 36: +1.0 cm^{-1}

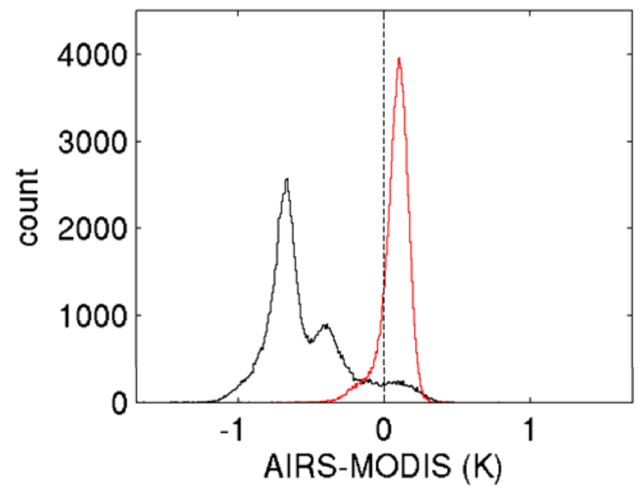
band 35: +0.8 cm^{-1}

band 34: +0.8 cm^{-1}

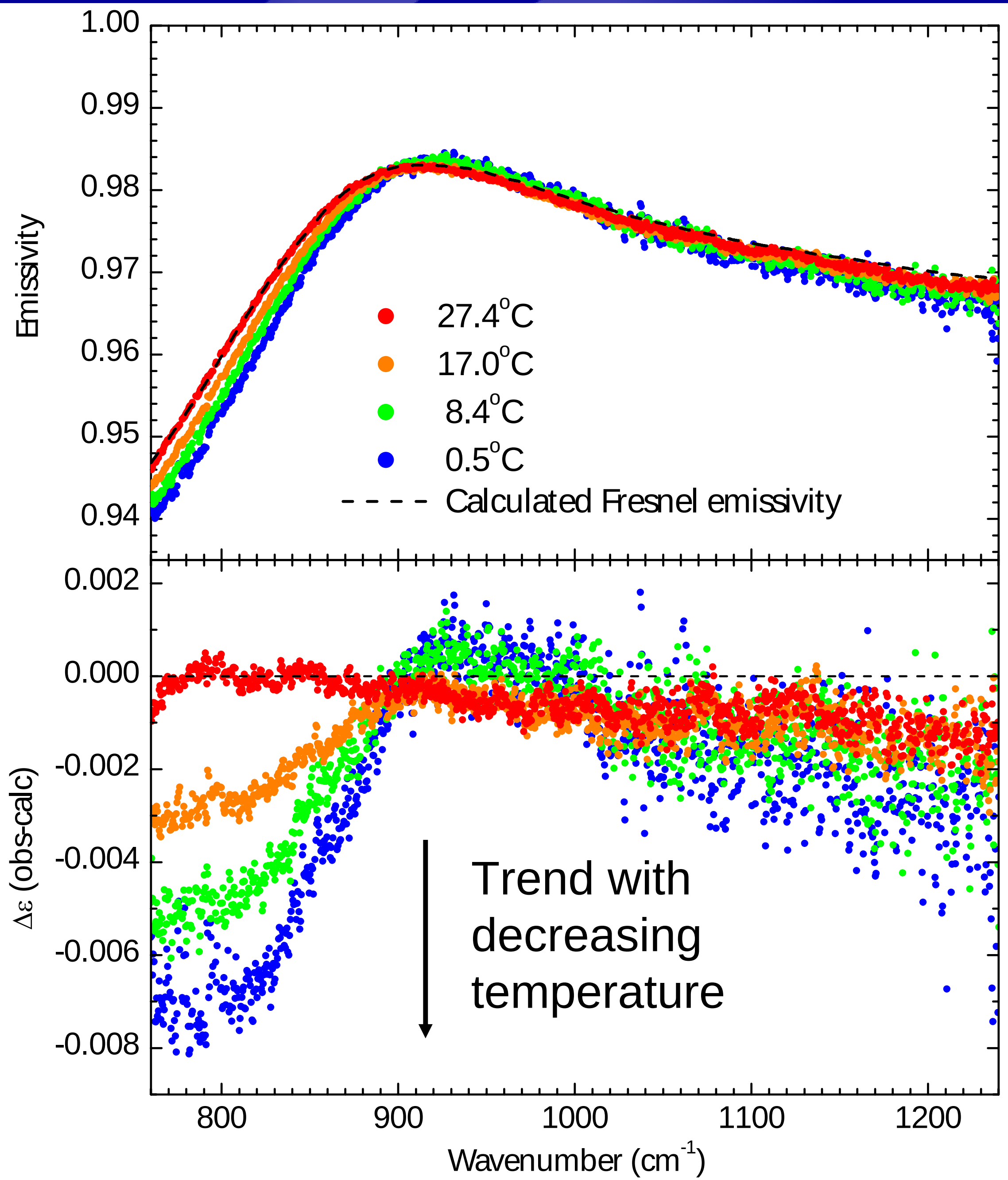
band 33: -0.15 cm^{-1}

show better agreement with AIRS for all temperatures





Emissivity temperature dependence



From Newman et. al. 2005

- Pure water (zero salinity)
- No need to consider distribution of wave slopes, i.e. use Fresnel equations
- Calculated emissivity from Downing and Williams refractive indices (1975 paper, measured at 27°C)

Talk overview

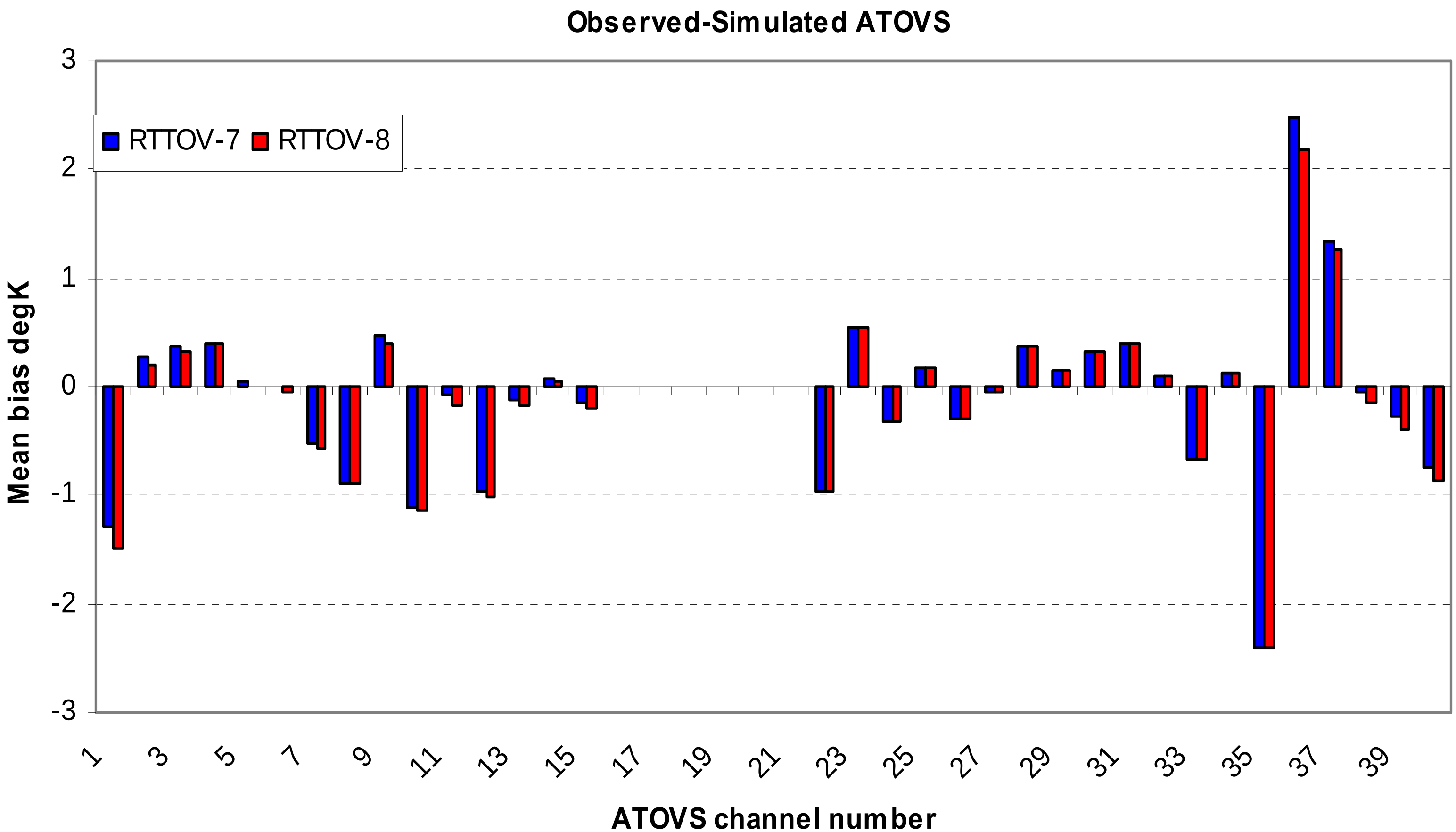
- RT models – the basics
- Possible sources of bias in RT models
- Examples of RT model bias
  - Forward model
  - Jacobians
- How can we reduce biases

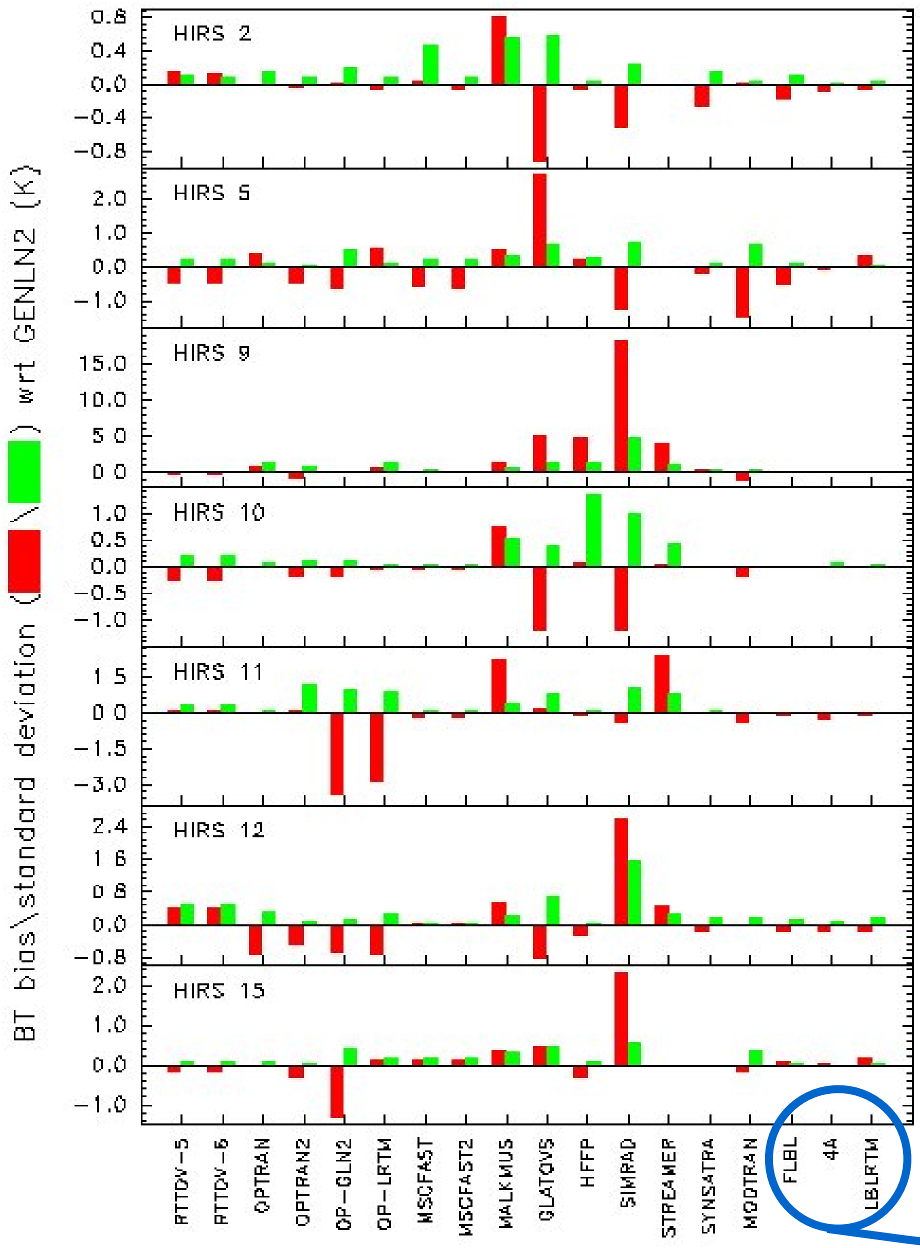
How to validate RT models?

- Use an independent set of profiles (e.g. ECMWF diverse 117 profile set) but with same LbL model computed transmittances
  - Gives estimate of inherent fast model accuracy of trasmittances and TOA radiances
- Fast model comparisons (e.g. Garand *et al* 2001 for HIRS and Saunders *et. al.* for AIRS) radiances *and jacobians*
  - Gives performance of model compared to others
- Line-by-line model comparisons (e.g. LIE)
  - Gives estimate of underlying LbL model accuracy
- Comparisons with real satellite data using NWP fields
  - Allows validation over wide range of atmospheres
- Comparison with aircraft data (e.g. NAST-I)
  - Limited sampling but can reduce uncertainties of variables

RTTOV biases in ECMWF model

21 days of O-B in March 2004

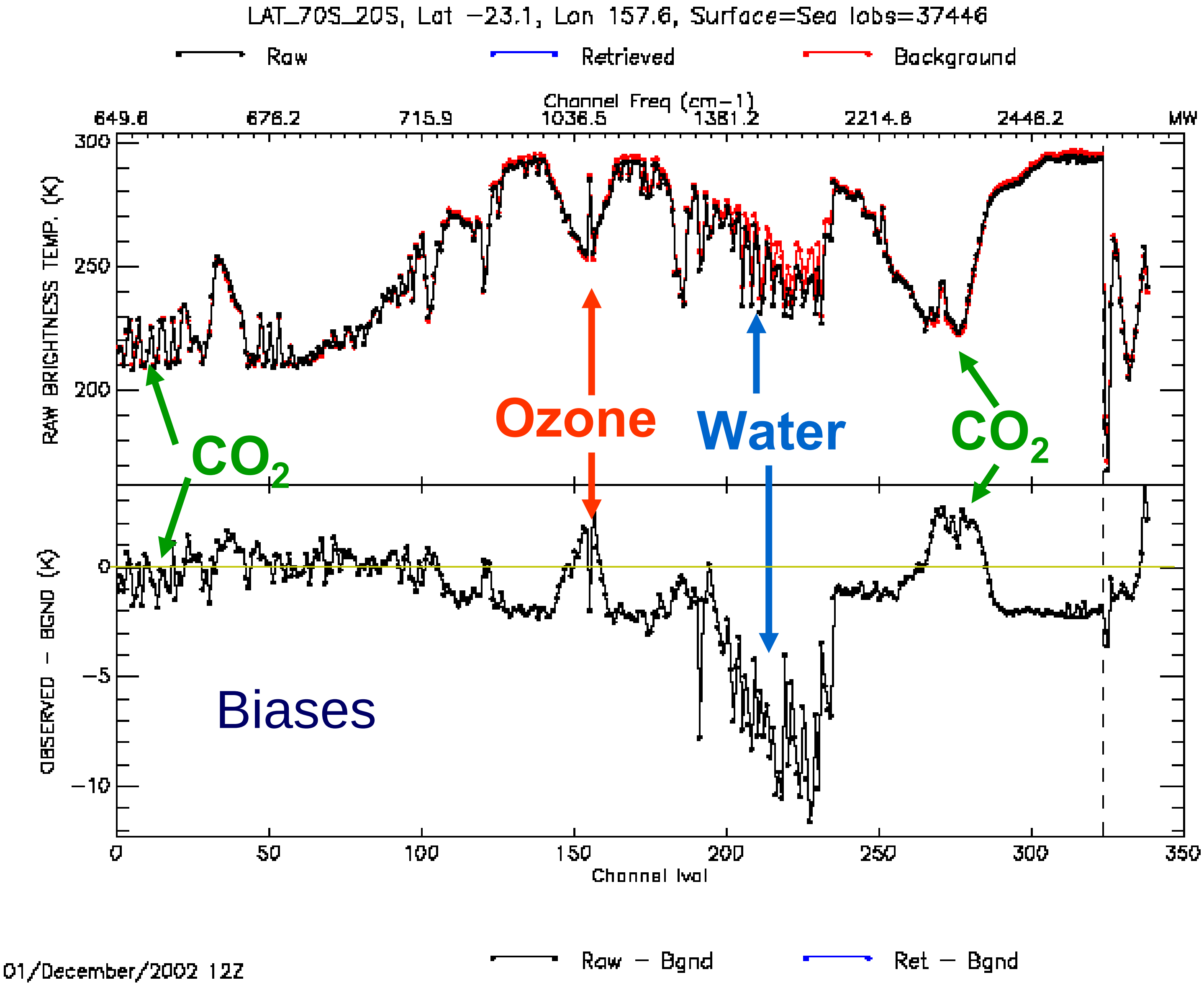




Garand fast model intercomparison for HIRS channels

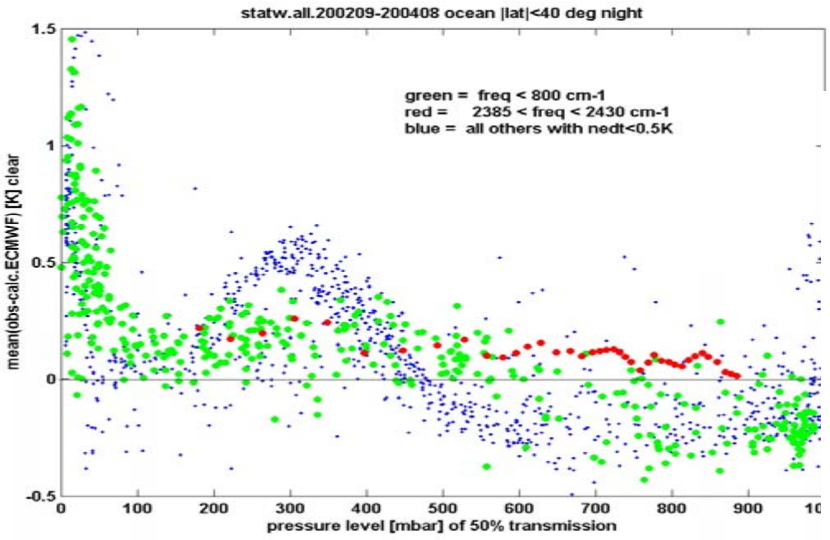
Line by line models

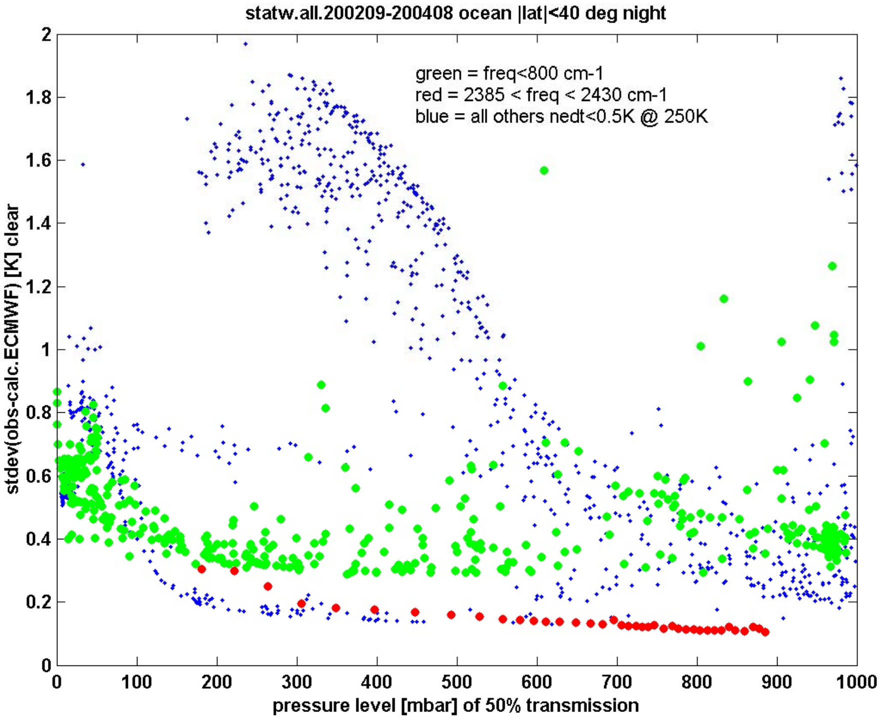
Observed - Calculated AIRS spectra



Some biases are from NWP model but some are from RT model

AIRS Observed-Simulated





The 4.2 micron CO_2 channel bias is +0.15K The bias of the 14 micron CO_2 channels is -0.2K below 500 mb and shifts to +0.15K between 500 and 100 mb The bias in the water channels shows a similar pattern

The 4.2 micron channels fit the T(p) within 0.1K. Almost equal to the NEDT.The 14 um channels with within 2-3 x NEDT The water channels differ from ECMWF by more than ten time NEDT Courtesy George Aumann/JPL

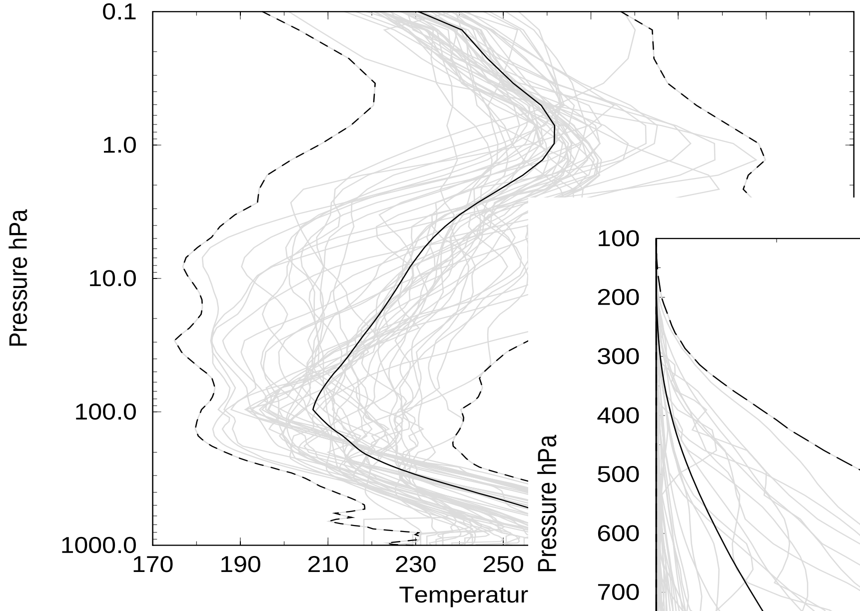
AIRS RT model comparison

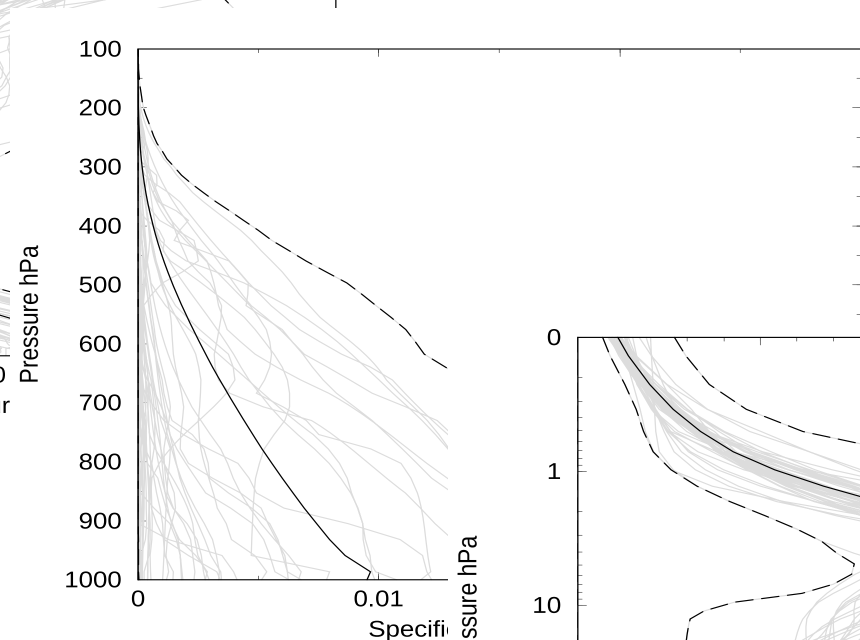
- Compare AIRS RT models
- Compute BTs for all 2378 channels for 52 profiles
- For some models compute jacobians for a selection of 20 channels
- For some models compute layer to space transmittances of 20 channels

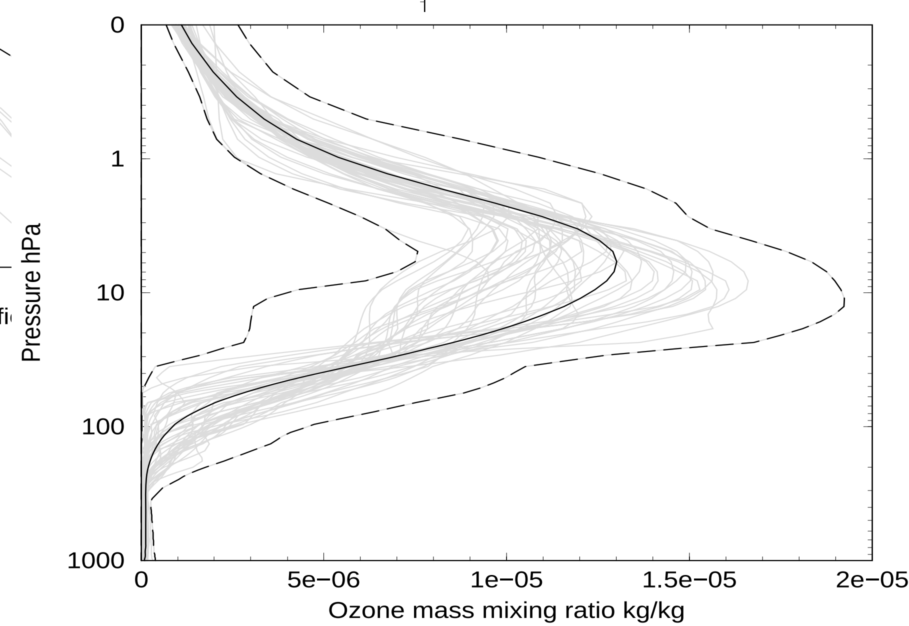
AIRS RT model Comparison

Model	Participant	Direct	Jacobian
RTTOV-7	R. Saunders, METO	Yes	Yes
RTTOV-8	R. Saunders, METO	Yes	Yes
Optran	Y. Han, NESDIS	Yes	Yes
OSS	J-L. Moncet, AER	Yes	Yes
LBLRTM	J-L. Moncet, AER	Yes	Yes
RFM	N. Bormann, ECMWF	Yes	Yes
Gastropod	V. Sherlock, NIWA	Yes	Yes
ARTS	A. Von Engeln, Bremen	Yes	No
SARTA	S. Hannon, UMBC	Yes	No
PCRTM	Xu Liu, NASA	Yes	Yes
4A	S. Heilliette, LMD	Yes	Yes
FLBL	D.S. Turner, MSC	Yes	Yes
σ-IASI	C. Serio, Uni Bas	Yes	Yes
Hartcode	F. Miskolczi, NASA	Yes	No

Diverse ERA-40 52 Profile set

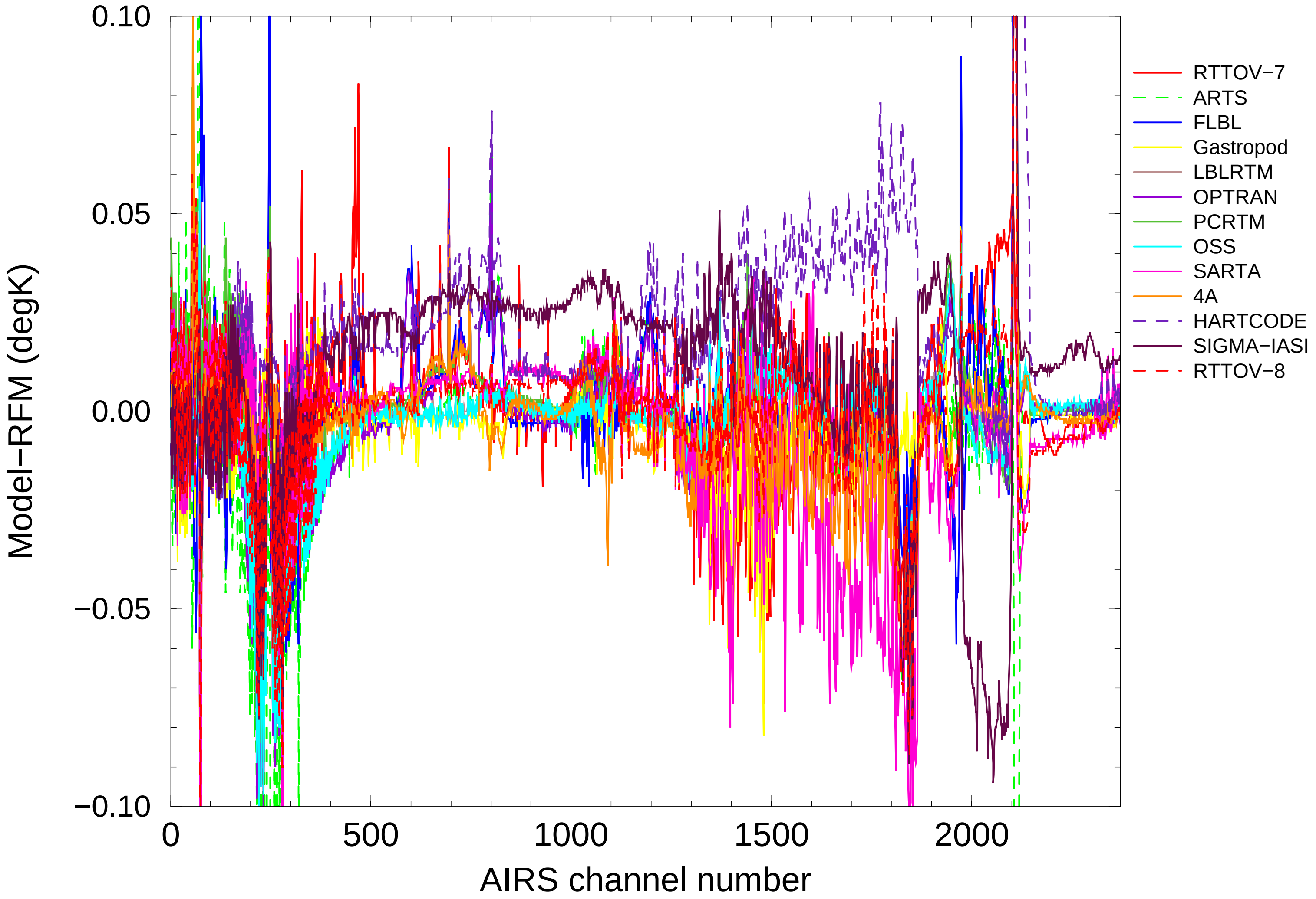




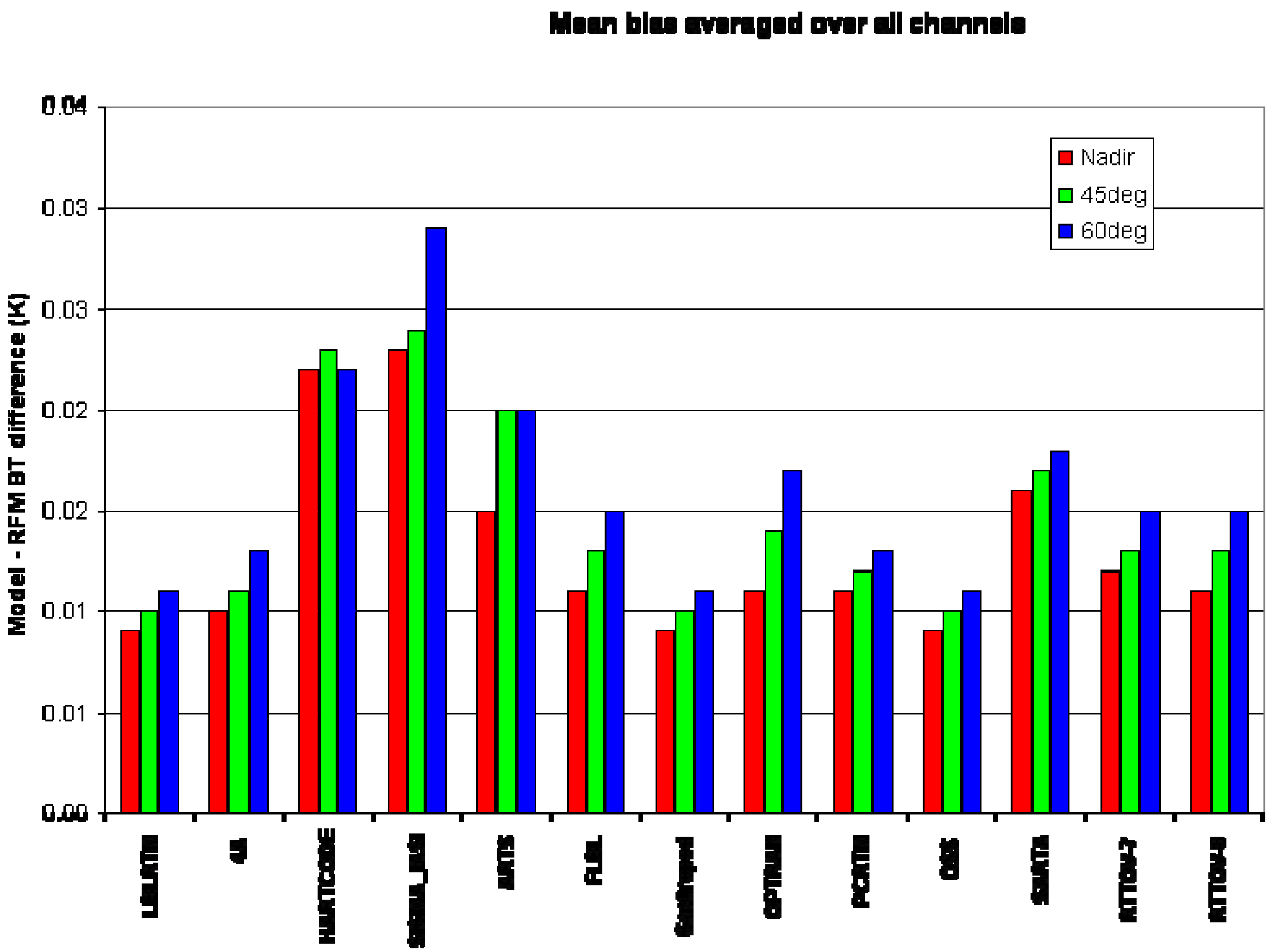


All 52 profiles dynamically consistent with all 3 variables

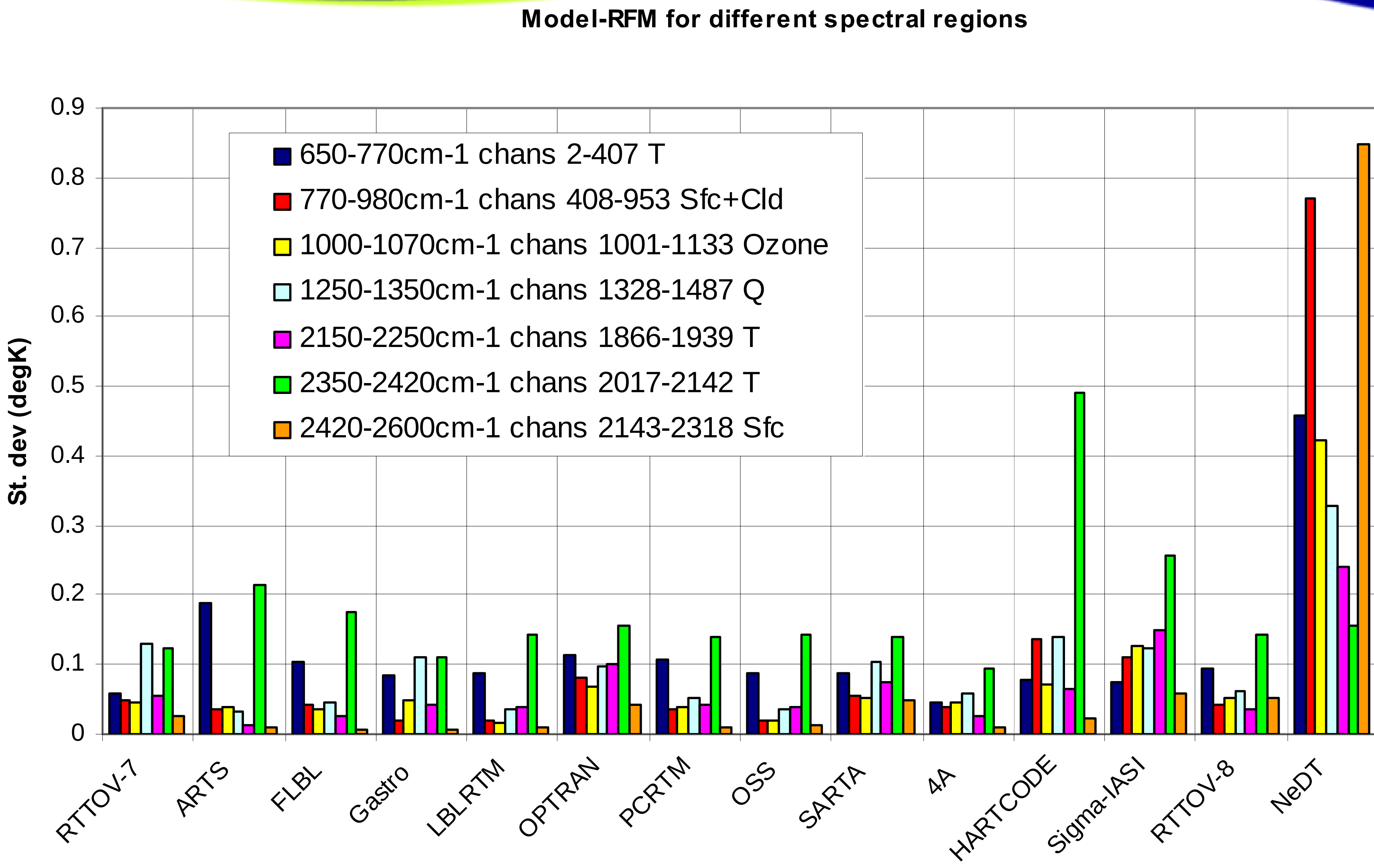
Mean bias for all 49 diverse profiles



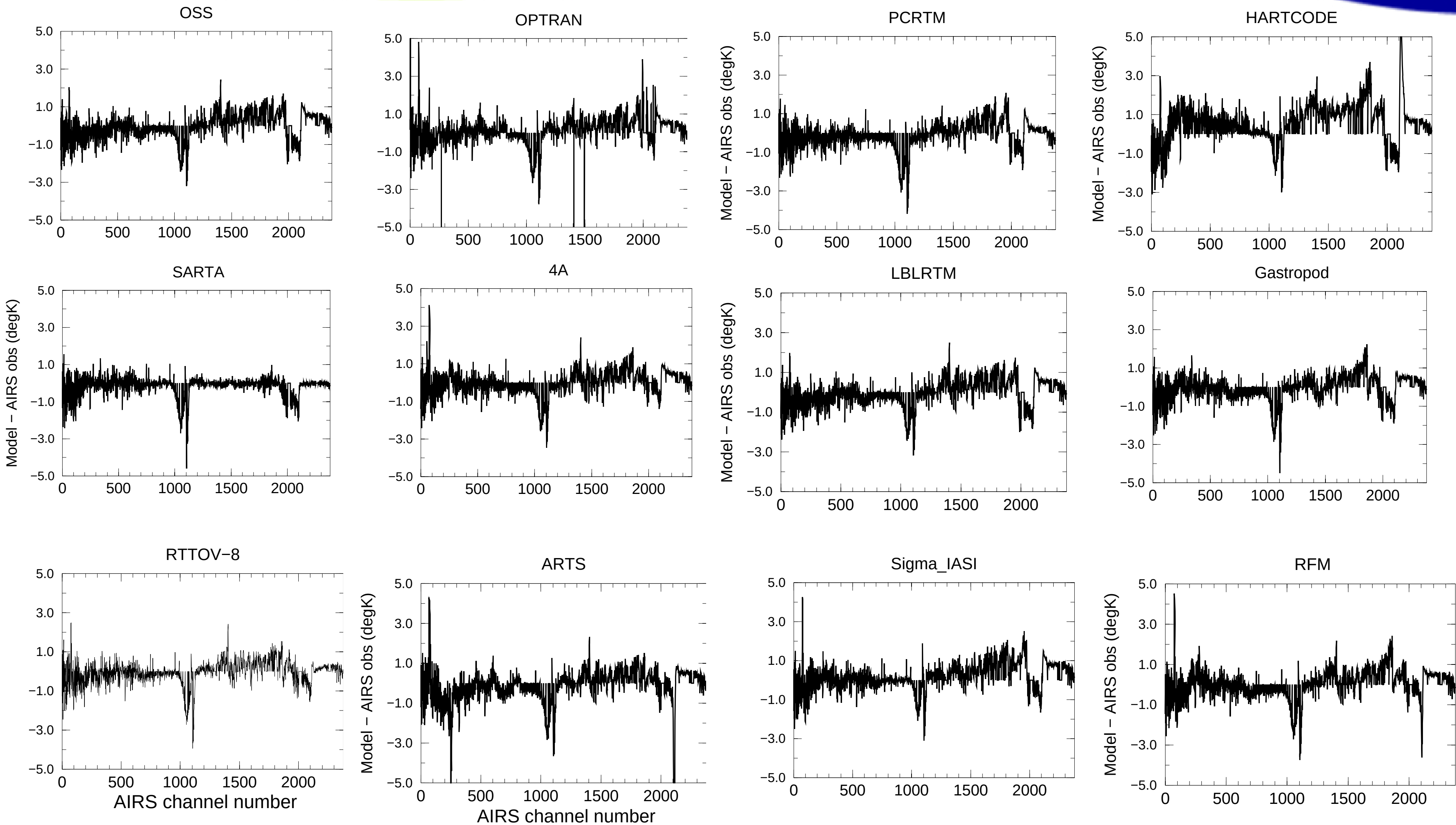
Bias averaged over channels



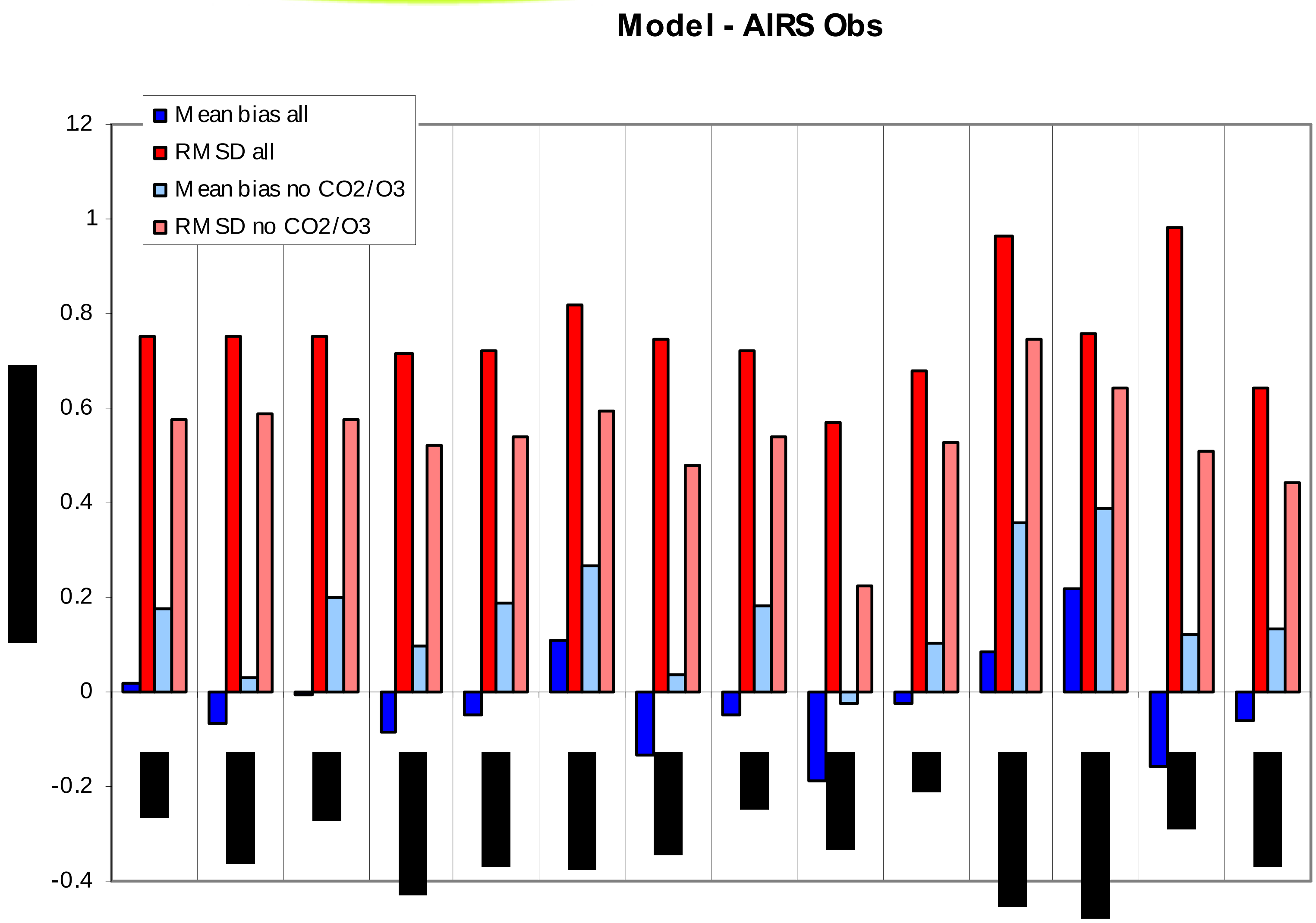
Model bias for different bands



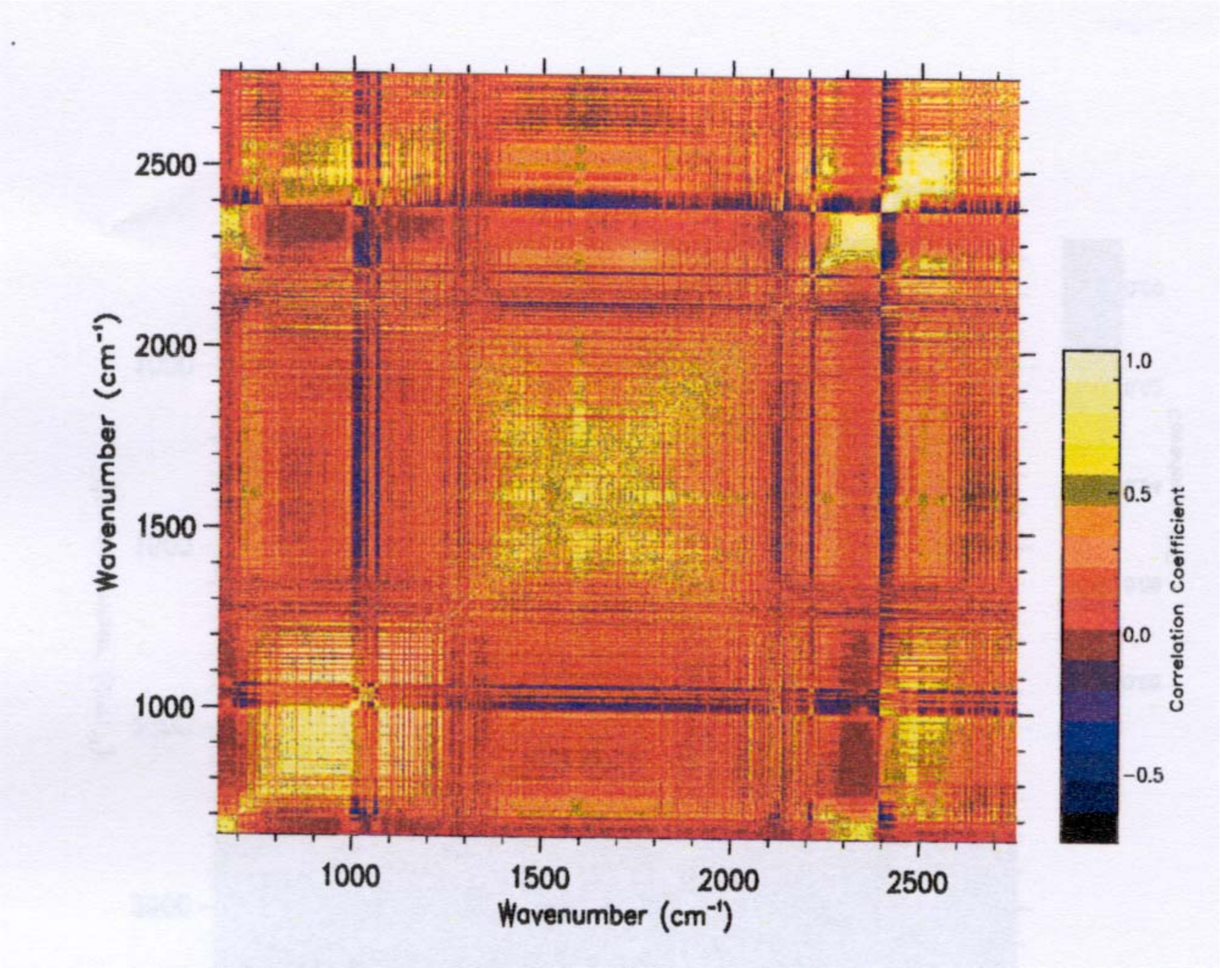
Comparison with observations



Summary of model –AIRS observations



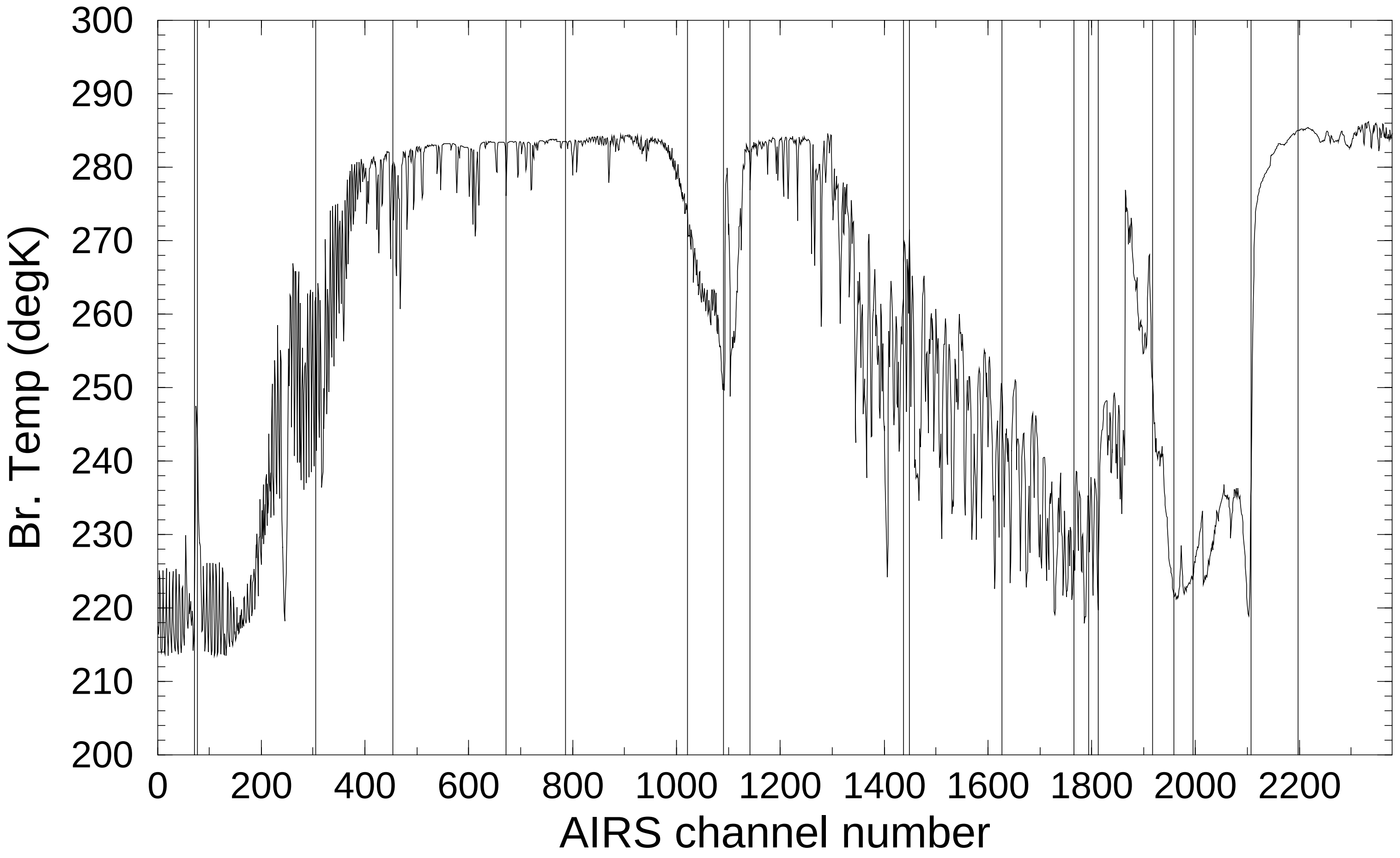
Forward model error correlation matrix for RTIASI



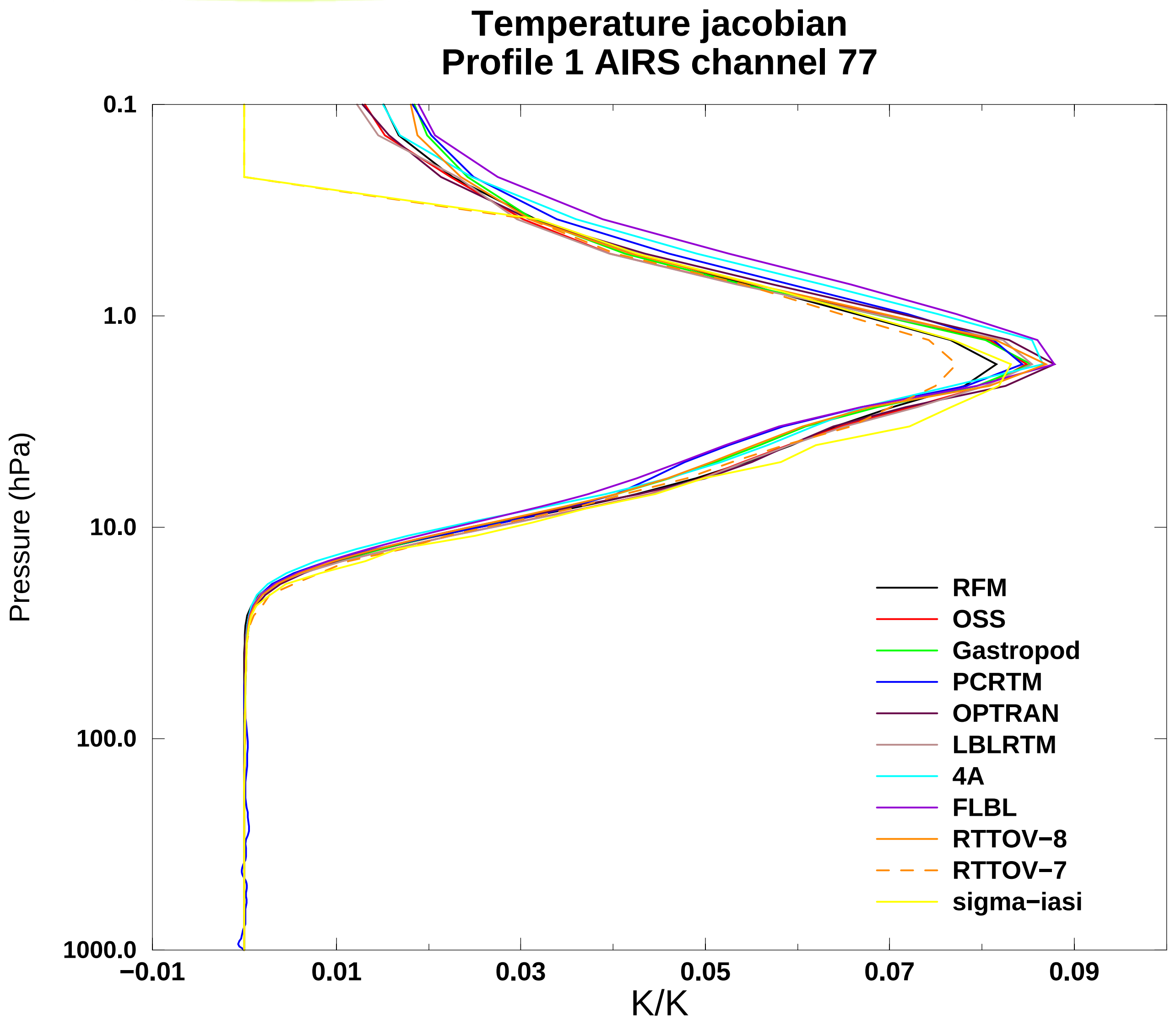
Talk overview

- RT models – the basics
- Possible sources of bias in RT models
- Examples of RT model bias
  - Forward model
  - Jacobians
- How can we reduce biases

AIRS channels selected



Comparison of Jacobians



Measure of fit

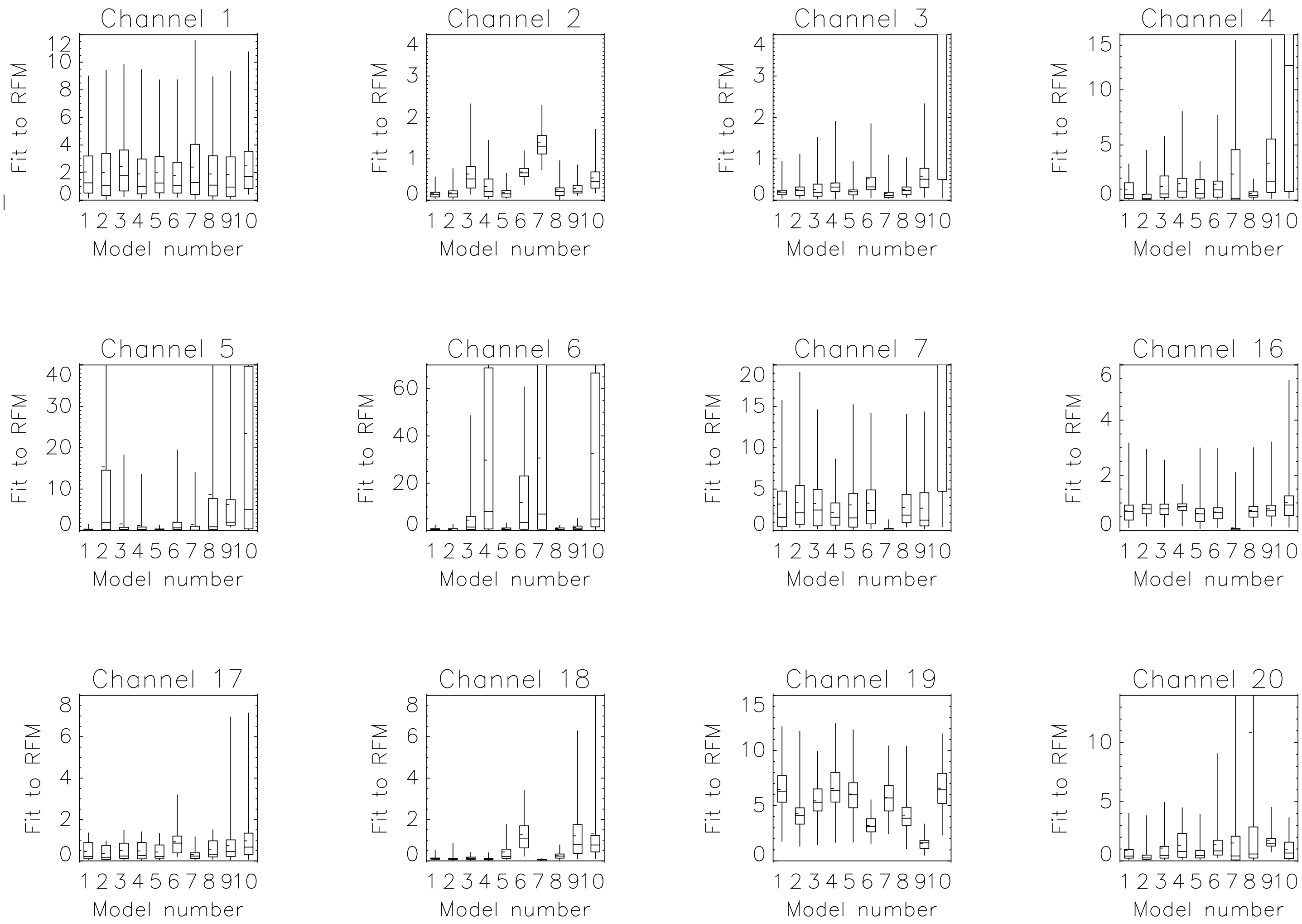
For the jacobians the results from each model were differenced with RFM one of the line-by-line models in order to be able to conveniently examine the inter-model differences. For the jacobians the "measure of fit" adopted by Garand et. al., [2001] was used defined as:

$$M = 100 \times \sqrt{\frac{\sum \left(X_i - X_{ref} \right)^2}{\sum \left(X_{ref} \right)^2}}$$

where X_i is the profile variable at level i and X_{ref} is the reference profile variable which was taken to be the RFM model profile for this study.

Comparison of temperature jacobians

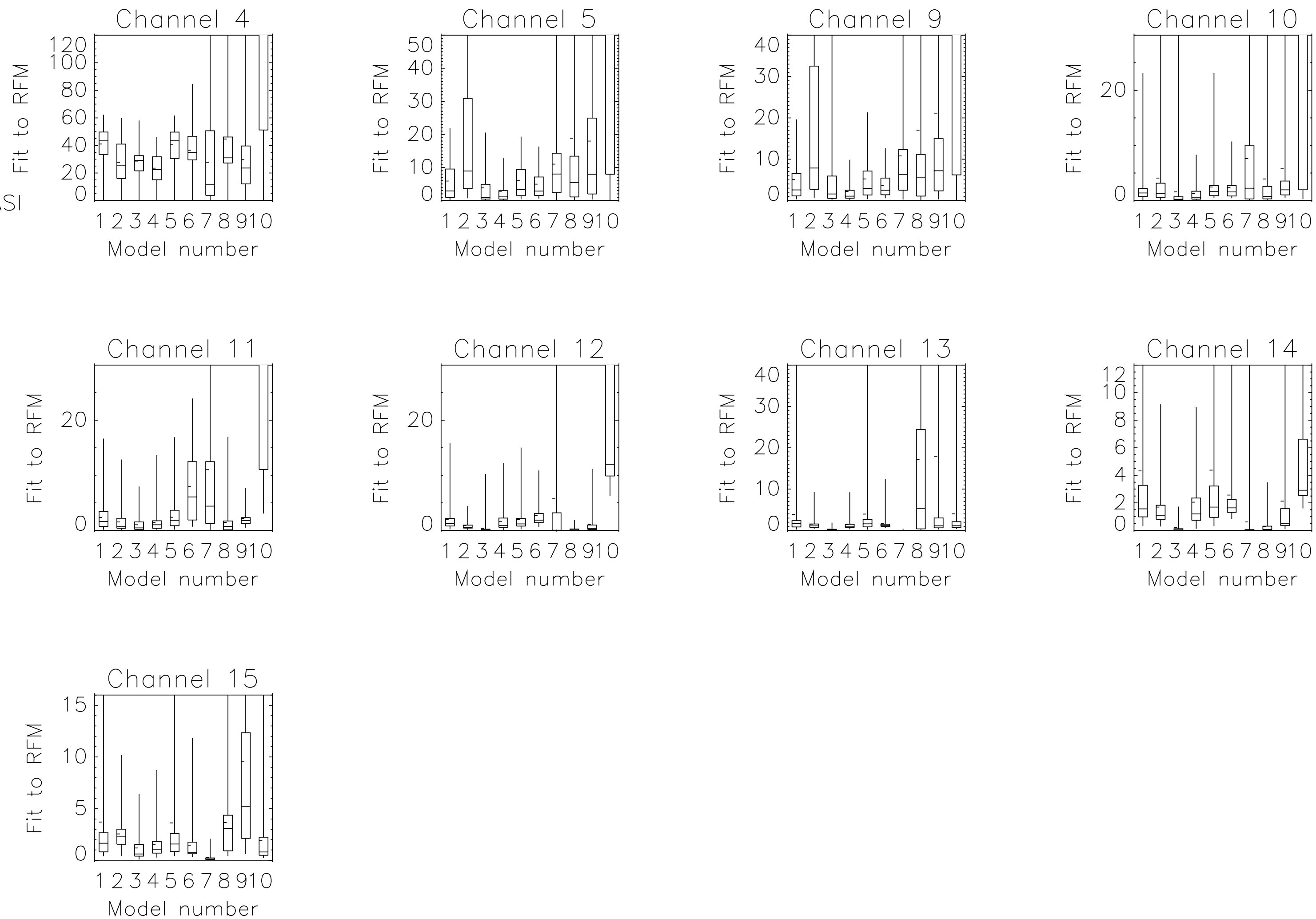
Model Key
1 OSS
2 Gastropod
3 PCRTM
4 Optran
5 LBLRTM
6 4A
7 FLBL
8 RTTOV−8
9 RTTOV−7
10 Sigma−IASI



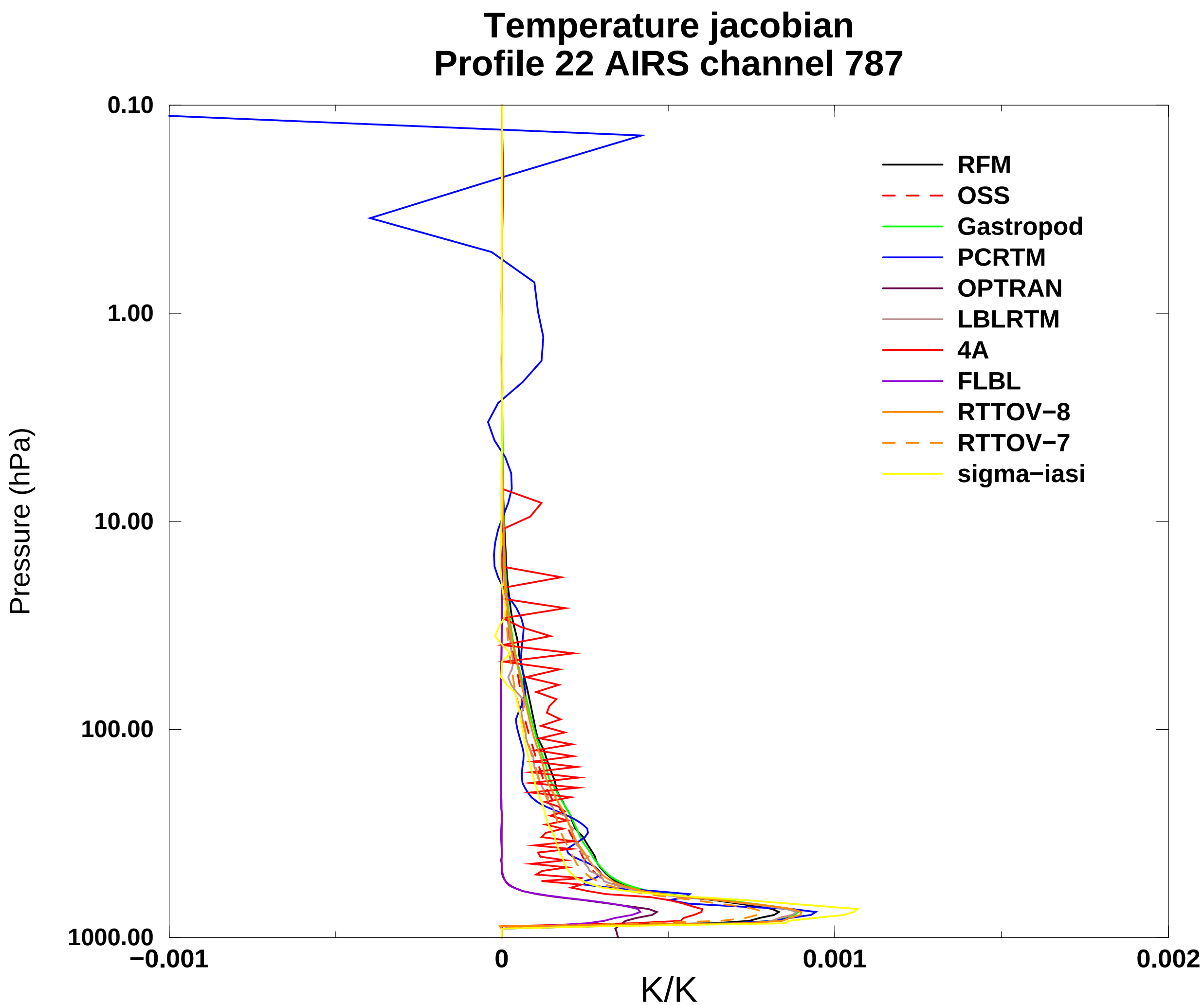
Comparison of water vapour jacobians

Model Key

1 OSS
2 Gastropod
3 PCRTM
4 Optran
5 LBLRTM
6 4A
7 FLBL
8 RTTOV−8
9 RTTOV−7
10 Sigma−IASI



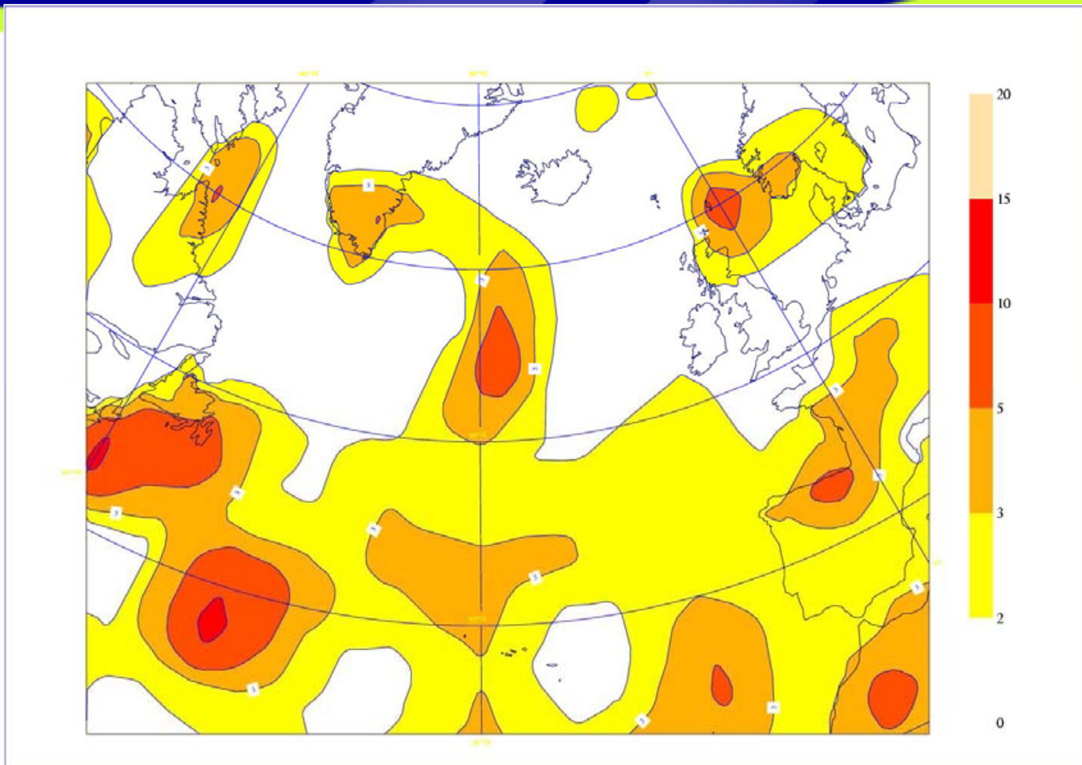
Issues for jacobians



This is a weak temperature jacobian but some of the models (e.g. 4A, PCRTM) have very unphysical structures. Does this matter?

The measure of fit is not ideal for assessing these features.

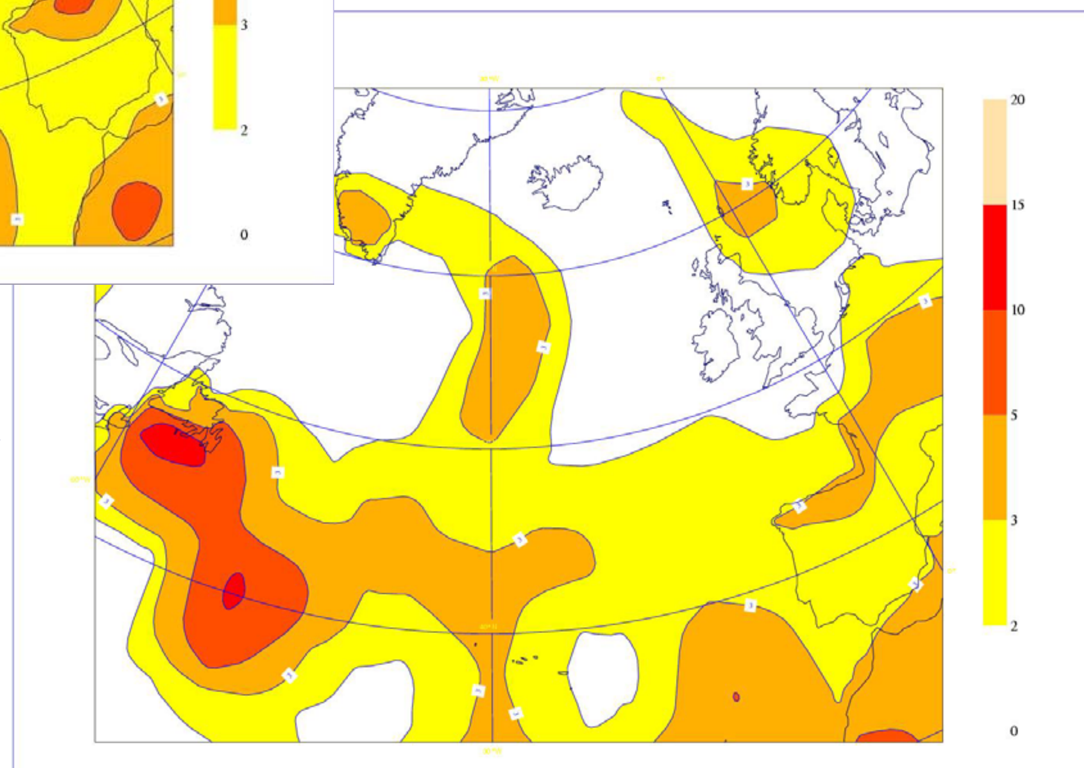
Validation within NWP model



RTTOV-5

Model background error as HIRS-12 radiance

RTTOV-7



HBH^T plotted

Talk overview

- RT models – the basics
- Possible sources of bias in RT models
- Examples of RT model bias
  - Forward model
  - Jacobians
- How can we reduce biases

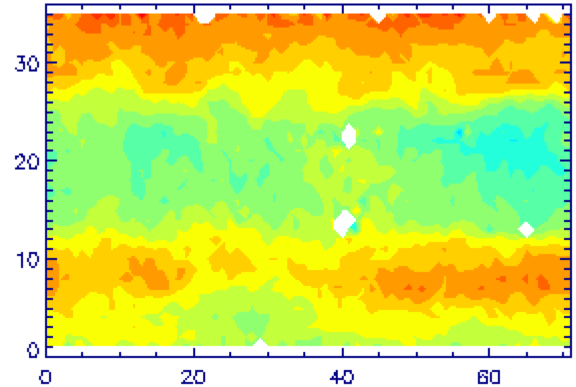
Reducing bias in fast RT models

- For RTTOV a γ factor was developed which scales the channel optical depth and can be useful if the filter response is in error.
- Another constant offset δ can also be employed which is the mean bias for that channel
- It was used with some success on AIRS data by Phil Watts at ECMWF and has been used in the past for HIRS.

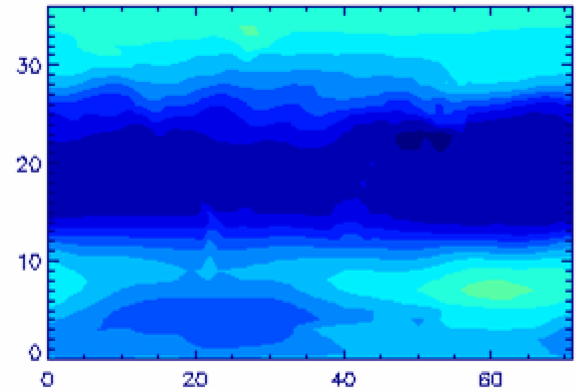
δ,γ - Estimation

1. Monthly mean ob-fg @ 5^o

+ Monthly mean NWP(T,Q,O)



2. Effect of γ=1.05 using NWP



3. Best fit x=[δ,γ] :

$$J = \frac{1}{2}\sum_m \frac{\left(d_m - \left[\delta + \varepsilon(\gamma)_{i,j}\right]\right)^2}{\sigma_o^2} + \frac{1}{2\sigma_b^2}(x - x_b)^2$$

How to reduce RT model bias

- Improve reference LbL model spectroscopy through new measurements (e.g. ARM, satellite, lab, a/c) and theoretical calculations (line mixing, w.v. continuum) *>>Encourage continuing research and measurements*
- Better characterise the channel spectral responses before launch and understand how they will change in orbit. *>>Space agencies conduct adequate pre-launch tests. Retain records of instrument characteristics.*
- Improve fast RT model accuracy, include more variable gases, reflected solar, aerosols etc and more levels*>>Encourage continuing research in fast RT models >> More powerful computers*
- Better surface emissivity models for 'window' channels.
- Better models of cloud and precip *>>Encourage continuing research and measurements*
- As a last resort apply a bias correction.

Thanks

Any questions?