Sources of biases in infrared radiative transfer models

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1. Introduction

Radiative transfer models (RTMs) are at the heart of the assimilation process for satellite radiances in Numerical Weather Prediction (NWP) models enabling the radiances measured by satellite radiometers to also be simulated from NWP model fields. To enable many radiance observations to be used in one assimilation cycle, fast RTMs have been developed since the early 1990's, for example ***RTTOV*** developed by Eyre (1991) and Saunders *et. al.* (1999) and ***OPTRAN*** by McMillin *et. al.* (1995). These fast RTMs can compute the radiances from many channels (~50) within a few milliseconds. They require accurate line-by-line models to 'train' them and so biases in both line-by-line models and the fast RTMs have to be considered when assessing the overall biases due to RTMs. For assimilation purposes the aim of the fast RTM developer should be to reduce the RTM biases to well below the instrument noise for the radiometer being modelled.

In addition to the 'forward' calculation (i.e. computation of radiances given an atmospheric state) the gradient of the RTM with respect to the atmospheric state is also used in the assimilation process to enable the conversion from radiance differences to increments in the model atmospheric state.

This paper will concentrate on biases in infrared RTMs and a companion paper by Bauer (2005) will describe the biases for microwave RTMs although many of the biases are common to both. A brief overview of infrared (IR) RTMs will be given followed by a summary of the possible sources of bias that can exist in RTMs. Examples of these biases and finally a strategy on how to reduce them is also presented. The associated presentation with this paper (Saunders, 2005) gives many more plots illustrating the points made here to which the interested reader is referred.

2. Overview of radiative transfer models

The forward model calculation (i.e. top of atmosphere radiances computed from a given atmospheric state) is given by the expression:

$$\boldsymbol{y} = H(\boldsymbol{X}) \tag{1}$$

where $\boldsymbol{y}$ is the vector of channel radiances (2378 for AIRS), $\boldsymbol{X}$ is the vector of atmospheric state variables of typically dimensions of number of levels × number of active gases and optionally cloud or precipitation profiles plus a few surface variables which can total ~100-300 elements. H is the observation operator referred to here as the forward radiative transfer model.

The gradient of the RT model radiances with respect to the profile variables is also an important component of RTMs and is referred to as the Jacobian and defined as:

$$\mathbf{H}(\boldsymbol{X}) = \frac{\partial \boldsymbol{y}}{\partial \mathbf{X}} \tag{2}$$

where **H** is the Jacobian matrix with dimensions of ***y*** by ***X***. It is the Jacobian which allows increments in 'radiance space' to be mapped back into increments in model state variables, assuming linearity about the model state ***X***, thereby bringing the NWP model state closer to the radiance observations. It is important to note that biases are possible in both the forward model *H* and the Jacobian operator **H** which can adversely affect the assimilation of the radiance observations.

There are several approaches to the formulation of a fast RTM which can be summarised as follows:

- Linear regression (profile ⇒ 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)
- Neural nets (developed at LMD)
- PCA approach for advanced IR sounders (PCRTM)

All these methods have been used with some success although currently the operational NWP centres only use fast RTMs based on linear regression.

Several years ago comparisons of radiative transfer (RT) models for ATOVS (Advanced TIROS Operational Vertical Sounder) infrared and microwave channels were made (Soden et. al., 2000; Garand et. al., 2001) that helped to better define the radiative transfer modeling errors for ATOVS. More recently, with the advent of high spectral resolution infrared sounders e.g. AIRS (Atmospheric InfraRed Sounder) and IASI (Infrared Atmospheric Sounding Interferometer), enhanced versions of the fast ATOVS radiative transfer models have evolved to include simulations of these sounders. The success of the AIRS spectrometer in providing very stable high spectral resolution top of atmosphere infrared radiances has also provided an impetus to improve and assess the RT modeling for atmospheric sounding applications in the thermal infrared.

3. Sources of bias in radiative transfer models

There are a variety of possible sources of bias in RTMs and these are described below. Firstly there are biases in the uunderlying spectroscopy used to run the line-by-line model on which the fast model is based. They can be classified as:

- Line parameters (frequency, strength, width, temp dependence, line mixing….)
- Water vapour and other gases continuum parameterisations
- Non-local thermodynamic equilibrium for shortwave IR channels
- Zeeman splitting for high peaking channels (high stratosphere and above)
- Chlorofluorocarbon absorption

There is research underway to address the uncertainties in most of these parameters either through observations (both in the laboratory and the real atmosphere) or through theoretical calculations of the molecular structure and its interaction with the radiation field.

Secondly there are assumptions made in the line-by-line model itself:

- Quantisation (levels, spectral)
- Line shape formulation
- Combination of line and continuum absorption

These assumptions have to be made in order to make the line-by-line calculation feasible. Some examples of these biases for AIRS simulations are shown in Figure 1.

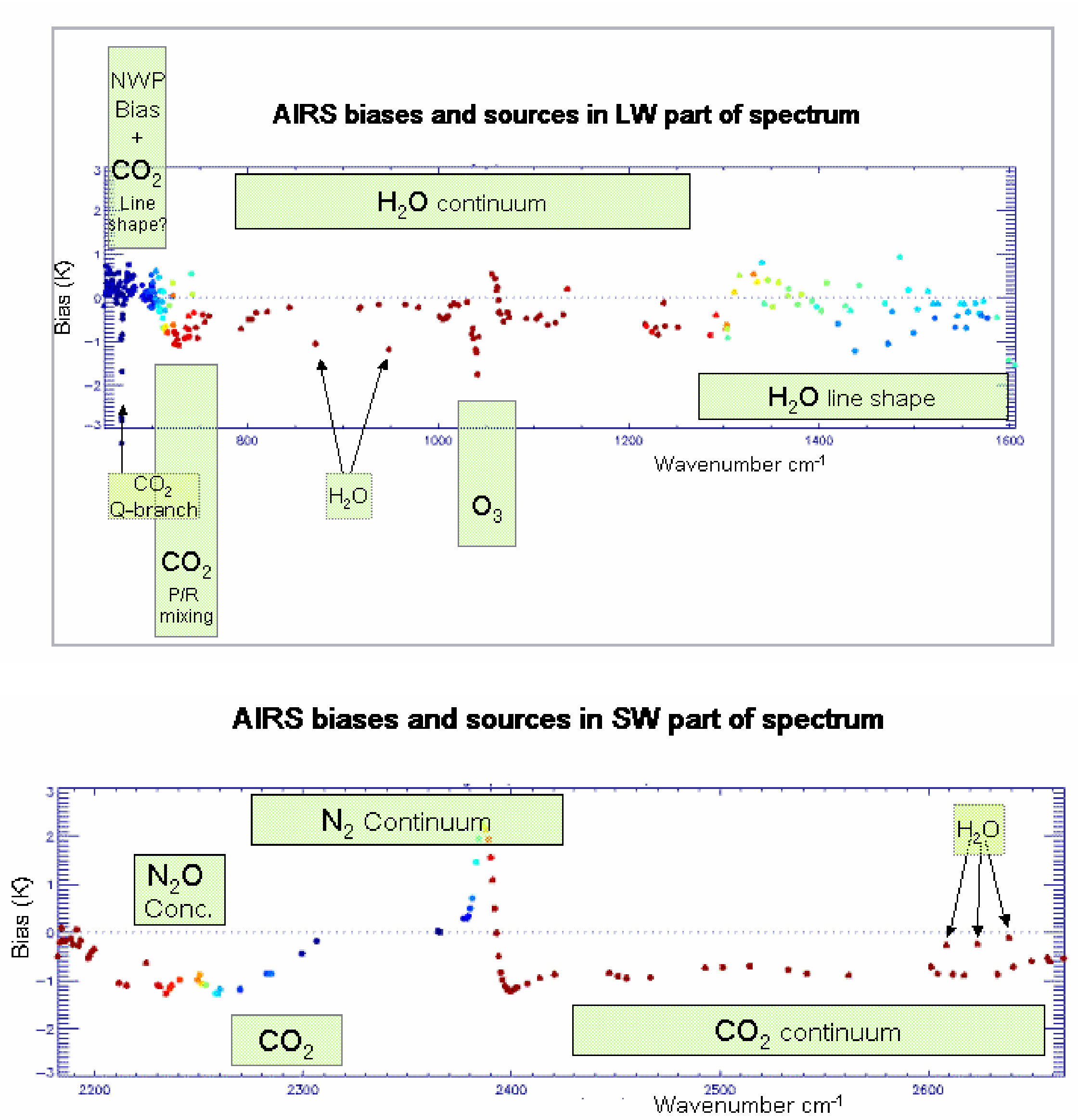

Figure 1. A plot of the difference between the AIRS observation and the simulation from the ECMWF model together with possible sources of the bias (courtesy of Phil Watts).

The next class of possible bias sources originate from the fast models themselves through the parameterisation employed to make the model 'fast'. They can be summarised as:

- Biases in regression or look up table technique
- Profiles used outside of training set limits
- Unrepresentative profile training set

- Insufficient level/layer quantisation
- Plane parallel assumption for oblique viewing angles
- Omission of reflected solar term
- Surface emissivity parameterisation (especially over the land)
- Errors in cloud or precipitation radiative properties (especially for ice crystals)

RT modellers are working on reducing the inherent errors in their model formulation and in adding additional capability to include effects such as reflected solar radiation which introduce biases. In general the fast model errors are now smaller than the underlying spectroscopic errors for the clear sky calculations. Figure 2 demonstrates this for RTTOV calculations of AIRS radiances. Nearly all the biases are well below 0.2K. However Garand et al (2001) did show some of the earlier fast models included in their comparison did have significant biases.

Finally there is another class of bias which is not model based but manifests itself as an RT model bias. This is from errors in the assumed instrument spectral response which although measured before launch can often be different in orbit. The new high resolution spectral sounders (e.g. AIRS, IASI) are less affected by this problem as they can resolve the individual lines and so any errors in the instrument spectral response function can be corrected using the measured data. This bias has recently been demonstrated by comparing MODIS radiances with AIRS radiances convolved over the assumed MODIS spectral response. It was found that for the MODIS band 35 (13.9µm) a shift in the spectral response of +0.8cm^{-1} gave a better fit to the AIRS radiances for all scene temperatures (see Tobin et al 2006).

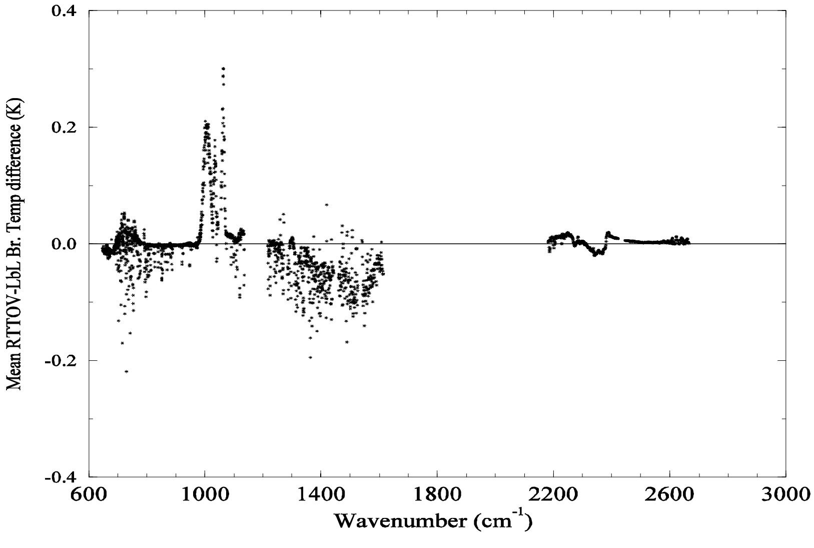

Figure 2. Mean errors of RTTOV-7 for AIRS calculations for a 117 profile dataset.

4. Quantifying forward model biases for AIRS radiative transfer models

To illustrate the biases in the current state of art infrared RTMs an AIRS radiative transfer model comparison was proposed at the first workshop for Soundings from High Spectral Resolution Observations at Madison, Wisconsin in May 2003. The aims of the inter-comparison were defined to be (i) to compare the forward model calculations for all AIRS channels for 49 diverse atmospheric profiles and one tropical Pacific profile coincident with AIRS data; (ii) to compare the profile transmittances for a representative subset of 20 channels; and (iii) to compare Jacobians from each model for these 20 channels. The results from this study would then allow the biases of AIRS fast RT models to be better estimated for retrieval and data assimilation applications. The comparison is documented in Saunders et al (2006) and a few of the results from that paper are presented here to illustrate the biases seen in RTMs for AIRS calculations.

The models which participated in the comparison are given in Table 1 some of which provided both forward model and Jacobian calculations. It is planned to make the model calculations available on the ITWG web site at: http://cimss.ssec.wisc.edu/itwg/groups/rtwg/rtairs.html. As an illustration of the forward model comparisons, Figure 3 shows a portion of the spectrum from 810 to 880 cm^{-1} (AIRS channels 500-700) for the mean profile. Some differences between the different RT models are clear in this part of the spectrum. The obvious differences in the region of channel 590 (845 cm^{-1}) are due to the different way each model treats the absorption due to chlorofluorocarbons, CFCs. There are also significant differences in the 'window' regions between the lines due to differences in the water vapour continuum formulation. Those fast models which are based on a line-by-line model included in the study generally follow the model on which they were trained on. For example, OSS follows LBLRTM closely. RTTOV-7, based on GENLN-2, which is similar to RFM, does follow RFM below 850 cm^{-1} but there are significant differences in the window regions at higher frequencies due to water vapour continuum differences, between the GENLN2 run and the current version of RFM.

Model	**Reference LBL**	**Contact**	**Jacobian**
RTTOV-7	GENLN2	R. Saunders, METO	Yes
RTTOV-8	GENLN2	R. Saunders, METO	Yes
Optran	LBLRTM	Y. Han, NESDIS	Yes
OSS	LBLRTM	J-L. Moncet, AER	Yes
LBLRTM		J-L. Moncet, AER	Yes
RFM	GENLIN2	N. Bormann, ECMWF	Yes
Gastropod	kCarta(1)	V. Sherlock, NIWA	Yes
ARTS		A. von Engeln, Bremen	No
SARTA	kCarta(2)	S. Hannon, UMBC	No
PCRTM	LBLRTM	Xu Liu, NASA, LRC	Yes
4A	STRANSAC	S. Heilliette, LMD	Yes
FLBL		D.S. Turner, IMAA-CNR	Yes
σ-IASI	LBLRTM	G. Massiello, IMAA-CNR	Yes
Hartcode		F. Miskolczi, NASA, LRC	No

Table 1. Models which participated in comparison

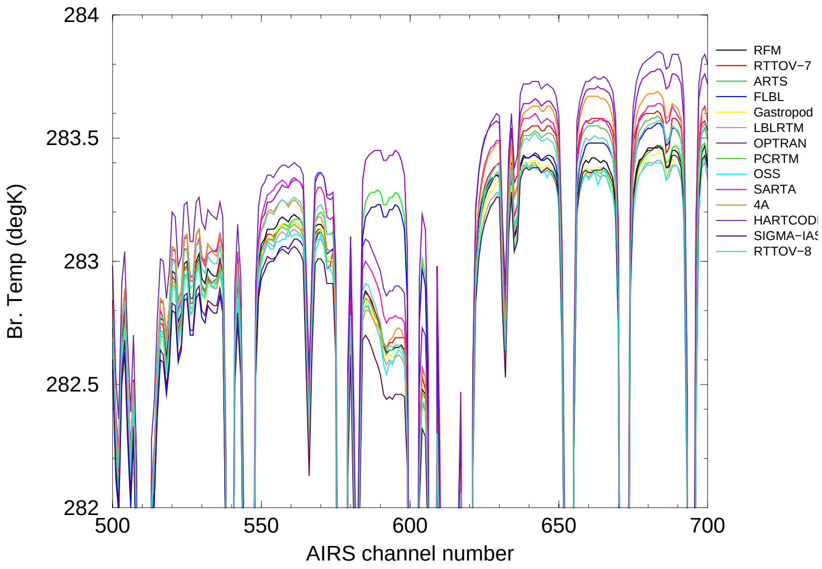

Figure 3. Comparison of AIRS RT models for the mean profile of the 52 set. The differences around channel 590 are due to the different treatment of CFCs in the different models.

To show the mean nadir view differences from RFM of the fast and line-by-line RT models for all channels Figures 4A and 4B show that all the differences when averaged over the 49 profiles are below the 0.1K level except in a few narrow spectral bands. σ-IASI is slightly warmer (~0.05K) than the other models in the atmospheric window and cooler in the short wave CO_2 band. Hartcode has a warm bias in most parts of the spectrum except the 'window' regions. SARTA generally has a cool bias in the water vapour band. *It is important to bear in mind that these biases are with respect to the RFM model and not with respect to an absolute truth. RFM may not provide the best reference in all spectral regions.* With a few exceptions, the differences of the models from RFM are similar. It is worth noting that the differences between line-by-line models (Fig. 4B) are of the same order of magnitude as for the fast models (Fig. 4A) suggesting that the different assumptions made in the spectroscopy and use of different line datasets dominate the RT model biases.

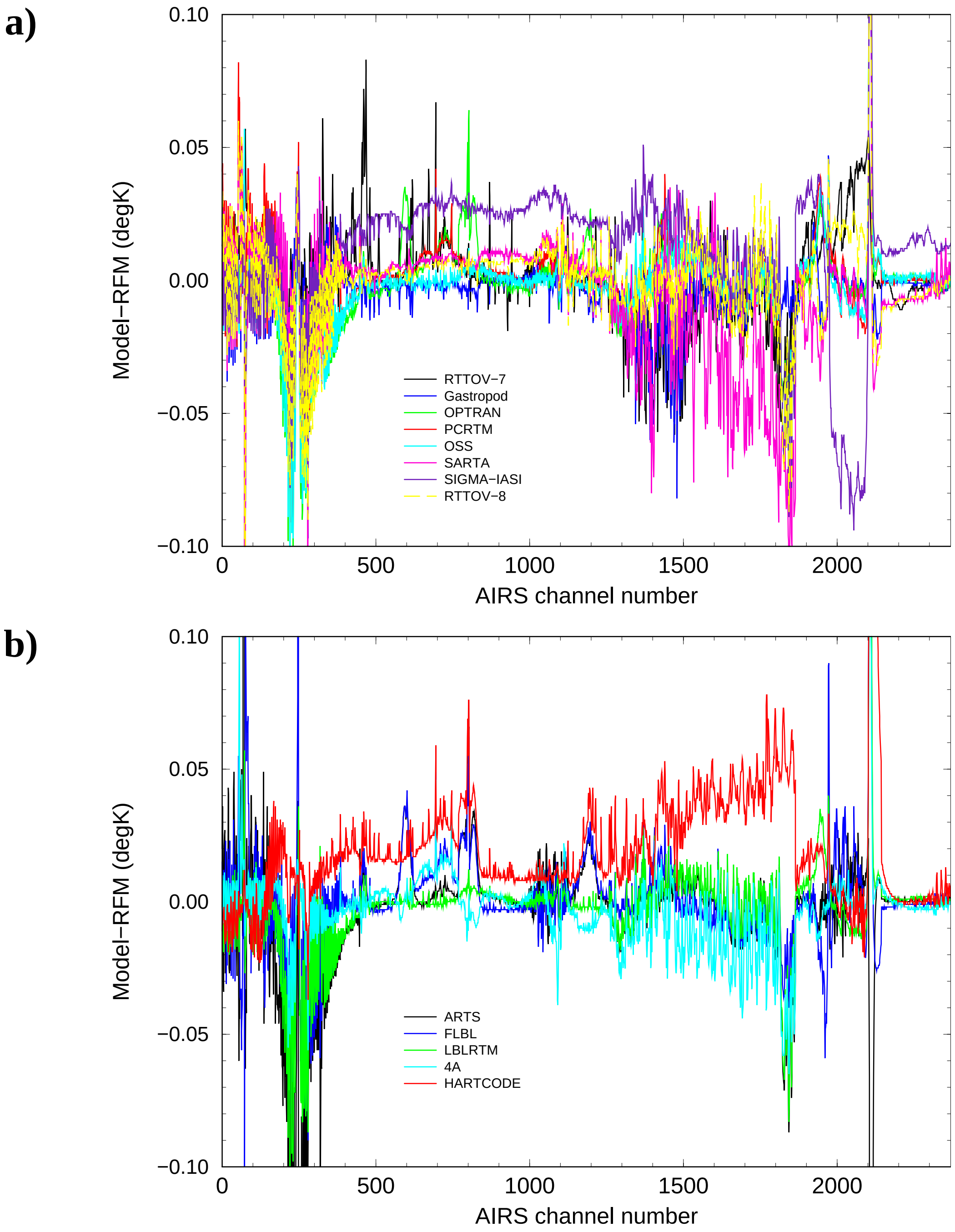

Figure 4. The mean difference from RFM for the 49 diverse profiles for all AIRS channels. The top panel (A) is for the fast models and the bottom panel (B) for the line-by-line models.

The AIRS instrument noise varies from 0.15-0.85K for a scene temperature of 250K. The mean biases over 49 profiles shown in Figure 4 are well below this level and so in general the RTM biases should not significantly affect the forward model calculations for AIRS. Infrared radiometers with broader spectral responses (e.g. HIRS, MODIS, SEVIRI etc) do have larger biases due to the uncertainties in the channel spectral response.

The comparison with observed AIRS radiances was made for one profile over the tropical western Pacific ARM site. The results are summarised in Figure 5 and the first thing to note is the much greater difference between models and observations than between models and models shown in Figure 4, with differences from the observations typically up to ±1K and in some spectral regions up to ±3K. Figure 5 also shows the cool biases of most of the models can be attributed to the deficiencies in the assumed profile as shown by the statistics which exclude the ozone and high peaking CO_2 bands. The RMSD values of all models are reduced, especially for SARTA, when these bands are excluded from the statistics. The good fit of SARTA is not surprising as the spectroscopic parameters it uses were tuned on a dataset that included this profile. RFM the reference model for this study agrees reasonably well except at the CO_2 4.3μm band edge and at the peak of the CO_2 15μm band.

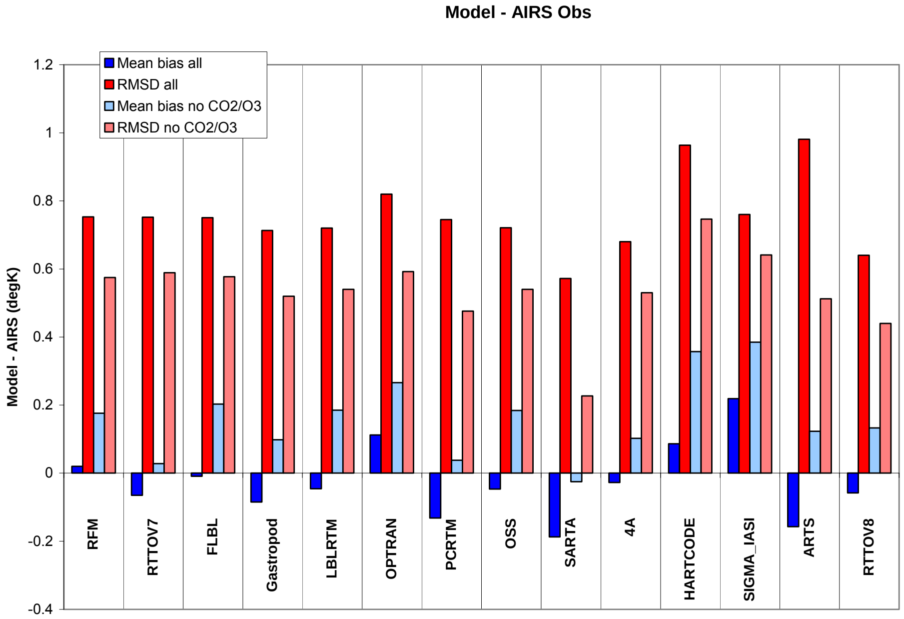

Figure 5. Mean differences averaged over the AIRS spectrum between the model and AIRS observation for one profile over the ARM tropical Pacific site.

5. Quantifying biases in Jacobians for AIRS radiative transfer models

A subset of the models, listed in Table 1, computed temperature, water vapour and ozone Jacobians for the 49 profile dataset. An example of the temperature Jacobians computed is shown in Figure 6(A) which plots the scaled Jacobian (i.e. the Jacobian matrix **H** multiplied by a small temperature increment of -0.1K) for each model for one profile. In general the models are in good agreement. However there are some Jacobians which show more subtle problems which could be detrimental to retrieval and data assimilation applications. One example for AIRS channel 787 is shown in Figure 6(B) which the majority of the models show as a weak smooth peak in the temperature Jacobian close to the ground (~800hPa). Some models however have a more variable structure in the vertical (e.g. 4A, PCRTM) which appears to be unphysical. A key question is whether these features matter for assimilation/retrievals as they are relatively weak in terms of absolute temperature changes. The results of the water vapour and ozone Jacobian comparison is given in Saunders et al (2006) and they show that all the models had problems in computing the Jacobians for particular profiles/channels and so more work is needed to improve the fast modeling of water vapour Jacobians. In particular water vapour Jacobians for cold dry atmospheres (e.g. over Antarctica) were problematic. Ozone Jacobians on the other hand appeared to be well modeled in most cases.

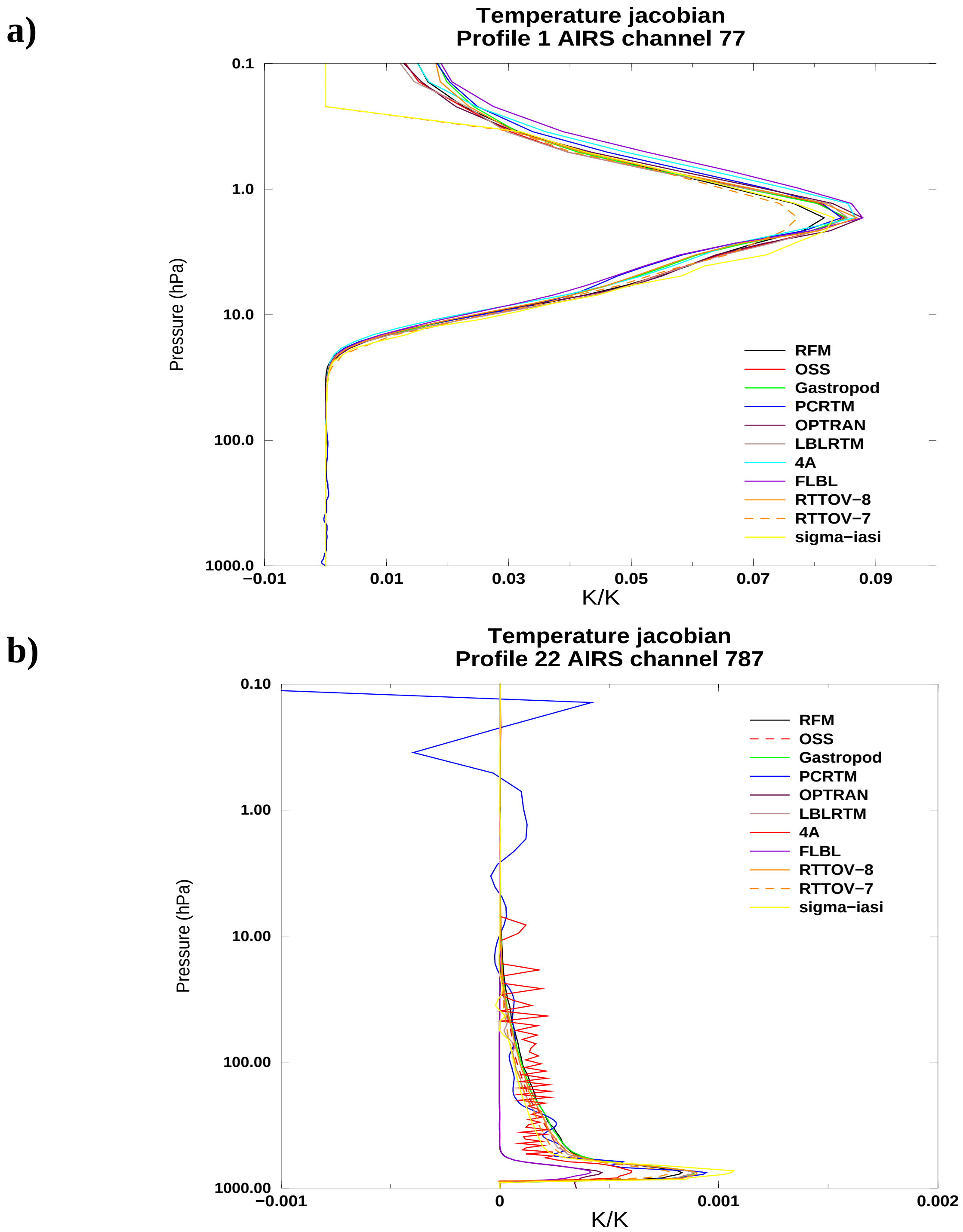

Figure 6. (A) An example of the temperature Jacobian comparison for profile 1 and AIRS channel 77 and (B) a temperature Jacobian for profile 22 and channel 787

6. Recommendations for reducing biases in radiative transfer models

There are several measures that could be taken to reduce the biases we currently see in the radiative transfer models used for radiance data assimilation. They are summarised below:

- Improve reference line-by-line model spectroscopy through new measurements (e.g. ARM sites, satellite radiances, laboratory measurement, aircraft campaigns).
- Continue theoretical calculations to improve spectroscopic parameters (e.g. line mixing, water vapour continuum).
- Better characterise the radiometer channel spectral responses before launch and understand how they will change in orbit.
- Improve fast RT model accuracy by including more variable gases, reflected solar, aerosols etc and more levels for high resolution infrared sounders.
- Improve modelling of surface emissivity for 'window' channels.
- Improve fast models of cloud and precipitation radiative effects.

Continuing research into the above topics should lead to better understood biases in radiative transfer models and hence improved impacts of satellite radiances in NWP models.

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