A simulation study of the impact of AIRS fast model errors on the accuracy of 1D-Var retrievals from AIRS radiances

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Abstract

We characterise the forward model differences between two AIRS fast models participating in the ITWG AIRS fast model intercomparison, Gastropod v0.3.0 (Sherlock et al., 2003) and RTTOV7.1 (Saunders et al., 2002). We then examine the impact of these model differences (and their spectral correlation) on the accuracy of full nonlinear iterative 1D-Var retrievals from synthetic AIRS radiances with and without bias correction using the NESDIS channel selection. Retrieval error covariance matrices and degrees of freedom for signal are estimated for ensembles of 1D-Var retrievals and are compared with predictions from linear theory. The results of the retrieval experiments undertaken suggest that if these fast model differences are representative of real fast model errors, and if bias correction can be performed accurately, the accuracy of temperature and humidity retrievals using the NESDIS channel selection should not significantly compromised by radiative transfer model errors.

Introduction

The results of the ITWG AIRS radiative transfer model intercomparison (Saunders et al., 2003, 2005) indicate that fast model differences are often significantly larger than fast model error estimates[1] derived from comparisons of the fast forward model with its reference (generating) line-by-line model. As a novel extension of this intercomparison study, we ask what the impact on retrieval accuracy would be if these fast model differences were indeed a useful proxy for real forward model errors.

In this paper we characterise the forward model differences between two AIRS fast models participating in the ITWG AIRS fast model intercomparison, Gastropod v0.3.0 (Sherlock et al., 2003) and RTTOV7.1 (Saunders et al., 2002), and compare these differences with independent estimates of transmittance prediction errors for the Gastropod model. We then examine the impact of these model transmittance prediction errors and forward model differences (and their spectral correlation) on the accuracy of full nonlinear iterative 1D-Var retrievals from synthetic AIRS radiances using the NESDIS channel selection.

[1] Referred to hereafter in the context of the Gastropod model as transmittance prediction errors.

The nomenclature which is used to refer to retrievals throughout this paper is as follows: in direct retrievals synthetic spectra are simulated and retrievals are performed with the same radiative transfer model; in cross retrievals synthetic spectra are simulated and retrievals are performed with different radiative transfer models.

Retrieval error covariance matrices and degrees of freedom for signal are estimated for cross retrievals from uncorrected and bias-corrected synthetic radiances, using full and diagonal specifications of the observation error covariance **R**. These error characterisations are compared with predictions from linear theory and with an equivalent error characterisation of direct retrievals using the Gastropod model and its associated transmittance prediction error covariance estimate (Sherlock et al., 2003).

Method

Radiances were simulated with Gastropod and RTTOV for a set of 69 tropical, mid and high latitude profiles drawn from the ECMWF 50-level diverse profile set (Chevallier, 1999). These simulations were used to estimate the bias correction and forward model error covariance for cross-retrievals and combined with realisations of AIRS intrumental noise (Sherlock et al., 2003) to generate synthetic AIRS spectra for the 1D-Var retrievals[2].

Each of the 69 profiles was perturbed (twice) in accordance with the 1D-Var background error covariance **B** (Collard and Healy, 2003) to generate background state vectors for retrievals (138 retrievals in total). 1D-Var retrievals of temperature (on 44 levels between 0.1 and 1013.25 hPa + Tskin) and humidity (on 27 levels between 122 and 1013.25 hPa) were performed using the Met Office 1D-Var v3.1 retrieval software (Collard, 2004) distributed by the Eumetsat NWP SAF.

We calculated the difference between the unperturbed profile (the true atmospheric state), the perturbed background profile and the 1D-Var retrieval for each member of the perturbed profile ensemble and used these differences to make standard statistical estimates of the ensemble background and retrieval error covariance matrices $\mathbf{B}_e$ and $\mathbf{A}_e$. Degrees of freedom for signal (DFS) were estimated using projection onto the eigenvectors $\mathbf{e}_i$ of **B**:

$$\mathrm{DFS} = \sum 1 - \frac{\mathbf{e}_i^{\mathrm{T}} \mathrm{A_e} \mathbf{e}_i}{\mathbf{e}_i^{\mathrm{T}} \mathrm{B_e} \mathbf{e}_i} \qquad (1)$$

to account for modification of the ensemble background error covariance due to 1D-Var profile checks (see Figure 1).

These results were then compared with optimal linear theory for full specification of the observation error covariance **R** (Rodgers, 1990), and suboptimal linear theory for a diagonal approximation to **R** matrix (Watts and McNally, 1988). The linear error covariance for the ensemble of 69 states was estimated (assuming independent errors) by $\mathbf{A}_{\mathrm{L}} = \frac{1}{\mathrm{N}} \sum \mathbf{A}_{\mathrm{L,k}}$ for the k=1 to N=69 atmospheric states.

[2] A realisation of the forward model error was added explicitly to synthetic spectra used in direct retrievals. Forward model error is implicitly included in the cross-retrieval process.

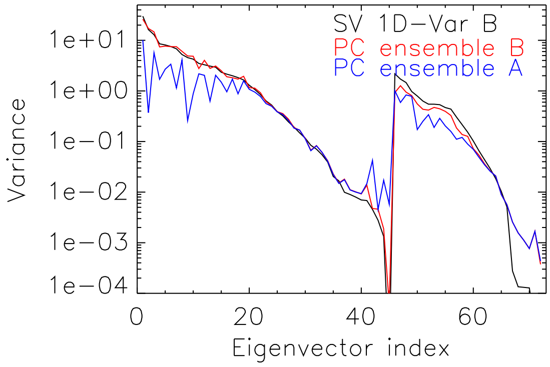

Fig. 1: Example of projection of the ensemble background and retrieval error covariance matrices onto the eigenvectors of **B**. SV are the singular values of the 1D-Var background error covariance matrix **B** and PC are the projection coefficients of the ensemble background and retrieval error covariances $\mathbf{B}_e$ and $\mathbf{A}_e$ onto the eigenvectors of **B**. Eigenvector indices 1–45 correspond to temperature modes, indices 46–72 correspond to humidity modes.

Characterisation of fast model differences

A statistical summary of RTTOV–Gastropod forward model differences estimated from radiance simulations for the 69 atmospheres is given in Figures 2 and 3. Figure 2 illustrates bias and standard deviation of the forward model differences, and Figure 3 illustrates the interchannel correlations in the corresponding estimate of the observation error covariance matrix **R**. Gastropod transmittance prediction error estimates (Sherlock et al., 2003) are illustrated for comparison.

RTTOV–Gastropod forward model difference statistics show:

- significant biases (0.5–2.0 K) in the CO_2 ν_2 and ν_3 bands, isolated water vapour lines in the longwave window region and some channels in the H_2O ν_2 band;
- standard deviations comparable or greater than instrumental noise levels in the O_3 ν_1 and ν_3 bands, the CO_2 ν_3 band, the shortwave window region, the H_2O ν_2 band and water vapour line centres in longwave window region;
- significant off-diagonal contributions to **R** across most of the spectrum because fast model differences are comparable with or greater than instrumental noise levels in many spectral intervals.

Most of these significant differences are attributable to differences in spectroscopy (Sherlock, 2004), although additional error sources – e.g. differences in stratospheric extrapolation assumptions and fast model transmittance prediction errors in the H_2O ν_2 and O_3 ν_1 and ν_3 bands – almost certainly also play a role.

Characterisation of retrieval accuracy

Direct retrievals

The impact of Gastropod transmittance prediction errors on retrieval accuracy has been quantified for direct retrievals using the NESDIS channel set. Estimated retrieval standard deviations and DFS are illustrated and tabulated in Figure 4 and Table 1 respectively.

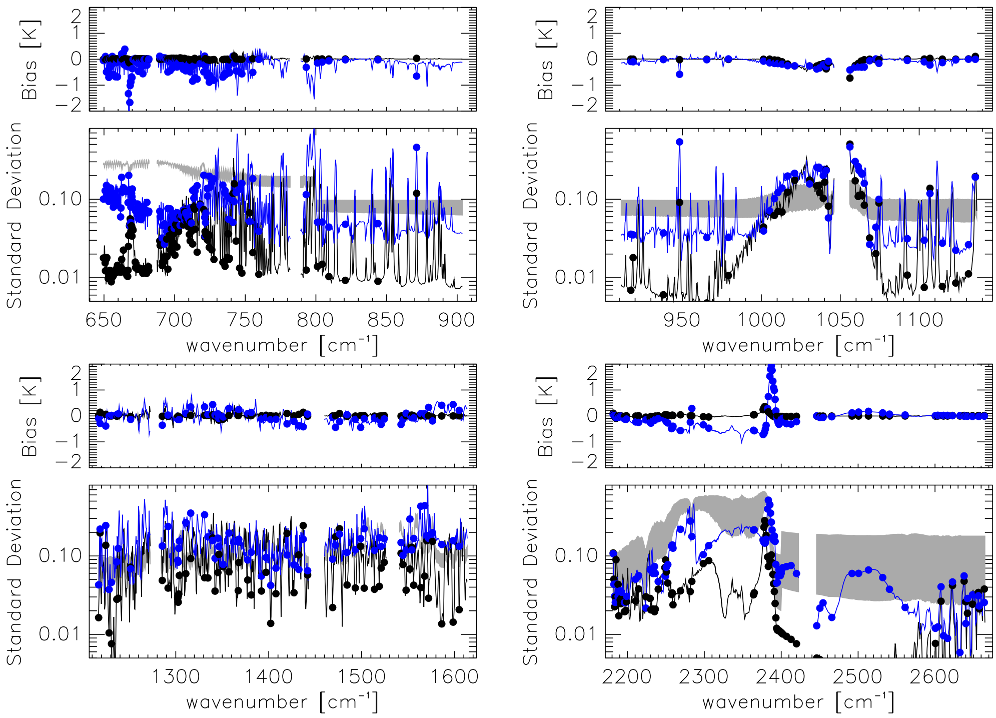

Fig. 2: Bias and standard deviation of Gastropod forward model errors (black) and Gastropod–RTTOV differences (blue) for the AIRS instrument. Lower bound estimates of AIRS instrumental noise levels for a representative range of scene temperatures are illustrated with grey shading. The NESDIS channel set is indicated with filled circles.

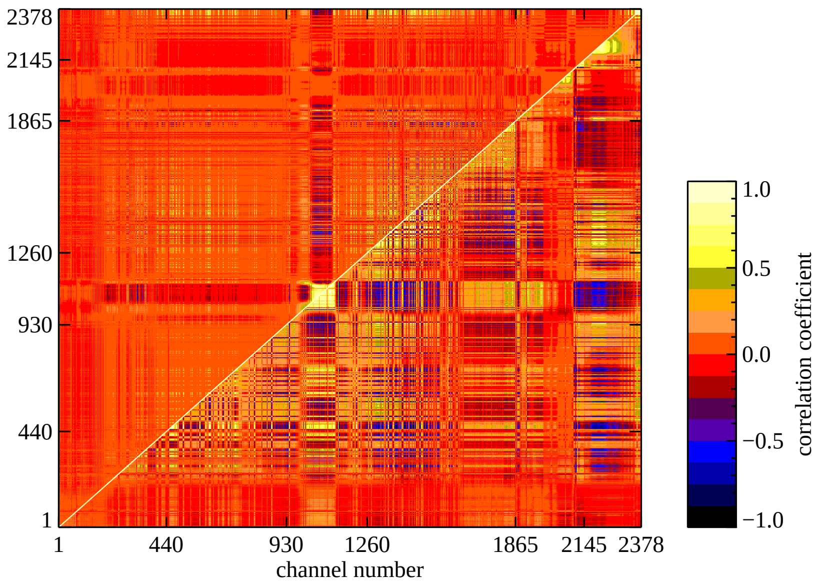

Fig. 3: Correlation coefficients for the observation error covariance matrix **R** = **E** + **F**. Upper triangle, correlations for the case where **F** is the Gastropod forward model error covariance matrix. Lower triangle, correlations for the case where **F** is the forward model error covariance matrix derived for the RTTOV–Gastropod differences.

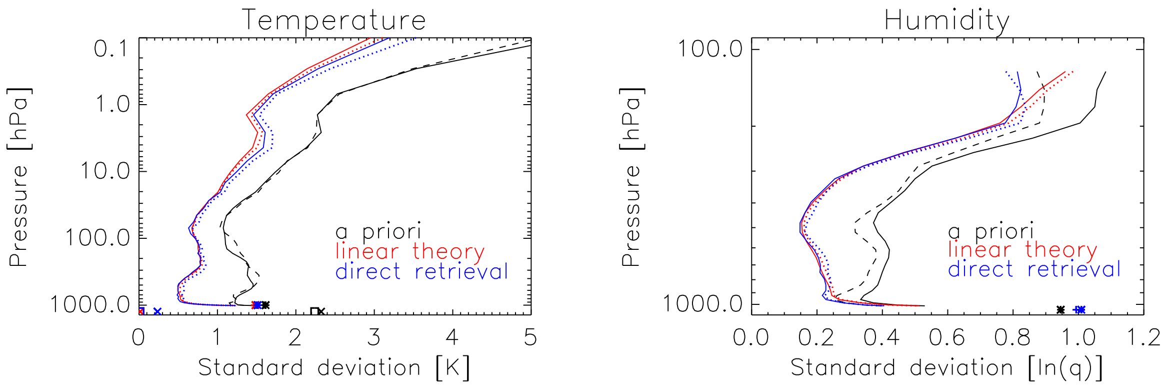

Fig. 4: Retrieval standard deviations derived from linear theory (red) and 1D-Var direct retrievals (blue) for full (solid) and diagonal (dotted) approximations to the forward model error covariance matrix. The diagonal elements of the a priori error covariance matrix (solid black) and the retrieval background ensemble (dashed black) are illustrated for reference.

Table 1: Summary of degrees of freedom for signal (DFS) derived from linear theory and 1D-Var direct retrievals. ret identifes the model used in retrievals. ref identifies the model used to simulate the spectra (G=Gastropod, R=RTTOV). N_{ret} is the number of converged 1D-Var retrievals (from 138 member ensembles).

Direct retrievals				N_{ret}		DFS	
	ret	ref	bias	full **R**	diag **R**	full **R**	diag **R**
1D-Var	G	G	-	138	134	16.1	14.3
Linear	G	-	-	-	-	17.6	16.7

Temperature and humidity retrieval errors for the ensemble of 1D-Var retrievals with full specification of **R** are generally in good agreement with the predictions from optimal linear theory. The DFS estimated for the 1D-Var retrievals with full specification of **R** are 1.5 DFS lower than the prediction from linear theory. This reduction is in part the result of the reduction in the ensemble background humidity error covariance due to 1D-Var profile checks (see also Figure 1), but the slightly higher 1D-Var stratospheric temperature retrieval errors also contribute.

Neglecting forward model error correlations leads to a small reduction in retrieval accuracy and slightly poorer convergence characteristics. Suboptimal linear theory gives a reasonable qualitative description of error inflation in stratospheric temperature and upper tropospheric humidity retrievals, but underestimates the actual error inflation and reduction in DFS for the 1D-Var retrieval ensemble. We attribute this to the effects of Jacobian errors, which are not accounted for in the suboptimal linear error covariance estimate.

Overall however, these 1D-Var simulations indicate that the effects of transmittance and Jacobian errors and their correlation do not have significant impact on retrieval accuracy when using the Gastropod model with the NESDIS channel selection.

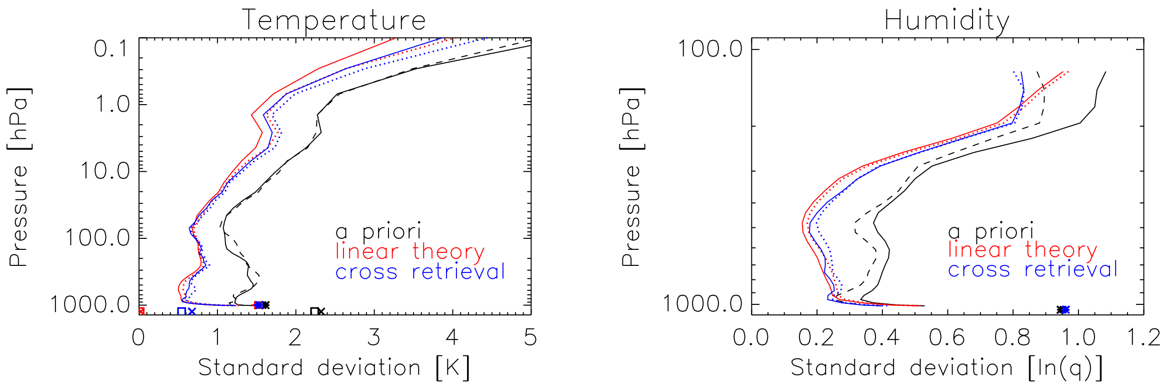

Fig. 5: Retrieval standard deviations derived from linear theory and bias corrected 1D-Var cross retrievals for full and diagonal approximations to the forward model error covariance matrix. All line styles are as defined in Figure 4.

Cross retrievals

The impact of RTTOV-Gastropod model differences on retrieval accuracy has been quantified for cross retrievals using the NESDIS channel set. Retrievals have been performed both with bias correction (simulated radiances are corrected for the ensemble mean forward model differences illustrated in Figure 2) and without bias correction. Estimated retrieval standard deviations for bias corrected cross retrievals[3] are illustrated in Figure 5. DFS for retrievals with and without bias correction are tabulated in Table 2.

With bias correction and full specification of **R**, there is a reduction in the accuracy of stratospheric temperature and tropospheric humidity retrievals (and a corresponding loss of 2.5–3.5 DFS) compared with direct retrievals. These reductions are more important when retrievals are performed with a diagonal approximation to **R** (and result in the loss of a further 2 DFS), but do not compromise the overall benefit of the radiance assimilation substantially. As in the case of direct retrievals, these results are in reasonable qualitative agreement with the predictions of linear theory.

On the other hand, if no bias correction is performed there is substantial loss of accuracy even with full specification of **R**, and essentially no benefit to assimilation with a diagonal approximation to **R** (the reader is referred specifically the third and fouth rows of Table 2).

Conclusions

Forward model differences have been characterised for two fast models participating in the ITWG AIRS radiative transfer model intercomparison. Calculated forward model differences, and their associated interchannel correlations, are substantially larger than independent estimates of fast model transmittance prediction errors, and are comparable with AIRS instrumental noise in several regions of the AIRS spectrum.

[3]Cross retrieval error characteristics are similar for the two sets of cross retrieval, so only one set (RTTOV retrievals from Gastropod simulations) is illustrated in Figure 5.

Table 2: Summary of degrees of freedom for signal (DFS) derived from linear theory and 1D-Var cross retrievals. The T/F bias logical indicates whether bias correction has been applied or not. All other parameters are as defined in Table 1.

Cross retrieval				N_{ret}		DFS	
	ret	ref	bias	full **R**	diag **R**	full **R**	diag **R**
1D-Var	R	G	T	133	133	13.5	11.6
	G	R	T	130	131	12.4	10.8
	R	G	F	131	123	7.3	0
	G	R	F	130	106	8.9	2.2
Linear	G	-	-	-	-	17.3	15.1

We have quantified the impact of these model differences on the accuracy of retrievals using the NESDIS channel set. The results of the retrieval experiments undertaken for a representative ensemble of atmospheric states with bias correction suggest that if these fast model differences are representative of real fast model errors, and if bias correction can be performed accurately, the accuracy of temperature and humidity retrievals using the NESDIS channel selection should not significantly compromised by radiative transfer model errors.

The accuracy of retrievals with a given channel selection depends critically on other aspects of the assimilation system (bias correction, specification of the observation error covariance matrix). For this reason 1D-Var simulation studies of the type undertaken here have a role to play in estimating and minimizing the impact of suboptimal retrieval choices in operational data assimilation systems.

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