ESTIMATION OF FAST RADIATIVE TRANSFER MODEL ERRORS AND THEIR IMPACT ON RETRIEVAL ACCURACY FOR IASI

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Abstract

This paper gives a quantitative summary of the forward model and Jacobian error characteristics of RTIASI, a fast radiative transfer model for IASI. The impact of these errors on temperature and humidity retrieval accuracy is examined within a linear retrieval framework to assess the adequacy of the current version of RTIASI, bearing in mind the requirements for both accuracy and efficiency in the variational data assimilation process. The increase in retrieval error and the decrease in the number of degrees of freedom for signal are quantified for two suboptimal retrieval scenarios: 1. retrievals performed using block diagonal and diagonal approximations to the forward model error covariance matrix and 2. retrievals performed with incorrect Jacobians. The results highlight the importance of accurate radiative transfer calculations for the H_2O ν_2 band.

1 INTRODUCTION

A comparison of two fast radiative transfer models for IASI, PFAAST (Hannon et al., 1996) and RTIASI (Matricardi and Saunders, 1999), has been undertaken to assess their suitability for use in a numerical weather prediction data assimilation system (Sherlock, 2000). As it is anticipated that IASI Level 1C radiances will be assimilated within a variational framework, both the forward model error covariances and the accuracy of modelled Jacobians have been examined.

While the fast model errors are generally acceptable – i.e. at or below instrumental noise levels – both models have specific problems or limitations which must be solved before integration into an operational data assimilation system is feasible. RTIASI, the model currently used in the development of a 1-D Var scheme at the Met. Office, has good error characteristics in the CO_2 bands used for temperature sounding and has the capability to generate analytic Jacobians. However, water vapour absorption is considerably less well modelled: forward model errors in the window regions and in the H_2O ν_2 band are larger than those obtained with the PFAAST model, and these errors are highly correlated. Moreover, significant errors were found in modelled water vapour Jacobians.

In this paper we give a quantitative summary of RTIASI-specific forward model and Jacobian error characteristics. We examine the impact of these errors on retrieval accuracy within a linear retrieval framework to assess the adequacy of the current version of RTIASI, bearing in mind the requirements for both accuracy and efficiency in the data assimilation process. The increase in retrieval error (standard deviation) and the decrease in the number of degrees of freedom for signal are quantified for two sub-optimal retrieval scenarios: 1. retrievals performed using block diagonal and diagonal approximations to the forward model error covariance matrix and 2. retrievals performed with incorrect Jacobians. The analysis presented here is a direct application of the methodology used by Watts and McNally (1988) to assess the sensitivity of a minimum variance retrieval scheme to the values of its principal parameters. The estimation of degrees of freedom for signal follows the method outlined by Rodgers (1996) .

Because water vapour absorption is less accurately modelled in RTIASI, two versions of the water vapour transmittance predictor scheme are considered. These are the November 1999 RTIASI Version 1 release three-regime and single-regime water vapour predictor schemes and are denoted version 1.3 (v13) and version 1.1 (v11) respectively. Revised CNES instrumental noise estimates (Cayla, 1999) have been used in the evaluation of the observation error covariance matrix and subsequent calculation of all results presented here. Sensitivity to instrumental noise levels is discussed. Similarly, all results presented here are based on calculations for the AFGL tropical atmosphere. Sensitivity to atmospheric state is described. A single *a priori* error covariance matrix – the ECMWF 40-level model background error covariance, interpolated onto RTIASI model levels (Collard, 1998) – has been used throughout. Thus results apply to retrievals/analyses within an operational/NWP framework where the *a priori* estimate of atmospheric state is reasonably well known, particularly for the tropospheric temperature field.

2 FORWARD MODEL ERROR CHARACTERISTICS AND IMPACT ON RETRIEVAL ACCURACY

2.1 Forward model error covariance estimates

Forward model errors have been estimated by comparing the Level 1C radiances predicted by the fast model with those calculated using the GENLN2 line-by-line code. RTIASI-GENLN2 radiance differences have been evaluated for a set of 117 diverse atmospheric states, as represented by the ECMWF 50-level forecast model (Chevallier, 1999), and processed to generate estimates of the full forward model error covariance matrix.

In Figure 1 we illustrate the standard deviation of the RTIASI-GENLN2 radiance differences, expressed as an equivalent brightness temperature difference[1] for a scene temperature of 280 K, as a function of wavenumber for the version 1.1 and version 1.3 models. Revised CNES instrumental noise estimates are also illustrated for reference. Note the low standard deviations in the CO_2 ν_2 and ν_3 bands and the structured and relatively high standard deviations in the 8–12 μm atmospheric window regions and the H_2O ν_2 band. The v11 and v13 RTIASI model errors differ in the H_2O ν_2 band: v11 model

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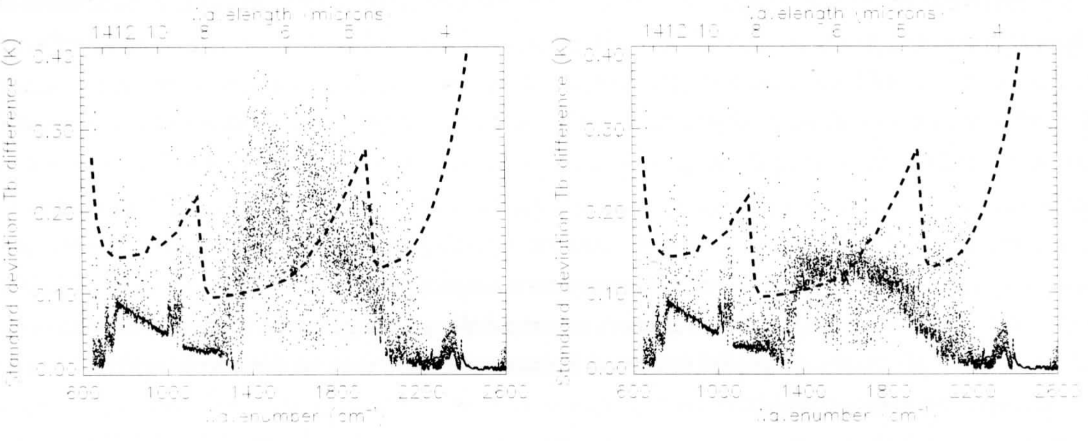
[1] $\sigma_{\mathrm{TB}}(\nu) = \sigma_{\mathrm{R}}(\nu)\left(\left.\frac{\partial B}{\partial T}\right|_{T_s=280\mathrm{K}}\right)^{-1}$ where $B \equiv B(\nu, T)$ is the Planck function.



version 1.1

version 1.3

Figure 1: Forward model error (standard deviation) for the RTIASI version 1.1 (lefthand panel) and version 1.3 (righthand panel) models illustrated as a function of channel wavenumber. Radiance errors have been converted to an equivalent brightness temperature difference for a scene temperature of 280 K in order to compare forward model errors with Level 1C NEΔT_B IASI instrumental noise estimates. Revised CNES instrumental noise estimates are traced with the dashed curve. Statistics are derived for 117 spectra simulated using atmospheric profiles selected from the 50-level ECMWF profile set.

errors are comparable with or greater than v13 model errors over this spectral interval.

Under the (reasonable) assumption that forward model errors and instrumental noise are uncorrelated, the observation error covariance O is given by the sum of the instrumental error covariance E and the forward model error covariance matrix F: O = E + F. With the exception of the H_2O ν_2 band, the random component of forward model error is significantly less than the instrumental noise: forward model errors typically make contributions of 1/5 to the diagonal elements of the observation error covariance matrix. Forward model error contributions to the observation error covariance are significantly higher within the H_2O ν_2 band: contributions are of the order of 1/2 and 3/4 for the v13 and v11 models respectively.

Forward model errors present a high degree of correlation within spectral bands and within the window regions. Stong correlations are also found between errors in the two CO_2 bands and between errors in the different window regions. The spectral structure of forward model error correlations suggests that with some reordering of channels (regrouping CO_2 bands and regrouping the window regions) a block diagonal specification of the forward model error covariance would capture most of the relevant error correlation structure[2].

Inter-channel instrumental noise correlations are localised spectrally – only correlations out to fourth nearest neighbours (1.5 cm^{-1}) are significant for practical purposes. Thus long range measurement error correlation structures are governed by the forward model error contribution to the observation

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[2] Each block specifies the covariance within a limited spectral interval (e.g. spectral bands and window regions). Correlations with channels outside the given spectral interval are neglected.

error covariance matrix. In the H_2O ν_2 band, where forward model errors and instrumental noise are comparable in magnitude, correlated forward model errors make significant contributions to the off-diagonal elements of the observation error covariance matrix.

We now quantify the retrieval errors associated with the sub-optimal but computationally advantageous block-diagonal and diagonal approximations to the forward model error covariance matrix. Because we seek to quantify the effect of neglecting long range error correlations on retrieval accuracy, the computational load of impact studies can be lightened by using a subset of 1057 channels – every eighth channel – in calculations. This channel selection does not significantly modify the sampling of absorption regimes/features, so retrieval error covariances are essentially unchanged apart from a small reduction in absolute accuracy. At the resampled resolution instrumental noise may be considered uncorrelated and is specified by a diagonal matrix.

2.2 Impact of simplifying approximations to the full forward model error covariance matrix on retrieval accuracy

If we consider an ensemble of retrievals where an observation error covariance O has been assumed in the evaluation of the gain matrix W, but the true observation error covariance is O', then the retrieval error covariance is given by (Watts and McNally, 1988):

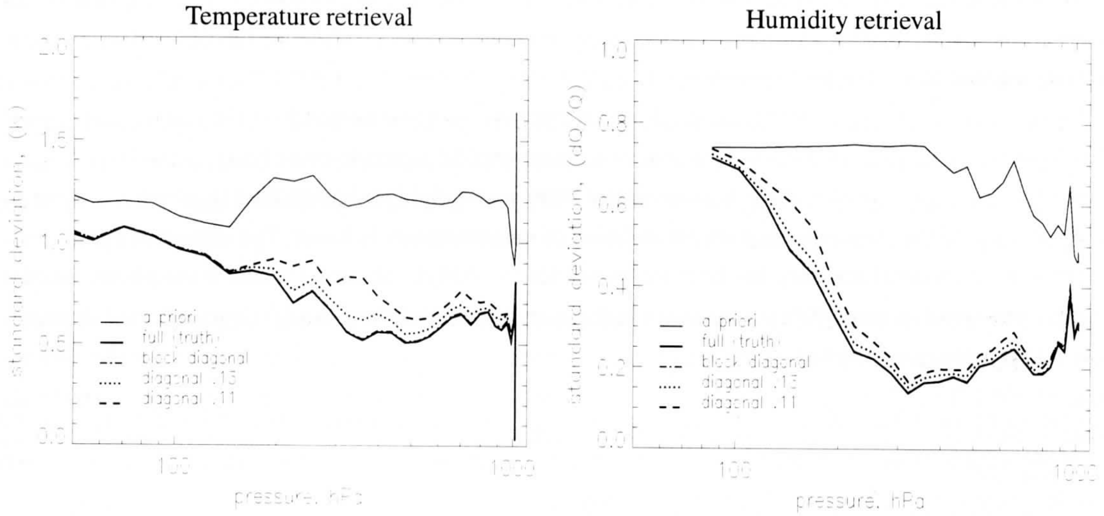
$$A' = A + W(O' - O)W^T, \tag{1}$$

where A is the error covariance for the optimal retrieval scenario. Errors in the assumed observation error covariance matrix give an additional contribution to the propogated measurement error – the minimum variance solution or optimal retrieval requires $O{=}O'$.

In Figure 2 we illustrate the *a priori* and *a posteriori* retrieval standard deviations for temperature and humidity for full, block and diagonal approximations to the forward model error covariance matrix F. Retrieval errors are practically identical for the two full forward model error covariance scenarios and only the v13 full F retrieval standard deviations are illustrated here.

It is immediately apparent that the block diagonal approximation does capture all relevant correlation structures. The diagonal approximation gives a small, arguably tolerable degradation in retrieval accuracy for the v13 model. Larger increases in errors in mid and upper tropospheric temperature retrievals and upper tropospheric humidity retrievals are found in the case of the v11 model. In these regions the fraction of unexplained variance can increase by up to 25% for temperature retrievals and by up to 10% for humidity retrievals.

In Table 1 we present the degrees of freedom for signal (Rodgers, 1996) for retrievals using full, block and diagonal approximations to the forward model error covariance matrix for versions 1.1 and 1.3 of the RTIASI model. The reduction of 0.1 degrees of freedom for signal (full F specification) in passing from the v13 to the v11 model is negligible for all practical purposes. Similarly, the reduction of 0.2 degrees of freedom associated with the block diagonal approximation to the forward model error covariance matrix is negligible for all practical purposes. The diagonal approximation to F leads to a



Temperature retrieval

Humidity retrieval

Figure 2: *A priori* and *a posteriori* standard deviations for temperature and humidity for retrievals using full, block and diagonal approximations to the forward model error covariance matrix. AFGL tropical atmopshere.

Model	DFS Full F	DFS Block F	DFS Diag. F
version 1.1	21.5	21.3	18.2
version 1.3	21.6	21.4	20.1

Table 1: Degrees of freedom for signal for retrievals using a full forward model error covariance specification and block and diagonal approximations to the full F matrix. AFGL tropical atmosphere.

loss of 3.2 degrees freedom for signal for the v11 model, and a loss of 1.5 degrees of freedom for signal for the v13 model. These changes can usefully be compared with the losses in degrees of freedom for signal due to forward model error: for this instrumental noise scenario there are 23.0 degrees of freedom for signal for retrievals with a 'noiseless' forward model, so forward model errors in the H_2O ν_2 band give rise to a loss of at most 1.4 degrees of freedom for signal. Thus the diagonal approximation to the forward model error covariance effectively doubles (quadruples) the loss of information due to forward model errors.

Both measurement information content and the impact of approximations to F on retrieval accuracy do depend on atmospheric state. In colder drier atmospheres the signal-to-noise levels in the H_2O ν_2 band decrease. As a consequence these measurements carry less weight in determining tropospheric analysis increments and the error reduction on assimilation of measurements is lower. The impact of approximations to F on retrieval accuracy has been examined for the AFGL sub-arctic winter atmosphere. Similar results are found in terms of the forward model dependencies and the altitude ranges affected, however the additional errors in temperature retrievals due to the diagonal F approximation are significantly reduced ($<$0.1 K at all levels for both models). Conversely, errors in upper tropospheric humidity retrievals due to the diagonal approximation are greater – the fraction of unexplained variance can increase by as much as 30%.

The magnitude of errors associated with the diagonal approximation to the forward model error covariance matrix increase with decreasing instrumental noise levels i.e., as the relative contribution of forward model error to the observation error covariance matrix increases. For AIRS-type noise levels (0.05 K NEΔT$_B$ across the H_2O ν_2 band) the diagonal approximation leads to degradations of 0.1 to 0.2 K and 5 to 10% in dq/q for v13 tropospheric temperature and humidity retrievals, and to degradations of 0.2 to 0.4 K and 10 to 30% in dq/q for v11 tropospheric temperature and humidity retrievals. For the AFGL tropical atmosphere, this increase in retrieval error corresponds to a decrease (from a full F DFS of $\sim$27.5) of 5.5 and 9 degrees of freedom for signal for the v13 and v11 models respectively .

To conclude, the current magnitude of RTIASI forward model errors in the H_2O ν_2 band is such that a diagonal approximation to the forward model error covariance matrix, neglecting forward model error correlations, leads to suboptimal retrievals of mid and upper tropospheric temperature and humidity. For IASI instrumental noise levels the decrease in retrieval accuracy remains tolerable, even for the version 1.1 model. The diagonal approximation to the forward model error covariance matrix compromises the benefit of the very low AIRS-type instrumental noise levels, although never leads to retrieval errors which are larger than the uncertainty in the *a priori* estimate of atmospheric state, at least for the cases considered here. A block diagonal approximation captures all relevant forward model error correlation structure in all cases.

3 IMPACT OF JACOBIAN ERRORS ON RETRIEVAL ACCURACY

3.1 Jacobian error estimates

RTIASI v11 and v13 model tangent linear Jacobians have been compared with finite difference (brute force) Jacobians calculated using the GENLN2 line-by-line code for the AFGL tropical and sub-arctic winter atmospheres on three spectral sub-intervals: 645–800 cm^{-1}, 885–995 cm^{-1} and 1300–1450 cm^{-1}. These sub-intervals were selected based on previous information content/channel selection studies (Rodgers 1996, Collard 1999 private communication) to reduce the computational load of the line-by-line Jacobian calculations. Examples characteristic of the accuracy of the fast model Jacobians are illustrated in Figure 3.

Temperature Jacobians are well modelled by both versions of the RTIASI code: the maximum relative error in modelled Jacobians (in regions of maximum sensitivity) are typically less than 5% in all spectral intervals and for both atmospheres considered. Water vapour Jacobians are considerably less well modelled. In the AFGL tropical atmosphere version 1.3 water vapour Jacobians may be in error by 10 to 30%. Version 1.1 water vapour Jacobians are better modelled: errors are generally less than or of the order of 10%. In the AFGL sub-arctic winter atmosphere the version 1.3 water vapour Jacobians are more accurately modelled: maximum Jacobian errors vary between 5 and 10%. Version 1.1 performance is poorer: water vapour Jacobians are typically in error by 20%.

3.2 Impact on retrieval accuracy

If an ensemble of retrievals are performed assuming a Jacobian $\nabla_x\mathcal{H}$ when in fact $\nabla_x\mathcal{H}'$ is the true Jacobian, the retrieval error covariance is given by (Watts and McNally, 1988):

$$A' = (I - W\nabla_x\mathcal{H}')B(I - W\nabla_x\mathcal{H}')^T + WOW^T. \tag{2}$$

Retrieval errors are increased through incorrect mapping of the *a priori* information and incorrect interpretation of measured information – the optimal (minimum variance) solution requires $\nabla_x\mathcal{H} = \nabla_x\mathcal{H}'$.

In Figure 4 we illustrate retrieval standard deviations for the reference scenario – optimal retrieval (no Jacobian errors) on the three spectral sub-intervals (thick solid line) – and the three sub-optimal gain scenarios; retrieval in the presence of temperature Jacobian errors (dot-dashed line), v11 water vapour Jacobian errors (dashed line) and v13 water vapour Jacobian errors (dotted line). As previously, the uncertainty in the *a priori* estimate of atmospheric state is illustrated with the thin solid curve.

Errors in temperature Jacobians have a negligible impact on retrieval accuracy in all cases, suggesting a target accuracy for fast model Jacobians of the order of 5%. While water vapour Jacobian errors degrade the accuracy of the humidity retrieval, the benefit of the assimilation process is not seriously compromised. This is not the case for temperature retrievals: errors in modelled water vapour Jacobians give a marked increase in retrieval standard deviation, and in the case of the v13 model there is no significant error reduction in the 200–400 hPa region. Note errors in water vapour Jacobians de-

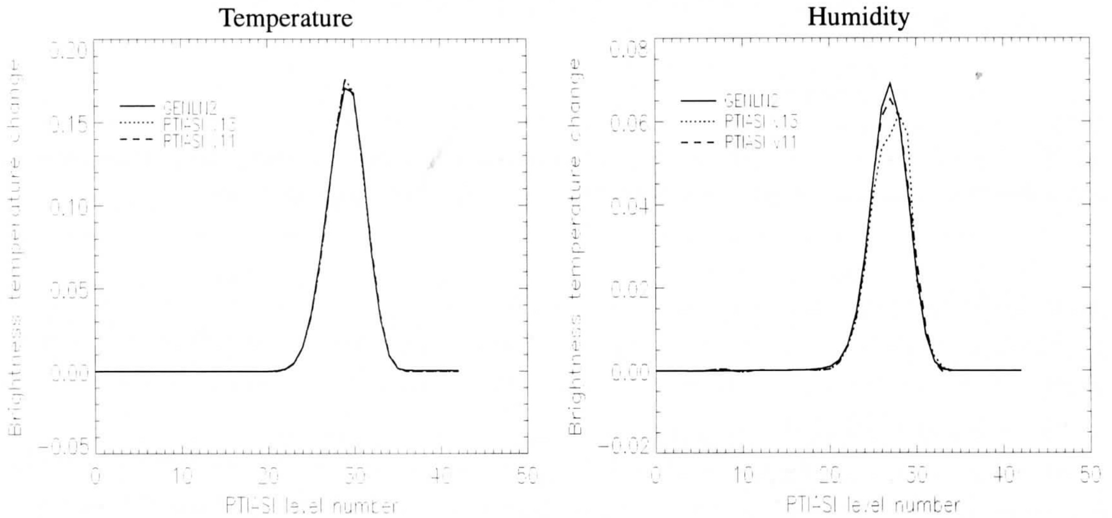


Figure 3: Left-hand panel: brightness temperature change for the IASI channel at 1390 cm^{-1} on a +1 K perturbation to level temperatures (AFGL tropical atmosphere). Right-hand panel: brightness temperature change for the IASI channel at 1386 cm^{-1} for a 5% reduction in level water vapour mixing ratios (AFGL tropical atmosphere). The GENLN2 reference calculations are illustrated with a solid line. The RTIASI version1.1 model predictions are illustrated with dashed line, RTIASI version1.3 model predictions are illustrated with a dotted line.

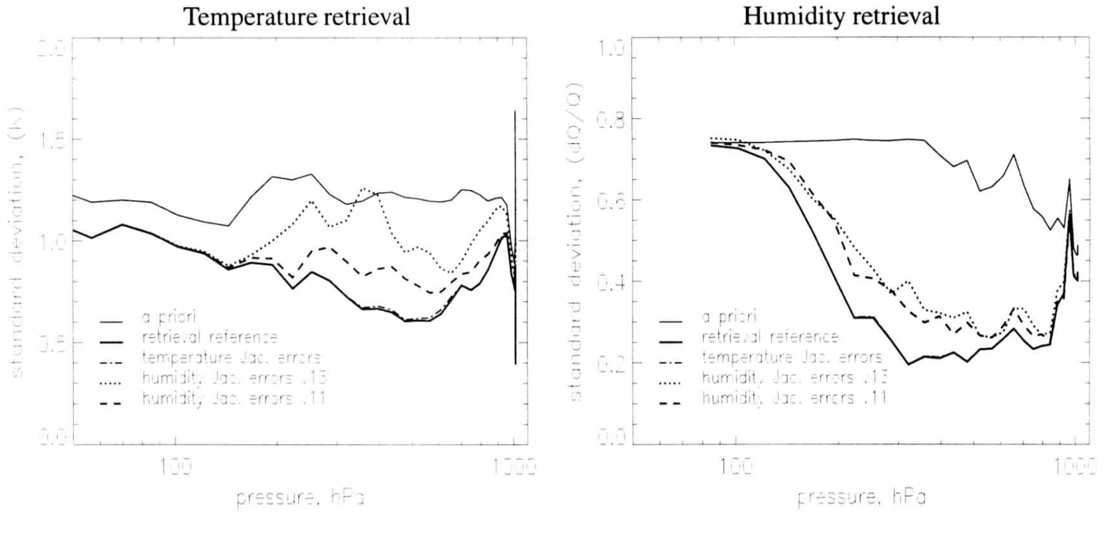


Figure 4: *A priori* and *a posteriori* standard deviations for temperature and humidity retrievals for optimal retrievals on the targetted spectral subintervals (no Jacobian errors, v13 model) and for retrievals in the presence of temperature Jacobian errors (v13 model) and water vapour Jacobian errors (v11 and v13 models). AFGL tropical atmosphere.

Model	DFS Ref.	DFS T_{err}	DFS H_{err}	DFS $[T+H]_{err}$
version 1.1	14.9	14.8	10.9	10.8
version 1.3	15.8	15.7	7.7	7.5

Table 2: Degrees of freedom for signal for optimal retrievals on the targetted spectral subintervals (no Jacobian errors) and for retrievals in the presence of temperature Jacobian errors, water vapour Jacobian errors and temperature and water vapour Jacobian errors. AFGL tropical atmosphere.

grade temperature retrievals because water vapour departures (differences between the true and *a priori* water vapour profiles) contribute to tropospheric temperature increments. This reflects the ambiguity in interpretation of radiances (partitioning of temperature and humidity signatures) in the H_2O ν_2 band (absorption by a variable gas).

In Table 2 we present the degrees of freedom for signal for three sub-optimal retrieval scenarios: retrievals where fast model temperature Jacobians are in error, retrievals where fast model water vapour Jacobians are in error and retrievals where both fast model temperature and water vapour Jacobians are in error. The degrees of freedom for signal for an optimal retrieval (no Jacobian errors) on the targetted wavenumber intervals is given for reference. Errors in temperature Jacobians have a minimal impact on the degrees of freedom for signal in both cases. Errors in water vapour give large reductions in degrees of freedom for signal, particularly for the version 1.3 case, and account for almost all of the reduction in degrees of freedom for signal in the combined T+H error case.

The use of selected spectral sub-intervals leads to a reduction in degrees of freedom for signal and an increase in the reference retrieval errors, as compared with the 'Full F DFS' results in Table 1 and Figure 2. Thus, while Jacobian error characteristics are not expected to be significantly different on the full IASI spectral interval, the null space contribution to retrieval errors and hence the impact of Jacobian errors will be smaller: these reductions in degrees of freedom for signal and associated increases in retrieval retrieval standard deviation should be interpreted as an upper bound for the changes expected if the full spectral interval had been used in retrievals (for this instrumental noise scenario).

The impact of water vapour Jacobian errors on temperature retrievals is much smaller in the case of the AFGL sub-arctic winter atmosphere. This is because Jacobian errors are smaller, but also because the 'mixing' of humidity departures into temperature retrievals is reduced in the dry atmosphere. The only significant increases in humidity retrieval errors are found for the v11 model retrievals in the upper troposphere (recall v11 model errors are of the order of 20% for the AFGL sub-arctic winter case). As previously, the impact of temperature Jacobian errors on retrieval accuracy is negligible in all cases.

In summary, accurate water vapour Jacobians are critical for upper tropospheric temperature and humidity retrievals. In the context of this study, this is the only instance where the adequacy of the current RTIASI models are seriously called into question.

4 CONCLUSIONS

The results of the impact studies detailed in the preceding sections highlight the importance of accurate radiative transfer calculations for the H_2O ν_2 band when undertaking simultaneous retrieval of temperature and humidity. Errors in the RTIASI fast model water vapour Jacobians have been shown to give a significant degradation in retrieval accuracy. Similiarly, the current magnitude and degree of correlation of RTIASI forward model errors in H_2O ν_2 band is such that a diagonal approximation to the forward model error covariance matrix leads to suboptimal retrievals of mid and upper tropospheric temperature and humidity. While the decrease in retrieval accuracy remains tolerable for IASI instrumental noise levels, the diagonal approximation to the forward model error covariance matrix compromises the benefit of low AIRS-type instrumental noise levels.

A revision of the water vapour transmittance prediction/regression scheme is planned in the upcoming months. We are optimistic that this revision will significantly improve the accuracy of modelled Jacobians and reduce forward model errors in the H_2O ν_2 band. In this case, neglecting forward model error correlations may well be justifiable. However, there are many sources of correlated observation errors (spectroscopic and representativity errors, undetected cloud, surface emissivity specification etc.) which have not been considered here. The choice as to whether to represent these correlations explicitly when specifiying the observation error covariance matrix should be based on further impact studies. If information on correlation structure is required, compact representations of the error covariance – leading eigenvector decompositions or block diagonal error covariance matrix specification (combined with channel selection) – should be considered for computational efficiency.

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