An Attempt to Understand and Correct Some of the Errors of Forward Radiative Transfer Models

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1. INTRODUCTION

Data assimilation relies on fast radiative transfer (RT) models for assimilating vast amounts of satellite observations. The most accurate models are those of the line-by-line (LBL) class which determine transmittances and radiances from basic physics. Unfortunately these models are inappropriate for use in data assimilation since the LBL can be as computationally expensive as the assimilation process itself. Instead, fast parameterized models such as RTTOVS (Eyre, 1991) are used.

In order to use a parameterized model in data assimilation a good understanding of its error characteristics is required. In addition to being used to derive coefficients for a parameterized model, the LBL is also a useful tool in evaluating RT models. Statistics generated from comparisons to the LBL provide a useful estimate of the forward model errors and in particular its systematic error which for data assimilation should be very small. To ensure that the systematic error is small, radiance bias correction schemes have been created which effectively reduce the globally averaged error to something very close to zero (Eyre, 1993).

Systematic errors in an RT model are generally due to missing physics. For example, the effect of neglecting increasing CO_2 in the atmosphere can lead to systematic errors of up to 1K in brightness temperature in the longwave sounding channels (Turner, 1994). Elimination wherever possible of systematic errors is desirable since they will have a negative impact on data assimilation. Another source of discrepancies may be due to the parameterization itself; ie, which parameters are used.

The following study attempts to improve the water vapour and ozone components of the RT model and to introduce a mechanism to account for spectral overlap between water vapour and ozone. In order to facilitate this, two new transmittance databases are introduced to which parameterizations may be created from and checked against. In addition, estimates of the forward model errors are presented.

2. PREPARATION OF ATMOSPHERIC PROFILE DATABASES

Most parameterized RT models currently in use have been created by regressing against a small database of 32 profiles (Kleespies, private communication). This small sample is deficient in high altitude water vapour and lacks simultaneous ozone profiles. Consequently, the 32 profiles lack variability and generally are inadequate for generating new parameterizations or studying the spectral overlap between absorbing groups. Hence, a larger set of simultaneous profiles of temperature, H_2O, O_3 and the Uniformly Mixed Gases, UMG (CO_2, N_2O, CH_4, N_2 and O_2), is required. In addition it would be advantageous to form a database that would be useful for current and future instruments.

To meet these requirements a database of profiles was created by collocating

SAGEII (Wang et al, 1992) retrievals (upper atmosphere) and NMC analysis. This database of 3309 collocated profiles has been described elsewhere (Turner, 1995).

The full dataset of 3309 collocated profiles was reduced using a method similar to that outlined in Wark et al, (1992). The covariance matrix from which a limited set of eigenvectors are defined uses only temperature, T, and water vapour, q, profiles. The full temperature profile used extends from the surface to 0.1mb, but the water vapour profile used is constrained to below 135mb which should be sufficient to capture most of the H_2O variability. The profiles of O_3 and UMG, although not used for the reduction, remain associated to each of the T-q profile. The T-Q observation matrix, X, is defined as

$$X = \begin{bmatrix} \Upsilon_{1,1} & \Upsilon_{1,2} & \Upsilon_{1,3} & \cdots & \Upsilon_{1,NP} \\ \Upsilon_{2,1} & \Upsilon_{2,2} & \Upsilon_{2,3} & \cdots & \Upsilon_{2,NP} \\ \Upsilon_{3,1} & \Upsilon_{3,2} & \Upsilon_{3,3} & \cdots & \Upsilon_{3,NP} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \Upsilon_{NT,1} & \Upsilon_{NT,2} & \Upsilon_{NT,3} & \cdots & \Upsilon_{NT,NP} \\ Q_{1,1} & Q_{1,2} & Q_{1,3} & \cdots & Q_{1,NP} \\ Q_{2,1} & Q_{2,2} & Q_{2,3} & \cdots & Q_{2,NP} \\ Q_{3,1} & Q_{3,2} & Q_{3,3} & \cdots & Q_{3,NP} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ Q_{NQ,1} & Q_{NQ,2} & Q_{NQ3} & \vdots & Q_{NQ,NP} \end{bmatrix}$$

where

$$\Upsilon_{i,j} = \frac{T_{i,j} - \overline{T}_i}{\overline{\sigma}_T}$$

$$Q_{i,j} = \frac{\log(q_{i,j}) - \overline{Q}_i}{\overline{\sigma}_Q}$$

$$\overline{T}_i = \frac{1}{NP}\sum_{j=1}^{NP} T_{i,j}$$

$$\overline{\sigma}_T = \sqrt{\frac{1}{NT}\sum_{i=1}^{NT}\left(\frac{1}{NP-1}\sum_{j=1}^{NP}(T_{i,j}-\overline{T}_i)^2\right)}$$

$$\overline{Q}_i = \frac{1}{NP}\sum_{j=1}^{NP}\log(q_{i,j})$$

$$\overline{\sigma}_Q = \sqrt{\frac{1}{NQ}\sum_{i=1}^{NQ}\left(\frac{1}{NP-1}\sum_{j=1}^{NP}(\log(q_{i,j})-\overline{Q}_i)^2\right)}$$

The reduced set is developed by projecting each profile on the three largest eigenvectors of the covariance matrix X^tX and characterizing each profile as a point, $(\vec{e}_1\cdot\vec{x}_j,\ \vec{e}_2\cdot\vec{x}_j,\ \vec{e}_3\cdot\vec{x}_j)$ in 3D space. The volume of points is sub-divided into boxes and the point nearest to the centre of each box becomes a member of the reduced set. Unfortunately, since this method uses only three eigenvectors, it effectively excludes outlyers. To alleviate this problem, outlyers were identified and included in the reduced set. As the collocated SAGEII/NMC database is deficient in tropical atmospheres, the reduced set is further supplemented with profiles from the AES global spectral model (Ritchie et al, 1994), henceforth referred to as the NWP, and the appropriate AFGL CO_2, N_2O, CH_4, N_2 and O_2 profiles.

All the profiles are on an 83 level pressure grid, which is the TOVS grid supplemented with extra levels in-between and four extra levels at 1010mb, 1020mb, 1030mb and 1040mb.

3. PARAMETERIZED TRANSMITTANCE MODELS

To complete the reduced set, the top of the atmosphere (TOA) transmittances are required. Transmittance profiles are produced using the Fast Line-By-Line radiative transfer model (FLBL, Turner, 1995). Seven categories of transmittances, UMG, H_2O, O_3, UMG+H_2O, UMG+O_3, H_2O+O_3, UMG+H_2O+O_3, at 10 zenith angles, $\sec\theta$=1 → 3.25 at .25 intervals, were calculated for each profile. This database is used as the dependent set in all regressions described below.

A second dataset, the independent database, was also created to validate and test various parameterizations. This data set consists of 470 profiles over ocean taken from the NWP. FLBL transmittances for UMG+H_2O+O_3 category only are produced at six zenith angles, secθ=1 → 3 @.25 intervals.

The basic parameterized forward model is recursive and formulated as

$$\tau_i = e^{-\chi_i}, \qquad \chi_i = \chi_{i-1} + \sum a_{i,j} x_{i,j} \tag{1}$$

where χ is the optical depth at pressure level i. x_{ij} and a_{ij} are parameters and the regression coefficients derived from the dependent database. The recursion starts at TOA and works its way down to the surface. Generally there are two separate transmittance models, one for UMG, and one for water vapour. The basic parameter for UMG is T and the basic parameters for H_2O are T and q. The third absorber, O_3, is usually parameterized in terms of the total column amount and does not have the form of Eqn. 1. The total optical depth is the sum of the three contributing optical depths.

The total ozone model does not account for distribution. Although this may be suitable as a first order approximation for the O_3 contributions in most HIRS longwave channels, it is not suitable for HIRS 9. It is doubtful that a O_3 profile can be retrieved directly from the current TOVS channels, however HIRS 9 may provide information when used in conjunction with data assimilation correcting NWP trial O_3 fields. In principle, accounting for O_3 distribution should improve the sounding channels. In addition, reformulating the O_3 component into a model similar to the other transmittance components would simplify codes.

Although it is commonly understood that HIRS 11 and 12 contains information from the upper troposphere and lower stratosphere water vapour, many parameterizations do not account for this very well. They are either cutoff at 300mb or cutoff at 300mb and an extrapolation is applied to the top of the atmosphere. For the models presented here, coefficients for H_2O are found to TOA.

Current transmittance models assume that the monochromatic product rule holds for mean transmittances; ie,

$$\overline{\tau}_{UMG+H_2O+O_3} - \overline{\tau}_{UMG}\,\overline{\tau}_{H_2O}\,\overline{\tau}_{O_3} = 0$$

which is equivalent to stating that there is no significant spectral overlap between the three main absorbing groups, UMG, H_2O and O_3. However LBL simulations of this difference using the dependent database (see Fig.1) show that for some channels this is not true, most notably HIRS 11. It appears that inter-group cross terms (X-TERMS) should be included as was attempted in this study.

Two parameter sets were chosen to experiment with, the parameters set forth by Brunel et al (1995) at CMS, which are similar to the RTTOVS parameters plus ozone parameters, and a parameter set being pursued by this group, Tables 1 and 2 respectively.

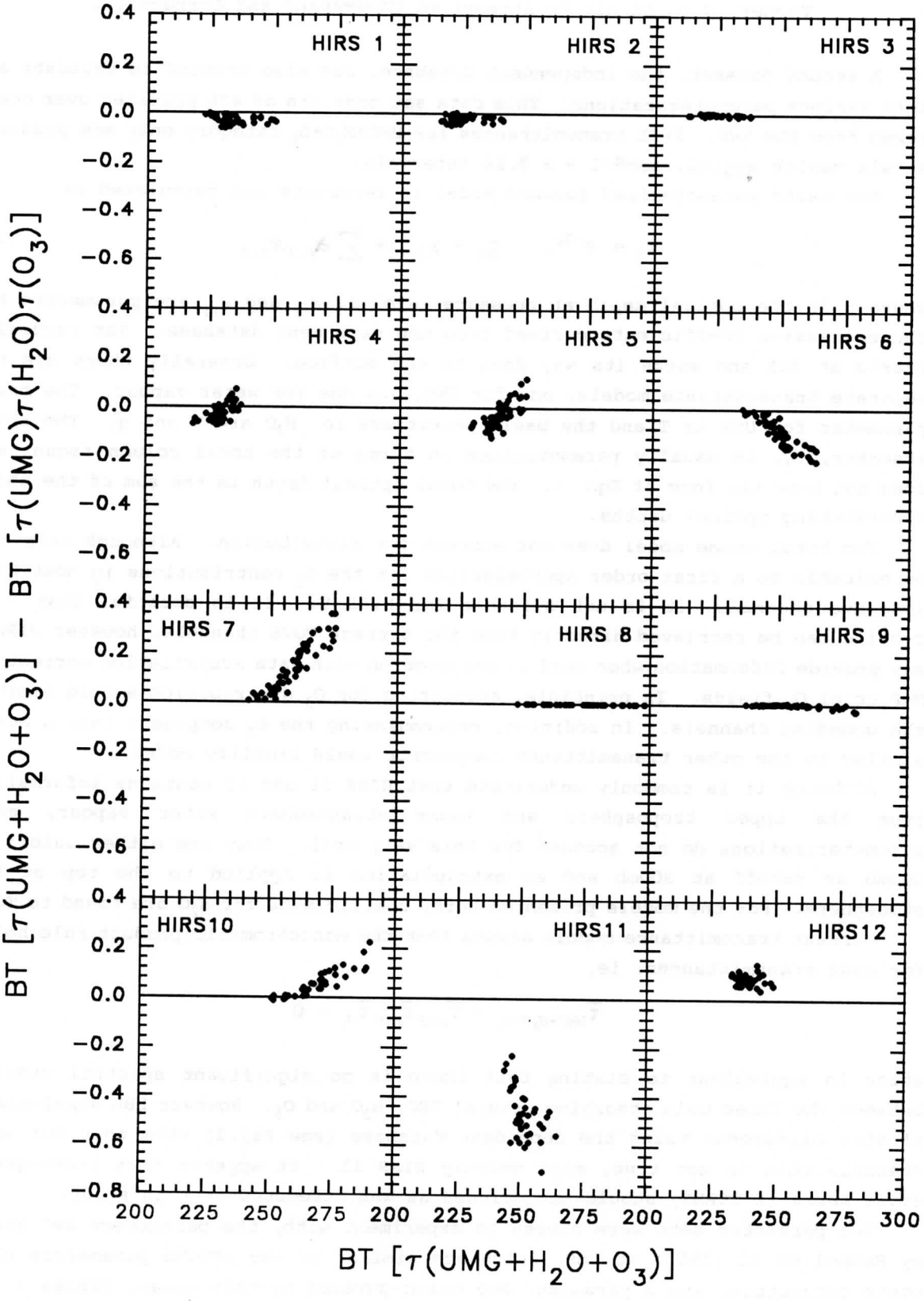

Fig. 1 FLBL simulations showing the degree of product rule violations for TOA radiances eminating from a black surface at 1000mb.

Table 1: Parameters of CMS model (Brunel et al,1995) plus X-TERMS

	UMG		H_2O		O_3		X-TERMS
$x_{i,1}$	$\delta T_i \cdot \sec\theta$	$x_{i,11}$	$\delta T_i \cdot \sqrt{u_{i,q} \cdot \sec\theta}$	$x_{i,21}$	$\delta T_i \cdot \sqrt{u_{i,c} \cdot \sec\theta}$	$x_{i,31}$	$\delta q_i \cdot \delta c_i \cdot \sqrt{\sec\theta}$
$x_{i,2}$	$\delta T^2_i \cdot \sec\theta$	$x_{i,12}$	$\overline{p \cdot \delta T_i} \sqrt{u_{i,q} \cdot \sec\theta}$	$x_{i,22}$	$\overline{p \cdot \delta T_i} \sqrt{u_{i,c} \cdot \sec\theta}$	$x_{i,32}$	$\delta q_i \cdot \delta c_i \cdot \sec\theta$
$x_{i,3}$	$\overline{\delta T_i} \sec\theta$	$x_{i,13}$	$\delta q_i \cdot \sqrt{u_{i,q} \cdot \sec\theta}$	$x_{i,23}$	$\delta c_i \cdot \sqrt{u_{i,c} \cdot \sec\theta}$	$x_{i,33}$	$\delta q_i \cdot \delta c_i \cdot \delta T_i \cdot \sqrt{\sec\theta}$
$x_{i,4}$	$\overline{p \cdot \delta T_i} \sec\theta$	$x_{i,14}$	$\overline{p \cdot \delta q_i} \sqrt{u_{i,q} \cdot \sec\theta}$	$x_{i,24}$	$\overline{p \cdot \delta c_i} \sqrt{u_{i,c} \cdot \sec\theta}$	$x_{i,34}$	$\overline{p \cdot \delta q_i \cdot \delta c_i} \cdot \sqrt{\sec\theta}$
$x_{i,5}$	$\sec\theta - 1$	$x_{i,15}$	$\delta T_i \cdot u_{i,q} \cdot \sec\theta$	$x_{i,25}$	$\delta T_i \cdot u_{i,c} \cdot \sec\theta$		
$x_{i,6}$	$(\sec\theta - 1)^2$	$x_{i,16}$	$\delta T^2_i \cdot u_{i,q} \cdot \sec\theta$	$x_{i,26}$	$\delta T^2_i \cdot u_{i,c} \cdot \sec\theta$		
$x_{i,7}$	$\overline{\delta T_i} (\sec\theta - 1)$	$x_{i,17}$	$\delta q_i \cdot u_{i,q} \cdot \sec\theta$	$x_{i,27}$	$\delta c_i \cdot u_{i,c} \cdot \sec\theta$		
$x_{i,8}$	$\overline{p \cdot \delta T_i} (\sec\theta - 1)$	$x_{i,18}$	$\delta q^2_i \cdot u_{i,q} \cdot \sec\theta$	$x_{i,28}$	$\delta c^2_i \cdot u_{i,c} \cdot \sec\theta$		
$x_{i,9}$	$\delta T_i (\sec\theta - 1)$	$x_{i,19}$	$\delta T_i \cdot \delta q_i \cdot u_{i,q} \cdot \sec\theta$	$x_{i,29}$	$\delta T_i \cdot \delta c_i \cdot u_{i,c} \cdot \sec\theta$		
$x_{i,10}$	1	$x_{i,20}$	$\sqrt{u_{i,q} \cdot \sec\theta}$	$x_{i,30}$	$\sqrt{u_{i,c} \cdot \sec\theta}$		

Table 2: Parameters of AES model

	UMG		H_2O		O_3		X-TERMS
$x_{i,1}$	$\delta p \cdot \sec\theta$	$x_{i,7}$	$\delta q_i \cdot \delta p \cdot q_i \cdot \sec\theta$	x_{13}	$\delta c_i \cdot \delta p \cdot c_i \cdot \sec\theta$	x_{19}	$\delta c_i \cdot \delta q_i \cdot \delta p \cdot \sec\theta$
$x_{i,2}$	$\delta T_i \cdot \delta p \cdot \sec\theta$	$x_{i,8}$	$\delta q_i \cdot \delta T_i \cdot \delta p \cdot q_i \cdot \sec\theta$	x_{14}	$\delta c_i \cdot \delta T_i \cdot \delta p \cdot c_i \cdot \sec\theta$	x_{20}	$\delta c_i \cdot \delta q_i \cdot \sqrt{\delta p \cdot \sec\theta}$
$x_{i,3}$	$\delta T^2_i \cdot \delta p \cdot \sec\theta$	$x_{i,9}$	$\delta q^2_i \cdot \cdot \delta p \cdot q_i \cdot \sec\theta$	x_{15}	$\delta c^2_i \cdot \delta p \cdot c_i \cdot \sec\theta$	x_{21}	$\delta T_i \cdot \delta c_i \cdot \delta q_i \cdot \delta p \cdot \sec\theta$
$x_{i,4}$	$\sqrt{\delta p \cdot \sec\theta}$	$x_{i,10}$	$\delta q_i \cdot \sqrt{\delta p \cdot q_i \cdot \sec\theta}$	x_{16}	$\delta c_i \cdot \sqrt{\delta p \cdot c_i \cdot \sec\theta}$	x_{23}	$\delta T_i \cdot \delta c_i \cdot \delta q_i \cdot \sqrt{\delta p \cdot \sec\theta}$
$x_{i,5}$	$\delta T_i \cdot \sqrt{\delta p \cdot \sec\theta}$	$x_{i,11}$	$\delta q_i \cdot \delta T_i \cdot \sqrt{\delta p \cdot q_i \cdot \sec\theta}$	x_{17}	$\delta c_i \cdot \delta T_i \cdot \sqrt{\delta p \cdot c_i \cdot \sec\theta}$	x_{24}	1
$x_{i,6}$	$\delta T^2_i \cdot \sqrt{\delta p \cdot \sec\theta}$	$x_{i,12}$	$\delta q^2_i \cdot \sqrt{\delta p \cdot q_i \cdot \sec\theta}$	x_{18}	$\delta c^2_i \cdot \sqrt{\delta p \cdot c_i \cdot \sec\theta}$		

where $\overline{\delta T_i} = \frac{1}{p_i} \sum_{j=1}^{i} \delta T_i \, (p_i - p_{i-1})$ $\qquad \overline{p \cdot \delta \alpha_i} = \frac{2}{p_i^2} \sum_{j=1}^{i} p_j \delta \alpha_j \, (p_i - p_{i-1})$

$u_{i,\alpha} = \frac{1}{2} (\alpha_i + \alpha_{i-1}) \, (p_i - p_{i-1})$ $\qquad \delta \alpha_i = \frac{1}{2} (\alpha_i - \alpha_i^{ref} + \alpha_{i-1} - \alpha_{i-1}^{ref})$ $\qquad \alpha = c, \, p, \, q, \, T$

4. METHODS OF REGRESSION

The coefficients for Eqn. 1 are solved by first normalizing the independent and dependent parameters and then solving for the normalized system for $\tilde{a}$ (~ denotes the normalized variables) ; ie,

$$\tilde{\tilde{a}}_i = (\tilde{X}_t \tilde{X})^{-1}_i \, \tilde{\tilde{X}}^t_i \, \tilde{\tilde{y}}_i, \qquad y_i = \chi_i \chi^{-1}_{i-1}$$

These coefficients are transformed back to the original system by

$$a_{i,j} = \frac{\sigma_{y_i}}{\sigma_{x_j}} \tilde{a}_{i,j}, \qquad a_{i,N} = \overline{y}_i + \sum_{j=1}^{N} \frac{\sigma_{y_i}}{\sigma_{x_j}} \overline{x}_j \tilde{a}_{i,j}, \qquad x_N = 1$$

where σ and the barred variables are the standard deviations and the means of the normalized variables respectively.

The parameterization is usually viewed as three separate series which are summed together for the total optical depth. Alternatively, a single series with

"sections" devoted to a particular absorber may be used; ie,

$$\chi_i = \chi_{i-1} + \underbrace{\sum_j a_{i,j}x_{i,j}}_{UMG\ section} + \underbrace{\sum_j a_{i,j}x_{i,j}}_{H_2O\ section} + \underbrace{\sum_j a_{i,j}x_{i,j}}_{O_3\ section} + \underbrace{\sum_j a_{i,j}x_{i,j}}_{X\text{-}TERMS} \qquad (2)$$

where unwanted sections can be turned off by setting their coefficients to zero. There are 7 ways in which the 3 basic absorbing groups can be combined and 15 when the X-TERMS are included.

Sectional fitting, the usual method of regressing, is where coefficients for each section are found by regressing that section's parameters against the appropriate TOA optical depths. Afterwards they are re-allocated to their appropriate place in Eqn. 2. This is equivalent to the product rule.

Global fitting regresses all the required sections against the total TOA optical depths. Regressing in this manner enables some of the spectral overlap between absorbing groups, if X_TERMS are ignored, to be indirectly accounted for and to spread some of the system noise across all terms.

5. RESULTS AGAINST THE FLBL

The TOA brightness temperatures are calculated from the TOA radiances using either the FLBL or forward model (FWD) transmittances; ie,

$$R_i^{TOA} = B(T_i)\,\overline{\tau}_i + \sum_{j=1}^{i} \tfrac{1}{2}\,[B(T_j) + B(T_{j-1})]\cdot[\overline{\tau}_{j-1} - \overline{\tau}_j]$$

For comparisons against the FLBL, the following definitions of bias, δ, and standard deviation, σ, are used;

$$\delta = \frac{1}{N}\sum (BT^{LBL} - BT^{FWD}) \quad and \quad \sigma = \sqrt{\frac{1}{N-1}\sum [(BT^{LBL} - BT^{FWD}) - \delta]^2}$$

where BT denotes the TOA brightness temperature from a "black" surface located at 1000mb.

Coefficients are derived from the dependent set for all possible combinations of the four sections using global and sectional fitting for both the AES and CMS models. The coefficients of the each possible combination of sections, MASK, excluding and including the X-TERMS are saved. The MASK is a four character string of 1's and 0's that represents a combination. The string read from left to right indicates the status of UMG, H_2O, O_3 and X-TERMS respectively. A status of 1 means that section's parameters are included and a 0 means excluded. The best MASK is the combination that minimizes the χ^2 ($=\Sigma(BT^{LBL}-BT^{FWD})^2$) of the TOA BTs. The coefficients of the best MASK are used to compare the forward model against the independent set. Table 3 contains the MASK and the comparison statistics for the dependent set and table 4 contains the comparative statistics against the independent set.

As one would expect (cf Fig 1), even where the minimization selected a combination with X-TERMS, there was little or no improvement to the dependent and

independent statistics in most of the channels. Channels where X-TERMS were selected, but with little effect, the χ^2 values were fairly close to a MASK with no X-TERMS. It is likely that these χ^2 values are inside the noise of the system and were consequently picked over MASKS that did not contain X-TERMS.

The AES model HIRS 7 was the only channel that showed improvement with X-TERMS. Its bias was decreased by about the expected amount, .23K, with no effect on σ. However the CMS model showed bias improvement in HIRS 7, 10 and 11 from .2K to 0.K, .1K to 0.K and -.6K to .25K respectively with little change in σ.

Global fitting with X-TERMS did not show any significant changes over fitting with no X-TERMS. This is probably due to the regression absorbing some of the X-TERMS variance into existing parameters. For example, any overlap between UMG and H_2O could be parameterized as $\delta T \delta q$ which already exists in the H_2O section.

In general, the global fitting method is better than the sectional fitting method and the CMS model is better than the AES model. In addition to absorbing some of the spectral overlap between sections this method distributes the variance over more parameters.

In Tables 5 and 6 the statistics of observed (TOVS cloud cleared radiances) against collocated forward model estimates using an NWP trial field are presented. This so-called 'total error' is made up of instrument plus RT model and NWP trial field error expressed in BT. As expected, the error is significantly larger than either the RT model (columns 4, 6, 9, and 11 of Tables 3 and 4) or instrument errors which are generally less than .2K. For data assimilation purposes, it is necessary to estimate the sum of RT plus instrument errors which can now estimated from Tables 3, 4, 5 and 6.

The NWP currently does not produce trial fields for ozone. Ozone was fixed to the US standard profile, consequently the statistics for HIRS 9 are not meaningful and are omitted from Tables 5 and 6. It should be noted that FLBL simulations (not shown) indicate that the biases for the temperature sounding channels (1-7) can be affected by as much as .5K.

When compared against TOVS cloud-cleared radiances (Table 5), the AES and CMS models produce similar δ's and σ's for the temperature sounding channels, whereas the CMS model does better in the H_2O channels. This indicates that some of the parameters in the CMS UMG channels may not be required, possibly some of the "summation" terms (ie x_3, x_4, x_7 and x_8 of Table 1). Conversely, the summation terms for H_2O and probably O_3 are required by the AES model.

When compared against the untuned RTATOVS model the standard deviations of are generally similar for all the channels. Depending on the channel the biases are sometimes a little worse or a little better than RTATOVS. They are notably better for the AES and CMS globally fitted models in HIRS 5 and 7.

6. CONCLUSIONS

Two new LBL databases for calculating coefficients and validating forward models have been created. These provide a large set of "truths" for creating and evaluating parameterized RT models. The databases were designed provide as much temperature, water vapour and ozone variability throughout the atmosphere as possible in order that they can be used to develop RT models, not only for TOVS,

but other satellite platforms.

The CMS model has been independently validated and some possible improvements have been identified. Of the various methods of deriving coefficients for both the AES and CMS models, it was found that fitting all the parameters simultaneously improves the models and appears to account for some spectral overlap between absorbing groups without the need for additional parameters. There are also indications that some of the UMG terms in the CMS model may not be required, whereas the AES model requires additional terms to describe water vapour and ozone. In addition, the comparative statistics between the models and the FLBL provide a good estimate of the forward model error.

When the forward models were tested against cloud-cleared radiances, it was found that the standard deviations were all of the same order, including the RTATOVS model and that biases are improved over RTATOVS in some channels.

7. REFERENCES

Brunel, P., L. Lavanant and G. Rochard, Infrared Transmittance Database for Fast Transfer Model, 1995: Technical Proceedings for the 8th ITSC, Queenstown, New Zealand, 5-11 April, 77-86.

Eyre, J.R., G.A. Kelly, A.P. McNally and E Anderson, 1993: Applications of Statistics of Departures Between Measured and Forecast TOVS Brightness Temperatures, Technical Proceedings for the 7th ITSC, Igls, Austria, 10-16 February, 129-140.

Eyre, J.R., 1991: A New Fast Radiative Transfer Model for TOVS, Technical Proceedings for the 6th ITSC, Airlie, Virginia, 1-6 May, 118-133.

Ritchie, H. and C. Beaudoin, 1994: Approximations and Sensitivity Experiments With a Baroclinic Semi-Lagrangian Spectral Model, Mon. Wea. Rev., V122, 2391-2399.

Turner, D.S., 1995: A Fast Line-By-Line Radiative Transfer Model for TOVS Radiance/Transmittance Studies, Technical Proceedings for the 8th ITSC, Queenstown, New Zealand, 5-11 April, 465-473.

Turner, D.S., 1995: Absorption Coefficient Estimation Using A Two-Dimensional Interpolation Procedure, J.Q.S.R.T., V53(6), 633-637.

Turner, D.S., 1995: HIRS Sensitivity to CO2 Mixing Ratio and a Pragmatic Correction Term, J.A.M., V33(10), 1155-1162.

Wang, Pi-Huan, M.P. McCormick, W.P. Chu, J. lenoble, R.M. Nagatani, M.L. Chanin, R.A. Barnes, F. Schmiglin and M. Rowland, 1992: SAGEII Stratospheric Density and Temperature Retrieval Experiment, J.G.R. V97, D1, 843-863.

Wark, D., H. Drahos, L. McMillin, N. Grody, H. Fleming, M. Goldberg, D.Crosby, C. Hayden, D. Gray, A. Neuendorffer, D. Pick, D. Staelin, P. Rosenkranz, J. Foot, C. Walton, M. Uddstrum, C. Rao and A. Reale, 1992: Report to the Sounding Product Oversight Panel: Specifications for the Processing of Data from the NOAA-K Sounder, Draft Revision 3.12-03/20/92.

Table 3: Comparative statistics between FLBL simulations and the AES forward model calculations using the dependent and independent databases for the best MASKS for models with and without X-TERMS for both types of fitting.

AES MODEL		WITHOUT X-TERMS									AES MODEL		WITH X-TERMS								
		sectional fitting				global fitting							sectional fitting				global fitting				
		dependent		independent			dependent		independent				dependent		independent			dependent		independent	
HIR	MASK	δ	σ	δ	σ	MASK	δ	σ	δ	σ	HIR	MASK	δ	σ	δ	σ	MASK	δ	σ	δ	σ
1	1010	-.06	.23	-.36	.14	1110	.00	.15	.04	.29	1	1011	-.01	.23	-.31	.15	1011	.00	.14	.05	.29
2	1010	-.05	.14	-.12	.17	1110	.00	.07	.03	.13	2	1111	-.01	.13	-.09	.18	1011	.00	.06	.04	.12
3	1110	-.02	.14	-.08	.16	1110	-.01	.08	.03	.13	3	1111	-.02	.14	-.08	.16	1111	-.01	.07	.02	.11
4	1110	-.08	.23	-.08	.23	1110	-.02	.15	.00	.14	4	1111	-.02	.21	-.02	.21	1111	-.02	.15	-.01	.13
5	1110	-.06	.47	-.05	.53	1110	-.03	.22	-.05	.22	5	1111	.02	.44	.01	.50	1111	-.02	.22	-.05	.22
6	1110	-.04	.50	-.06	.62	1110	-.01	.19	-.08	.22	6	1110	-.04	.50	-.06	.62	1111	-.01	.19	-.08	.22
7	1110	.23	.67	.25	.88	1110	-.01	.26	-.14	.32	7	1111	.00	.66	-.07	.84	1111	-.01	.26	-.13	.31
8	1110	-.02	.30	-.03	.38	1110	.00	.14	-.06	.13	8	1111	-.02	.30	-.03	.38	1110	.00	.14	-.06	.13
9	1110	.46	3.79	.36	4.62	1110	.06	1.00	-.66	.69	9	1110	.46	3.79	.36	4.62	1111	.05	.86	-.56	.69
10	1100	.07	.78	.08	.95	1110	.00	.32	-.21	.36	10	1111	-.03	.78	-.08	.95	1111	-.01	.30	-.17	.35
11	1110	-.07	3.49	-.53	3.08	1100	.02	1.82	-.70	1.86	11	1110	-.07	3.49	-.53	3.08	1111	.02	1.76	-.64	1.73
12	1110	.91	3.98	.18	2.92	0110	.74	3.47	-.07	2.80	12	1110	.91	3.98	.18	2.92	1001	.23	2.78	-1.46	2.86

Table 4: Comparative statistics between FLBL simulations and the CMC forward model calculations using the dependent and independent databases for the best MASKS for models with and without X-TERMS for both types of fitting.

CMS MODEL		WITHOUT X-TERMS									CMS MODEL		WITH X-TERMS								
		sectional fitting				global fitting							sectional fitting				global fitting				
		dependent		independent			dependent		independent				dependent		independent			dependent		independent	
HIR	MASK	δ	σ	δ	σ	MASK	δ	σ	δ	σ	HIR	MASK	δ	σ	δ	σ	MASK	δ	σ	δ	σ
1	1010	-.05	.15	-.22	.14	1010	.00	.11	.00	.22	1	1111	.00	.15	-.17	.13	1111	.01	.10	.03	.23
2	1010	-.04	.06	-.09	.07	1110	.00	.05	.03	.11	2	1011	.00	.06	-.05	.06	1111	.00	.04	.03	.12
3	1110	-.01	.05	-.04	.05	1010	.00	.04	.03	.10	3	1111	.00	.05	-.04	.05	1011	.00	.04	.04	.10
4	1110	-.05	.07	-.03	.08	1110	.00	.05	.04	.07	4	1111	.01	.08	.04	.10	1111	.00	.05	.03	.07
5	1110	-.07	.10	-.02	.10	1110	.00	.06	.04	.07	5	1111	.01	.10	.06	.12	1111	.00	.05	.03	.06
6	1110	-.09	.09	-.07	.07	1110	.00	.05	.03	.05	6	1111	.00	.09	.05	.07	1111	.00	.05	.03	.05
7	1110	.21	.17	.32	.14	1110	.00	.06	.02	.06	7	1111	-.01	.14	.03	.14	1111	.00	.05	.02	.07
8	1110	-.07	.31	.01	.08	1110	-.01	.07	.00	.05	8	1111	-.07	.31	.01	.08	1111	-.01	.06	.01	.05
9	1110	-.02	.25	.04	.16	1110	.00	.14	.06	.14	9	1111	-.02	.25	.05	.16	1111	.00	.13	.02	.16
10	1100	.11	.17	.20	.16	1110	.00	.06	.02	.11	10	1111	.00	.15	.06	.13	1111	.00	.06	.02	.11
11	1110	-.58	.37	-.37	.36	1100	-.03	.31	.25	.43	11	1101	.25	.51	.38	.59	1100	-.03	.31	.25	.43
12	1110	.04	.55	.32	.46	0100	-.07	.48	.33	.44	12	1110	.04	.55	.32	.46	0101	-.06	.44	.35	.46

Table 5: Comparative statistics between observed BT's and AES forward model calculations using an NWP trial field that has been collocated with the observed BT's. The BT's calculated using RTATOVS are also included.

AES MODEL WITHOUT X-TERMS							WITH X-TERMS							
	sectional fitting			global fitting			sectional fitting			global fitting			RTATOVS	
HIR	MASK	δ	σ	MASK	δ	σ	MASK	δ	σ	MASK	δ	σ	δ	σ
1	1010	0.66	1.65	1110	0.79	1.69	1010	0.75	1.67	1011	0.81	1.69	.17	1.54
2	1010	-0.92	1.04	1110	-0.60	1.06	1010	-0.85	1.04	1011	-0.56	1.05	-1.15	1.04
3	1110	-1.40	0.93	1110	-1.27	0.91	1110	-1.41	0.92	1111	-1.37	0.93	-1.72	.94
4	1110	-0.61	0.58	1110	-1.10	0.78	1110	-0.44	0.58	1111	-1.25	0.71	-1.01	.62
5	1110	1.40	0.67	1110	0.25	0.79	1110	1.52	0.70	1111	-0.04	0.70	1.05	.77
6	1110	0.57	0.87	1110	-0.71	0.96	1110	0.57	0.87	1111	-0.96	0.95	.56	.90
7	1110	2.04	1.33	1110	0.16	1.43	1110	1.64	1.35	1111	0.02	1.42	-1.72	1.44
8	1110	2.55	2.08	1110	2.04	2.20	1110	2.55	2.08	1110	2.04	2.20	2.40	2.23
10	1100	0.48	1.75	1110	-0.95	1.93	1100	0.29	1.77	1111	-0.93	1.92	2.13	1.82
11	1110	5.76	4.04	1100	2.36	4.19	1110	5.76	4.04	1111	2.26	4.23	-1.73	3.45
12	1110	7.10	5.20	0110	6.02	5.06	1110	7.10	5.20	1001	1.30	4.31	-1.69	4.43

Table 6: Comparative statistics between observed BT's and CMS forward model calculations using an NWP trial field that has been collocated with the observed BT's. The BT's calculated using RTATOVS are also included.

CMS MODEL WITHOUT X-TERMS							WITH X-TERMS							
	sectional fitting			global fitting			sectional fitting			global fitting			RTATOVS	
HIR	MASK	δ	σ	MASK	δ	σ	MASK	δ	σ	MASK	δ	σ	δ	σ
1	1010	0.87	1.66	1010	0.88	1.69	1111	0.95	1.68	1111	0.88	1.69	.17	1.54
2	1010	-0.57	1.05	1110	-0.59	1.05	1011	-0.51	1.05	1111	-0.58	1.05	-1.15	1.04
3	1110	-1.10	0.91	1010	-1.10	0.90	1111	-1.10	0.91	1011	-1.12	0.90	-1.72	.94
4	1110	-0.60	0.58	1110	-0.70	0.59	1111	-0.41	0.60	1111	-0.65	0.59	-1.01	.62
5	1110	0.71	0.67	1110	0.64	0.65	1111	0.86	0.71	1111	0.67	0.65	1.05	.77
6	1110	-0.52	0.89	1110	-0.43	0.89	1111	-0.38	0.88	1111	-0.41	0.89	.56	.90
7	1110	0.88	1.33	1110	0.54	1.33	1111	0.51	1.36	1111	0.56	1.33	-1.72	1.44
8	1110	2.14	2.16	1110	2.08	2.17	1111	2.15	2.16	1111	2.08	2.16	2.40	2.23
10	1100	-0.46	1.78	1110	-0.65	1.78	1111	-0.66	1.80	1111	-0.64	1.78	2.13	1.82
11	1110	2.22	3.85	1100	2.57	3.97	1101	3.11	3.76	1100	2.57	3.97	-1.73	3.45
12	1110	2.85	5.27	0100	2.72	5.08	1110	2.85	5.27	0101	2.80	5.12	-1.69	4.43

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