
The use of TOVS clear radiances for numerical weather prediction using an updated forward model

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SUMMARY

The impact of TOVS clear radiances, processed using a new transmittance database, on the ECMWF forecast system, is evaluated. This involved the production of a line-by-line transmittance database, of sets of coefficients for the operational fast radiative-transfer scheme, and the use of the operational bias-correction procedure to reduce residual long-term systematic differences. Two case-studies are used to examine data from TOVS instruments on three NOAA satellites, and the differences in radiances measured by the various platforms are discussed. Measured and simulated data are compared before and after the operational bias-removal scheme, and a final impact assessment is made using an assimilation and forecast experiment.

KEYWORDS: NWP assimilation Radiative transfer TOVS clear radiances

1. INTRODUCTION

Satellite radiances obtained from the TIROS†-N Operational Vertical Sounder (TOVS) (Smith et al. 1979) are operationally processed by the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite and Data Information Service (NESDIS) (Brown 1994). The TOVS comprises three separate instruments: the High-resolution Infra-Red Sounder (HRS), the Microwave Sounding Unit (MSU) and the Stratospheric Sounding Unit (SSU). One of the products is the so-called clear radiances, a set of radiances corrected to a nadir view that are either identified as clear or are derived from partially cloudy measurements using a cloud clearing procedure (McMillin and Dean 1982).

These radiances are used operationally at the European Centre for Medium-Range Weather Forecasts (ECMWF). At the time of the present study a one-dimensional variational (1D-Var) analysis scheme (Eyre et al. 1993) was used to derive temperature and humidity profiles from the radiances, while from January 1996 a three-dimensional scheme (3D-Var) (Anderson et al. 1994) is used to assimilate the radiances directly. In this paper when reference is made to operational ECMWF procedures or products it refers to the use of radiances in the 1D-Var scheme.

The quality of the 1D-Var retrieved profile is dependent upon very diverse components. First is the quality of the clear radiances themselves, and of the various processing steps which are required; from an accurate and fast radiative-transfer scheme, to the procedure aimed at eliminating systematic differences between satellite data and true atmospheric state, and finally to the details of the implementation of the final retrieval scheme.

This paper deals with the methods that were applied at the ECMWF to improve our understanding of the causes of large systematic differences being observed between NESDIS radiances data and model predictions based on the 3 to 9-hour forecast that is used for the first guess (FG). This has involved the production of a line-by-line transmittance database (section 2), of sets of coefficients for the operational fast radiative-transfer scheme (section 3), and the use of the operational bias-correction procedure to reduce residual long-term systematic differences (section 4). In section 5 results of comparisons of data measured by different platforms, and also a comparison of simulated and measured data over extended

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periods are described both before and after bias correction. Two periods were selected for the latter comparison, from 20 December 1994 to 5 January 1995 and from 16 to 30 June 1995; these will be referred to as the December and June cases respectively. In the same section results are also shown of an assimilation experiment, and associated forecasts, to evaluate the impact of the clear radiances processed using the new transmittance database. Conclusions are given in section 6.

2. LINE-BY-LINE TRANSMITTANCE DATABASE

The database of line-by-line atmospheric infrared transmittances is calculated using the High-resolution Atmospheric Radiance-Transmittance Code (HARTCODE) (Miskolczi et al. 1988; Miskolczi 1994). The High-resolution Transmission (HITRAN) molecular database (Rothman et al. 1992) is used, with corrections to eliminate problems that were identified after the release of the 1991 version of the database (Rothman, personal communication). HARTCODE is used to compute transmittances from 0.005 hPa to each of 40 standard levels, spectrally integrated in intervals of 0.5 cm$^{-1}$, for each atmospheric profile and five scan angles, namely the angles for which the secant has equally spaced values from 1.0 to 2.0 at the top of the atmosphere. The effects caused by the earth’s curvature and diffraction are fully accounted for. The monochromatic computations are made at a number of points that are dependent upon the structure of all lines that have an effect in the interval. For each line four points (and three sub-intervals) are defined per half-width at the lowest pressure, and in each interval a two-point Gaussian integration is performed (i.e. six monochromatic computations every halfwidth for each line). Two sets of transmittances are computed for each profile: one for the combined effect of the so-called mixed gases ($\text{CO}_2$, $\text{N}_2\text{O}$, $\text{CO}$, $\text{CH}_4$ and $\text{O}_3$) and one for mixed gases plus water vapour, respectively $\tau^M$ and $\tau^{M+W}$. The water vapour transmittance is determined by:

$$\tau^W = \frac{\tau^{M+W}}{\tau^M} \quad (1)$$

so that the total transmittance can be computed as

$$\tau = \tau^W \times \tau^M \quad (2)$$

which produces values identical to the total transmittance $\tau^{M+W}$ computed with HARTCODE. This technique is required since the fast-forward model, discussed in the next section, treats mixed gases and water vapour separately, so that the proper water vapour transmittance used is the one that produces the correct total transmittance. The water vapour transmittance is computed using Eq. (1) only for values of $\tau^M > 10^{-6}$, otherwise the transmittance $\tau^W$ is set to zero.

A set of 32 diverse atmospheric profiles, 31 of which are extracted from a database of 1200 profiles compiled by NESDIS, and the 32nd being the mean of the 1200 profiles, is used for the computations. With few modifications, the same set has been used in numerous research and operational centres to generate a number of databases for different instruments. The profiles are diverse in the sense that they are chosen to represent variations in temperature and water vapour mixing ratio as wide as found in the real atmosphere. However, the set of profiles does not exhibit an even geographical distribution, as shown in Fig. 1, where the location and the total number of profiles is reported. In terms of Total Precipitable Water (TPW), the set provides a description which seems to be biased toward dry tropospheres since 13 profiles show a TPW of less than 5 kg m$^{-2}$, nine a TPW between 5 and 30 kg m$^{-2}$ and eight a TPW between 30 and 57.5 kg m$^{-2}$. Since the water vapour profiles contained in the database do not extend beyond 300 hPa, we have extrapolated
specific humidity above 300 hPa using a power law up to 70 hPa, from which level up to 0.1 hPa a constant value (0.003 g kg\(^{-1}\)) is used for all profiles. As some HIRS channels show absorption features even for very low pressure values, transmittances are computed also for an additional layer between 0.1 and 0.005 hPa, by setting temperature and specific humidity equal to the value at 0.1 hPa.

The computed transmittances are convolved with the instrument spectral filter functions to obtain the line-by-line transmittance for each HIRS channel for the satellites NOAA-11, NOAA-12 and NOAA-14.

Microwave line-by-line transmittances for the MSU are calculated using a formulation due to Liebe (1989). This model has been validated by comparison with aircraft and ground-based radiometer measurements (English et al. 1994). In this spectral region, only water vapour and oxygen have significant absorption features, and so oxygen provides the mixed-gas transmittance.

3. Fast-forward model

Fast radiative-transfer models are used to compute radiances emitted at the top of the atmosphere, along the viewing direction of the instrument, and averaged over the spectral response of each instrument channel, for a given profile of atmospheric and surface conditions.

The model used at the ECMWF to process data from the HIRS and the MSU is the Radiative Transfer for TIROS Operational Vertical Sounder (RTTOV) model (Eyre 1991). Although the TOVS suite includes the SSU, mention of TOVS in the context of this work excludes the use of SSU.
The RTTOV transmittance model treats the absorption by uniformly mixed gases separately from that by water vapour. Calculation of the optical depth for the layer from pressure level \(j\) to space along a path at an angle \(\Theta\) involves a polynomial with terms that are functions of temperature, specific humidity and pressure at this level.

The optical depth in channel \(i\), for each gas, from level \(j\) to space can be written as:

\[
d_{ij} = d_{ij,j-1} + Y_j \sum_k a_{ijk} X_{kj} \quad k = 1, \ldots, L; j = 1 \ldots, 40. \tag{3}
\]

The functions \(X_{kj}\) and \(Y_j\) (for details see Eyre (1991)) constitute the basic predictors of the fast transmittance model, and the \(a_{ijk}\) are the expansion coefficients. In the present implementation \(L = 10\) and the predictors also depend on the viewing angle, although this feature is not needed with current operational limb-corrected data.

Following the discussion of Eq. (1) and Eq. (2) the contributions to the transmittance are separable, i.e. if the optical depths for uniformly mixed gases, water vapour and ozone are respectively \(d_{ij}^M, d_{ij}^W\) and \(d_{ij}^O\), then their combined optical depth is assumed to be:

\[
d_{ij}^T = d_{ij}^M + d_{ij}^W + d_{ij}^O. \tag{4}
\]

The accuracy of Eq. (4) has been substantially tested by one of the authors (RR) and found to be adequate for the HIRS infrared channels.

Finally, we note that the model used for ozone transmittance within the RTTOV is rather crude. It is probably adequate to account for the weak effects of ozone in HIRS channels 1–7, but not for simulating HIRS channel 9. A better model for ozone could be implemented by making use of a parametrization of the same form as the water vapour transmittance model. In the current work HIRS channel 9 is not used.

The set of predictor values \(X_{kj}\) is calculated from the profile variables for each of the 32 profiles at five different viewing angles. The \(a_{ijk}\) coefficients have been computed by linear regression of \((d_{ij} - d_{ij,j-1})/Y_j\) against \(X_{kj}\) for mixed gases and water vapour separately.

An obvious difficulty arises when determining the coefficients for water vapour transmittance at or above 70 hPa, since there is no variance of water vapour amount, as already mentioned, and any difference in line-by-line water vapour transmittance among the diverse profiles at these levels is due solely to the different temperature structure. It was decided not to generate water vapour coefficients at or above 70 hPa, and therefore the water vapour transmittance is set equal to unity. It is noted here that the line-by-line computations indicate that the transmittance for channel 12 of HIRS, the mid-upper tropospheric channel, is significantly different from unity when using a stratospheric water vapour amount of 0.003 g kg\(^{-1}\), a value considered reasonable at these levels. It is estimated that if realistic measurements of water vapour were available at or above 70 hPa, the fast model would account for upper-layer water vapour transmittances and, for example, this would change the brightness temperature (BT) of HIRS channel 12 by at least \(-0.6\) K (i.e. we would get a lower computed BT).

Consistency of the procedure adopted to compute the regression coefficients was checked by comparing BTs, computed using the line-by-line transmittances, convoluted with the instrumental filter functions, against BTs computed using the transmittances \(\tau_{ij}(RTTOV)\) calculated using Eq. (3) for the five viewing angles on each of the 32 profiles. Table 1 shows the mean BT error, the standard deviation of the error, and the maximum error for NOAA-12 channels. Similar results are obtained for NOAA-14 and NOAA-11. Differences arise only as a result of the different spectral location of channel 10, centred around 795 cm\(^{-1}\) (NOAA-11 and 14) and 1020 cm\(^{-1}\) (NOAA-12). The best results are
TABLE 1. **Comparison between brightness temperatures from the line-by-line and RTTOV transmittances**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mean brightness-temperature error (K)</th>
<th>Standard deviation of the error (K)</th>
<th>Maximum error for NOAA-12 channels (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.022</td>
<td>0.024</td>
<td>0.113</td>
</tr>
<tr>
<td>2</td>
<td>0.011</td>
<td>0.011</td>
<td>0.066</td>
</tr>
<tr>
<td>3</td>
<td>0.009</td>
<td>0.011</td>
<td>0.054</td>
</tr>
<tr>
<td>4</td>
<td>0.018</td>
<td>0.014</td>
<td>0.066</td>
</tr>
<tr>
<td>5</td>
<td>0.025</td>
<td>0.019</td>
<td>0.092</td>
</tr>
<tr>
<td>6</td>
<td>0.035</td>
<td>0.030</td>
<td>0.132</td>
</tr>
<tr>
<td>7</td>
<td>0.063</td>
<td>0.060</td>
<td>0.308</td>
</tr>
<tr>
<td>8</td>
<td>0.060</td>
<td>0.077</td>
<td>0.418</td>
</tr>
<tr>
<td>10</td>
<td>0.103</td>
<td>0.117</td>
<td>0.664</td>
</tr>
<tr>
<td>11</td>
<td>0.276</td>
<td>0.208</td>
<td>0.991</td>
</tr>
<tr>
<td>12</td>
<td>0.346</td>
<td>0.237</td>
<td>1.115</td>
</tr>
<tr>
<td>13</td>
<td>0.033</td>
<td>0.028</td>
<td>0.123</td>
</tr>
<tr>
<td>14</td>
<td>0.029</td>
<td>0.020</td>
<td>0.091</td>
</tr>
<tr>
<td>15</td>
<td>0.033</td>
<td>0.034</td>
<td>0.154</td>
</tr>
<tr>
<td>16</td>
<td>0.026</td>
<td>0.039</td>
<td>0.164</td>
</tr>
<tr>
<td>17</td>
<td>0.012</td>
<td>0.015</td>
<td>0.076</td>
</tr>
<tr>
<td>18</td>
<td>0.013</td>
<td>0.016</td>
<td>0.078</td>
</tr>
<tr>
<td>19</td>
<td>0.052</td>
<td>0.066</td>
<td>0.330</td>
</tr>
<tr>
<td>21</td>
<td>0.063</td>
<td>0.058</td>
<td>0.168</td>
</tr>
<tr>
<td>22</td>
<td>0.027</td>
<td>0.023</td>
<td>0.076</td>
</tr>
<tr>
<td>23</td>
<td>0.007</td>
<td>0.006</td>
<td>0.025</td>
</tr>
<tr>
<td>24</td>
<td>0.009</td>
<td>0.010</td>
<td>0.050</td>
</tr>
</tbody>
</table>

obtained for those channels for which mixed gases are the dominant contributors. Water vapour channels 11 and 12 exhibit the worst performance, with channel 12 mean BT error peaking at 0.346 K.

For the period of the present study the operational \( a_{ijk} \) coefficients (OPE) used at the ECMWF within the RTTOV scheme are generated using the transmittance model obtained from the NOAA/NESDIS Development Laboratory in Madison, Wisconsin (NOAA-11) and at the NOAA/NESDIS in Washington (NOAA-12, 14). The procedure involves the generation of HIRS channel transmittances using the transmittance model used at the sites quoted above, and the use of this transmittance database for computing the RTTOV \( a_{ijk} \) coefficients. One of the main motivations for the work presented here was in fact to upgrade the transmittance model to generate the \( a_{ijk} \) coefficients.

The \( a_{ijk} \) coefficients computed using the line-by-line database, discussed in section 2 and the procedure of section 3, will be labelled from now on as LBL.

4. **Tuning of transmittances and bias correction**

Fast radiative-transfer models can provide simulated BTs that are sufficiently accurate to be compared with measured data. However, comparison of measured radiances with those calculated from collocated radiosondes and/or FG profiles has shown that some degree of empirical tuning is required. The causes for the discrepancies can be grouped into three main classes and will be discussed in the following subsections.

(a) **Errors arising from pre-processing of observations**

The nominal HIRS/2 instrument requirements for the noise equivalent BT variation (NEdT) is of 0.2 K for a scene of 280 K. In fact instruments flying in the last decade
have exceeded these requirements. The required absolute calibration accuracy is 0.5 K and the instruments used in this study are believed to meet this requirement. In order to produce clear-sky values the raw radiances undergo a processing that is likely to introduce errors larger than the radiometric error budget discussed above. The principal stages of this processing are an adjustment, called limb correction, aimed at producing a set of nadir-looking radiances, a correction for water vapour absorption in the window channel HIRS 8, and cloud detection and clearing. It is very difficult to evaluate the errors introduced by these latter stages because its implementation has changed considerably with time, with differences in the quality of the products. A study by Rizzi et al. (1994), based on a detailed analysis of a data set of limited extent and duration, concluded that the quality of the clear radiances produced by NESDIS in February 1989 was quite poor (i.e. the overall number of the clear fields of view (FOVs) was very small, some of the clear FOVs were quite severely cloud contaminated and the processing did not identify most of the clear spots). Since then clear radiances have been subject to a routine quality check before the analysis stage, and the six-hourly results have shown a reduction of clear radiances being rejected because of inconsistencies with the FG.

The nominal MSU instrument radiometric noise NEdT is 0.3 K but latest versions are believed to exceed the requirements. The nominal absolute calibration accuracy, defined as the difference between the physical temperature and the BT calculated from radiometric counts, is 0.5 K or less in the temperature range 100 to 300 K. One must, however, remember that all flight models, the last of the series flying with NOAA-14, were calibrated in the early 1980s (Mo, NESDIS, personal communication). Offsets between different instruments have been observed, but no adequate explanation of their causes has been found.

Several corrections are applied to account for surface emissivity and cloud liquid water and precipitation being present within the large FOV of the instrument. As part of the pre-processing a limb correction is applied and values are interpolated to the HIRS FOV. The cumulative effect of errors for all these corrections is not well known, but probably larger than the radiometric errors.

(b) Forward modelling errors

The LBL transmittance computations suffer from uncertainties in line parameters which should be reduced as new results from laboratory and field measurements are incorporated into the databases. The treatment of line shape, particularly at the wings of lines, and of continua are still partially open questions, and HARTCODE relies for the latter on available laboratory measurements. The version of the code which was used to compute the HIRS database did not include effects caused by line coupling which produce large differences in transmittance in very localized spectrally narrow regions. Errors may also be introduced by some approximations such as the choice of the spectral positions at which monochromatic computations are made, and by the usual pre-selection of absorption lines that are believed sufficiently strong and are included in the computations. Care is taken to reduce these errors to below the level introduced by the more fundamental uncertainties discussed earlier.

It has already been pointed out that the selection of representative profiles used for the LBL computations, and for the generation of the coefficients of the fast-forward model, is itself a growing concern, especially for the representativeness of the water vapour profiles. Errors are also obviously introduced by the mandatory use of a fast-forward model and by the vertical layering for radiance computations, which for the time being is identical to the vertical layering used for the transmittance computations.
(c) Deficiencies in the atmospheric profile

There are two potential deficiencies in the profile. Firstly, all unresolved temperature and humidity structures in the forecast FG profile, which is used to generate the computed BT, and, secondly, forecast errors in structures that are resolved by the model. Since the atmospheric profile used to compute the BT must extend from the ground to 0.1 hPa, extrapolations are required above the ECMWF upper model level at 10 hPa which makes it particularly difficult to assess the causes of observed discrepancies between measurements and simulations for channels whose weighting functions extend above the model’s upper level.

The mean global concentration of some of the gases which absorb in the spectral channels, for example CO₂, NO₂ and CH₂, change with time, but the LBL computations were done with the concentrations appropriate for 1991. Moreover there is evidence for latitudinal variations of total column abundances as well as of seasonal changes in concentrations. This variability is not modelled in the LBL computations.

As pointed out by Watts (1989) a condition for the minimum variance retrieval equation to represent the most likely solution is that measurements, background and forward calculations, are unbiased with respect to the truth. However, no error-free truth is available. The data gathered by the radiosonde network do not contain any information on surface skin temperature, water vapour concentration is seldom measured above 100 hPa, and temperature above 10 hPa. The network is made up of different sensors that, for a variety of reasons, produce results that show differences, especially but not exclusively, in the water vapour profile determination (Knuteson 1995). These problems are well known since it is common practice at the ECMWF, and in other operational numerical centres, to apply corrections to radiosonde data to reduce biases against the FG field.

To deal with the combined effects of the aforementioned error sources the operational bias correction suite at the ECMWF is made of three parts:

(i) A correction to the calculated optical depth, for any given channel, by multiplying it by γ; this correction does not require an update for as long as the sensors’ characteristics do not change appreciably during mission lifetime. Since the effect of the coefficient γ is to raise or lower the whole weighting function, it affects the BT bias, and so the bias correction coefficients are specific to the particular value of γ used.

(ii) A scan-bias correction to the calculated BT at each scan angle relative to nadir, which is required to compensate for some unwanted effects caused by the procedure of limb-correction, i.e. the statistical reduction of measurements at different scan angles to nadir.

(iii) A bias correction to reduce residual systematic differences between measured data and simulated data computed with the FG fields.

To account for a marked variation as a function of ‘air mass’ of the bias between measured and simulated BT, the current operational bias correction method (iii) relies on MSU channels 2, 3 and 4 to represent the air-mass predictors, and any long-term bias between clear and computed radiances which is correlated with these predictors is removed (Eyre 1992). The coefficient of the linear correction, usually denoted by δ, requires frequent tuning (currently once per month) since some biases exhibit a seasonal cycle. MSU channels 2, 3 and 4 are sensitive to the atmospheric temperature structure. Therefore the correction does not filter differences which are correlated with BT in the humidity channels since the quality of the humidity field generated by the model is still particularly difficult to assess. It is felt preferable not to assume as errors those differences which could be originated by inadequate representation of the model’s humidity field.
5. Results

A series of experiments was run over two periods, from 20 December 1994 to 5 January 1995 (December case) and from 16 to 30 June 1995 (June case), to test the performance of the LBL set of coefficients against the OPE set used at the ECMWF. For the December case the two satellites NOAA-11 and NOAA-12 were operational; during the June case NOAA-14 had replaced NOAA-11 in the afternoon orbit.

Quality control and data selection of TOVS clear radiances were performed by the same code that has been used to generate, for all FOVs over ocean, differences between measured and FG BTs, the latter from the atmospheric state specified by the FG profile.

(a) Inter-satellite differences

For the initial comparison of inter-satellite differences, the \( \gamma \) values for both the LBL and OPE fast models were set equal to unity and the data were not subjected to any bias correction. Only a gross check was used: if any BT for a predictor channel was outside limits (currently 150 K to 350 K) or BT departure from FG was outside limits (currently \(-20 \text{ K to } +20 \text{ K}\) then the data in all channels was rejected. Since the same quality control thresholds were applied, different sets of coefficients (OPE and LBL) have generated slightly different samples.

As a preliminary step we computed, for the December period, BTs using the same HIRS channel filter functions for both satellites, to understand the effect of different time and spatial sampling among the two platforms. In December 1994 the time difference between equatorial crossing time for the two satellites was about three and a half hours, much less than the nominal six hours. The results of this comparison are in Table 2 which shows the 15-day global mean for computed BTs for NOAA-12 and for NOAA-11 but with the filter function of NOAA-12. Only those channels that are used in the operational

<table>
<thead>
<tr>
<th>Channel</th>
<th>NOAA-11 (44705 samples)</th>
<th>NOAA-12 (48637 samples)</th>
<th>Brightness-temperature difference (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>231.46</td>
<td>231.42</td>
<td>-0.04</td>
</tr>
<tr>
<td>2</td>
<td>221.06</td>
<td>221.26</td>
<td>0.20</td>
</tr>
<tr>
<td>3</td>
<td>220.86</td>
<td>221.00</td>
<td>0.14</td>
</tr>
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<td>4</td>
<td>230.39</td>
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<td>-0.11</td>
</tr>
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<td>241.98</td>
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<td>-0.18</td>
</tr>
<tr>
<td>6</td>
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<td>-0.16</td>
</tr>
<tr>
<td>7</td>
<td>267.61</td>
<td>267.59</td>
<td>-0.02</td>
</tr>
<tr>
<td>8</td>
<td>282.70</td>
<td>282.57</td>
<td>-0.13</td>
</tr>
<tr>
<td>9</td>
<td>277.44</td>
<td>277.95</td>
<td>0.51</td>
</tr>
<tr>
<td>10</td>
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<td>258.19</td>
<td>-0.11</td>
</tr>
<tr>
<td>11</td>
<td>245.15</td>
<td>245.05</td>
<td>-0.10</td>
</tr>
<tr>
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<td>271.90</td>
<td>271.66</td>
<td>-0.24</td>
</tr>
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<td>260.05</td>
<td>-0.26</td>
</tr>
<tr>
<td>14</td>
<td>247.59</td>
<td>247.30</td>
<td>-0.29</td>
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</tr>
<tr>
<td>17</td>
<td>212.02</td>
<td>212.65</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Filter functions of NOAA-12 are used for computing NOAA-11 and NOAA-12 radiances.
processing are shown, the numbering being 1 to 20 for HIRS/2 and 21 to 24 for MSU. It is seen that the differences in computed BT are very small, in all cases less than 0.5 K. It follows that only a small part of the differences that will be shown between measured BT by the two satellites can be ascribed to differences in sampling, the result being applicable for all those channels for which the model’s FG can be considered an adequate representation of the atmosphere. This should be the case for all tropospheric temperature channels and for channels peaking at the surface, since the model’s sea surface temperature is a blend of in-situ and remote-sensing estimates (Reynolds 1988).

Figure 2(a) shows the differences \( D_j = T_{Bj}(12) - T_{Bj}(11) \) between the BT measured during the December case by the instruments (HIRS/2 and MSU) on board the platforms operational at the time (NOAA-12 and NOAA-11). Also shown are the differences in computed BT using LBL coefficients, without any correction, between the two satellites. Figure 2(b) shows the same quantities but for NOAA-12 and NOAA-14 (i.e. \( D_j = T_{Bj}(12) - T_{Bj}(14) \)) in operation in June 95.

We will discuss only those channels where measured and calculated BTs show different trends, that is, for example, large differences in measured data are not matched by similar differences in simulated data, and the measured differences are much larger than the absolute calibration accuracy of the instruments.

Channels 3 and 4 of the MSU, and to a lesser extent channel 2, show large inter-satellite differences in mean measured temperatures for the December case. These differences could point either to calibration problems in one of the instruments, or to some difference in NESDIS pre-processing (not known to us) of the data from the two satellites. We have assumed that MSU channels have the same spectral response in all satellites based on available documentation from the NESDIS.

For the December and June cases, channel 1 of HIRS/2 shows large differences in mean measured BT between satellites. This may be caused by a slight difference in the actual instrument filter function from that assumed, since the HIRS-1 spectral width is smaller than the other HIRS channels, and is located in a spectral region where absorption varies rapidly with wave number. One cannot rule out also some kind of calibration problem possibly caused by ageing of the instrument, but this is considered unlikely since NOAA-11 and NOAA-14 behave very similarly with respect to NOAA-12. A further possibility is that the diurnal variability of the temperature profile in the upper troposphere and lower stratosphere is much larger than predicted by the forecast model, see results in Table 2. An extrapolation is required to obtain the temperature profile above the model’s upper boundary and it is possible that the FG and particularly the extrapolated part only poorly represent the temporal variability of the actual temperature structure. The difference between NOAA-12 and NOAA-14 is indeed greater than between NOAA-11 and NOAA-12. However, although the latter hypothesis can lead to errors it is not thought capable of explaining the whole difference between measured data from the two satellites.

The inter-satellite difference in measured BT in the HIRS water vapour channels 10, 11 and 12 is smaller than 1 K in both periods. One should note that channel 10 on NOAA-11 and NOAA-14 is centred around 795 cm\(^{-1}\), while it is centred around 1220 cm\(^{-1}\) on NOAA-12 and the observed differences are in good agreement with the differing properties of the channels.

Large differences are seen in measured BTs for HIRS channel 13 in December and especially in June, and for channel 15 in December. While the differences are mirrored by differences in computed BT for the December case, this is not so for the June case. The filter functions of channel 13 on NOAA-11 and NOAA-12 are slightly different, NOAA-11 channel 13 peaking in a more opaque region of the spectrum. It is sufficient to produce a mean difference of about 2 K, while using the same filter function the difference
Figure 2. Bar charts of inter-satellite mean difference between measured (white bars) and line-by-line computed ($\gamma = 1$) (grey bars) brightness temperatures, versus channel number. Channels 1 to 19 identify infrared HIRS/2 channels; channels 21 to 24 are MSU channels: (a) mean difference (NOAA-12 minus NOAA-11) for the December case; and (b) mean difference (NOAA-12 minus NOAA-14) for the June case.
is 0.24 K (shown in Table 2). Similarly, channel 13 on NOAA-14 is more opaque and therefore colder. The large discrepancy observed between measured and computed BT for the June case is, however, without a clear explanation: it could be due to inaccuracies in filter function or to the fact that channel 13 senses mostly N₂O emission close to sea level and may be therefore sensitive to diurnal variations in concentration that are ignored in our simulations. Some daily variability could also be possible since the two satellites are six hours apart. A difficulty with the latter explanation is that one would expect, based on the results presented previously for the US standard atmosphere, a similar behaviour also in channels 14 and 15, which is not the case. According to the filter functions at our disposal, channel 15 on board NOAA-12 is more opaque and therefore colder than the same on NOAA-14. However, the measured BT indicates that NOAA-14 channel 15 is slightly colder, and there is no firm explanation also for this discrepancy.

Channels 5 and 7 of HIRS show, in both periods, a large inter-satellite difference in calculated temperatures, but not in measured temperatures. An explanation for this effect is that the documentation of the filter function does not entirely match the actual instrument filter function since the inter-satellite mean difference in computed BT is zero (see Table 2) when the same filter function is used. The results are very similar for the June case and in fact the HIRS-7 documented filter functions for NOAA-11 and NOAA-14 are practically identical, and differ from NOAA-12.

In summary, a clear indication emerges from Figs. 2(a) and 2(b) that a bias correction is needed at least to reduce the systematic deviations that are found between measured BT and that are not matched by the simulated values.

(b) Difference between model FG and observations before bias correction

Figures 3(a) to 3(d) show mean bias and standard deviation (SD) of measured minus computed BT for the June case involving NOAA-12 and 14. Results are shown for both the OPE and the LBL forward models. Both forward computations are performed with \( \gamma = 1 \) and no scan or bias correction is applied. The use of \( \gamma = 1 \) implies there is margin to optimize the forward computations to a better agreement with observations. However, there is no general procedure to define an optimal \( \gamma \). The method we have adopted is outlined in section 5(d) and is aimed at minimizing the variance between measurements and FG in each channel since the reduction of bias is obtained by the subsequent application of the scan and bias corrections.

It should be emphasized that the differences shown in Figs. 3(a) to 3(d) are 15-day means for a specific period, since these differences do have a seasonal cycle. Both day and night data are processed and since no correction for solar contamination is used, the biases for short-wave HIRS channels are large. In fact channels 17, 18 and 19 are not used in the assimilation.

It can be seen that the OPE and LBL sets produce similar biases and SD in most temperature-sounding channels. In the water vapour sounding channels (10, 11 and 12) the LBL results show a much lower bias. The SD for the temperature-sounding channels is lower than for the water vapour channels, which is probably caused by the known lower quality of the mid- and upper-tropospheric FG humidity field.

The biases of NOAA-14 HIRS channels 1 to 7 show a monotonic increase from \(-2.3 \) K in channel 1 to \(+2.3 \) K for channel 5. A similar situation is observed between channels 2 to 5 of NOAA-12. Since the atmospheric transmittance increases with increasing channel number, a component of the bias can indeed be caused by problems in the LBL computations, in particular the treatment of the wings of the lines and the set of spectroscopic parameters being used, as explained earlier.
Figure 3. Statistics of the difference between measured and computed brightness temperatures for HIRS/2 and MSU channels used operationally for the June case. No scan-dependent or bias corrections are applied. White bars denote computations with OPE and grey bars with line-by-line, both with $\gamma = 1$ (see text): (a) global systematic difference, or bias, for NOAA-12; (b) global standard deviation of the difference for NOAA-12; (c) global bias for NOAA-14; and (d) global standard deviation for NOAA-14.
Figure 3. Continued.
(c) Difference between model FG and observations after bias correction

For the comparison between model FG and observations after bias correction the scan and bias-correction coefficients are computed for both OPE and LBL after setting the spectral $\gamma$ values to unity, for the same reasons as given in the previous subsection. The global mean biases, averaged over the 15-day period, shown in Figs. 4(a) and 4(b) for the June case, are very small when compared with those shown in Figs. 3(a) and 3(c), and very similar for the OPE and LBL sets. The SDs are very similar for the two sets and are not shown. Although the data rejection algorithms are identical for the two computations, the samples are not identical because rejection is based on differences between computed and measured BT and the former are different.

Examination of the geographical distribution of bias shows that OPE and LBL sets behave very similarly in all channels except channel 10, which will be discussed later. It also shows that in some channels the relatively small global difference is the result of large local biases being averaged. This is particularly true for the channels sensing the upper troposphere and stratosphere, i.e. HIRS channels 1 to 3. For example, for channels 1 and 2 the differences are dominated by regional variations in bias of the order of $\pm 3$ K and $\pm 1$ K respectively as a result of the stratospheric extrapolation discussed previously.

The only channel for which significant geographical bias distribution differences (averaged over the June period) are found between OPE and LBL is channel 10, shown in Figs. 5(a) and 5(b). As only clear radiances over the sea are assimilated, the contours are restricted to oceanic regions. It is seen that apart from both polar regions where the bias is very similar, the fields computed with OPE agree less with measured data. Since the content of Fig. 5(a) is the average of the data that are being assimilated, the analysis is modified to improve the agreement with observations; however, Fig. 5(b) indicates that the same FG is in better agreement with observations when the LBL system is used to simulate the satellite observations.

Examination of the corresponding values in Figs. 3 and 4 provides an indication of the amount of correction that is needed globally over the June period. However, locally, corrections can be large, of the order of several degrees, larger in fact than the final difference between measured and bias-corrected simulated BT, that is the 'signal' to be assimilated. In fact in many situations the extent of the correction is bigger than the signal, and this is obviously a great concern.

(d) Data assimilation and forecast-impact experiments

For data assimilation and forecast-impact experiments the scan and bias-correction coefficients were recomputed, for both the OPE and the LBL sets, after setting the $\gamma$ values. For the OPE set the $\gamma$ are the ones computed by the agencies providing the regression coefficients, as detailed at the end of section 3. For the LBL several computations were made of the differences between measured and computed BT from the FG, for both periods, each time with a different set of $\gamma$ in the range from 0.75 to 1.25. It was felt that values outside that range would imply very large and totally empirical modifications to the transmittances. The following criteria (labelled from (i) to (iii)) were applied to each spectral channel to arrive at the definition of the appropriate $\gamma$:

(i) $\gamma$ is selected to minimize the SD of measured minus calculated BT, if a minimum exists inside the interval excluding the boundaries;
(ii) if the SD changes monotonically, or varies by less than 1%, within the interval, a value is chosen for $\gamma$ that minimizes the bias, if a minimum exists inside the interval excluding the boundaries; and
(iii) in all other cases $\gamma$ is set equal to 1.
Figure 4. Global systematic differences (bias) between measured and computed brightness temperatures for HIRS/2 and MSU channels used operationally for the June case. White bars denote computations with OPE (see text) and grey bars with line-by-line. Scan-dependent correction and bias correction are applied, with coefficient computed with $\gamma = 1$: (a) bias for NOAA-12; and (b) bias for NOAA-14.
Figure 5. Geographical distribution of mean difference between model first guess and observations for HIRS/2 channel 10 of NOAA-14 after bias correction (with $\gamma = 1$) for the June case. Light shading $>1$ K; dark shading $<-1$ K; contour level $=0.5$ K; (a) OPE and; (b) line-by-line (see text).

Table 3 lists the selected LBL $\gamma$ values and the criteria adopted for each channel. OPE $\gamma$ values are listed as well.

An initial check of the performance of LBL coefficients after $\gamma$ tuning, against the operational ones, was performed using 'uncorrected' data, that is data after the gross check mentioned earlier. Examination of histograms of the BT departures (measured minus computed) for all channels and all satellites shows a great smoothness and an expected slight asymmetry due to residual cloud influence which in most occasions lowers the BT value.

The final form of the LBL scheme has been tested by two impact experiments over the periods 10–24 January 1995 and 5–18 September 1995 starting at 12 UTC. After each day of assimilation a 10-day forecast was run at spectral resolution T106 and with 31 levels in the vertical. Two parallel control experiments with the operational OPE coefficients were run over the same periods of time. A small positive impact on the temperature profiles is
TABLE 3. VALUES OF THE $\gamma$ COEFFICIENT FOR EACH CHANNEL FOR LBL AND OPE (SEE TEXT) TRANSMITTANCE COMPUTATIONS FOR THE SATELLITES USED IN THIS STUDY

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Bracketed figures show the criteria applied to arrive at the definition of the appropriate gammas for the LBL set, as explained in the text.

observed. For both experiments the 14 days averaged LBL 1D-VAR water vapour profiles are closer to the model FG for the lower troposphere at least in the northern hemisphere and in the tropics. Forecasts were run from the analyses. The forecast scores expressed as anomaly correlations at the 500 hPa level show a slight positive impact in the southern hemisphere whereas in the northern hemisphere the signal is less clear as the impact is slightly positive in September and clearly negative in January. The anomaly correlation plots for the 1000 hPa geopotential have the same characteristics. These results indicate that longer data-impact studies are needed to obtain a statistically significant result.

6. Conclusions

The processing of clear TOVS satellite radiances before the analysis stage in a numerical weather-prediction environment involves a detailed knowledge of several diverse components:

(i) The instrumental error characteristics.

(ii) The procedures applied to the raw data to derive the clear radiances themselves.

(iii) A fast radiative-transfer scheme which relies on accurate line-by-line computations.

(iv) The method to eliminate systematic differences between satellite data and model first guesses, including the systematic differences found between data extracted from identical or similar instruments carried on different platforms.

(v) The error covariance of the quantities that are to be assimilated, either the clear radiances or the products obtained from a retrieval scheme.
In our study we have used a new LBL transmittance database but have used the operational fast-forward model. Also the scan-bias, bias-correction, and the retrieval schemes are those operational at the time of our study (September 1995). The objective of our study was to evaluate the impact on forecasts of the same satellite data processed using the new transmittance computations. The results presented in section 5 ultimately show that it is possible to improve the performance of a numerical weather-prediction (NWP) model, by exerting a tighter control over some of the items outlined above, but that further work is required to make better use of data available today. The areas which certainly require further attention are briefly discussed below. No mention is given to improvements needed in the assimilation of satellite data in the analysis only because this is outside the scope of the present study.

In the two cases studied, channels 3 and 4 of the MSU (and channel 2 to a lesser extent) show inter-satellite differences in mean measured BT that are larger than instrument specifications. For the case studied it can be ruled out that the observed differences are caused by different sampling of the atmosphere and surface. Since the filter functions for these channels are the same, then calibration problems and/or preprocessing by the data provider are the likely cause. All MSU instruments that have flown or will fly in the NOAA series were calibrated on the ground in the early 1980s and the large span of time between ground characterization and operational service may be one of the causes of the problem. Calibration errors can also explain the behaviour of channel 1 of HIRS, which shows, in the case studied, differences in mean measured BT exceeding 2.7 K between NOAA-12 and NOAA-14 and 2 K between NOAA-12 and NOAA-11. These findings point to the necessity of an accurate characterization of the instrument to be performed as close as possible to launch date.

Another problem seen is when large differences in calculated BT are accompanied by a small difference in measured BT; as, for example, for channels 5, 7, 13 and 15 of HIRS, and also partly for channel 1. In this case one of the possible causes is a mismatch between the actual instrument filter functions and the documentation provided to the users, since we have found that the different sampling of the two spacecraft cannot explain the observed differences. This problem points to the need of great care when measuring and documenting the instrument filter functions.

Examination of the mean systematic differences before and after bias correction provides an indication of the mean correction that is needed globally over a period of 15 days. However, as pointed out in section 5(c), local (in space and time) corrections can be of the order of several degrees, much larger than the signal that is finally assimilated, i.e. the difference between bias-corrected measured BT and simulated BT from first guess. This is obviously a cause of great concern, and some of the reasons behind the large corrections required are indicated below because urgent work is needed to reduce this problem:

(i) A component of the bias seen in HIRS channels 1 to 7, especially for NOAA-14, is probably caused by the treatment of line wings within the LBL computations and by the quality of the spectroscopic parameters used. It is believed that more up-to-date spectroscopic databases should provide parameters for CO₂ that would correct some of the deficiencies reported in the quoted spectral range. A critical review of the parameters used in the LBL computations should be carried out together with a review of the atmospheric profiles used to generate the database.

(ii) Limb-corrected radiances are not necessary for the processing at the ECMWF. In fact a scan-bias correction has to be performed to reduce some of the artifacts introduced by the primary limb correction.

(iii) Cloud detection and clearing is probably the single processing step that intro-
duces the largest error, but this processing is, at the same time, unavoidable since NWP models are not yet capable of assimilating cloudy radiances. The errors introduced are not Gaussian and are spectrally dependent since lower peaking channels are likely to be more cloud-contaminated than the rest. This error could be reduced by the use of data from the 'companion' imager AVHRR*, but the latter are not currently available with the global HIRS data.

(iv) An improved forward model for ozone would have reduced to some extent the observed biases between measurements and simulations but since ozone is not currently a model variable, the improvements in the computations of the transmittances would not have been matched by a sufficiently accurate knowledge of ozone amounts. Some of the evidence presented, namely the large discrepancy observed between measured and computed BT in channel 13, indicates that more attention may need to be given to the geographical variability of gases which are assumed constant, in particular of N₂O, and also in their daily time variability.

This study was completed as we move toward the end of the operational use of the current TOVS system. When the Advanced TOVS (ATOVS) system becomes operational the Advanced Microwave Sounding Unit will be the main sounding system, complemented by the HIRS. However, if the problems described above are not addressed the optimal use of ATOVS data will not be possible.

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REFERENCES

Anderson, E., Pailleux, J., Thépaut, J., Eyre, J. R., McNally, A., Kelly, G. and Courtier, P.


Eyre, J. R. 1991 'A fast radiative transfer model for satellite sounding system'. ECMWF Technical Memorandum 176. (Available from ECMWF, Shinfield Park, Reading, Berks. RG2 9AX, UK)

1992 'A bias correction scheme for simulated TOVS brightness temperatures'. ECMWF Technical Memorandum 186. (Available from ECMWF, Shinfield Park, Reading, Berks. RG2 9AX, UK)

Eyre, J. R., Kelly, G. A., McNally, A. P., Andersson, E. and Persson, A.


* Advanced Very High Resolution Radiometer.
McMillin, L. M. and Dean, C.


Miskolczi, F.


Miskolczi, F., Rizzi, R., Guzzi, R. and Bonzagni, M. M.


Reynolds, R. W.

1988 A real-time global sea-surface temperature analysis, *J. Climate*, 1, 75–86

Rizzi, R., Serio, C., Kelly, G., Tramutoli, V., McNally, A. and Cuomo, V.


Smith, W. L., Woof, H. M., Hayden, C. M., Wark, D. Q. and McMillin, L. M.


Watts, P. D.