APPLICATIONS OF STATISTICS OF DEPARTURES BETWEEN MEASURED 
AND FORECAST TOVS BRIGHTNESS TEMPERATURES 

J R Eyre, G A Kelly, A P McNally and E Andersson 
ECMWF, Reading, UK

1. INTRODUCTION
Since April 1991, ECMWF has been running routinely a scheme called "PRESAT" which performs a number of pre-processing functions on TOVS data prior to their assimilation into the numerical weather prediction (NWP) system. The initial operational use of PRESAT was to improve the quality control and data selection of TOVS temperature/humidity profiles received from NOAA/NESDIS (see Kelly, 1992). Since June 1992, it has also been used as the data processing framework within which runs the one-dimensional variational analysis (1DVAR) of TOVS clear-column brightness temperatures which accompany the NESDIS retrievals (see Eyre et al., 1993; McNally et al., 1993). The 1DVAR scheme now runs operationally at ECMWF as part of the operational assimilation of TOVS radiance information. Another important function of PRESAT is to calculate and store the departures of TOVS brightness temperatures from corresponding values computed from short-range (nominally 6-hour) forecast profiles. These data sets have been stored since April 1991 and are being used for a number of applications, two of which are described here.

The first activity concerns the development and operational use of a scheme to adjust for biases in the TOVS radiative transfer model. The scheme provides air-mass dependent bias corrections for use within the TOVS 1DVAR scheme. The same bias correction method is also applicable within the three- and four-dimensional variational assimilation schemes under development at ECMWF (see Andersson et al., 1993). The theory of the bias correction method and aspects of its implementation are described in section 2. A more detailed description is given by Eyre (1992).

The second area of application concerns the study of bias fields in water vapour channels. Monitoring of statistics of residual brightness temperature departures, after the bias correction has been applied, has been conducted primarily to ensure that the scheme is working satisfactorily. For critical troposphere temperature sounding, residual biases are found to be small. However, for the water vapour channels, HIRS channels 11 and 12, the monitoring has revealed large and systematic biases which originate in the NWP model's humidity field. These results are described in section 3.

2. TOVS BIAS CORRECTION SCHEME
2.1 The bias correction problem
It is not possible to monitor the bias in a radiative transfer scheme in isolation. We can accumulate statistics of the differences between measured radiances and those calculated from collocated atmospheric profiles (from forecasts, analyses or radiosondes) and study their bias characteristics. These data may contain contributions to the bias from several sources. It is important to recognise these and to consider which we
may wish to correct and which we may not (see Watts, 1989). We have decided to adopt, at least for the
time being, the following strategy:

(a) Biases between measured brightness temperatures and those calculated from forecast profiles are
corrected as described in this paper.

(b) Only forecast profiles close to active radiosonde stations are used. Since the forecast/assimilation
system will have used radiosonde data from these stations recently, this should prevent significant
problems caused by any model drift.

(c) Statistics of radiosonde-forecast differences are to be used to remove relative biases between
different radiosondes (in a separate system, not described here). Data from radiosonde comparison
campaigns will be used to confirm results on relative and absolute radiosonde errors.

In this way it is planned to use the NWP model as a transfer medium to tune radiosondes against each other
and against satellite radiance data in a consistent manner. In any operational context, the observing systems
and the NWP model are subject to frequent changes, and so the whole bias correction system will require
continual monitoring. Moreover, the biases themselves will be specific to the particular NWP system within
which they are derived; they will not necessarily be applicable to other NWP systems.

The biases in the radiative transfer model for some channels are found to vary systematically between the
equator and the poles, and a successful correction scheme for global data must take account of this. Various
schemes have been proposed to apply a correction which is a function of "air-mass", in some sense. In this
work, we demonstrate acceptable performance from a simple scheme which uses selected measured
brightness temperatures as detectors of "air-mass" and hence as predictors in a regression relation which
generates a spatially-varying bias. In this context, "air-mass" is rather a loose term but can refer to any
aspect of the atmospheric profile which is correlated with the predictors.

2.2 The data
The TOVS brightness temperatures on which the scheme has been developed are global, cloud-cleared data
generated by NOAA/NESSDIS and available in Europe in near real-time as part of the "120 km BUFR
TOVS" data set. These data have already undergone substantial pre-processing at NESDIS (see Smith et
al, 1979) followed by cloud-detection and cloud-clearing (McMillin and Dean, 1982; Reale et al, 1986).
The cloud-clearing route is identified with the data and can be either "clear", "partly cloudy" or "cloudy".

NWP model fields at 3-hour intervals are interpolated quadratically in time and bilinearly in space to the
location of each TOVS sounding. The temperature and humidity profiles are then interpolated linearly from
the NWP model levels to the 40 pressure levels of the TOVS radiative transfer scheme (Eyre, 1991). Above
the top of the NWP model (i.e. currently for pressures less than 10 hPa), the profile is extrapolated as described by Eyre (1989). The radiative transfer scheme then operates on the input atmospheric profile to generate corresponding brightness temperatures for all the TOVS channels required. An important aspect of the radiative transfer model which affects the subsequent bias correction is the use of the so-called $\gamma$-correction method (Smith et al., 1984). The computed transmittance from each pressure level to space is raised to the power $\gamma$, where $\gamma$ is a constant for each channel. At present, the values of $\gamma$ are obtained from NOAA/NESDIS once for each satellite. Since their effect is to raise or lower the whole weighting function, they affect the brightness temperature bias, and so the bias corrections will be specific to the particular value of $\gamma$ used.

2.3 The method

The correction scheme is in two parts: firstly a correction for the bias in the measurement at each scan angle relative to nadir (if scan angle information is available), followed by a bias correction which varies as a function of "air-mass". The cloud-cleared brightness temperature in channel $j$ measured at scan angle $\theta$ (but adjusted to nadir) is $T_j(\theta)$. The datum to be corrected is the departure of this measurement from the corresponding forecast brightness temperature $T_j^F$ calculated at nadir:

$$d_j(\theta) = T_j(\theta) - T_j^F.$$ (1)

The first step is to use the information on the scan angle (if available) to make a correction for the relative mean biases between measurements at different scan angles. The scan bias correction is given by:

$$s_j(\theta) = \overline{d_j(\theta)} - \overline{d_j(\theta - \theta)}.$$ (2)

where the overbar represents a global mean for data at scan angle $\theta$ calculated from a large quantity of data. $s_j(\theta)$ is thus a mean bias relative to scan centre $(\theta = 0)$. The scan bias correction is applied as follows to form corrected departures:

$$d'_j = d_j(\theta) - s_j(\theta).$$ (3)

Since the cause of this relative bias lies in the measurements or their pre-processing, the same correction can also be applied to the measurements themselves:

$$T'_j = T_j(\theta) - s_j(\theta).$$ (4)

The second step is to correct for biases which are correlated with "air-mass" as sensed by the measurements themselves. A sub-set of channels is selected to represent the air-mass predictors, and any bias in the departures which is correlated with these predictors is removed. The bias correction is given by:
\[ b_j - a_{eq} + \sum_{i=1}^{M} a_q T_i^p, \]  
where \( T_i^p, i = 1 \rightarrow M, \) is a sub-set of the corrected measurements \( T_j, j = 1 \rightarrow N. \) Using the notation \( T^p \) and \( A_j \) to represent vectors with elements \( T_i^p \) and \( a_q (i = 1 \rightarrow M) \) respectively, the coefficients \( A_j \) are calculated by linear regression as follows:

\[ A_j = S(d_j^p, T_j^p) \cdot [S(T^p, T^p)]^{-1}, \]

where \( ^{-1} \) represents matrix inverse and \( S(...) \) represents a covariance matrix calculated from a large quantity of global data. The offset constant, \( a_{eq}, \) is given by:

\[ a_{eq} = -d_j - A_j^T \cdot T_j^p \]

where \( T \) represents matrix transpose. The bias correction is then applied as follows to form further corrected departures:

\[ d_j'' = d_j' - b_j \]

2.4 Application

Fourteen days of data have been found more than adequate for calculation of stable coefficients and also sufficient for studying spatial variations in the residual bias fields. At present only clear soundings over sea are used. Clear soundings are likely to be the highest quality measurements and contain data for all channels. Data over the sea are likely to have the least problems from residual cloud-contamination, because the sea surface temperature is used in one of the cloud detection tests, and also to have the most accurate surface temperature for the forecast brightness temperature calculation. A potential problem with this approach is that the corrections generated are biased towards clear areas. Examination of the corrections applied to data from partly cloudy areas has shown that this does not appear to be a significant problem in practice.

The data tends to be dominated by soundings in the tropics and southern hemisphere mid-latitudes. In order to create a more balanced distribution between different latitude bands, soundings are selected every nth sample, where n is 3 in the band 30-60°S, 4 in the band 30°S-30°N and 1 elsewhere.

Before data are used to calculate coefficients, they are subjected to the following stages of quality control:

a) Gross check. If any brightness temperature for a predictor channel is outside limits (currently 150 K to 350 K) or any brightness temperature departure is outside limits (currently -20 K to +20 K), then the data in all channels are rejected.
b) Window channel check. If the departure in a selected window channel is too great then data in all channels are rejected. Ideally, HIRS channel 8 should be used here. However, at present NESDIS apply a water vapour absorption correction to this channel, and the correction itself has peculiar error characteristics which differ between satellites. HIRS channel 10 is used; it is not such a clean window but is free from these problems. Data are rejected at present if the departure is outside the limits, -4 K to +8 K.

A further check, rejecting areas of sea-ice, has also been tried but is not currently used. It was found to lead to coefficients which produced large errors when applied back to data over sea-ice, because the atmospheric profiles there tend to be well outside the range of the profiles used in the generation of coefficients.

The mean and standard deviation of departures are then calculated in all channels for data which pass the above tests. All data are then processed a second time with an additional check.

c) Rogue check. If the departure in any channel differs from the mean departure by more than R times the standard deviation (currently R = 3), then data in all channels are rejected.

At present, bias corrections are only calculated for the following channels: HIRS channels 1-8 and 10-15, and MSU channels 2-4 and SSU channels 1-3. Only the departures in these channels determine quality control decisions.

As an option in the quality control, data can be selected inside a "radiosonde mask" which identifies only those areas within a given radius of an active radiosonde station. This is to address the potential problem of model drift discussed in section 2.1. A radius of 5 degrees (latitude equivalent) is currently used, which causes about 35% of data over sea to be accepted.

After the quality control, the bias correction coefficients are calculated using eqs. 6 and 7. For most of the work performed so far, the predictors have been MSU channels 2, 3 and 4. They were selected because they are always present (whereas most HIRS channels are unavailable for cloudy soundings). They appear to give satisfactory results for use in the 1DVAR scheme. However recent experiments have suggested that the inclusion of HIRS channel 1 would lead to significant improvement in stratospheric channels.

2.5 Results
Fig. 1 shows the typical monthly mean biases in MSU channel 3 before and after correction. This channel has the largest airmass dependent bias prior to correction, but one which is removed very effectively by the bias correction procedure.
Fig. 2 shows, for the same data, the bias and standard deviation of departure in HIRS channel 15, a mid-tropospheric temperature sounding channel. After correction the biases are acceptably small. The residual bias in the southern oceans is a persistent feature and is thought to be caused by the forecast/analysis system and the data it uses (i.e. probably the NESDIS retrievals which, at the time of writing, are still assimilated in the southern hemisphere). Further results and a more detailed discussion are given by Eyre (1992).

3. **SIGNS IN WATER VAPOUR CHANNELS**

Whereas the biases in tropospheric temperature sounding channels are generally small ($\leq 1 \, K$), and even smaller after bias correction, this is not so for the vapour water channels, HIRS channels 11 and 12. They show very large biases in places with a very distinct regional structure. Moreover, these patterns are not significantly affected by the bias correction procedure. Investigations have shown that they are almost certainly caused mainly by biases in the forecast model fields, not by errors in the data or in the radioactive transfer model.

Figures 3-6 show results for HIRS channel 11, a water vapour channel with a weighting function peak around 700 hPa (i.e. about the same level as HIRS channel 15). Biases of up to 4 K are seen in the monthly mean for large areas of the tropics and sub-tropics.

Fig. 3 shows the field for July 1991. During this period TOVS data in the form of NESDIS temperature/humidity retrievals were being assimilated over the extra-tropical oceans of the southern hemisphere but not elsewhere (except for temperature in the stratosphere). From June 1992, IDVAR retrievals were added to the system over the extra-tropical oceans of the northern hemisphere (see Eyre et al., 1993).

Fig. 4 shows the results for July 1992. Note that the assimilation of water vapour information through the 1DVAR scheme has significantly reduced biases in the northern hemisphere.

Fig. 5 shows the field for December 1992. This is a typical pattern for the season and is characterized by a negative bias (NWP model too dry) along the ITCZ and a positive bias (NWP model too moist) in the sub-tropical subsidence regions. This is consistent with results from comparisons between ECMWF model analysis and total precipitable water vapour derived from SSM/I data (Phalippou, 1992). The interpretation of these plots is not straightforward, as the relationship between brightness temperature difference and humidity profile difference depends on the lapse rates of both temperature and humidity. However a bias of 1 K in HIRS channel 11 represents a bias of about 10-20% in mid-tropospheric specific humidity. The measurements used are only cloud-free data, whereas the model values attempt to represent the local mean of clear and cloudy conditions. There is therefore a concern that the measured values will tend to show a dry bias. However, in the moist areas of the deep tropics, where we might expect this effect to be a
problem, we find that the model is currently drier than the measurements indicate. The model shows a moist bias in the subsidence regions of the sub-tropics, where problems of clouds at mid and upper levels are not expected to be significant.

Fig. 6 shows the field derived using NWP model data from a 15-day assimilation experiment in which 1DVAR products were assimilated globally. The field for the same period but without assimilating 1DVAR products is shown for comparison. It can be seen that the biases between measured and forecast brightness temperatures are greatly reduced. These results (and equivalent plots for HIRS channel 12) demonstrate the potential of HIRS water vapour channel data to alter significantly the mean structure of the model's humidity field in the mid- and upper troposphere in the tropics and sub-tropics. They also show that, when these data are not being assimilated into a model, they can act as a useful tool for diagnosing problems with the model's humidity field. Apart from satellite data, very little humidity data are available for assimilation in the tropics and sub-tropics. Also the model's "memory" for such data is rather short. Therefore the features of the model's analyzed and forecast humidity fields are largely determined by the dynamics and physical parameterizations of the model itself, rather than by observations. In this respect, the NWP model is similar to a climate model. Thus, these results illustrate how radiances from these channels might be used to study the performance of both NWP and climate models in representing the humidity of the mid- and upper troposphere.

References


Fig. 1 Local mean departure between measured and forecast brightness temperatures in MSU channel 3, NOAA-11, in October 1992 (a) before bias correction and (b) after bias correction. Contour interval = 0.2 K; light shading > 0.4 K; dark shading < -0.4 K.
Fig. 2  Statistics of local departure between measured and forecast brightness temperatures (after bias correction) in HIRS channel 15, NOAA-11, in October 1992:
(a) mean departure, with contour interval = 0.2 K; light shading > 0.4 K; dark shading < -0.4 K,
(b) standard deviation of departure, with contour interval = 0.1 K; shading > 0.4 K.
Fig. 3  Local mean departure between measured and forecast brightness temperatures (after bias correction) in HIRS channel 11, NOAA-11, for July 1991. Contour interval = 0.5 K; light shading > 1.0 K; dark shading < -1.0 K.

Fig. 4  As Fig. 3, except for July 1992.

Fig. 5  As Fig. 3, except for December 1992.
Fig. 6
(a) As Fig. 3, except for 2-15 May 1991, with model fields taken from an assimilation experiment in which TOVS 1DVAR products were assimilated over all ocean areas. (b) As (a), but without assimilating 1DVAR products.
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Edited by

J R Eyre

European Centre for Medium-range Weather Forecasts
Shinfield Park, Reading, RG2 9AX, U.K.

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