A satellite radiance-bias correction scheme for data assimilation

By B. A. HARRIS¹ and G. KELLY²

¹Bureau of Meteorology, Australia
²European Centre for Medium-Range Weather Forecasts, UK

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SUMMARY

Recently, much progress has been made in the direct assimilation of satellite radiance measurements in numerical weather-prediction systems. In order to use radiance from the TIROS Operational Vertical Sounder (TOVS), biases between the observed radiances and those simulated from the model first guess must be corrected. The original scheme for TOVS radiance-bias correction at the European Centre for Medium-Range Weather Forecasts utilized a global scan correction, and a linear air-mass correction, with the observed radiances from the Microwave Sounding Unit channels 2, 3 and 4 as predictors. The new scheme differs in two fundamental ways. Analysis of radiance data shows a significant residual scan bias which depends strongly on latitude for some channels. The new scheme applies a latitudinally dependent scan correction to take this into account. The air-mass predictors are now computed from the background field, since the background field contains a more consistent representation of the air mass and surface characteristics than the observed microwave radiances. Four new predictors are used, 1000–300 hPa thickness, 200–50 hPa thickness, model surface skin temperature and total precipitable water. In particular, the skin-temperature predictor is able to differentiate between ocean and sea-ice, performing much better than the old scheme in the winter hemisphere. The use of model predictors is a change in philosophy away from correction of the observations to correction of the computed forward radiances. This leads to a natural extension where the gradient of the bias correction can be taken into account in variational retrieval schemes.

KEYWORDS: ECMWF MSU Numerical weather prediction TOVS Variational retrieval

1. INTRODUCTION

The TIROS† Operational Vertical Sounder (TOVS) unit, carried on the National Oceanic and Atmospheric Administration (NOAA) series of polar-orbiting satellites, has High-resolution Infra-Red Sounder (HIRS), Microwave Sounder Unit (MSU) and Stratospheric Sounder Unit (SSU) instruments (see Smith et al. (1979)), which provide passive measurements of the radiation emitted from the earth’s surface and throughout the atmosphere. The radiances contain temperature and humidity information, but in order for this information to be directly assimilated in a numerical weather prediction (NWP) system, biases between the observed radiances and those simulated from the model first guess must be corrected. While random errors can be handled as increased observation error, biases may be significant and may come from inaccuracies in the radiative-transfer model or from changes to the instrument characteristics over time.

The original radiance-bias correction scheme in use at the European Centre for Medium-Range Weather Forecasts (ECMWF) relied on the observed brightness temperatures from MSU channels 2, 3 and 4 as linear predictors of the bias in all channels that were used. The idea relied upon the air-mass dependent nature (Kelly and Flohbt 1988; McMillin et al. 1989; Uddstrom 1991; McNally et al. 2000) of the bias in the observed minus calculated radiance departures. The scheme is described by Eyre (1992), and while some minor changes were made involving the use of cloudy radiances, the basic scheme remained unchanged.

As part of the TOVS radiance pre-processing carried out by the NOAA National Environmental Satellite, Data Information Service (NESDIS), a limb correction is made

*Corresponding author: European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading, Berkshire RG2 9AX, UK. e-mail: dmk@ecmwf.int
†Television Infrared Observation Satellite.
to the radiance measurements. However, a residual scan bias remains, and the original ECMWF scheme applied a globally averaged scan-angle correction for each channel.

Since the microwave channels are relatively insensitive to cloud, and sense broad layers in the atmosphere, they have some skill in removing the geographically varying components of the bias due to air-mass differences. However, large biases still remain, particularly in those channels which sense the surface, especially in the winter hemisphere where areas over sea-ice have very different radiance characteristics to those over open water. It was also found that the residual scan biases varied with latitude band, especially for the MSU channels.

In section 2, the radiance-bias correction is discussed. Section 2(a) concentrates on the improvement in the scan correction, which now has latitudinally varying scan offsets, and section 2(b) on the more important change, that is the use of air-mass bias predictors derived from the model background field. Section 3 contains a description of the results of assimilation and forecast experiments, comparing the new scheme to the previous scheme. In section 4, the gradient extension of the new bias correction is discussed, in which the bias correction is adjusted in the three-dimensional variational assimilation (3D-Var) minimization loop. Section 5 provides a brief summary of the results presented in this paper.

2. RADIANCE-BIAS CORRECTION

The basis of any direct radiance assimilation system (1D/3D/4D-Var) is the minimization of a cost function:

\[ J = (x - x_b)^T B^{-1} (x - x_b) + (y_e - y(x))^T [E + F]^{-1} (y_e - y(x)) \]  

(1)

where \( x_b \) is the background field (first guess), \( y_e \) is the observed radiance, \( x \) is the control vector, \( B \) is the background-error covariance matrix, \( E + F \) is the observation and forward model error covariance, and \( y(x) \) is the forward operator and interpolation of model fields.

Lorenc (1986) showed that the minimization of this function is equivalent to optimal interpolation schemes due to the Gaussian form of the function. However, this assumes that the observations \( y_e \) and the forward operator \( y(x) \) are unbiased and have Gaussian errors. In general, due to instrument calibration, NESDIS processing, and errors in the forward model, this may not be the case.

The bias can be categorized into two types, scan bias and air-mass bias. Radiances in the NESDIS product are limb corrected but, nevertheless, residual biases relative to the centre of the swath still remain in the data. Biases in the forward model, due to inaccuracies in the fast model and transmittance coefficients, tend to vary with the air mass and surface characteristics.

(a) New scan correction

The NESDIS 120 km clear TOVS radiance product data set used at the ECMWF has already undergone much pre-processing as described by Smith et al. (1979). The radiances are cloud-cleared and identified as either 'clear' or 'cloudy'. In addition, the radiances are adjusted to nadir (see Wark (1993)). However, residual scan-dependent biases are still present. The previous scheme at the ECMWF was to compute global average differences for each scan position, relative to the mean of the two central positions, for each channel,

\[ d_j(\theta) = \bar{R}_j(\theta) - \bar{R}_j(\theta = 0), \]  

(2)
where $\bar{R}$ is the averaged observed radiance, $d$ is the observed radiance difference, $\theta$ is the scan angle and $j$ is the scan position. Examining the microwave channel MSU 2 in particular, dividing the data according to latitude band, in this case every $10^\circ$, it can be seen (Fig. 1) that the scan dependence varies significantly with latitude. A global correction will produce large errors, particularly at the edge of the scan, in bands which differ from the global average, such as polar regions. Historically, such observations have been excluded from the ECMWF assimilation system, and it is suspected that part of the problem was due to the global nature of the scan correction.

As a result of these studies, the scan correction has now been subdivided into 18 latitude bands of $10^\circ$ of longitude. Some smoothing is required to produce continuous correction coefficients across latitude bands. In the polar regions north and south of $60^\circ$ all data are combined in these bands to produce a sufficiently large sample.

After rebinning, the mean values for each scan position and each band are computed, and then used to compute the scan correction,

$$d_j(\phi, \theta) = \bar{R}_j(\phi, \theta) - \bar{R}_j(\phi, \theta = 0)$$  \hspace{1cm} (3)

where $\phi$ is the latitude band. Once the mean scan correction for each position and each band has been computed, a simple smoothing method is then used to produce a smooth transition between bands. Specifically the smoothed scan correction is given by

$$d_j'(\phi, \theta) = \frac{1}{2}d_j(\phi - 1, \theta) + \frac{1}{2}d_j(\phi, \theta) + \frac{1}{4}d_j(\phi + 1, \theta),$$  \hspace{1cm} (4)

except for the poles which have already been averaged by the sampling method.

Figures 2 and 3 show a comparison between the old scan-correction method and the new latitude-dependent scheme for MSU 2. In both cases the bias correction has been computed from an independent sample from January 1997, and applied to data taken in February 1997. It can be seen that the old global correction shifts the scan bias such
Figure 2. Residual scan bias, NOAA 12, MSU 2—old global scheme. See text for further explanation.

Figure 3. As Fig. 2 but for new scheme.
that the global mean is zero, but still leaves the large latitudinal variation unchanged. However, with the new scheme the large variations are almost completely removed. There does appear to be some seasonal dependence in the scan correction.

The main changes in the air-mass coefficients are related to seasonal changes and as such it may be considered necessary to update the coefficients to take into account possible instrument drift, as often as one wishes. It is possible to update the coefficients after every assimilation cycle with little computational cost if so desired.

\[(b) \quad \textit{Air-mass correction}\]

The air-mass regression scheme uses a set of bias predictors, \(X_i (i = 1, \ldots, n)\), to predict the radiance bias \(B_j\), in each channel \(j\), through the linear equation,

\[B_j = \sum_{i=1}^{n} A_{ji} X_i + C_j\]  \hspace{1cm} (5)

where the coefficients \(A_{ji}\) and \(C_j\) are computed by performing a least-squares fit on a large sample, usually around two weeks of data. Only radiances near radiosondes are used to prevent the procedure from becoming unstable, as it is assumed that the model is relatively unbiased at these locations. Diurnal variation of bias was investigated by restricting the data sets to given six-hour daily periods, and no diurnal signal was seen.

The coefficients are given by

\[A_{ji} = \sum_{k=1}^{n} (D_j, X_k) \cdot [(X, X)]_{ki}^{-1}\]  \hspace{1cm} (6)

where the \((\ldots, \ldots, \ldots)\) denote covariances, \(X\) is the vector \(X_i\), and the departure \(D_j\) in channel \(j\) is

\[D_j = (y_E - y(x))_j\]  \hspace{1cm} (7)

The previous scheme used the observed radiances from the microwave channels MSU 2, 3 and 4, where it was assumed that these radiances, mostly unaffected by cloud, provided a good representation of the atmospheric state. However, significant biases still remained, particularly over the ocean and sea-ice areas of the winter hemisphere. One major reason for this was that the surface characteristics also have an effect on the bias, and the MSU radiance predictors were unable to account for this.

The new scheme uses the background field \(x_b\) to identify the air mass, as well as the surface temperature. A large data set, containing radiance data and model first-guess profiles from January 1997, was compiled, in order to calculate radiance/temperature and radiance/humidity correlations at each level. These correlations were then used to investigate which combinations of model variables could act as bias predictors. These correlations can be seen in Figs. 4 and 5. From the plots, it can be seen that for temperature there are broad structures, most likely reflecting a combination of channel weighting functions and background-error correlations, and various dependencies within the forward model. These structures indicated high correlations between radiance bias and the layers 1000–300 hPa and 200–50 hPa. Also there was a high correlation between the model surface temperature and channels such as HIRS 13 and MSU 2 which sense the surface. Areas of sea-ice are significantly colder than sea water, and the regression procedure is able to compensate somewhat for the different emissivity characteristics of sea-ice for these channels. The biases over sea-ice with the previous scheme reflect difficulties in the forward model to model unusual atmospheric states, rather than any
problems with the observed radiances. The problem arises because there is insufficient information in the observed radiances to predict such states. While the relationship may not be strictly linear, it is a vast improvement over the previous scheme which had no surface temperature predictor at all. The moisture correlations showed much less structure, but nevertheless a significant correlation is seen for some channels, particularly some of the low-level HIRS channels such as HIRS 5, 6, 7, 8 and 15. However, surprisingly little correlation is seen for the water vapour channels HIRS 11 and 12. It is important to realize that we are talking about the departure between observed and calculated background radiances, not the radiances themselves. It does not necessarily follow that if a channel senses a given level of the atmosphere, that the bias will depend on this level; it may come from another level altogether, due to correlations present in the background field.

In the light of these findings, it was decided after some testing that the best combination of new predictors would be:

1. Model first-guess thickness (1000–300 hPa),
2. Model first-guess thickness (200–50 hPa),
3. Model first-guess surface skin temperature, and
4. Model first-guess total column water vapour.

Data from January 1997 were used to compute the regression coefficients for both the old and the new schemes, but only in the vicinity of radiosondes. These coefficients were used to apply the bias correction to independent data from February.
1997. The plots (Figs. 6 and 7) show the geographical distribution of mean corrected bias for a two-week period, as well as the standard deviation.

In some channels the reduction in bias using the new predictors is significant, in others the biases are similar. The standard-deviation plots also show a reduction in standard deviation of bias-corrected radiance departure between the old and new scheme. This indicates a better fit to the data. The plots were produced with a simple analysis method (Cressman 1959) using the large set of observed minus first-guess statistics. For MSU 2, during the northern hemisphere winter, there was a persistent bias in the north-west Pacific region with the old scheme, which is almost completely removed with the new scheme (Figs. 6(b) and 6(d)). It appears that the problem with the old scheme was that the regression lacked the skill to differentiate between ocean and sea-ice, and that the regression was fitting to the sea-ice points rather than the ocean. The new predictors with the surface temperature predictor is able to fit both cases simultaneously thus eliminating the large bias over the water. A similar problem appears to affect HIRS channels 13, 14 and 15, with a similar large improvement in bias using the new scheme.

As would be expected from the correlation results, the HIRS water vapour channels 11 and 12 are not as impressive. Comparing Fig. 7(b), for HIRS 12, with that for the new scheme in Fig. 7(d), there are indications that the bias is improved in the deep tropics over sea, since these channels were not used over land, where it is expected that the moisture predictor would have the most impact.
There is a potential problem with using a 1000–300 hPa thickness predictor over land with high orography. At present, no channels sensitive to this predictor are used over land, and there is a limit of 2000 m elevation to the use of any profile. As more channels are used over land, this problem may need to be addressed in detail. Perhaps 850–300 hPa may serve equally well without some of the possible difficulties.

3. Results

Two data-assimilation experiments were carried out using the new bias correction scheme, plus the use of radiances in the stratosphere. The experiments were:

- First experiment: new bias experiment (new), 23 June–7 July 1997 control (old).
- Second experiment: new bias experiment (new), 1 February–15 February 1997 control (old).
Figures 8(a) and (b) show in the first experiment (new) the positive impact on the forecast scores in both hemispheres for the 500 hPa geopotential height, reflecting the better use of TOVS channels through the improved bias correction. A similar result is seen at 200 hPa. This relative improvement is possibly due to a revised data-selection procedure in the regression, giving more weight to southern hemisphere observations. Note also, this case is during the southern hemisphere winter, where the new bias correction is expected to have most effect.

The other experiment in February does not show such a dramatic impact; however, there is some small improvement still apparent in the southern hemisphere (Fig. 8(d)). One can speculate on the lack of impact in this case, perhaps the northern hemisphere winter case has more cloudy soundings, and the impact of the TOVS in the northern hemisphere is at best marginal. The southern hemisphere summer would also benefit less from the new bias correction as there will be much less sea-ice in the southern oceans.
The new bias-correction scheme, plus extended use of radiances, became operational at the ECMWF on 27 August 1997.

A comparison can be made between the actual corrected biases for August using the old scheme, and the corresponding biases in August using the new scheme (Fig. 9) in parallel testing before operational implementation. In particular, the MSU 2 residual bias plots show a major improvement in the southern hemisphere, demonstrating the ability of the new scheme to differentiate between areas of ocean and areas of sea-ice.

There is a concern that there may be some feedback between the model and the bias-correction scheme, particularly if some unrelated aspect of the model is altered, causing a large-scale change in the temperature structure at some level. This problem is addressed in two ways. First, since the tuning is only performed near radiosonde sites, this should prevent the situation where the model runs away and the tuning reinforces the new configuration. If there is an abrupt change in the background field due to some
model change, then the biases will need to be carefully monitored on a daily basis, and if necessary the correction coefficients recalculated. Experiments conducted so far do not indicate that feedback will be a problem, provided the appropriate monitoring is performed.

4. EXTENSION OF THE NEW SCHEME

Since we now have

$$B_j(x_b) = \sum_{i=1}^{4} A_{ji}X_i(x_b) + C_j,$$  \hspace{1cm} (8)

and the bias-corrected departure (see Eq. (5)) is equal to

$$\delta y_j = y_E - (y(x_b) + B_j(x_b)),$$  \hspace{1cm} (9)
it is possible to regard the bias correction as a retuning of the forward operator \( y(x) \), rather than a correction of the observation \( y_0 \). At present, the bias correction is calculated once in the 1D-Var screening routine, and the observations \( y_0 \) are adjusted. However, in the 3D-Var minimization, the forward operator is called whenever the control vector is changed. If the bias correction is viewed as a retuning of the forward model, then the full bias-corrected forward operator should be used in the minimization. That is if we have

\[
y'(x) = y(x) + B(x),
\]

then we also have

\[
K'(x) = \frac{dy}{dx} + \frac{dB}{dx},
\]
and so we will need a bias-corrected K matrix in 1D-Var, and bias-corrected adjoint and tangent-linear forward operators in 3D/4D-Var.

The gradient operator was first tested in 1D-Var by comparing the standard deviation of the retrieved departures for the gradient scheme with that of the usual scheme. A small reduction in retrieval error was observed, mainly in the surface channels. This suggests that the skin-temperature predictor may be acting to reduce the biases during the minimization. The adjoint and tangent-linear code was written and a full 3D-Var experiment was performed.

An assimilation was run for the period 12 September to 5 October 1997, with the ECMWF operational model as the control. There was little improvement in the forecasts, and overall the result is considered neutral. Consequently this part of the scheme has not been implemented operationally to date. However, since the skin temperature is not in the 3D-Var control vector, only the remaining three predictors can have any effect. It is
possible to include the skin temperature in the control vector, and it is hoped that with this inclusion a more significant improvement may result.

5. CONCLUSIONS

The new TOVS radiance-bias correction procedure at the ECMWF is a significant improvement on the previous system for the following reasons. The revised scan-correction method improves the data quality on the edge of the swath, and allows for a greater use of these observations in the future. The air-mass bias correction reduces the geographical biases, particularly in the surface sensing channels. The greatest
improvement appears to be due to the model-based predictors being better able to differentiate between ocean and sea-ice in the winter hemisphere.

Another useful aspect of the new scheme is that it may be used when there are no microwave channels present. Such is the case for geostationary satellites such as GOES-10 which carries a HIRS instrument, or for the water vapour channels on Meteosat.

The scheme also involves a change in the philosophy of the bias correction. It shifts the air-mass dependent part away from the observations, and back to the forward operator, which is the main source of air-mass bias. Since the bias correction itself is background dependent, the procedure can be considered as an empirical retuning of the forward model. This then leads to a natural extension incorporating the bias correction into the adjoint forward operator in a variational assimilation system.
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