# Bias correction of satellite data at the Met Office

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## 1. Introduction

At the Met Office, radiances from the ATOVS and AIRS instruments are assimilated operationally within the 4D-Var system for Numerical Weather Prediction (NWP). Accurate bias correction is known to be important in maximizing the forecast impact. There are many error sources that can cause a discrepancy between radiances predicted from the NWP model and those measured by the instruments, including:

- bias in the NWP background fields
- errors in the forward modelling, for instance in the radiative transfer
- residual contamination of the observations from cloud or other sources
- instrument calibration errors
- inaccurate specification of instrument spectral response filters

This paper does not discuss these error sources in detail, but rather describes the techniques that are used to alleviate their impact. It also describes the practical aspects of implementing bias correction schemes and monitoring trends.

The following instruments are covered within the scheme described here:

- AMSU-A (NOAA satellites and EOS Aqua)
- AMSU-B
- HIRS (though not currently assimilated)
- AIRS (on EOS Aqua)

AMSU-A and AMSU-B are typically re-mapped to the HIRS grid (with 56 spots per scan) by the ATOVS and AVHRR Pre-processing Package (AAPP – Atkinson and Doherty, 2005) before being presented to the NWP system.

The scheme will be extended in the future to cover SSMIS (on DMSP) and IASI (on METOP).

## 2. Techniques

Bias correction is done within the 1D-Var component of the Observation Processing System (OPS) – which prepares observations for 4D-Var.

The basic technique is based on Eyre (1992). For each channel, $i$, and scan position, $s$, the bias, $\Delta T$, is modelled as the sum of a scan-dependent term, $c_{i,s}$ , and a term that varies linearly with certain air mass predictors, $p_j$ :

$$\Delta T_{i,s} = \sum_j a_{i,j} p_j + c_{i,s} \tag{1}$$

Prior to 2004, the air mass predictors used were observed brightness temperatures of a “tropospheric” AMSU channel (channel 5) and a “stratospheric” channel (channel 9). In 2004 the system switched to the use of model-based predictors (Harris and Kelly, 2001). Two predictors are used operationally:

1. 200-50 hPa thickness (stratospheric thickness)
2. 850-300 hPa thickness (tropospheric thickness)

The use of model-based predictors has several advantages over observation-based predictors, including:

- Allows use of observations over high land. AMSU channel 5 is not a good air mass predictor over high land because it sees the surface.
- Does not rely on valid data from a specific channel, e.g. we can work with AMSU-B data alone if required.

The NWP model assimilates data from a number of different sources. Observation types that are not bias corrected (e.g. radiosondes) are regarded as “truth”, and constrain the model profiles in the geographical areas close to those observations. Any biases in the satellite data will be most obvious in these areas, but will also be present to some extent in other areas due to the model’s requirements for dynamical self-consistency. For the Met Office global model we compute the bias coefficients ($a_{i,k}$ and $c_{i,j}$ in (1)) so as to mimimise $\Sigma(C_i - B_i)^2$ , summing over all acceptable observations, where $C_i$ is the corrected radiance for channel $i$ and $B_i$ is the background radiance (from a short-term forecast). The system does not use a radiosonde mask when computing this global error sum, though it is arguable that bias correction updates might converge faster if such a mask were used.

In addition to the two predictors listed above, other predictors have been coded and were examined during the testing of the new scheme. These are:

3. Skin temperature
4. Total column water vapour
5. Background brightness temperature (per channel)
6. Temperature lapse weight convolved with weighting function (per channel)

Predictor 3 (skin temperature) was found to be effective in reducing geographical bias variations for AIRS, which is used over ocean only, but has the disadvantage that it has sharp step changes at land/sea boundaries so is not a good predictor for those ATOVS channels that are used over both land and sea. Predictor 4 (column water vapour) is not used operationally because of concerns that it could mask real variations in the atmospheric humidity structure.

Predictor 5 (background brightness temperature) was included because some sources of bias are dependent on the incoming radiance, e.g. the error due to non-ideal antenna reflectivity for microwave instruments. However, when this predictor was tested in trials it actually gave a degradation, so was not considered further. Predictor 6 was designed to correct for errors in the height assignment of the weighting functions. However it involves extra computation and is not currently used.

## 3. Computing the bias coefficients

Bias coefficients are computed by linear regression. In Eyre (1992), the bias coefficients are computed in 2 stages – firstly the scan correction and secondly the air mass correction once the scan correction has been applied. In practice this is sub-optimal if some of the predictors vary with scan position (as is the case with predictors 5 and 6). So a single step is preferred:

$$\mathbf{a}_i = \left( \overline{\mathbf{p}\mathbf{p}^\mathbf{T}} - \overline{\mathbf{p}}\ \overline{\mathbf{p}^\mathbf{T}} \right)^{-1} \left( \overline{\mathbf{p}y_i} - \overline{\mathbf{p}}\ \overline{y_i} \right) \qquad \text{(2a)}$$

$$c_{i,s} = \overline{y_{i,s}} - \mathbf{a}_i^{\mathbf{T}}\,\overline{\mathbf{p}_{\mathbf{s}}} \tag{2b}$$

where **p** is a column vector of predictors, $y_{i,s}$ is the (Observed–Background) radiance difference for channel $i$, scan position $s$. Thus we need to compute the covariance matrix of the predictors and the cross-covariance between the predictors and the radiance errors. The over-bars denote either global means or (if the $s$ subscript is present) global means for each scan position.

Harris and Kelly (2001) describe the use of different scan dependent constants in different latitude bands; however, in the Met Office system the scan dependent coefficients are global.

For stratospheric channels a slightly different approach is taken, since radiosonde profiles are known to have biases and in any case have limited vertical coverage. The satellite radiances in the centre of the swath are assumed to be unbiased and a simple scan correction is applied to the remainder of the swath.

## 4. Accumulating the bias statistics

Bias statistics are accumulated "on the fly" each time the OPS is run. Statistics are accumulated separately for each of 5 latitude bands (90-60S, 60-30S, 30S-30N, 30-60N, 60-90N) and 3 surface types (land, sea, sea-ice). A single "Bstats" file is maintained for each satellite, containing the quantities given in Table 1.

| **Quantity** | **Dimensionality** (assuming ATOVS on HIRS grid; 2 air-mass predictors) |
|---|---|
| Number of observations | 40 × 56 × 5 × 3 |
| Mean $O - B$ | 40 × 56 × 5 × 3 |
| Mean $(O - B)^2$ | 40 × 56 × 5 × 3 |
| Mean $(P \times (O - B))$ | 40 × 56 × 5 × 3 × 2 |
| Mean $P$ | 40 × 56 × 5 × 3 × 2 |
| Mean $(P \times P)$ | 40 × 56 × 5 × 3 × 2 |

*Table 1: Contents of "Bstats" file for ATOVS*

Table 1 assumes that the predictors $P$ can vary with channel and scan position (though in practice the predictors used operationally are the same for all channels).

Before performing the regression it is useful to adjust the number of observations in each latitude band so as to avoid giving undue weight to bands that have more observations than average (i.e. the tropics). Also, we equalise the number of observations in each scan position. This is done automatically.

In the case of AIRS, the OPS does not generate a Bstats file directly, but instead saves $O$, $B$, $P$, latitude, longitude and other quantities for all observations. This has the advantage of flexibility for research purposes, but the disadvantage that large data files are generated.

Not all channels are used in the statistics. The basic principal is that we include all channels that are used in the 1D-Var retrieval – and this channel selection varies from observation to observation depending on surface type, cloud type, surface height, etc. For example,

- AMSU 1-3 and 15-17 are not used at all
- AMSU 4, 5 and 18-20 are only used over sea
- In rain, only the stratospheric channels are used

In addition, to ensure that no outliers are included in the statistics, an observation is excluded if $C–B$ for any used channel exceeds a pre-defined threshold (currently 6K for all AMSU channels).

## 5. Examples

As an illustration, Figure 1 plots the bias characteristics of an AMSU-A channel on EOS Aqua. This instrument has some rather large scan-dependent biases on most channels, up to 1.8K in Figure 1(a). Although the means of the air-mass corrections are very close to zero (plot (b)), the air-mass predictors do substantially reduce the variability of the overall bias error (plot (c) – compare the dotted line with the solid).

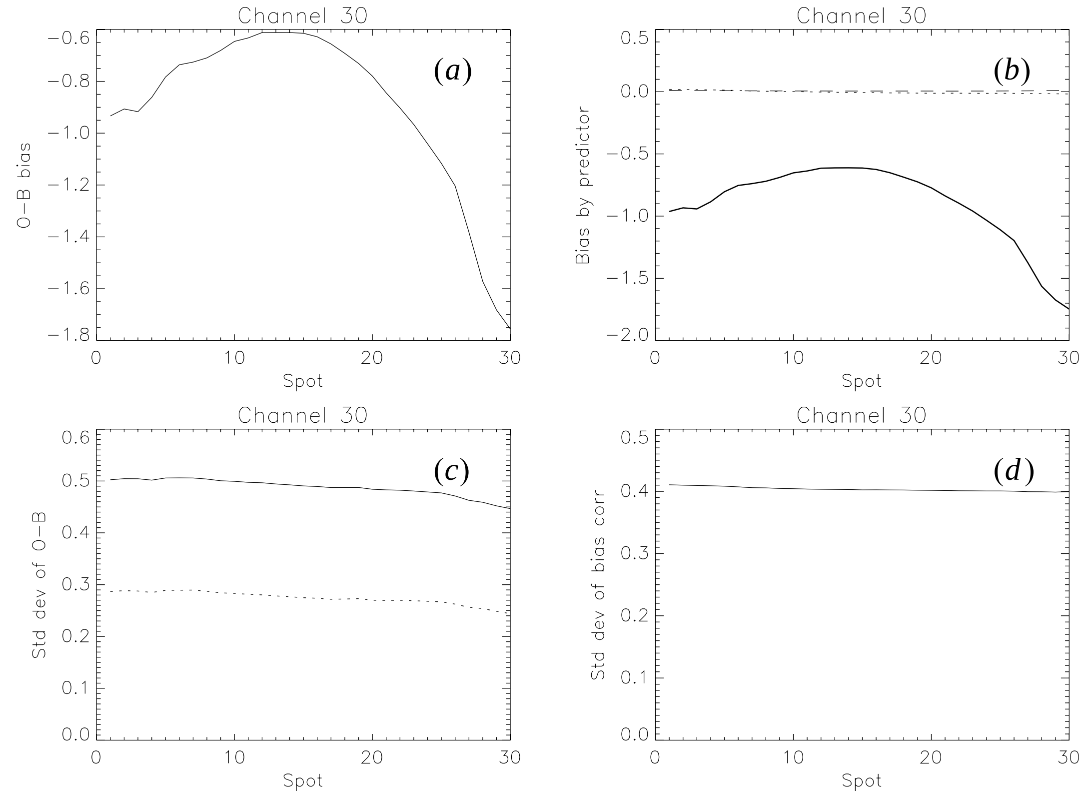
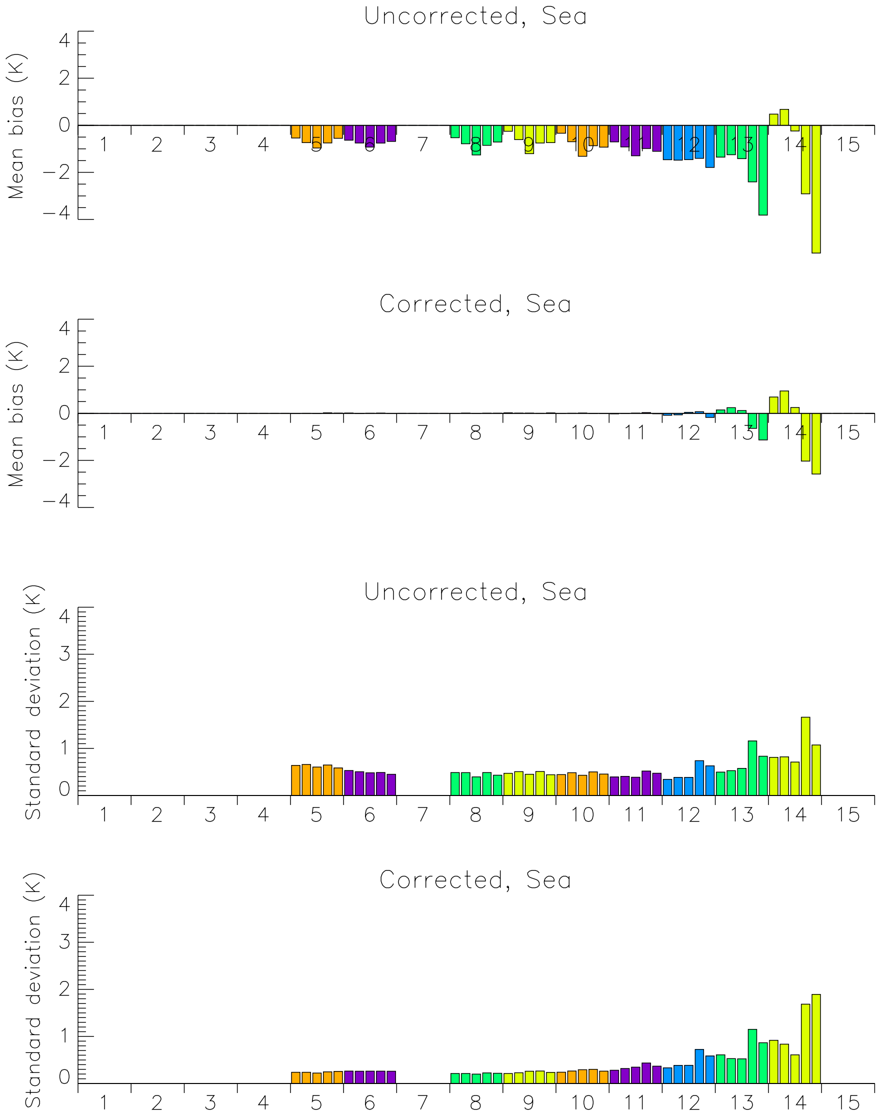


*Figure 1: Global bias characteristics for Aqua AMSU-A channel 10 (referred to as ATOVS channel 30): (a) Mean bias as a function of scan position, (b) Scan dependent correction term (solid) and mean of the air mass corrections (dotted and dot-dash); (c) Solid: standard deviation of (O-B), dotted: standard deviation of (C-B), (d) Standard deviation of the bias correction. Data are for December 2004.*

Figure 2 shows bias characteristics for all the AMSU-A channels, for the 5 latitude bands. We see that the bias corrections reduce the mean bias to close to zero for channels 5 to 12, though there is some residual bias for channels 13 and 14. Channels 5 to 11 show a substantial reduction in standard deviation when corrected.



Uncorrected, Sea

Corrected, Sea

Uncorrected, Sea

Corrected, Sea

*Figure 2: Mean and standard deviation of O-B and C-B for Aqua AMSU-A, as a function of channel number. For each channel, 5 latitude bands are plotted (left to right): 90-60S, 60-30S, 30S-30N, 30-60N, 60-90N. The bias coefficients are calculated globally but only sea data are shown in this figure. Data are for December 2004.*

## 6. Comparison of predictors

Prior to introducing the new model-based predictors into operations in 2004, some comparisons were made of the relative effectiveness of the various predictors in reducing the bias variance. Figure 3 is derived from a Bstats file for NOAA-16 and shows the reduction in *O-B* variance and the overall *O-B* standard deviation when predictors are introduced in turn. Note that the order in which the predictors are introduced affects their relative importance – since they are not independent. Nevertheless some interesting trends emerge:

- Stratospheric thickness is an excellent predictor for the tropospheric AMSU channels
- Tropospheric thickness is more useful than stratospheric thickness for the stratospheric AMSU channels
- Background brightness temperature also appears to be significant for the stratospheric channels
- Total column water vapour only really contributes for the HIRS channels that are most sensitive to water vapour, notably channel 11. There could be a risk of removing real atmospheric humidity variations if this predictor were used operationally.

Trials were run for two cases – 2 predictors (tropospheric and stratospheric thickness) and 3 predictors (add background brightness temperature). The 2-predictor trial was neutral compared with the old observation-based predictors, whereas the 3-predictor trial gave a degradation of 1 point in the Met Office global index.

The 2-predictor system was selected for operations – at the same time allowing other system enhancements such as the use of ATOVS data over high land.

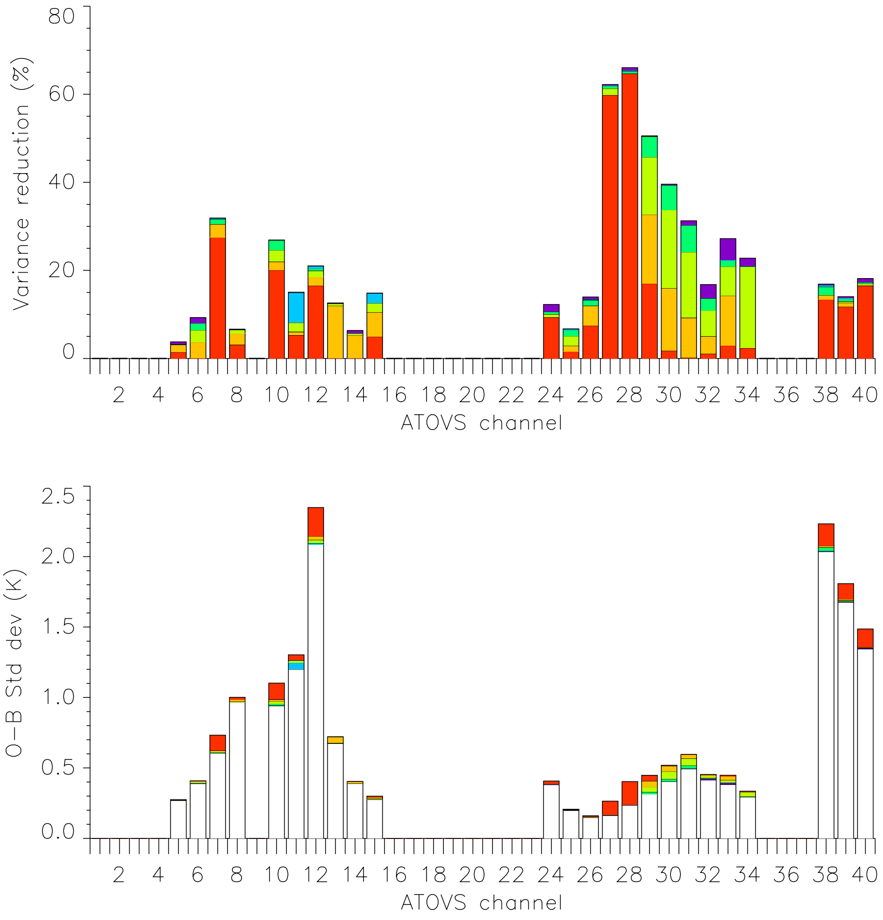


*Figure 3: O-B variance reduction and resulting overall standard deviation when predictors are introduced in turn, in the following order: (1) red – 200-50 hPa thickness; (2) orange – 850-300 hPa thickness; (3) yellow – background TB; (4) green – skin temperature; (5) light blue – water vapour column; (6) purple – lapse rate convolved with weighting function. HIRS channels are numbered 1-20; AMSU channels are 21-40. Data are for NOAA-16.*

Similar experiments for AIRS showed that for reducing the bias variance there was little to choose between the combination of stratospheric and tropospheric thickness and the combination of skin temperature and background brightness temperature. Eventually the thickness predictors were selected for operations, i.e. as for ATOVS.

## 7. Monitoring of biases

Time series plots and other monitoring reports, from the Met Office and other centres, are available in the context of the EUMETSAT NWP Satellite Application Facility (NWPSAF). The NWPSAF web page is at http://www.metoffice.com/research/interproj/nwpsaf/index.html. The Met Office plots provide time series of

(O-B), (C-B), O, B and C for AMSU and HIRS. The user is able to select data over land, sea, sea-ice, all surfaces or specific latitude bands, and to choose from different cloud categories. Time scales are either 1 month (for examining day-to-day variability) or 2 years (for long term monitoring).

Figure 4 shows an example of a 2-year plot for a channel that is known to exhibit significant drift – AMSU channel 6 on NOAA-15. This illustrates the problem of keeping track of biases in a static system: a bias coefficient update uses statistics from the previous month; by the time the update is implemented the bias has drifted further. To alleviate the problem for this channel, a correction proportional to instrument temperature was implemented outside the NWP system in the local implementation of AAPP – this was in early 2005. Since them drifts have been somewhat reduced, though not eliminated.

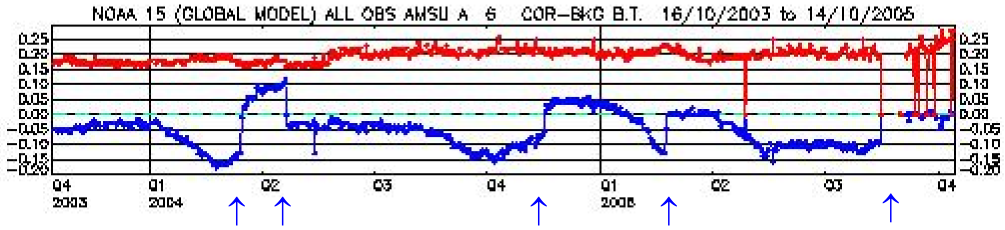


*Figure 4: C-B over 2 years for AMSU channel 6 on NOAA-15. Vertical arrows mark the dates of bias coefficient updates. Top (red) – standard deviation, bottom (blue) – mean.*

## 8. Future work

The preceding sections have focussed on biases from the Global Model. For regional models current practice is to use the global biases. However, this has serious shortcomings, e.g.

- model biases can differ between global and regional models
- different combinations of instruments may be used for regional models

For example, in the near future regional models will be able to use AMSU-B at full spatial resolution (i.e. not mapped to HIRS) and will be able to use AMSU-B in the absence of AMSU-A (e.g. for NOAA-17). The intention is that the Met Office North Atlantic-European model (NAE) will generate its own bias corrections, though the detailed approach is still being developed.

A second development is that in order to improve the ability of the system to track slowly varying biases, consideration is being given to implementing a *variational* bias correction scheme, in which the bias coefficients are added to the list of Control Variables in 4D-Var (Dee, 2004). Thus the system would automatically adjust itself to any long-term shifts in instrument or model characteristics. This also has the effect of minimising departures from the *analysis* rather than departures from the background – which is theoretically preferable.

## 9. Conclusions

Bias correction is a key part of the NWP assimilation system. The Met Office bias correction scheme has been in place for many years and has recently been updated to use model-based air-mass predictors rather than observation-based predictors. The system has also been extended to encompass AIRS.

Time series plots showing short-term and long-term bias trends are made available via the NWP-SAF web pages.

Current work includes extending the techniques to apply to regional models and also the possible implementation of variational bias correction techniques.

## 10. Acknowledgements

The AIRS bias correction system was developed by Brett Harris (Australian Bureau of Meteorology) and Andrew Collard (now at ECMWF). Thanks also to Richard Renshaw and Dave Jones for past work on the ATOVS scheme.

## References

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