The testing and implementation of variational bias correction (VarBC) in the Met Office global NWP system

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Abstract

Variational bias correction (VarBC) has been used in the Met Office global NWP system for the bias correction of satellite sounding instruments since 15 March 2016. The initial implementation only adjusts the bias of actively assimilated channels. The predictors used for the majority of satellite sounding instruments continue to be the 850-300 hPa thickness and 200-50 hPa thickness. The VarBC system is configured so that the biases evolve according to a user-specified bias halving time. Four Legendre Polynomial predictors are used to analyse small corrections to the fixed cross-scan bias correction. SSMIS data suffer from complex biases driven by solar heating and solar intrusions. The bias of SSMIS is modelled using a Fourier series where the phase angle is the position in the orbit measured from the intersection of the orbital plane and the ecliptic.

The VarBC system was extensively tested, including trials of winter and summer seasons from 2013, 2014 and 2015, as well as a 7.5 month trial and control. Results were consistently positive against analysis for geopotential heights, temperature and winds over all seasons tested. Short-range forecasts errors of extra-tropical geopotential height as verified against analysis are typically improved by 5-10% (RMSE). The fit of the 6 hour forecast to observations was improved; for example the standard deviation of the fit to ATMS channels was improved by between 2 and 6%.

Contents

1 Introduction

Satellite radiance observations are biased relative to observations simulated from the forecast model background. The bias may be a combination of instrumental effects, systematic errors in the radiative transfer model, and the bias of the forecast model. In many cases it might be better not to remove the effect of forecast model bias. Pragmatically, however, it is difficult to separate forecast model bias from other sources of bias so they are treated together at present. Bias correcting satellite observations has been found to be empirically necessary for the maximum benefit to forecast accuracy.

Variational bias correction (VarBC) has been used operationally at the Met Office in the global NWP system since 15 March 2016. The bias correction system used prior to VarBC is here referred to as the *static scheme*. The static scheme is loosely based on the method of Harris and Kelly [Harris and Kelly, 2001], and is briefly outlined in section 2.1. In the static scheme the bias correction is fitted using roughly a month's worth of data. In recent years the static bias correction was updated at 6-12 month intervals, or as required following a significant shift in the monitored residual biases.

Most other NWP centres, including ECMWF, Meteo-France and NCEP use variational bias correction (VarBC) [Auligné et al., 2007] as part of their NWP systems. The scheme developed at the Met Office is similar to the formulation of Auligné, and is outlined in section 2.2. Recent enhancements to VarBC are summarised in section 2.3, the current choice of predictors are listed in section 2.4, and desirable future developments summarised in section 2.5.

VarBC was extensively tested prior to becoming operational at the Met Office, including a 7.5 month trial and control. The trial results were consistently positive and the main features are outlined in section 3. The source of the impact of VarBC is not fully understood, and possible candidates are discussed in section 4. Conclusions and acknowledgements are given in sections 5 and 6.

2 Bias correction at the Met Office

2.1 Overview of the static bias correction scheme

The satellite radiance bias correction scheme used at the Met Office prior to VarBC is here referred to as the *static* bias correction scheme, and is based on the method of Harris and Kelly [Harris and Kelly, 2001].

The bias is modelled as a constant, a scan bias correction, and a set of coefficients and predictors:

$$y_k^o := y_k^o - \left(c_k + s_k + \sum_{i=1}^{I_k} \beta_i p_{k,i} \right) \tag{1}$$

where:

$:=$	Assignment.
k	Observation and channel subscript.
i	Predictor subscript.
I_k	Total number of predictors used for observation k.
y_k^o	Observation.
c_k	Constant bias offset for the channel.
s_k	Scan bias value for the observation scan position.
β_i	Bias coefficient for predictor i.
$p_{k,i}$	Bias predictor value for observation k and predictor i.

The scan bias is adjusted so that the mean scan bias across all scan positions is zero (or that the mean scan bias of user-specified scan positions is zero); this is why a separate constant offset is required. The air-mass predictors used are the model 850-300 hPa thickness and 200-50 hPa thickness.

New bias corrections were typically generated using between 10 days' and one month's worth of data, although longer periods were sometimes used. In recent years the bias correction was updated infrequently, typically every 6–12 months, unless there was a significant change in the bias as flagged by satellite radiance monitoring.

2.2 Main features of VarBC

The variational bias correction scheme implemented at the Met Office closely follows the incremental formulation described by Auligné [Auligné et al., 2007].

The VarBC bias model is very similar to that of the static scheme:

$$y_k^o := y_k^o - \left(s_k + \sum_{i=1}^{I_k} \beta_i^b p_{k,i} \right) \tag{2}$$

where β_i^b is the first-guess (background) bias coefficient. The main difference from the static scheme is that the first predictor is set to be 1 so that the first coefficient takes on the role of the constant bias offset. The ability to apply a fixed cross-scan bias correction, s_k, has been retained, although there is currently no mechanism to generate or update this in VarBC.

The bias correction is applied to observations in the 1D-Var pre-processing and quality control step. An increment to the bias coefficients, β_i', is then analysed as part of the 4D-VAR data assimilation stage. The data assimilation stage minimises a penalty function, and the observation part of the penalty function (J_o) includes an increment to the bias correction:

$$J_o = \frac{1}{2} \sum_k \left(\left(y_k + \sum_{i=1}^{I_k} \beta_i' p_{k,i} - y_k^o \right) R_k^{-1} \left(y_k + \sum_{j=1}^{I_k} \beta_j' p_{k,j} - y_k^o \right) \right) \tag{3}$$

where y_k are the model observations and R_k^{-1} is the observation error covariance matrix. The vector of increments to the bias coefficients $\boldsymbol{\beta}'$ is not directly included in the control vector. Instead the coefficients are derived from the control vector using a transformation ($\mathbf{U}$) which has been chosen to improve the conditioning of the problem. The transformation is calculated following the approach of Dee [Dee, 2004].

$$\boldsymbol{\beta}' = \mathbf{U}_\beta \mathbf{v}^\beta \tag{4}$$

To prevent the coefficients being made too specific to the current assimilation cycle a background term penalises large increments to the coefficients:

$$J_\beta = \frac{1}{2} \boldsymbol{\beta}'^T \mathbf{B}_\beta^{-1} \boldsymbol{\beta}' \tag{5}$$

where $\mathbf{B}_\beta$ is the background error covariance matrix for the increments to the bias coefficients. The covariance matrix is taken to be diagonal with error variances V_{β_i}:

$$V_{\beta_i}^{-1} = (N_{bgerr}/m) \sum_{k=1}^{m} p_{k,i}^2 R_k^{-1} \tag{6}$$

At the Met Office N_{bgerr} is set to be:

$$N_{bgerr} = \mathtt{MAX}(m_{avg}, M_{min}) \left(\frac{1}{2^{\frac{1}{n}} - 1} \right) \tag{7}$$

where m_{avg} is the expected number of observations per data assimilation cycle for the channel in question, M_{min} is a minimum number of observations, and n is the bias halving time in units of data assimilation cycles and is chosen by the user. With a bias halving time of 2 days and an M_{min} of 1000, this corresponds to a minimum N_{bgerr} of about 11,000. This approach to setting N_{bgerr} is discussed further in appendix A. An example of VarBC working to correct the bias of a channel on FY3C is shown in figure 1. Note that VarBC adjusts the bias so that the observed minus analysis (O-A) corrects towards zero, not the observed minus background (O-B). The O-B can be non-zero due to spin-up or spin-down in the model temperature or humidity.

Figure 2 visualises the effective weight given to data in recent data assimilation cycles for an idealised VarBC system for various bias halving times. Roughly speaking, half the bias correction is derived from data within the previous bias halving time. There is a balance to be struck between averaging the bias correction over a number of data assimilation cycles, in order to average out geographical and diurnal variations, and the responsiveness of the system to a change in bias. Consider the case where there has been a shift in bias of 0.8 K. After one bias halving time, the residual bias will be 0.4 K, followed by 0.2 K, 0.1 K, 0.05 K and so forth. If the bias halving time is set to 2 days then it will take 8 days for the residual bias to fall to 0.05 K.

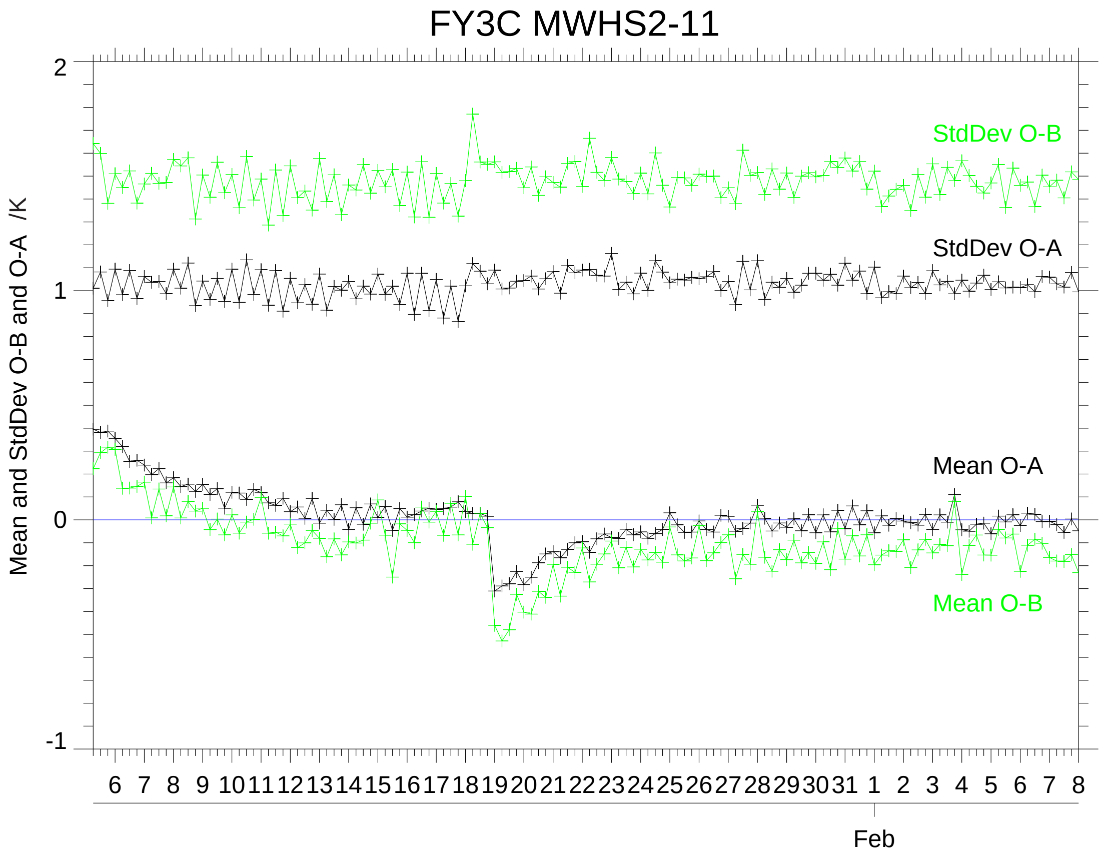


Figure 1: The mean and standard deviation of observed minus background (O-B) and observed minus analysis (O-A) for MWHS-2 channel 11 on FY3C for each data assimilation cycle taken from the start of an assimilation trial. The initial bias is not perfect and VarBC improves the correction with a bias halving time of around 2 days. A planned change was made to the way the data was processed at CMA on 19 January, resulting in a change in the instrument bias. VarBC again adjusts the bias correction with a bias halving time of around 2 days.

2.3 Met Office enhancements to VarBC

The current implementation of VarBC at the Met Office includes several enhancements, in both the predictor model and the adaption rate of bias coefficients, relative to the scheme implemented at most other NWP centres:

Maximum adaption rate: In the initial version of VarBC at the Met Office, the adaption rate was controlled by N_{bgerr}. Channels that were present in a large number of observations would adapt more rapidly than channels present in small numbers. In the current implementation the adaption rate is set by a bias halving time, subject to a minimum number of observations. The use of a bias halving time, subject to a minimum number of observations, ensures that all channels are able to strike a balance between proper sampling of geographical and diurnal variations, and rapid convergence.

Legendre Polynomial scan bias correction: The VarBC system retains the ability to apply a static offset to each scan position. There is also the option to apply a set of (orthogonal) Legendre Polynomial scan bias predictors to correct any residual scan bias, see figure 3.

Fourier series orbital bias predictors: As documented by Booton [Booton, 2014] and Bell [Bell, 2008] the Special Sensor Microwave Imager/Sounder exhibits complex biases due to several features of the calibration of the instrument. These primarily manifest themselves as orbital biases. A scheme has been developed to correct for these biases based on a Fourier series expansion in the orbital angle.

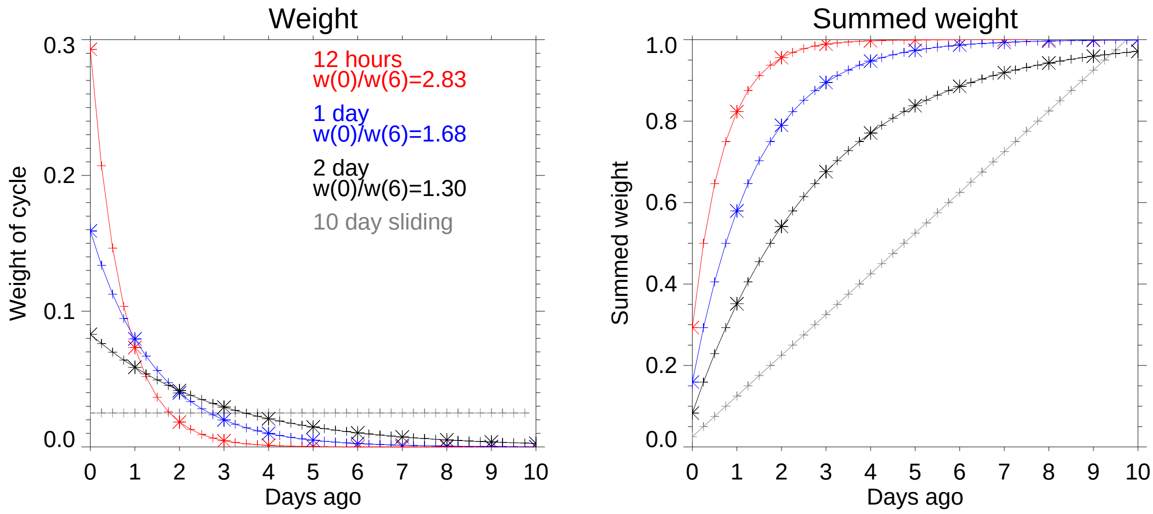


Figure 2: An illustration of the weight given to the most recent and to prior data assimilation (DA) cycles for an idealised VarBC system using different bias halving times. Every fourth DA cycle is marked by an asterisk. The grey line shows the weights given to each cycle for a hypothetical bias correction system that uses a sliding window of the last 10 days' worth of data. The key also shows the ratio of the weight given to the 00Z cycles to the 06Z cycle (3 DA cycles prior). The plot on the right shows the summed weight of all DA cycles up to a given time in the past.

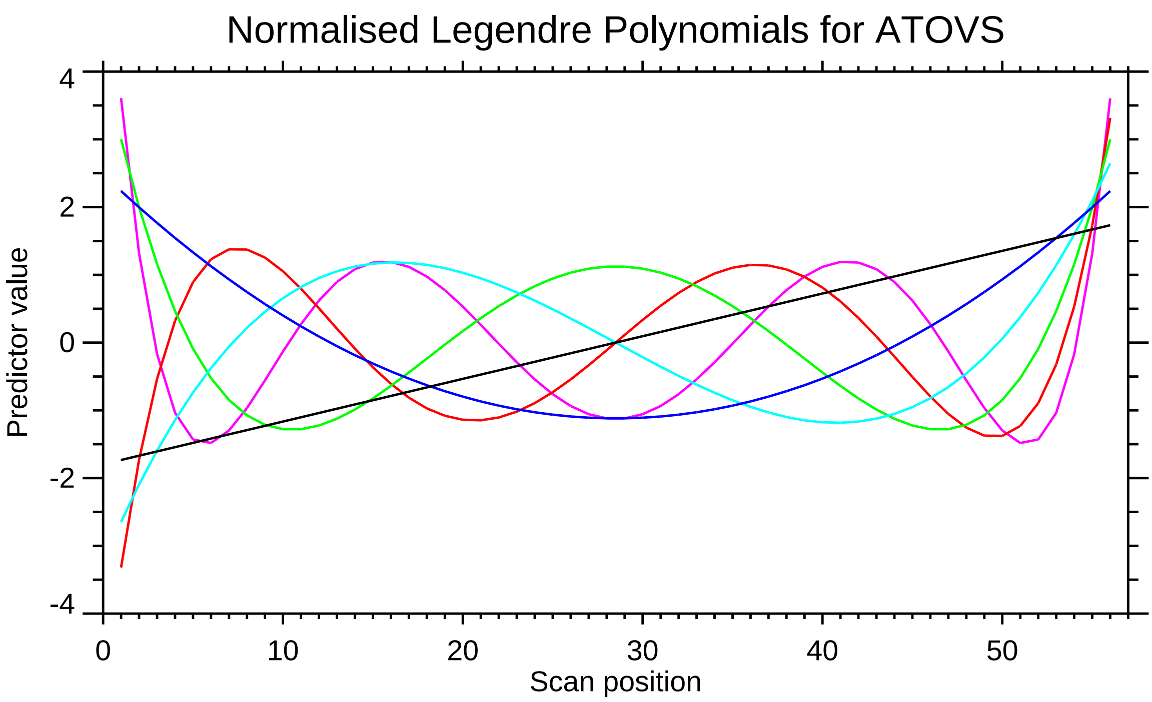


Figure 3: The first 6 Legendre Polynomials in scan position for ATOVS, normalised to a standard deviation of 1.

2.4 Predictors used in the global NWP system

The Met Office global NWP system currently uses the following predictors:

All polar satellites, except SSMIS: Constant, 850-500hPa thickness, 200-50hPa thickness, First 4 Legendre Polynomials

SSMIS: Constant, 4 Legendre Polynomials, plus between 4 and 12 orbital predictors (depending on the channel).

Geostationary satellites: Constant, 850-500hPa thickness, 200-50hPa thickness

All predictors coefficients are set to a bias halving time of 2 days and a M_{min} of 1000, corresponding to an N_{bgerr} of about 11,000.

2.5 Future development of VarBC

There are a number of ways in which the implementation of VarBC at the Met Office may be improved in the future:

Passive channels: In the VarBC scheme at the Met Office there is not presently any mechanism to generate a bias correction for channels that are used for quality control in the 1D-Var but are not assimilated. These channels are currently still bias corrected using the static scheme.

Observation selection: It is planned to introduce a mechanism to select which observations affect the bias correction based on surface and cloud type.

The scan bias: The VarBC scheme at the Met Office retains the option to apply an offset to each scan position, but there is currently no automatic mechanism for generating or updating these values. The cross-scan bias is currently copied from the static scheme biases.

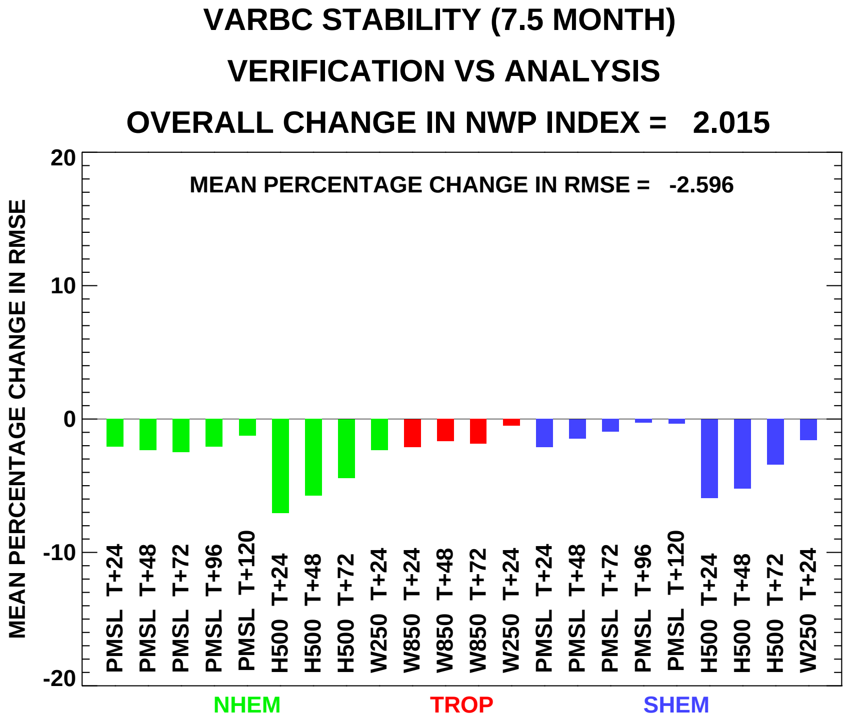
Non-satellite data: Both schemes currently only apply to satellite radiance observations.

3 Performance of the VarBC trials

VarBC was tested, in various configurations, for summer and winter seasons of 2013, 2014 and 2015, and for a 7.5 month (230 day) period from 2 December 2014–20 July 2015. The control for the 7.5 month trial used the static biases that were used operationally in the global NWP system from 9 December 2014 - 23 March 2015. It was clear in early trials of VarBC that the forecast backgrounds and observation biases were changing. Therefore, the 7.5 month VarBC was started with spun-up biases from previous VarBC trials and with the bias of passive channels recalculated using VarBC forecast backgrounds from previous trials.

The verification of the 7.5 month VarBC stability run against its own analysis and against observations is shown in figure 4. The PMSL and 500 hPa heights in the extra-tropics, 250 hPa and 850 hPa winds in the tropics are improved at all forecast ranges examined when verified against analysis. There are 7.1% and 5.9% improvements in the RMSE of 500 hPa heights at T+24 for the Northern and Southern Hemispheres respectively. The verification against observations shows some apparently large degradations to the fit of 500 hPa heights at T+24, with the effect declining with forecast lead time, and, in the case of the Northern Hemisphere, even reversing sign. As will be shown, this degradation is actually due to a shift in the bias of the forecast 500 hPa heights, as verified against sondes. These results are typical of the VarBC trials. Figure 5 shows the time series of the NWP index, verified against analysis, during the 7.5 month run. It shows consistently good performance throughout, as evidenced by the stable running mean.

The VarBC trials were found to produce colder, drier analyses, and less rainfall in the hours following a data assimilation cycle. The reason for the difference is not known with certainty. Possible explanations are discussed in section 4. Figure 6 shows the difference in zonal temperature at T+6 between a winter VarBC trial (2 December 2014 - 12 January 2015) and the control. The VarBC experiment is generally cooler, but especially at 850 hPa. Figure 6 also shows a map of the mean difference in temperature at 850 hPa between trial and control. The change in temperature is primarily over the oceans



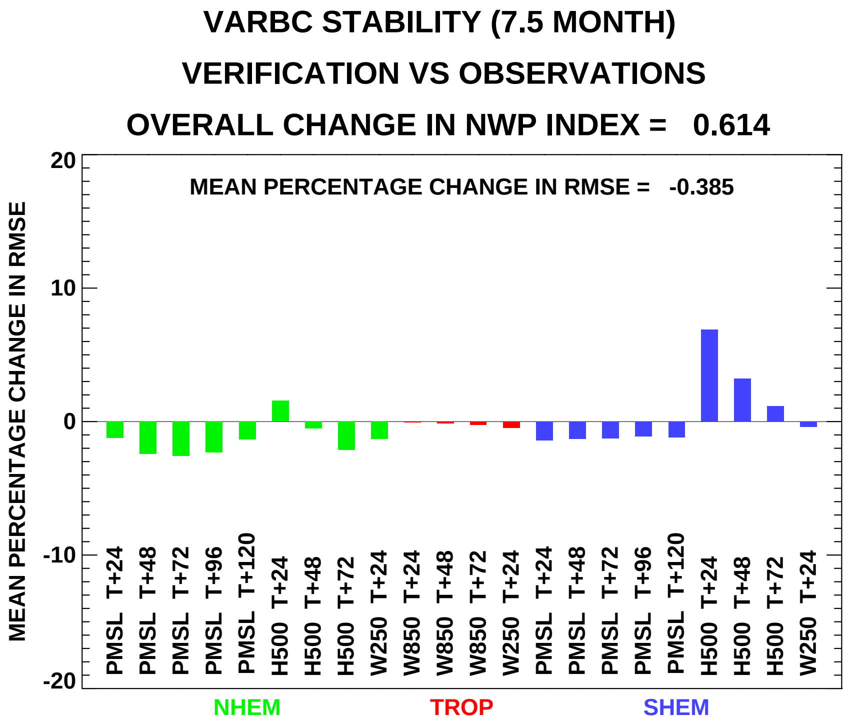


Figure 4: The verification of the long 7.5 month (230 day) VarBC stability run against its own analysis and against observations. The verification against analysis is strong for all variables, especially the 500 hPa heights where the RMS is 7.1% lower in the NH and 5.9% lower in the SH at T+24. In the verification against observations the 500 hPa heights shows apparently large degradations. It will be shown that this is due a change in bias, which is thought to be within the uncertainty of sonde measurements.

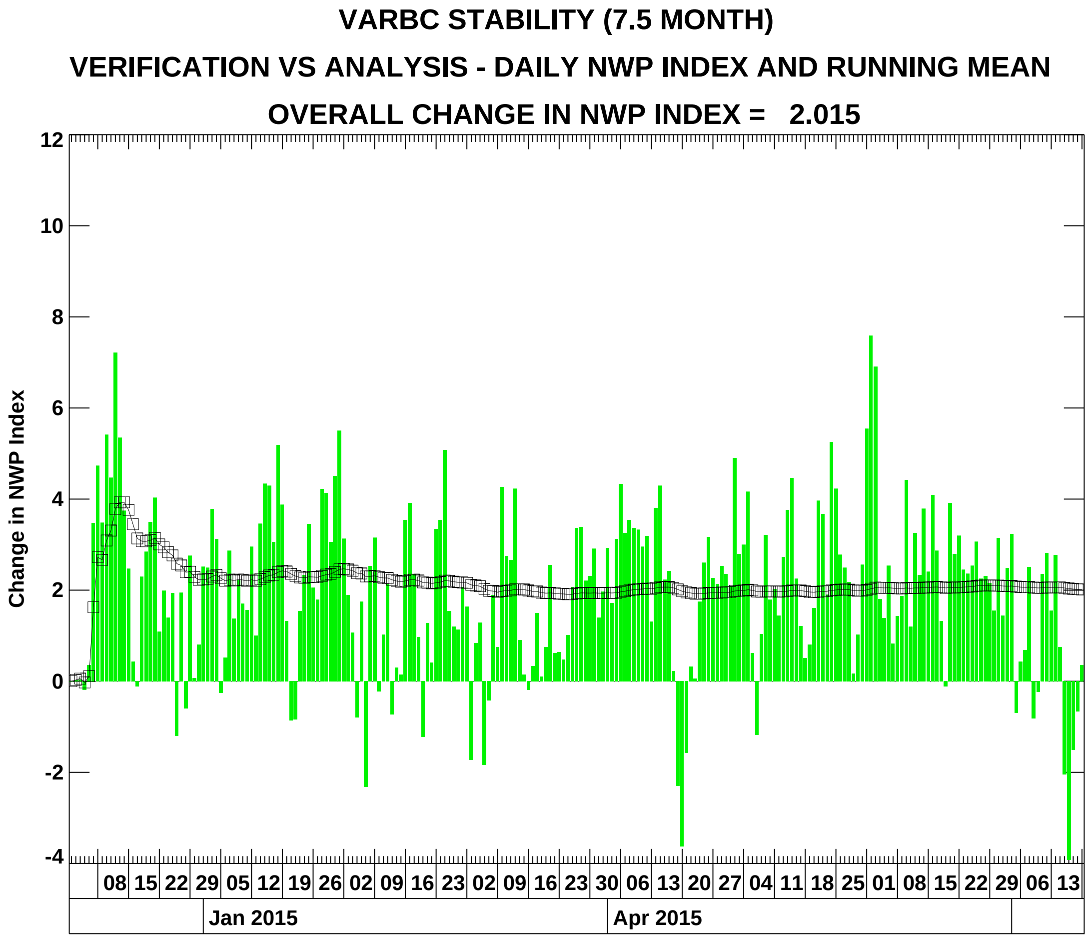


Figure 5: Time series of the NWP index, verified against analysis, for the long 7.5 month VarBC stability trial. The trial shows consistent benefit across the trial, as evidenced by the stable running mean.

and especially in marine stratocumulus regions. Figure 7 shows the difference in zonal relative humidity between trial and control. The VarBC trial is drier at the lowest levels, especially in the sub-tropics of the summer hemisphere.

The lower temperatures in VarBC, shown in figure 6, lead to lower values of 500 hPa height. Figure 8 shows the verification of 500 hPa height against sondes, versus forecast range, for the 7.5 month trial. It can be seen that the VarBC heights are typically a couple of metres lower than for the control. This increase in bias is the cause of the apparently negative verification of 500 hPa height against sondes, but is thought that the bias is still within the uncertainty of sonde measurements. The RMS fit of forecast 500 hPa heights is worse at short range due to the increase in bias. However, with increasing forecast range the bias becomes a less significant component of the RMS, and in the case of the Northern Hemisphere the RMS error is lower in the VarBC experiment than in the control at long range.

The verification of 500 hPa heights against sondes was investigated further. Figure 9 shows the verification of H500 for ECMWF and the Met Office operational systems, relative to both analyses and radiosondes, during the period 2000–2015. Figure 9 also shows that at T+24 forecasts now have errors below the noise floor of the radiosondes. The radiosondes are unable to differentiate between the performance of ECMWF and the Met Office systems since 2005. In this situation, the radiosondes have become relatively insensitive to changes in forecast performance. At the same time the changes in bias relative to radiosondes have become a more significant driver of changes in RMSE. With T+24 errors at around 5-10 metres, bias changes of 2-3 metres (well within the uncertainty limits of radiosonde measurements) dominate the RMSE changes. This is believed to be the reason for the anomalous performance relative to observations.

Figure 10 shows the verification of the temperature at 850 hPa against analysis for the 7.5 month trial and control. The difference between forecast and analysis tends to become more negative for both trial and control with increasing forecast lead time; however, the effect is larger in the control. The VarBC

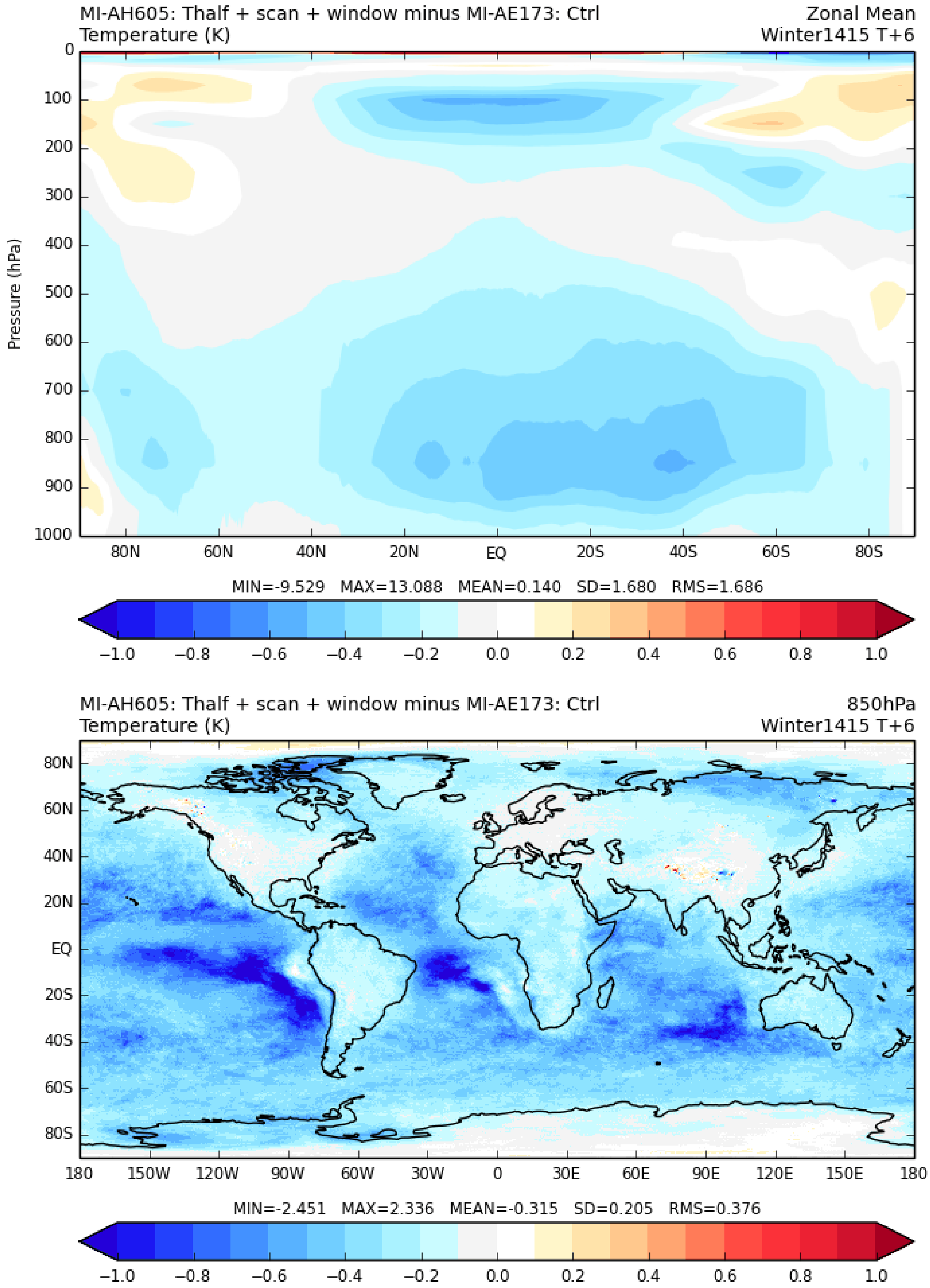


Figure 6: The upper figure shows the zonal mean of the difference in temperature between a winter VarBC experiment and the control. The VarBC experiment is generally cooler, but especially at 850 hPa. The lower figure shows a map of the mean difference in temperature at 850 hPa. The change in temperature is primarily over the oceans and especially in marine stratocumulus regions.

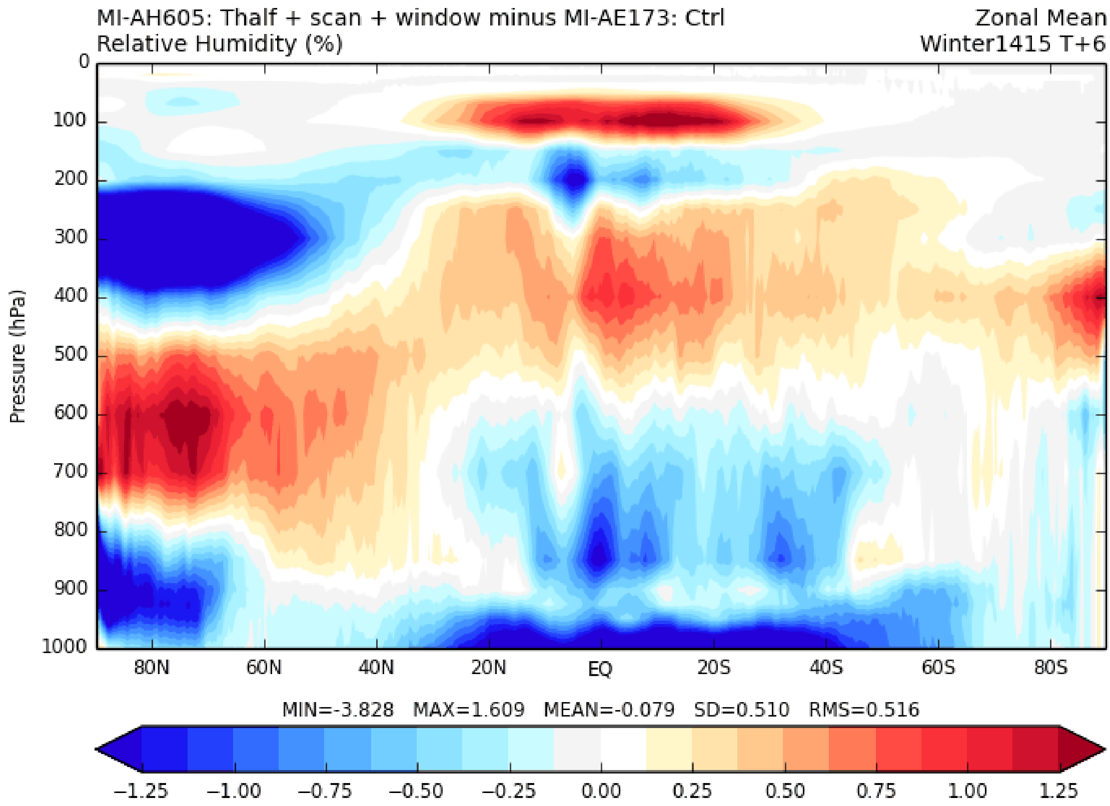


Figure 7: Zonal mean of the change in relative humidity for a winter VarBC experiment minus the control. At the lowest levels the VarBC experiment is predominantly drier.

trial is analysing colder temperatures, and therefore has less far to spin down to the preferred model climate. The reduction in spin-down naturally leads to better verification against analysis.

Figure 11 shows the change in convective and large-scale rainfall. Perhaps unsurprisingly for a cooler and drier forecast there is typically less rain in the ITCZ and at mid-latitudes at T+24. Verification of the 7.5 month VarBC stability run shows improvements in the UK index scores. The UK index is +0.12 for the Northern Hemisphere, +0.02 for the tropics, and +0.11 for the Southern Hemisphere. The UK index for the British Isles is +0.33 and for the UK index stations +0.31. In all these UK index score results the most striking factor is an improvement in the 6 hour precipitation accumulation equitable threat score.

The residual bias of AIRS window channels were stable to within 50 mK across the VarBC stability run but it was discovered that the applied bias drifted by 0.5 K over the 7.5 months (see figure 12). This drift in applied bias is offset by changes to the fitted skin temperature, and somewhat to the fitted cloud parameters, in the 1D-Var. These fitted parameters are used in data assimilation for forward modelling but do not feed into the analysis. The static scheme avoided this type of drift by using the first-guess skin temperature in the bias calculation rather than the 1D-Var fitted value. With VarBC the 1D-Var analysed skin temperature is only loosely tied to the first guess skin-temperature through the background error. A trial where the bias corrections of 8–9 window channels on AIRS, IASI and CrIS were held fixed was run for a summer and winter period. These trials gave similar results to before and so this configuration was used for the operational VarBC system.

Figures 13 and 14 show the mean O-B and O-A for ATMS and MetOp-B IASI for the long stability run trial and control. Note that the mean O-A is essentially zero for all bias corrected ATMS channels, whereas the O-B is positive. VarBC bias corrects to the analysis. The forecast tends to run colder, which leads to a positive O-B at the next assimilation cycle. For IASI it is a similar picture for the long-wavelength CO_2 sounding channels, but the O-A for the window channels is off by around 20 mK.

Figures 15 and 16 show the percentage change in the standard deviation of O-B and O-A for ATMS and IASI in the long stability trial. The bias corrected ATMS channels show improvements of 1.5–6%

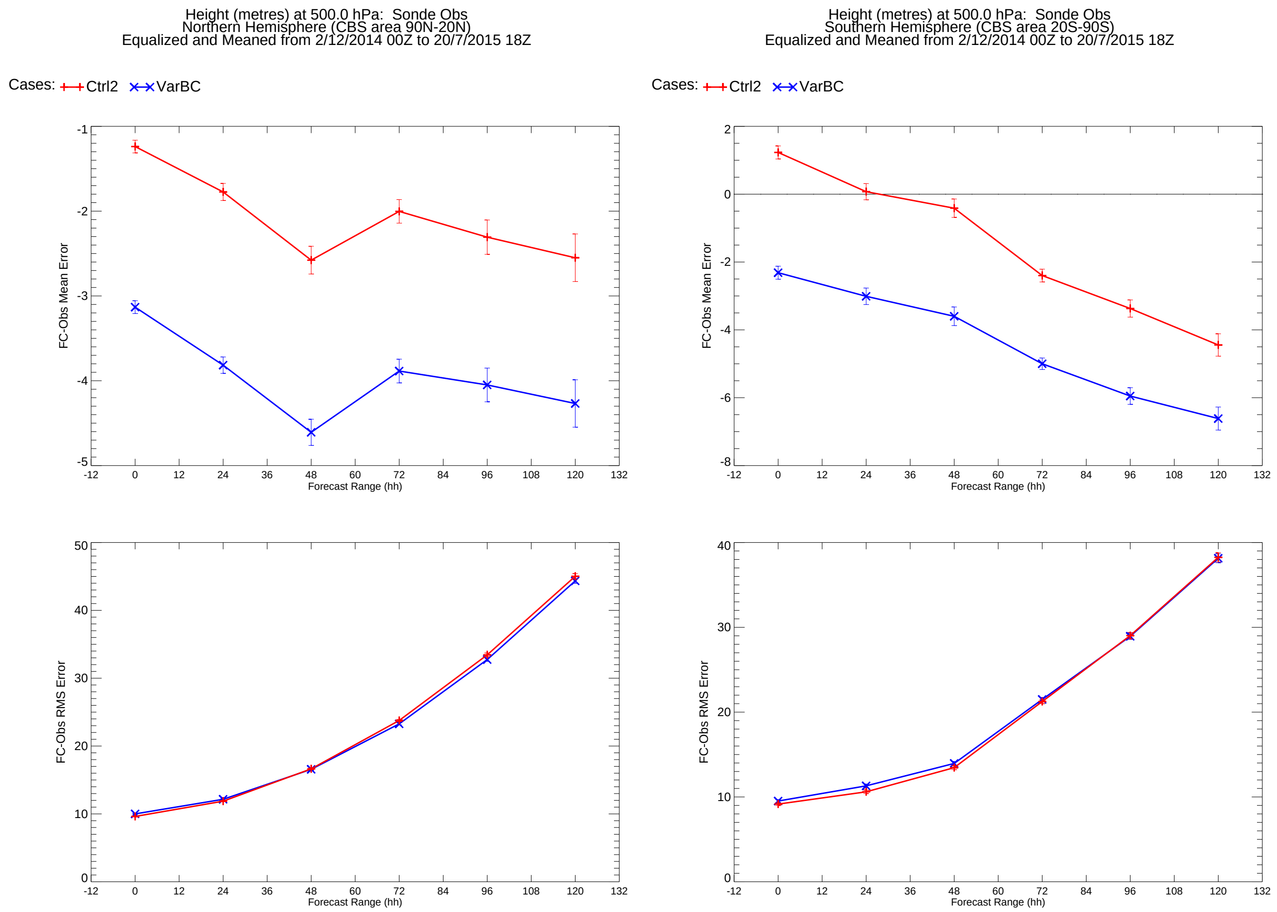


Figure 8: The verification of 500 hPa heights for the 7.5 month VarBC trial and control versus sondes for Northern and Southern Hemisphere regions. The trial is more biased with respect to sondes, but is thought to be within the systematic uncertainty of sonde measurements. The RMS is slightly larger at short range due to the increased bias, but note that at longer lead times in the Northern Hemisphere the RMS is lower in the VarBC trial, despite the larger bias.

in standard deviation. The long-wavelength CO_2 sounding IASI channels appear well behaved, but the window channels show increases in standard deviation in the range 3–14%. There is an increase in standard deviation of the window channels for all advanced IR sounders. Interestingly this increase was still present when the bias of 8–9 window channels was fixed and it even persisted when using static biases derived from the VarBC forecast backgrounds.

4 The source of the impact of VarBC

The source of the impact of VarBC is not known with certainty. VarBC and the static scheme have a similar form for the bias correction, so it was not anticipated that VarBC would have such a large impact.

The most likely underlying reason for the impact of VarBC is that under VarBC the bias correction and data assimilation use precisely the same forward model. There are some known, and mostly very subtle, differences between the forward modelling used in the 1D-Var quality control stage, which drives the static bias correction scheme, and the forward modelling in the data assimilation system. The most significant known difference is that cloud liquid water is analysed in the 1D-Var, and is included in the static bias correction forward modelling, but cloud liquid water is not used in the VAR data assimilation. Cloud liquid water particularly affect the forward modelling of AMSU-A channels 4 and 5, and these channels might be expected to affect low level temperature and humidity. Attempts to definitively

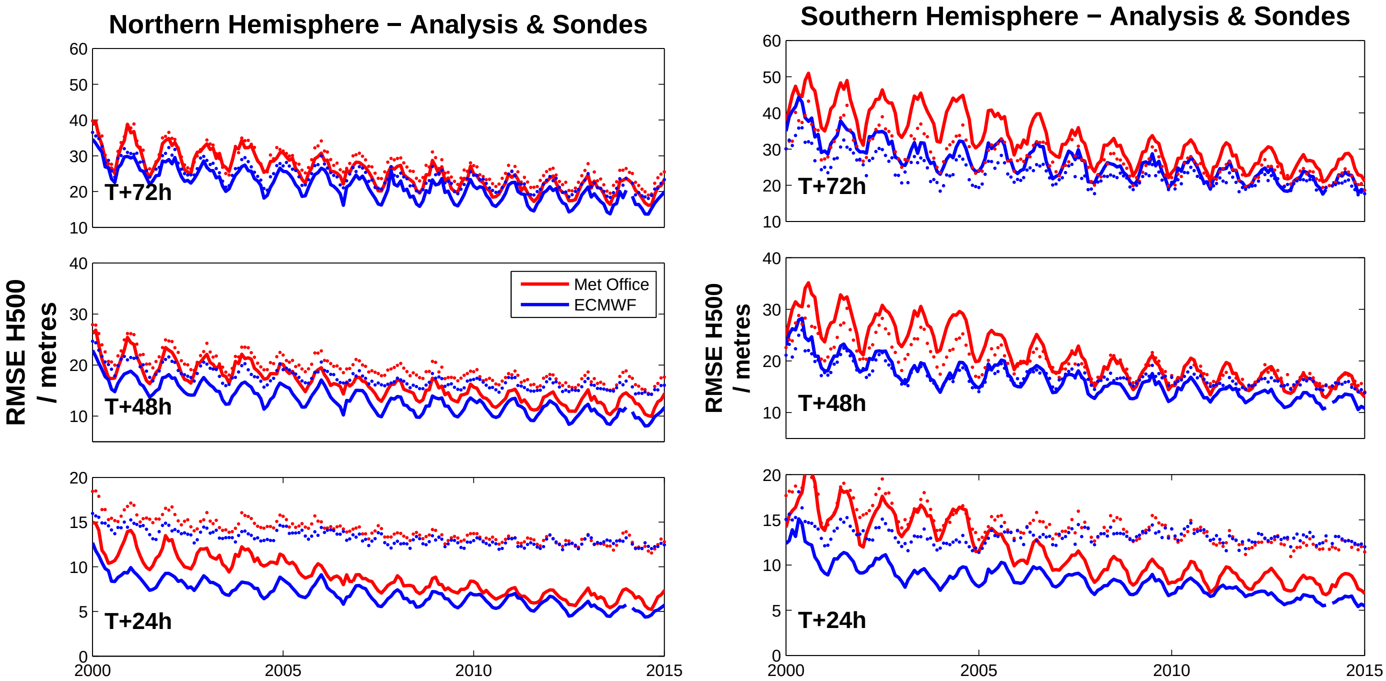


Figure 9: The verification of 500 hPa heights for the Met Office and ECMWF. Northern Hemisphere verification is shown on the left and Southern Hemisphere on the right. The verification against analysis is shown by solid lines and verification against radiosonde 500 hPa heights by dotted lines. The forecast ranges shown are for T+72, T+48 and T+24.

demonstrate that the treatment of cloud liquid water is the source of the impact of VarBC have not been successful, and yet it seems such a good candidate it is difficult to completely discount.

Another difference between VarBC and the static scheme is that VarBC bias corrects to the analysis whereas the static scheme corrects to the forecast background. An experiment was run where the bias correction was updated in a separate minimisation where the forecast background was held static by making the background error very small for atmospheric variables. The data assimilation minimisation was run using bias corrected observations and the normal background error, but without actively updating the bias correction in VarBC. This trial gave very similar benefits to the standard VarBC run, indicating that bias correcting to the analysis is not the source of the impact of VarBC.

5 Conclusions

VarBC has been used operationally at the Met Office since 15 March 2016. It was extensively tested before implementation, including a 7.5 month trial and control. The VarBC scheme, in most respects, closely follows the implementation at other NWP centres, but several novel features have been introduced. These are: a minimum bias halving time; a hybrid scan bias correction scheme comprising (static) spot-dependent offsets together with the use of Legendre Polynomial predictors to remove any residual, time-dependent biases; and a series of Fourier orbital predictors to correct for complex orbital biases.

The performance of VarBC has been consistently beneficial. VarBC produces cooler and drier analyses and a long-standing spin-down effect, in which initially high analysed tropospheric temperatures gradually relax back to climatological values, is much reduced in the VarBC experiments. The verification of extra-tropical 500 hPa heights against analysis were improved by 5–10% in the VarBC experiments. Forecast wind fields and surface pressure fields are also improved. Both large scale and convective precipitation are reduced in the hours following a data assimilation cycle, relative to control experiments using static biases. In terms of diagnostics from the data assimilation system, short range

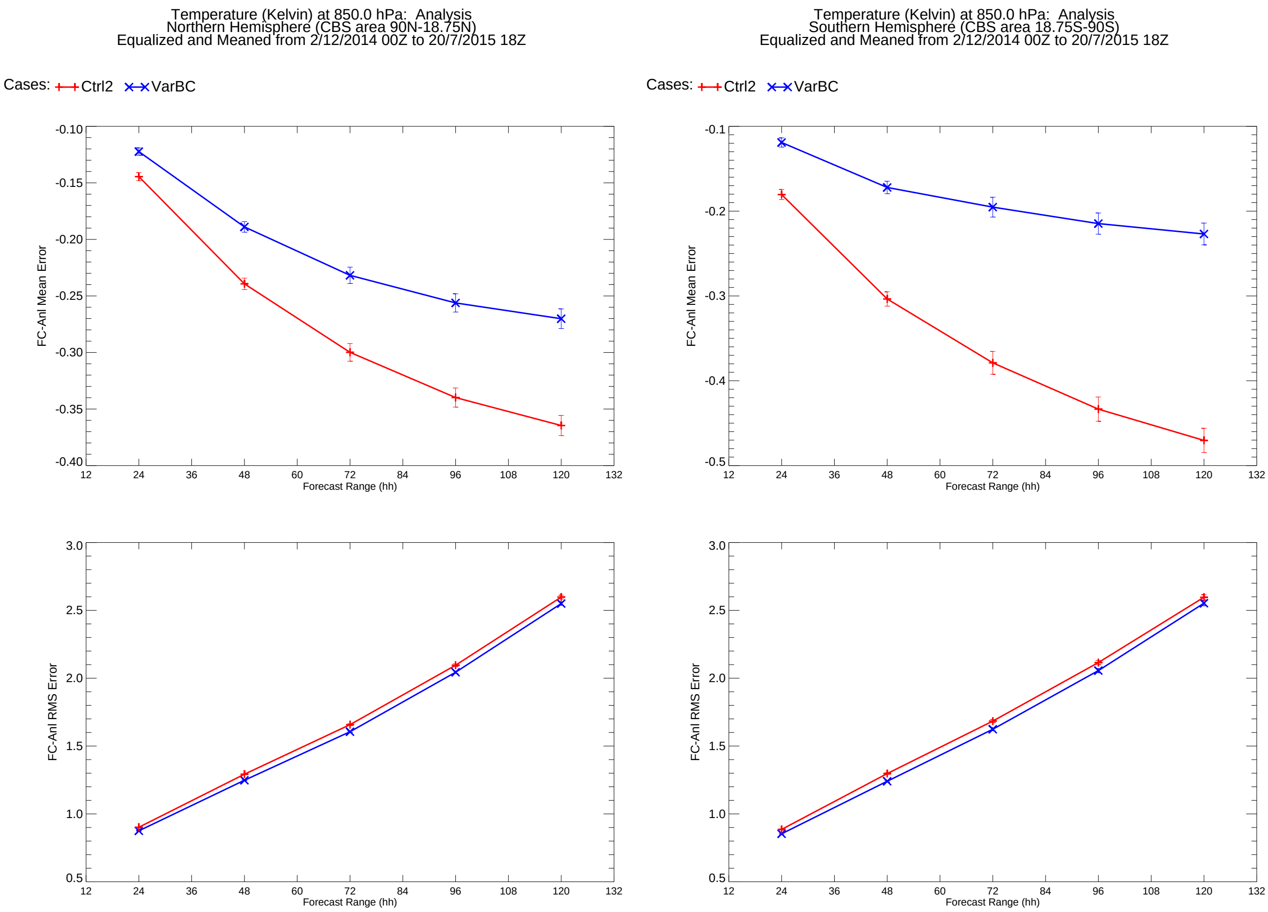


Figure 10: The verification of the temperature at 850 hPa against analysis for the long VarBC experiment (red) and control (blue) for Northern (left) and Southern (right) Hemisphere regions. The mean forecast minus analysis error is shown in the top two plots and the RMS error at the bottom. For both VarBC trial and control the forecast temperature runs colder with time but the effect is reduced in the VarBC trial.

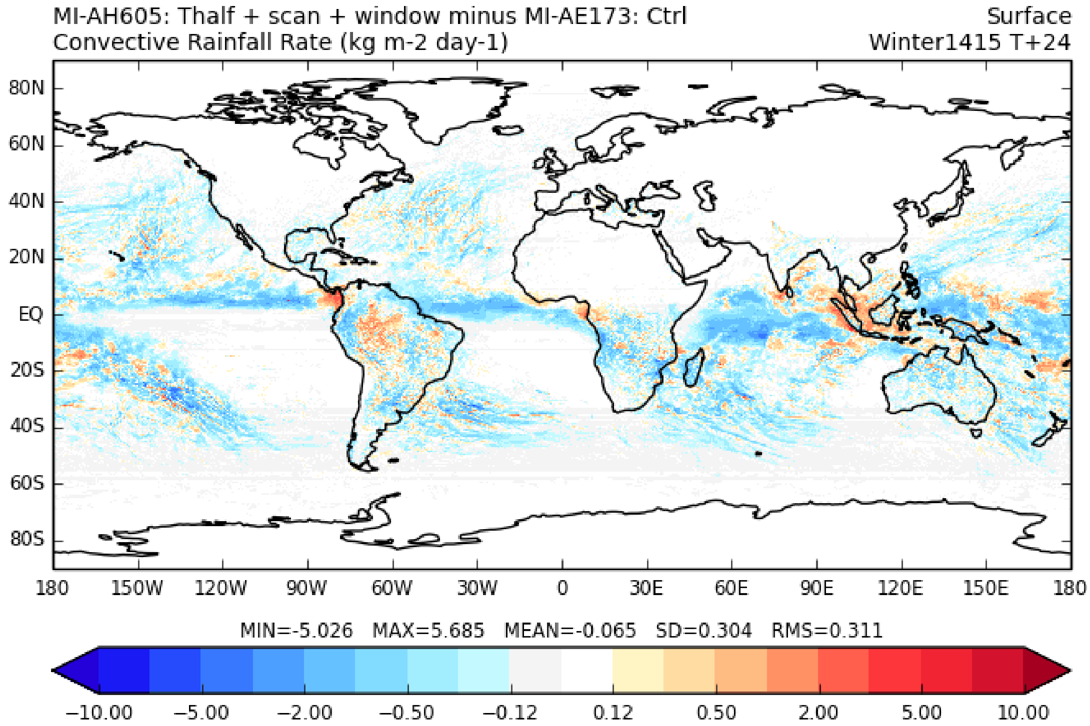
forecast fits to almost all observations are significantly improved. For satellite radiances, in most cases the improvements are in the range 1–5%.

Desirable future developments include:

- Establishing a means of updating the bias correction applied to channels used for quality control, but are not assimilated.
- Introducing a mechanism to selecting which observations influence the bias correction by surface or cloud type.
- Implement a method for updating the cross-scan bias correction that does not rely on the static scheme.

6 Acknowledgements

This report is only slightly expanded from the ITSC-20 proceedings paper by Cameron and Bell [Cameron and Bell, 2016]. Dingmin Li began the VarBC project at the Met Office, conducting a scientific review and producing an initial design document. He coded the OPS part of the code, together with some of the VAR code. Andrew Lorenc reviewed the system, wrote the VAR minimisation part of the code, did some initial testing with Dingmin, and wrote the VAR scientific documentation. The final adjustments to the system and full length trials were conducted by James Cameron, with input from William Bell, Fiona Smith, Masashi Ujiie, Anna Booton, and Peter Weston.



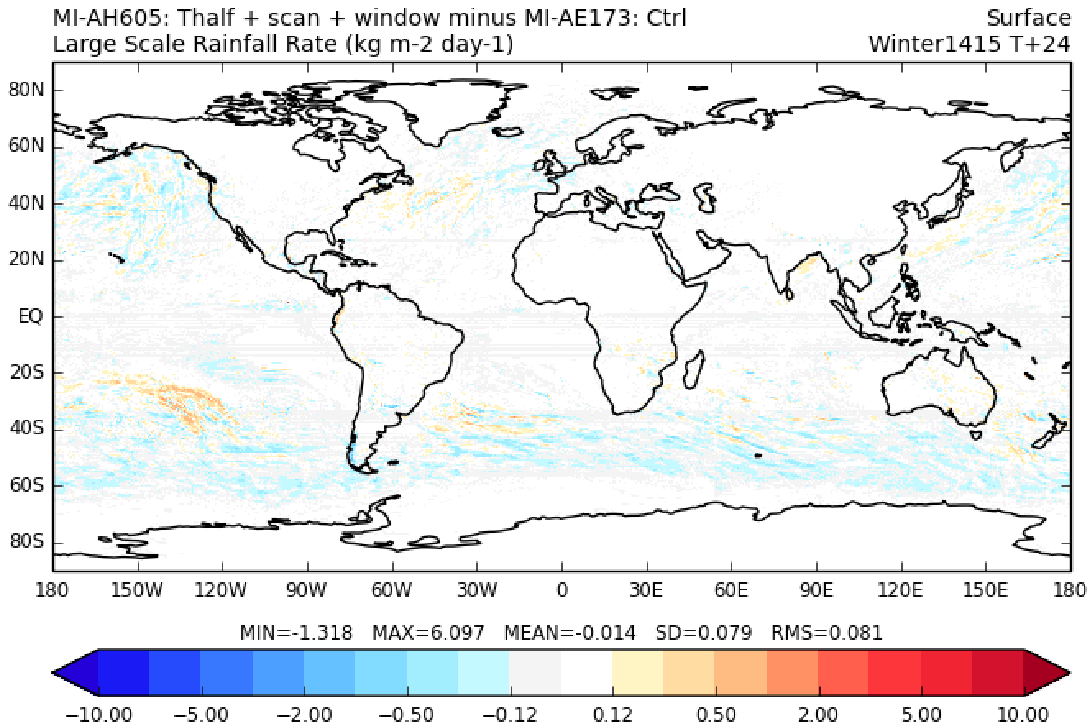


Figure 11: The change in convective rainfall rate and large scale rainfall rate at T+24 for the winter 2014/15 VarBC experiment minus the control. The ITCZ is generally less active in the VarBC experiment and there is a general reduction in rainfall in the mid-latitudes.

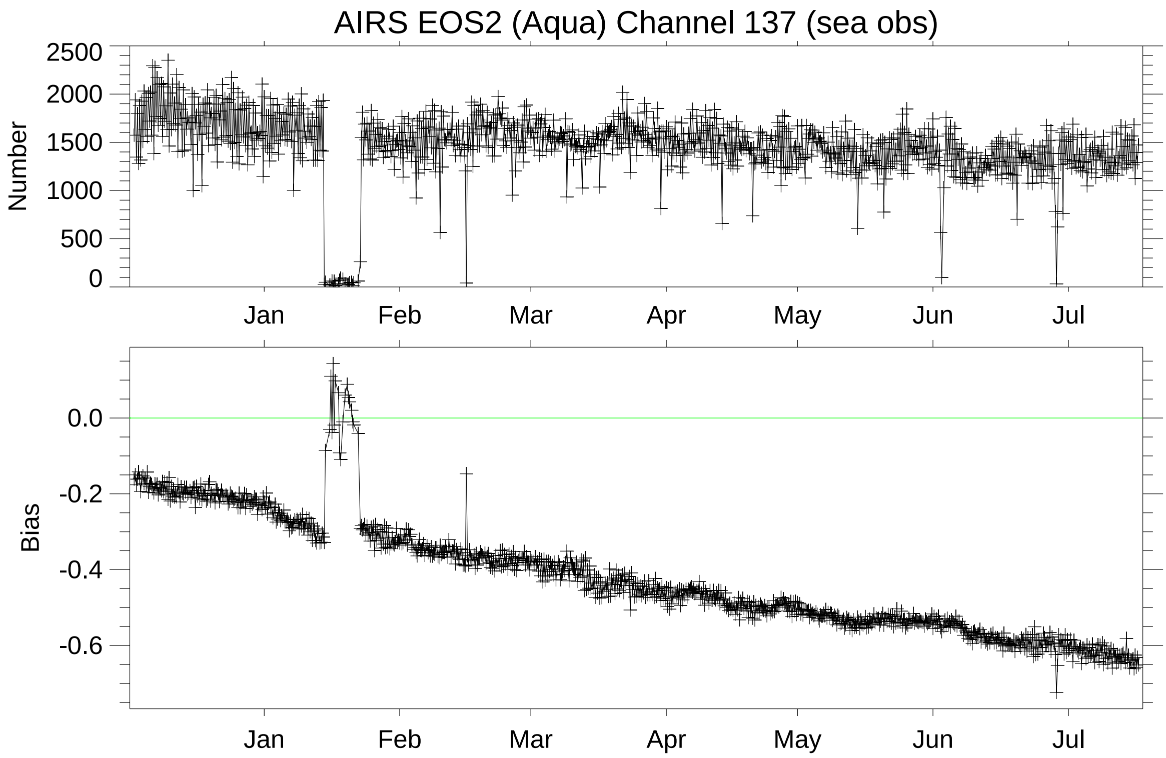


Figure 12: The applied bias for an AIRS window channel (absolute channel number 791 at 10.88 microns) from the 7.5 month VarBC stability trial. The applied bias drifts by around 0.5 K across 7.5 months.

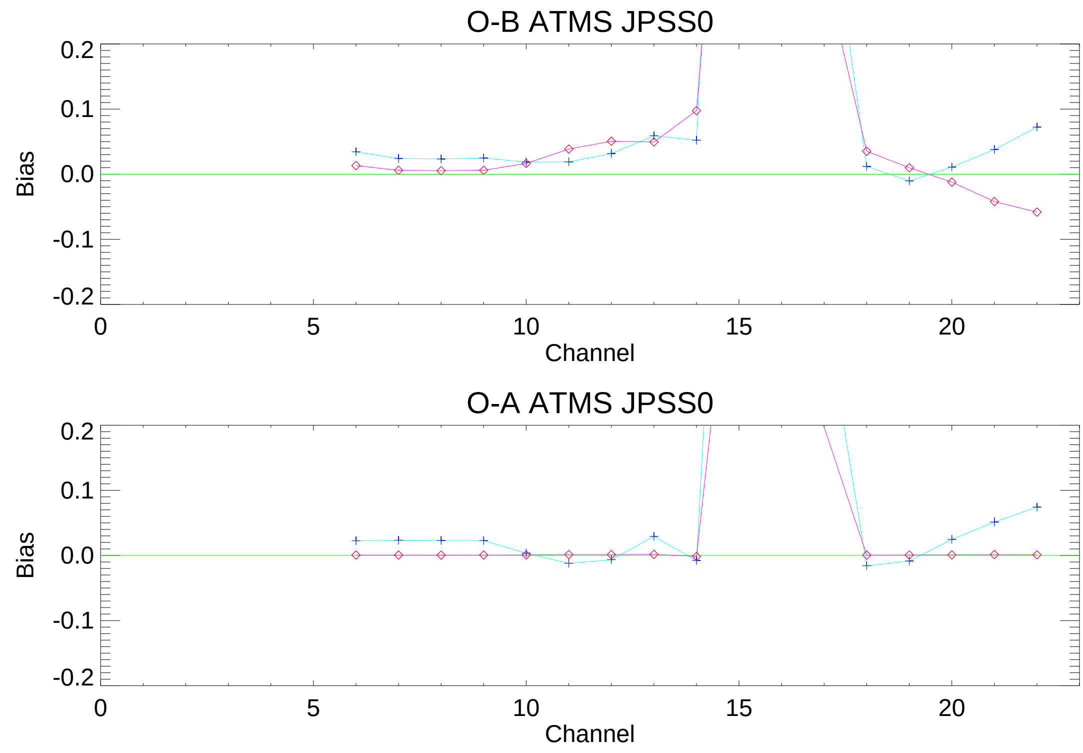


Figure 13: Mean O-B and O-A for ATMS for the 7.5 month control (blue/cyan) and VarBC trial (red/magenta). VarBC bias corrects to the analysis and the mean O-A is essentially zero for all bias corrected channels (ATMS-15 is not bias corrected).

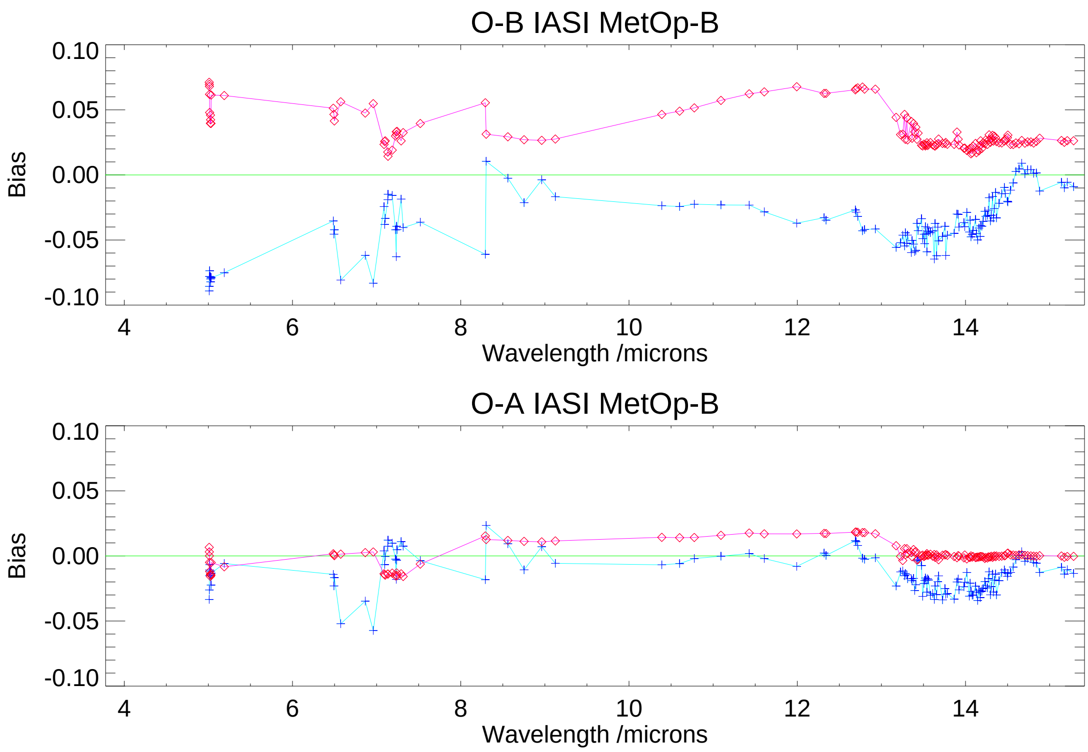


Figure 14: Mean O-B and O-A for IASI MetOp-B for the 7.5 month control (blue/cyan) and VarBC trial (red/magenta). The O-A for the long-wavelength CO_2 sounding channels is very close to zero, but there are small residuals of around 20 mK for the window channels.

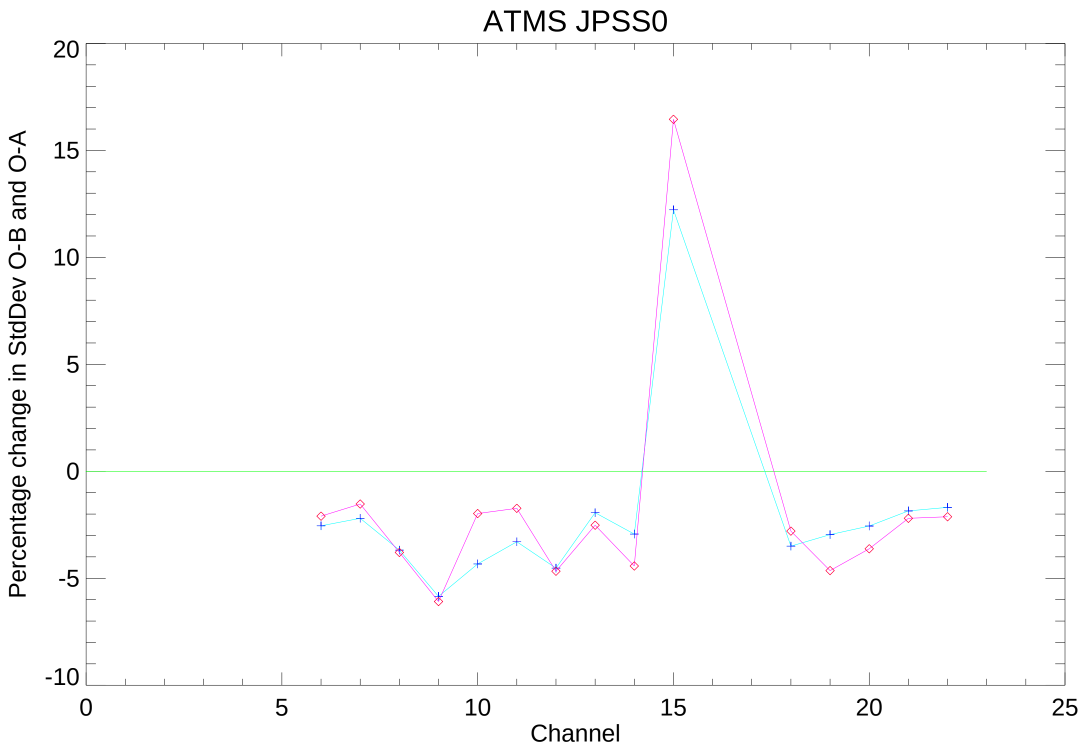


Figure 15: The percentage change in the standard deviation of O-B (blue/cyan) and O-A (red/magenta) for ATMS in the 7.5 month VarBC trial versus control. ATMS-15 is not bias corrected.

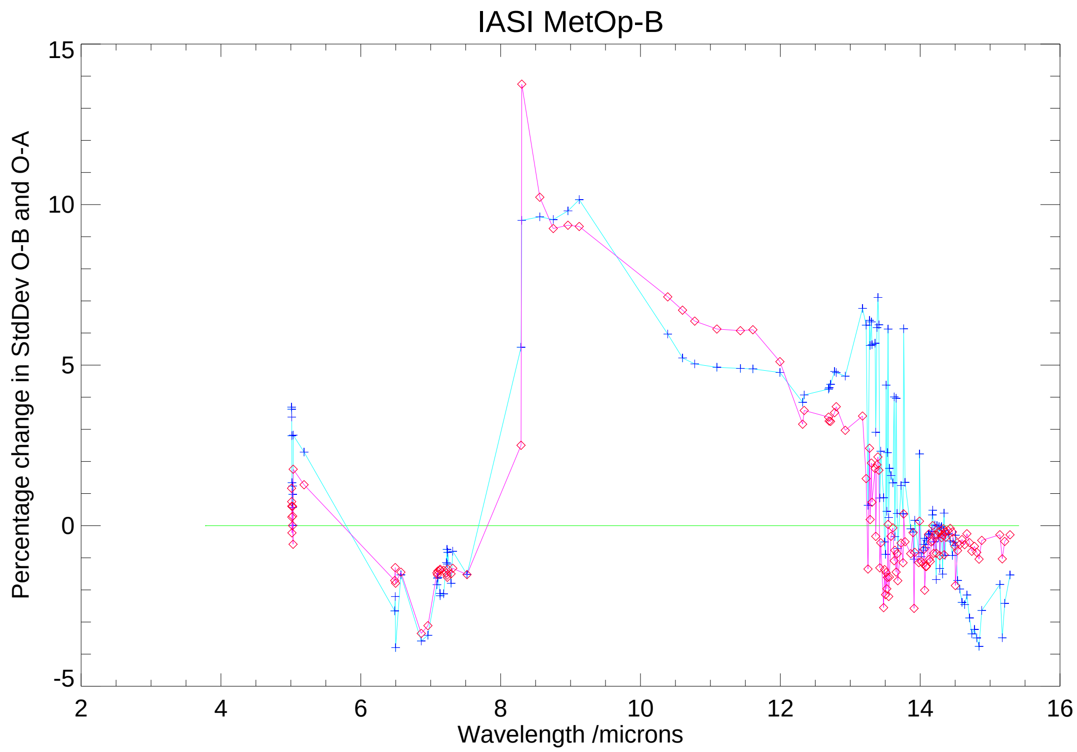


Figure 16: The percentage change in the standard deviation of O-B (blue/cyan) and O-A (red/magenta) for IASI MetOp-B in the 7.5 month VarBC trial versus control. The long-wavelength CO_2 sounding channels are well behaved but there is an increase in standard deviation for the window channels.

A The bias adaption rate

The weighted mean of two numbers β_b and β_o with errors σ_b and σ_o is usually calculated as:

$$\overline{\beta} = \frac{\dfrac{\beta_b}{\sigma_b^2} + \dfrac{\beta_o}{\sigma_o^2}}{\dfrac{1}{\sigma_b^2} + \dfrac{1}{\sigma_o^2}} \tag{A.1}$$

If $\sigma_b^2 = \frac{m}{N}\sigma_o^2$ then this simplifies to:

$$\overline{\beta} = \frac{N}{N+m}\beta_b + \frac{m}{N+m}\beta_o \tag{A.2}$$

In VarBC the background error for the bias coefficients is chosen so that the weight of the prior is N_{bgerr}/m times the weight of the observations when determining the analysed β, where N_{bgerr} is a constant chosen by the user and m is the number of observations that include a particular channel in the assimilation cycle.

In the special case where the data assimilation control vector only contains increments to the VarBC bias coefficients (no atmospheric variables) then after the n^{th} assimilation cycle the coefficient would be:

$$\beta_n = \frac{N_{bgerr}}{N_{bgerr}+m}\beta_{n-1} + \frac{m}{N_{bgerr}+m}\beta_{\text{best}} \tag{A.3}$$

where β_{n-1} is the previous bias coefficient, and β_{best} is the value of the coefficient that minimises the observation penalty. Note that if $m = N_{bgerr}$ then the difference between β_n and β_{best} will halve each assimilation cycle (this follows directly from the how N_{bgerr} is defined). If the initial bias coefficient was β_0 then after n assimilation cycles:

$$\beta_n = \left(\frac{N_{bgerr}}{N_{bgerr}+m}\right)^n \beta_0 + \left[1 - \left(\frac{N_{bgerr}}{N_{bgerr}+m}\right)^n\right]\beta_{\text{best}} \tag{A.4}$$

This represents an exponential decay from an initial value β_0 towards the best fit value β_{best}. The difference from the best fit value will halve when

$$\left(\frac{N_{bgerr}}{N_{bgerr}+m}\right)^n = \frac{1}{2} \tag{A.5}$$

Re-arranging for the N_{bgerr} that will lead to the difference halving in n assimilation cycles:

$$N_{bgerr} = m\left(\frac{1}{2^{\frac{1}{n}}-1}\right) \tag{A.6}$$

At the Met Office the N_{bgerr} is set for each bias predictor as:

$$N_{bgerr} = \texttt{MAX}(m_{avg}, M_{min})\left(\frac{1}{2^{\frac{1}{n}}-1}\right) \tag{A.7}$$

where m_{avg} is the expected number of observations in a data assimilation cycle that contain a given channel, M_{min} is a fixed number chosen by the user (e.g. 1000 observations), and n is set by the user to be the desired residual bias halving time in units of data assimilation cycles (e.g. 8 DA cycles). At the Met Office a running estimate of m_{avg} is stored in the VarBC coefficients file and automatically updated each DA cycle.

In equation A.7 the minimum possible value for N_{bgerr} is determined by M_{min} and n. VarBC has been tested at the Met Office with $M_{min} = 1000$ and $n = 8$ (there are 4 data assimilation cycles per day at the Met Office so this corresponds to a bias coefficient halving time of 2 days), resulting in a *minimum* N_{bgerr} of about 11,000. M_{min} is an important safety mechanism in the system because in the case of a period of low data volumes then the estimate of m_{avg} would drift lower and the bias correction could end up being based on dangerously low numbers of observations. For channels where $m_{avg} > M_{min}$ (normally true for the vast majority of channels) then the N_{bgerr} will be set correspondingly larger such that the bias halving time is determined by n (8 DA cycles or 2 days), resulting in a harmonised, minimum bias halving time across channels. Setting a minimum bias halving time is important at the Met Office because the data assimilation window is only 6 hours. In 6 hours a polar orbiting satellite has not sampled the full globe and has not sampled the diurnal variation for the parts it has covered, and therefore may not have sampled the full range of biases and bias predictors it will later encounter. The bias halving time enables the retention of bias information from previous DA cycles, even for data-rich channels. The bias halving time formulation is also useful for running VarBC actively in the UK regional NWP system, where it averages out diurnal variations in data volume and bias.

Equation A.3 is for the special case that the control vector only contains the bias coefficients. In the case where the control vector consists of atmospheric variables as well as the bias coefficients, then equation A.4 is an *overestimate* of how quickly the bias coefficients will adapt. The adaption will be slowest where the analysis is most able to mould itself to the form of the bias. This will happen where observations errors are small and the background error is large.

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