J7.4 ASSIMILATION OF INFRARED METEOSAT DATA AT THE MET OFFICE

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1. INTRODUCTION

The Met Office has recently started assimilating clear-sky infrared (IR) radiances over land into its operation NWP models. The variational data assimilation method used at the Met Office requires the observing process to be simulated for each observation type. In IR window channels, simulated satellite brightness temperatures are strongly affected by the radiative skin temperature of the Earth's surface, so that errors in the model skin temperature introduce errors into the simulated brightness temperatures. The purpose of this paper is to describe the statistical characterisation of these errors in skin temperature and their effect on simulated brightness temperatures and clear-sky-radiance assimilation.

In order to minimise the impact of model skin temperature errors, the Met Office routinely uses a 1D-Var scheme to retrieve a more accurate skin temperature using both model fields and satellite observations, as shown in Figure 1. This retrieved skin temperature is typically then used as if it were the model background skin temperature in a 3D-Var or 4D-Var assimilation of the same satellite observations (along with the real observed radiances and the original model atmospheric fields).

The Met Office has introduced a variable resolution 1.5km UK version of the Met Office Unified Model (UKV) with explicit convection as part of the routinely-running operational system. The model has been running for around a year now and is described in Lean et al 2011. The model has 70 vertical levels extending to a height of 40km, with geographical coverage as shown in Figure 2. Boundary conditions are provided by a 12km resolution NWP model covering the North Atlantic and Europe, and data assimilation is

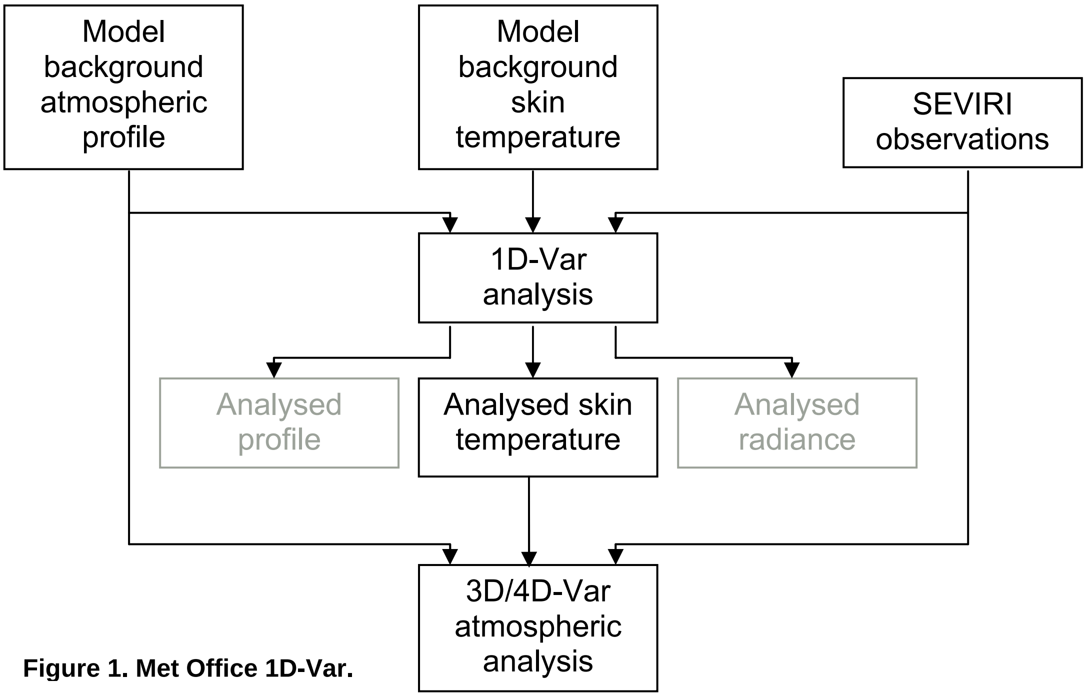

Figure 1. Met Office 1D-Var.

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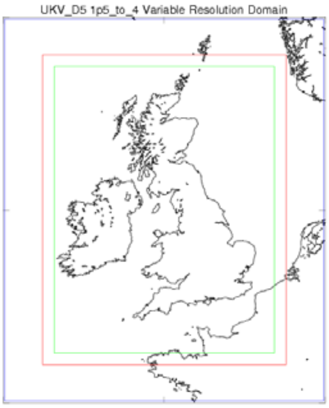


Figure 2. UKV domain. The horizontal grid resolution is 1.5km within the green rectangle, varying to lower resolution (1.5km × 4km or 4km × 4km) at the red rectangle. The grid resolution is constant between the red rectangle and the blue border of the UKV model. Further details can be found in Lean et al 2011.

performed every 3 hours using 3D-Var. Observation types assimilated include coarsely-thinned clear SEVIRI radiances, cloud pseudo-observations from a cloud nowcasting system which utilises satellite radiance observations, GPS water vapour, a range of satellite-derived wind observations and various conventional observation types such as 2m temperatures - see e.g. Ballard 2010. Presented here are results obtained with the UKV model, along with some assimilation trials using the less computationally costly UK4 (4km resolution) model.

2. METHOD FOR ASSESSING SIMULATED RADIANCES

Simulated infrared radiances were generated every three hours for forecast NWP fields from the operational UKV system for three periods in 2010:

1. 1st April – 6th June 2010
2. 8th October – 2nd November 2010
3. 19th November – 22nd December 2010

At times and dates during these periods where suitable, quality-controlled clear SEVIRI observations were available, intercomparisons were made between the observed and simulated radiances. For period 2 above, the observations were compared with both the operational UKV system at that time ("PS24") as well as the new UKV system which went operational on 2nd November 2010 ("PS25"). The changes made between PS24 and PS25 included:

Table 1. UKV changes between PS24 and PS25 relevant to surface fields.

1. Improvements to the interpolation of soil moisture from the global model to the UKV model resolution (the UKV soil moisture comes from an interpolated global model analysis).
2. Reduction of the linearization errors in the calculation of skin temperature by linearizing about the skin temperature rather than the upper soil temperature.
3. Analysis increments to the upper soil level were (inadvertently) not applied to the radiative skin temperature in PS25, although this has little impact as the skin temperature rapidly converges on an equilibrium value determined by the upper soil level and the lowest atmospheric level.
4. A technical change moving to a new land surface exchange infrastructure which will enable future science changes, but had no scientific impact here.

Observations were only selected for intercomparison with simulated radiances at locations where both the observations and the model background fields were flagged as clear for all locations within 5km of the observation location. This ensured that a like-with-like comparison was being performed, with no shadowing of the surface from nearby clouds in either the real observations or in the model.
The purpose of this analysis was to improve the impact of clear sky assimilation over land. Simulated clear sky radiances over land show greater differences from the observations than for radiances over sea.
Simulated radiances were generated using four radiance simulation algorithms (Table 2):

Table 2. The four radiance simulation algorithms used.

1. The first approach involved linear interpolation of the NWP model fields to a standard set of 43 pressure levels (see Table 2 of Saunders 2002) used for the radiative transfer package RTTOV v7. Clear radiances were then simulated for SEVIRI channels 7, 9, 10 and 11 (with corresponding central wavelengths of 8.7µm, 10.8µm, 12µm and 13µm).
2. The second approach taken was identical to the first, but the resulting radiances were spatially convolved with the expected Point Spread Function (PSF) for the SEVIRI instrument in each of the channels, as described in Tubbs & Kelly 2009.
3. The third approach involved providing NWP model fields on the levels of the NWP model to the radiative transfer package RTTOV v9. Clear radiances were then simulated for SEVIRI channels 7, 9, 10 and 11.
4. The fourth approach taken was identical to the third, but the resulting radiances were spatially convolved with the expected PSFs, as in 2 above.

Two types of additional Quality Control (QC) flags were tested for each of the above experiments (Table 3):

Table 3. Additional observation quality control flags

1. Excluding observations within 10km of coastlines.
2. Excluding geographical areas flagged as problematic in the UWiremis MODIS emissivity atlas (Seemann et al 2008).

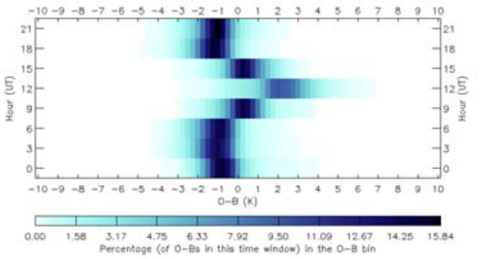
1D-Var retrievals of the atmospheric column and skin temperature were performed for each observation location using SEVIRI channels 5, 6, 7, 9, 10 and 11 and using the UKV model fields as the model background. The 1D-Var retrievals were performed on the UKV model levels using RTTOV v9 with the same 1D-Var minimisation technique as is described on the Met Office 1D-Var webpage: http://research.metoffice.gov.uk/research/interproj/nwpsaf/metoffice_1dvar/.
Finally, a 15-day assimilation trial was performed using SEVIRI observations which had the diurnal O-B bias subtracted (adjusting the observations to compensate for a bias in the model).

3. RESULTS

We begin here by discussing observations and simulated radiances from the period 8th October – 2nd November 2010, when UKV NWP model output was available for both the then-operational PS24 suite and the newer PS25 suite.
Figure 3 shows histograms of the observed-background brightness temperatures (O-Bs) for SEVIRI (IR window) channel 9. The percentage of O-Bs falling in each O-B bin are shown as a colour scale for histograms at eight times distributed across the diurnal cycle. Figure 3*a* shows the results for observations over land. This highlights significant diurnal variation of the bias in the O-B values during the period of maximum shortwave heating of the land surface. Figure 3*b* shows the same results over sea, where the diurnal variation in the bias is much smaller. The larger O-B variance seen at 00Z is partly due to a lack of data in this part of the diurnal cycle, as most data were rejected due to solar contamination in the SEVIRI instrument as the Sun passed by the disk of the Earth.

All of the histograms plotted show tails out to O-B values of large magnitudes (several Kelvin), particularly those over land. Similar histograms were calculated for both the PS24 and PS25 variants of the UKV (see Table 1) and for each of the radiance simulation algorithms described in Table 2. Histograms were also calculated with the additional observation quality control flags shown in Table 3. Gaussian fits were made to the peak of each histogram in order to obtain an assessment of the mode and standard deviation of the distribution.
The effect of the change from PS24 to PS25 is highlighted in Figure 4, where the O-B value at the peak of the fit to each histogram is plotted against time of day for the PS24 suite and the contemporaneous PS25 suite. The operational radiance simulation was used for these data (RTTOV v7). A change is seen in the shape of the diurnal bias, but the amplitude is not changed significantly, and the standard deviation of the O-Bs was essentially unchanged.
The switch from interpolating NWP fields onto the standard 43 RTTOV v7 levels for RTTOV v7 radiance simulation to direct simulation of radiances in RTTOV v9 on NWP model levels produced little change in the observed histograms – just a small reduction in the number of extreme outlier O-B values and a small overall shift in the mean O-B bias.
More beneficial impacts were seen from the spatial convolution with the SEVIRI PSF and from the additional observation QC-flagging, particularly on the standard deviation of the O-B values.

a data over land



b data over sea

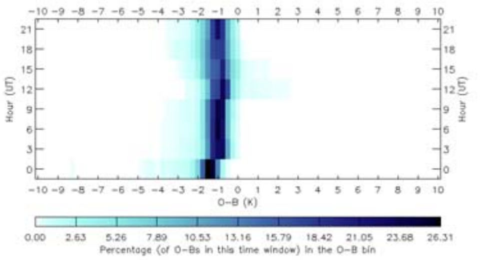


Figure 3. Histograms of O-Bs for SEVIRI channel 9. The radiance assimilation was performed as per current Met Office operations (RTTOV v7). Plot *a* shows on a colour scale, histograms of the O-Bs in three-hourly time bins throughout the diurnal cycle (aligned with the UKV data assimilation time windows). These histograms are binned for all the data selected over land in the 8th October – 2nd November 2010 date range. The horizontal axis gives O-B in Kelvin, and the vertical axis is time of day in the diurnal cycle. Plot *b* shows the same results for data over sea.

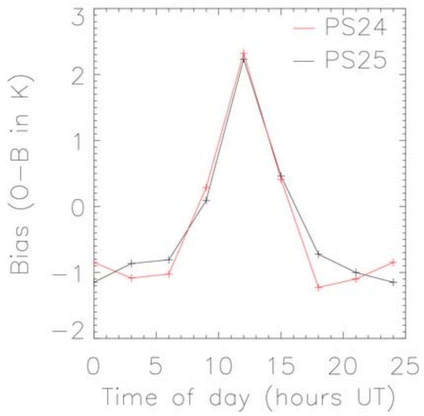


Figure 4. The effect of changes introduced into the UKV at PS25 (see Table 1). Histogram peaks were estimated using Gaussian fits for eight time windows throughout the diurnal cycle to highlight the diurnal variation in the bias.

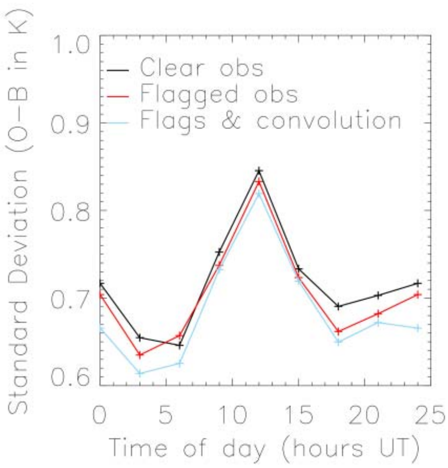


Figure 5. The reduction in standard deviation of O-B (about the bias) with the additional QC flagging listed in Table 3, and with both convolution and QC flagging. When applied individually, both types of QC flagging listed in Table 3 were roughly equally effective at improving the standard deviation (in fact many of the locations flagged in the MODIS atlas are also within 10km of coastlines).

Figure 5 shows the reduction in O-B standard deviation from flagging out the observations listed in Table 3, and the further benefit obtained from convolving the resulting image with the SEVIRI PSF. In both cases the diurnal bias was unchanged.

Figure 6 shows the overall impact of all the changes presented here on the O-B histograms for each time window in the diurnal cycle, for the 8th October - 2nd November 2010 date range. There is a significant reduction in the standard deviations of the O-Bs, but a significant diurnal bias still remains.
The reduction in the standard deviations is particularly evident for sea pixels, where the errors in skin temperature tend to be lower in the model. The diurnal variation in the bias over land is indicative of land surface skin temperature errors. For this reason, the Met Office are now testing the use of much larger background error estimates for the land surface skin temperature compared to the sea skin temperature. Trials in 1D-Var with these increased land surface skin temperature error estimates for the same October/November date range result in estimated diurnal bias in the land surface skin temperature which closely matches the bias in brightness temperatures seen in Figures 6*a* and 6*c*.

Much of this work was repeated for the other date ranges (1st April - 6th June 2010, using PS23 and 19th November - 22nd December 2010 using PS25). Figure 7 shows an intercomparison of the diurnal biases in each of the three date ranges studied. The diurnal bias remains broadly constant throughout the year, although the magnitude of the bias appears increased at times when there is a large radiative flux in or out of the land surface (during the day in summer, and during the night in winter).

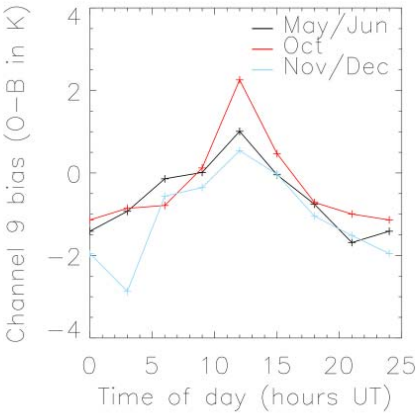


Figure 7. The diurnal variation in the O-B bias for several date ranges in 2010.

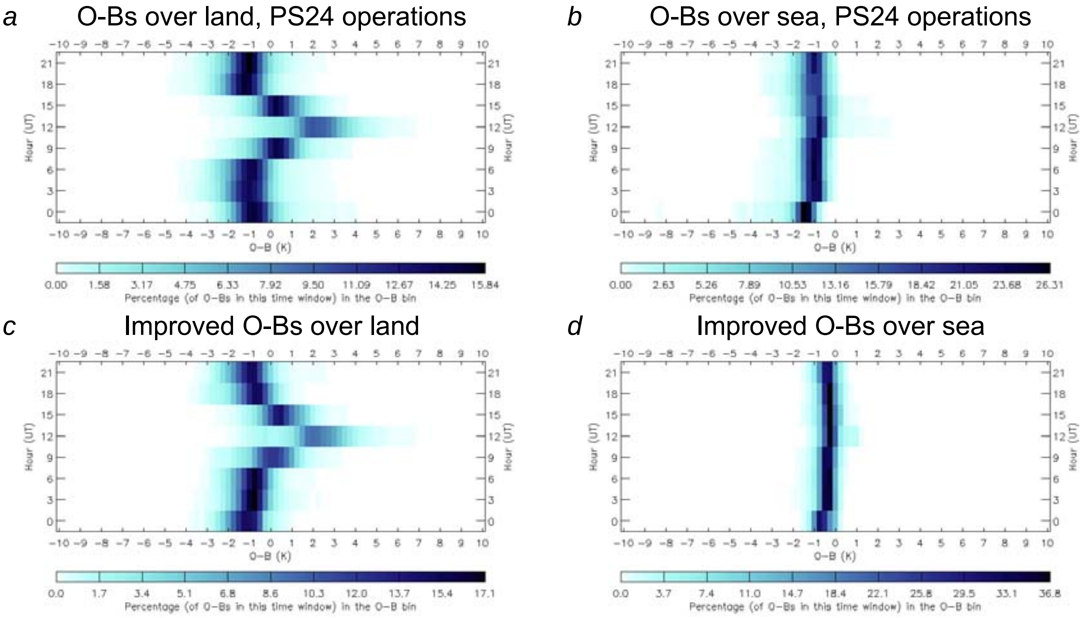


Figure 6. O-B histograms before and after the improvements presented in this paper. Panels *a* and *b* show histograms of the O-Bs from PS24 operations in October/November 2010, as in Figure 3. Panels *c* and *d* show similar histograms but using the PS25 version of the UKV (Table 1), radiance assimilation algorithm 4 from Table 2 and the additional QC flagging from Table 3. The left-hand panels (*a* and *c*) show results over land, whilst results over sea are shown in the right-hand panels (*b* and *d*).

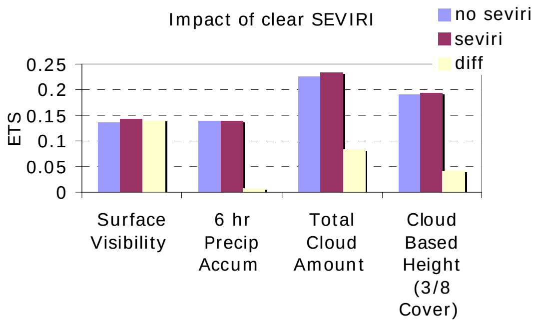


Figure 8. Impact of SEVIRI assimilation on Equitable Threat Scores (ETSs) after application of bias correction to the observations (to compensate for model biases). "diff" describes the contribution (positive = beneficial) towards the Met Office's UK forecast performance index.

In order to correctly address the O-B bias, it was clear that changes would be required to the land surface model. In the interim period before these changes could be made, we decided to test applying compensating biases to the SEVIRI observations, so that the observations had a better fit to the simulated brightness temperatures.

Trials were performed using the 4km resolution UK4 model as this is less computationally-intensive than the 1.5km UKV model. The operational satellite brightness temperature simulation was used (algorithm 1 in Table 2) as the other approaches were not in a suitable state for data assimilation trials. The diurnal biases shown in Figure 7 were subtracted from the observations before 3D-Var assimilation of the brightness temperatures. The trials showed beneficial impact on forecast performance – Figure 8 shows the impact on four Equitable Threat Scores (ETSs).

Discussion and Conclusions

All the O-B histograms for observations over land show strong evidence for a diurnal variation in the mean O-B (a diurnal bias). The seasonal dependence of this diurnal bias implies it may be dependent on errors in the radiative fluxes or in the thermal capacity of the radiative skin in the model.

The model errors may partly be explained by the temperature drop from the surface to the screen level being underestimated (probably in turn due to errors in the roughness length). The assimilation of screen-level temperatures keeps the 2m temperatures roughly correct. In the summer the net (downward shortwave – upward longwave) radiative flux can be too great, with most of the additional energy ending up in the latent heat flux. The data assimilation scheme adjusts soil moisture on the basis of screen-level temperature, compensating for this in the model. It is hoped that these model biases will be corrected later in 2011.

3D-Var data assimilation trials have shown that observational bias correction can be used in order to correct model biases, although we expect the forecast performance may increase further when improvements to the land surface modelling are made.

The improved approaches to satellite brightness temperature simulation gave significant reductions in the O-B standard deviations, which should help to improve the performance of the clear-sky radiance assimilation. Many of the improvements to the brightness temperature simulation may also be applied over other surface types and for other satellites to improve the data assimilation performance.

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