Prospects for IASI, CrIS and AIRS in the UKVD
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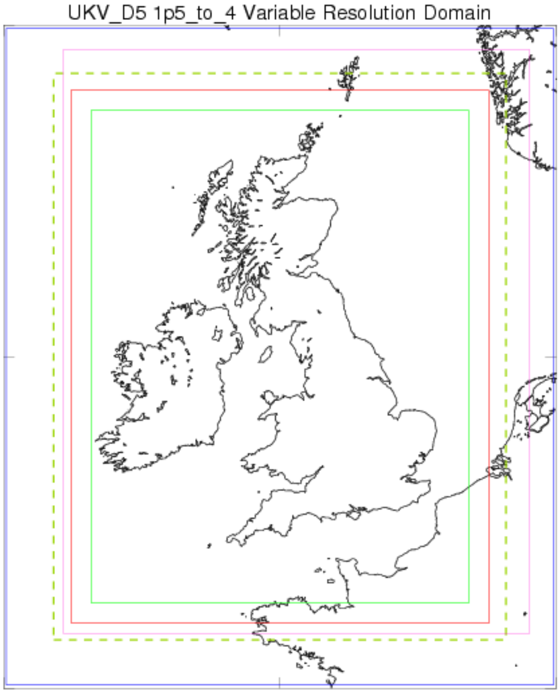

Figure 1: The domain of the UKVD model. The model has a resolution of 1.5km in the inner portion (the green box in the figure), goes through a variable resolution domain (red box) through to an outer region with 4km resolution (blue box).

1 Introduction

IASI and AIRS radiances have been used operationally at the Met Office for a number of years in the global and NAE models (Collard *et al.*, 2004; Pavelin *et al.*, 2008; Hilton *et al.*, 2009). This report explores the possibilities for assimilation of these datatypes in the UK variable resolution model (UKVD) which has a 1.5km grid over much of its domain.

The first part of this report explores the use and evaluation of infrared land-surface emissivity databases with particular reference to the product produced by the University of Wisconsin. The remainder explores the prospects for using advanced infrared sounders in high-resolution models through evaluation of IASI first-guess departure calculations.

2 Land Surface Emissivity

2.1 Background

The UKVD and UK4 domains have, relative to the global model, a large fraction of the surface being land (see Figure 1 for the UKVD domain). It would therefore be desirable to extend use of observations by IASI, AIRS and CrIS to include land points.

The high quality observations from the advanced infrared sounders themselves can be used to derive the land-surface emissivities (e.g., Huang *et al.*, 2004) and the development of such algorithms is being pursued at the Met Office. However, surface emissivities can only be derived when the surface is not obscured by cloud and a reliable cloud detection scheme is therefore required.

In the current processing of IASI and AIRS, cloud is either detected through the cloud detection scheme of English *et al.* (1999) or retrieved through the method of Pavelin *et al.* (2008). Both methodologies require accurate calculation of the first-guess radiances which in turn requires accurate knowledge of the surface emissivity.

Detailed maps of surface emissivity suitable for advanced infrared sounders are beginning to become available. Here we investigate the utility of the emissivity atlas produced by the University of Wisconsin (UW) for multi-spectral infrared observations (Seeman and Borbas, 2008). This product is currently being used by a number of groups in diverse processing systems including providing the emissivities that are operationally included in the SEVIRI BUFR stream by EUMETSAT.

At the time of writing the UW emissivity atlas is being incorporated into RTTOV-10 and this section of the report documents the issues that have arisen during the "beta-test" phase. Although many of these issues highlighted here have since been resolved they are reported here as they might be relevant to evaluation of other emissivity products and also because mostly earlier versions of the UW database are in use.

The UW emissivity product uses a "baseline-fit" method on the official MODIS land-surface emissivity product, MOD 11 (Wan and Li, 1997; Wan *et al.*, 2004). The MODIS product is derived for six MODIS channels using an algorithm that uses daytime and nighttime observations of the same scene (with similar viewing geometry) to infer emissivities for each MODIS channel. The UW baseline-fit method takes these values at the MODIS wavelengths and, using *a priori* knowledge of the expected spectral signatures from laboratory measurements, infers emissivity values for the 3.6-14.3μm wavelength range. The emissivities are stored for ten "hinge-point" wavelengths which are designed to represent the shape of the land-surface emissivity spectrum. In the RTTOV algorithm, the values at these hinge-points are converted, through linear regression, into principal component amplitudes which are then used to derive the full emissivity spectrum for the required instrument. The algorithm does not take into account any scan-angle dependence of the emissivity.

MODIS data products have been reprocessed a number of times with each reprocessed package being called a "Collection". The current collection is Collection 5, but the emissivity is not consistent with Collection 4 and validation exercises have shown it to be inferior. The University of Wisconsin product is therefore based on Collection 4. However, after 2007 the input data needed to produce the emissivities (level-1B radiance data, geolocation data, cloud mask, atmospheric profiles, and land and snow cover data) have been upgraded to Collection 5, so the Collection 4 emissivity product produced at this time is referred to as Collection 4.1. The differences between the Collection 4 and Collection 4.1 products are examined in the next section.

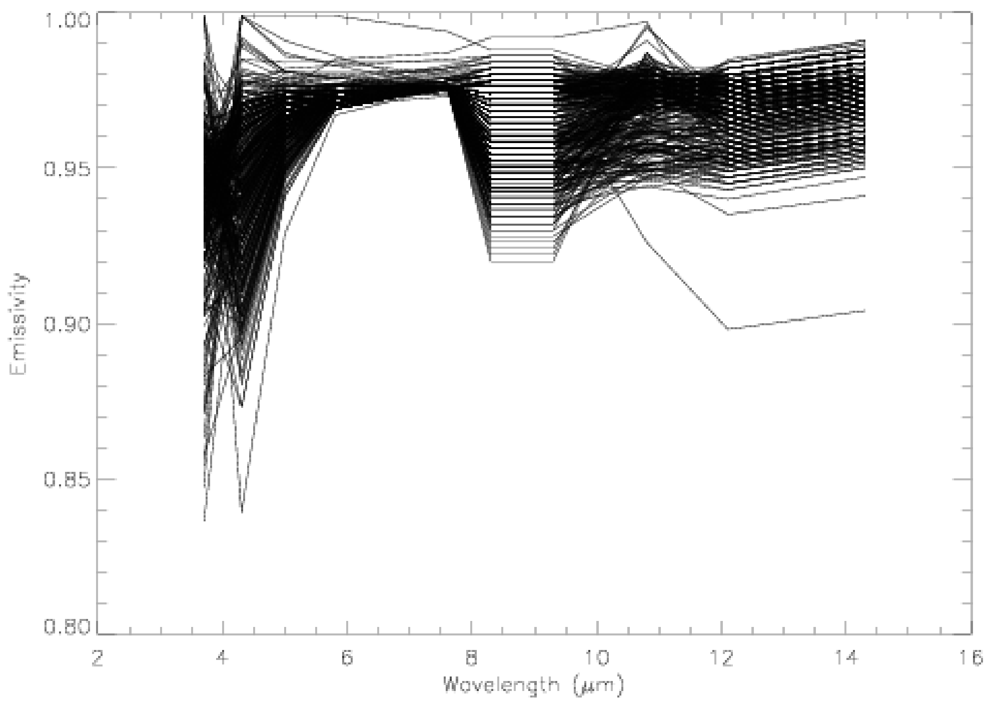

Figure 2: A selection of emissivity spectra plotted for the UKVD model region from the University of Wisconsin product. The emissivities are plotted for the ten “hinge-point” wavelengths.

2.2 Evaluation of the UW Emissivity Product

The original beta-test version of the RTTOV emissivity module was provided with emissivity data for 2006 from Collection 4. In Figure 2, a representative sample of spectra over the UKVD domain is shown for January 2006. The spectra generally show emissivities values above 0.95 except for lower emissivities in the 3–5μm range and in the quartz *reststrahlen* feature centred around 8.6μm. At wavelengths above 10μm the emissivity spectra are usually relatively flat with emissivities mostly in the 0.96–0.99 range. Figure 3, shows a histogram of all the land-surface emissivities in this domain for 10.8μm. A strong peak around 0.975 is seen but there is also a population of lower emissivities reaching below 0.94.

Figures 4 show where these lower emissivities are originating. The lowest emissivity values are almost exclusively confined to coastlines or regions with rivers or lakes (e.g., N.W. Ireland; the Rhine delta; the Loire and Seine rivers). The emissivity of water at these wavelengths is 0.98 or above (as can be seen in Lough Neagh in Northern Ireland) so it is unlikely that the emissivity signal of water is producing these values. An alternative explanation is that sand or bare rock is producing these values, but these wavelengths are longer than those of the *reststrahlen* bands and in many of the coastal regions with low emissivities the transition from vegetated landscape to sea is very abrupt (e.g., the channel between the north of Scotland and the Orkney Islands is marked by precipitous cliffs).

These low emissivity values can also be seen for North America (Figure 5). The low values can

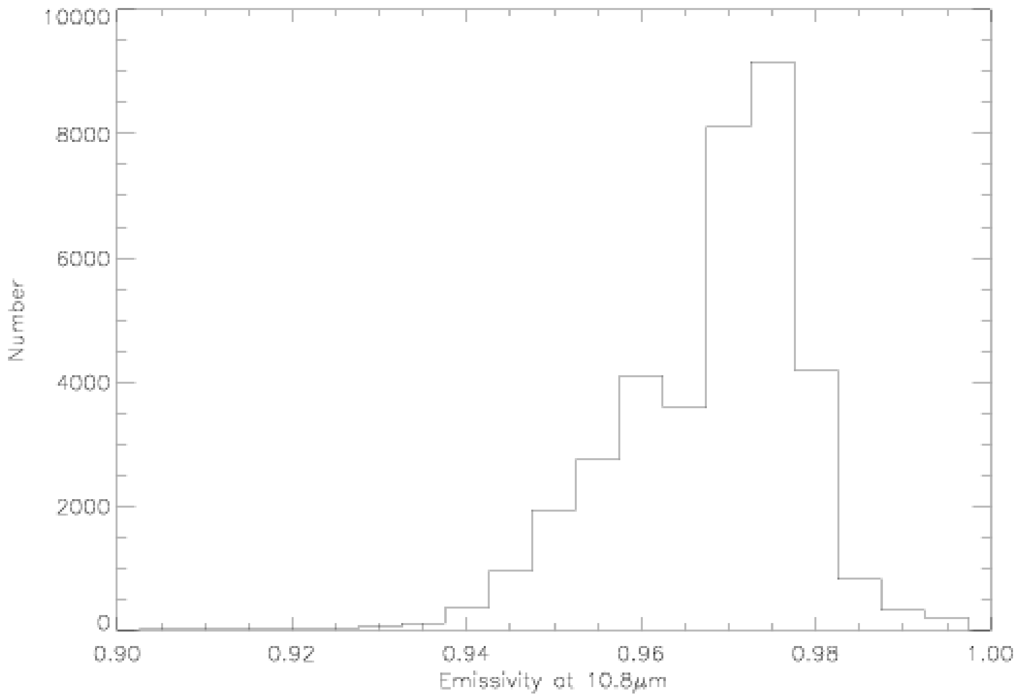

Figure 3: The distribution of emissivities at 10.8μm for the same case as Figure 2.

once again be seen in the river valleys, at the coasts, and in the Canadian Shield with its many small lakes. In contrast, extended bodies of water such as the Great Lakes have high emissivities.

The anomalous emissivities appear to be a manifestation of a known limitation of the MODIS algorithm in that the emissivity retrieval is prone to error in boundary regions between different surface types — particularly land-water boundaries. Such regions are generally problematic to retrieval schemes generally and are normally avoided in operational systems, however it is advisable to incorporate a quality control flag in the emissivity product itself to indicate where the product is not to be trusted. At the time of writing a quality control flag has been added (by Ben Ruston of NRL who is working with the University of Wisconsin team) that uses a more conservative coastline and inland water flag. On removing the points flagged in this way, the resulting emissivity maps are much improved (see Figures 6 and 7)

Figure 8 shows the time series of emissivities at 14.3μm for successive Augusts in the period 2003–2008. Period 2003-2006 is for Collection 4 while 2007–2008 is for Collection 4.1. Collection 4.1 appears to do a better job with the coastal regions which is probably afforded by improved quality control in the Collection 5 input data to the MODIS emissivity retrieval algorithm. However, both for Collection 4 and Collection 4.1 there is marked variability of the emissivity fields from year to year.

Figure 9 shows the difference between the August 14.3μm surface emissivity fields for 2008 and 2007 and it can be seen that the apparent variations are of continental scale. In general, vegetated areas show an increase in surface emissivity by up to around 0.01 while desert areas show a similar decrease. Figure 10 shows how the distribution of emissivities at this wavelength changes markedly

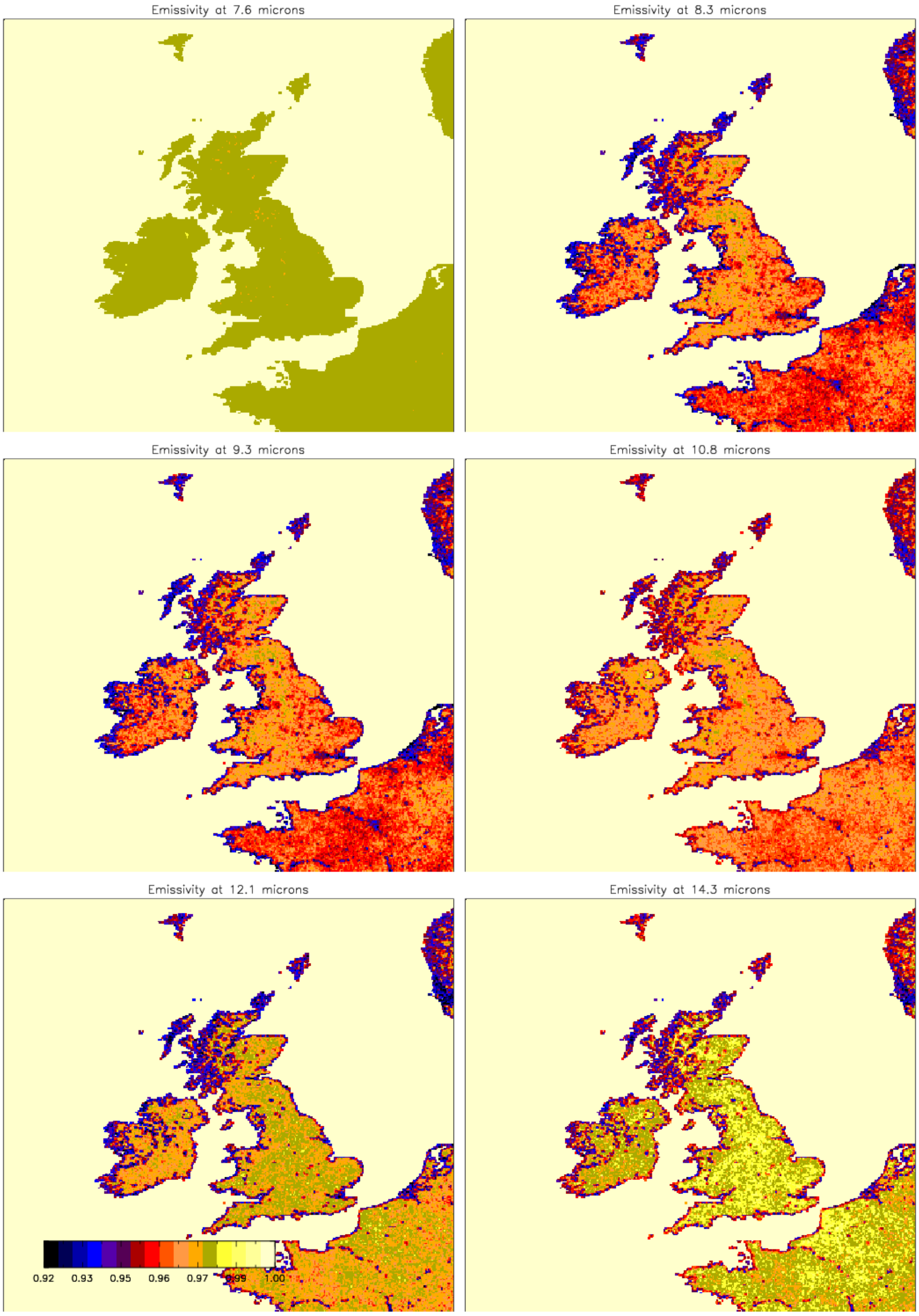

Figure 4: The spatial distribution of emissivities for August 2006 in the UW database for six thermal infrared wavelengths over the UKVD domain.

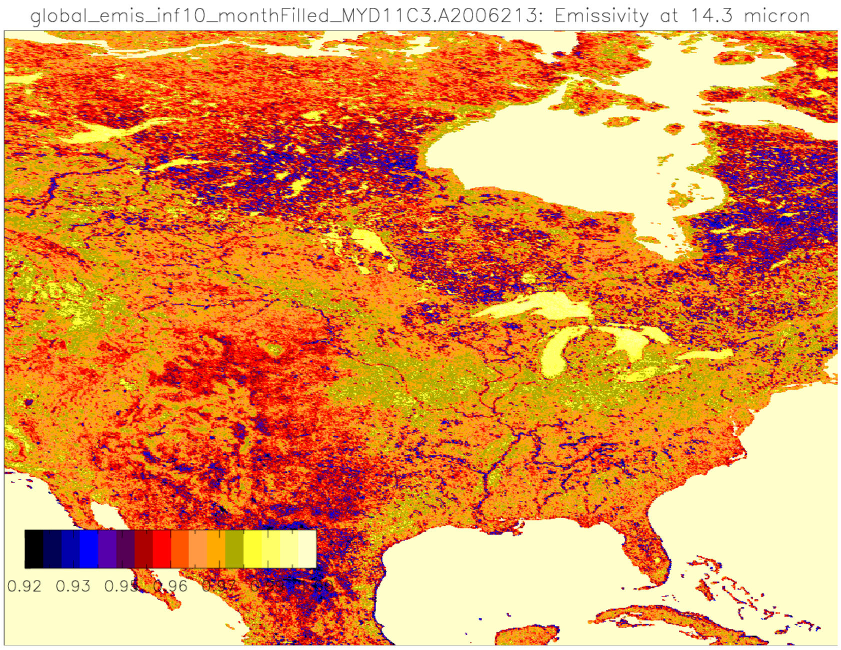

Figure 5: The spatial distribution of emissivities for June 2006 in the UW database at 14.3μm over North America.

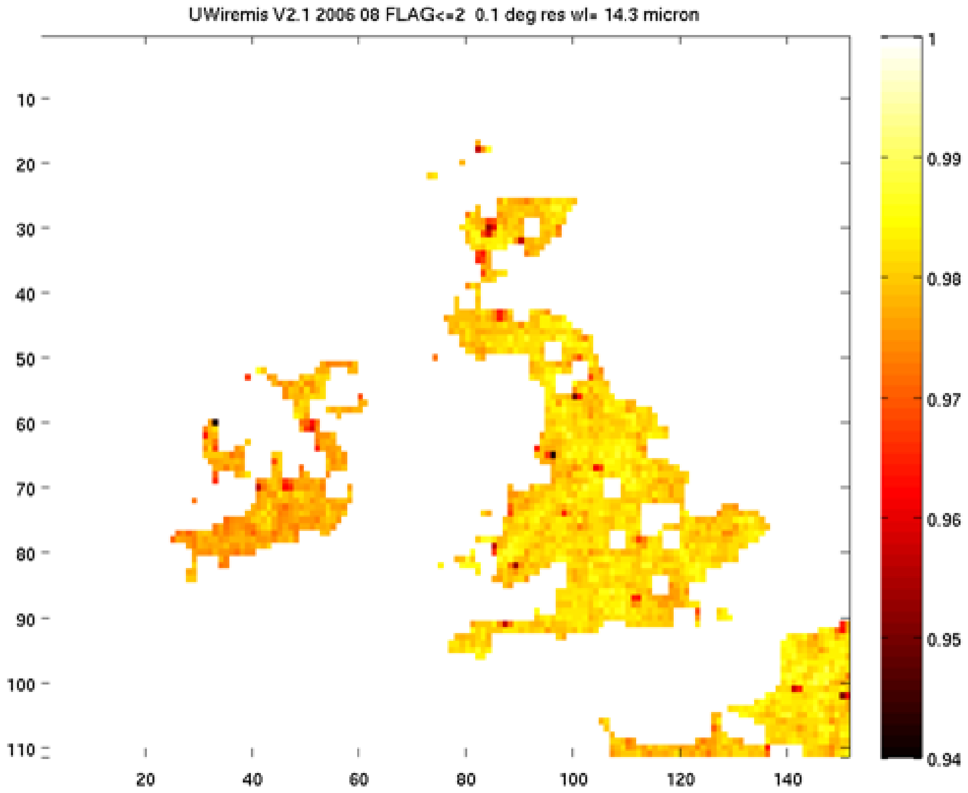

Figure 6: UW emissivity for the UK at 14.3μm after removal of points flagged by the improved coastline and inland water flag (Borbas and Ruston, priv. comm.)

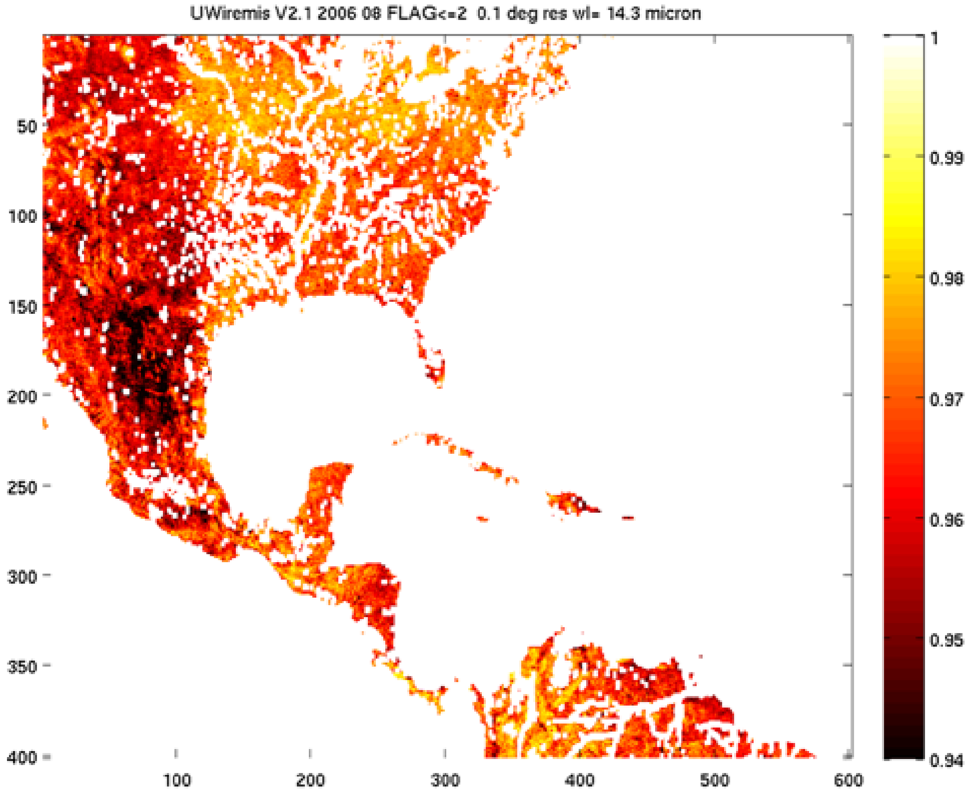

Figure 7: UW emissivity for North America at 14.3μm after removal of points flagged by the improved coastline and inland water flag (Borbas and Ruston, priv. comm.).

between seasons. These variations are an artifact of the retrieval for each month being dependent on the retrieval from the previous month as *a priori* data (R. Knuteson, priv. comm.) and so far efforts to correct this issue have been unsuccessful. However, the uncertainty of the emissivity data set (at least as manifested in the temporal variability) can be quantified through a covariance matrix that will be made available with the RTTOV deliverable.

2.3 Summary of UW Emissivity Product Evaluation and Next Steps

A number of issues have been identified with the proposed addition of the MODIS emissivity retrievals to RTTOV through the UW baseline-fit dataset. The anomalously low values associated with coastlines and inland water are mostly eliminated with stricter quality control flags. Using Collection 4.1 rather than Collection 4 might also yield better results in these cases.

The issue with the intra-annual and inter-annual variability of the retrieved emissivities has still not been completely resolved, but an important step has been made in characterising the variability as a covariance matrix that will be included in the RTTOV deliverable.

The variability of the emissivities in the MODIS retrievals over the UKVD domain is relatively small and in the longwave channels the inferred emissivities are mostly in the 0.97–0.98 range. The default RTTOV value of 0.98 for land-surface emissivity is actually a fairly good approximation in this case (0.97 might be slightly better). The real utility of a database such as this is for desert regions

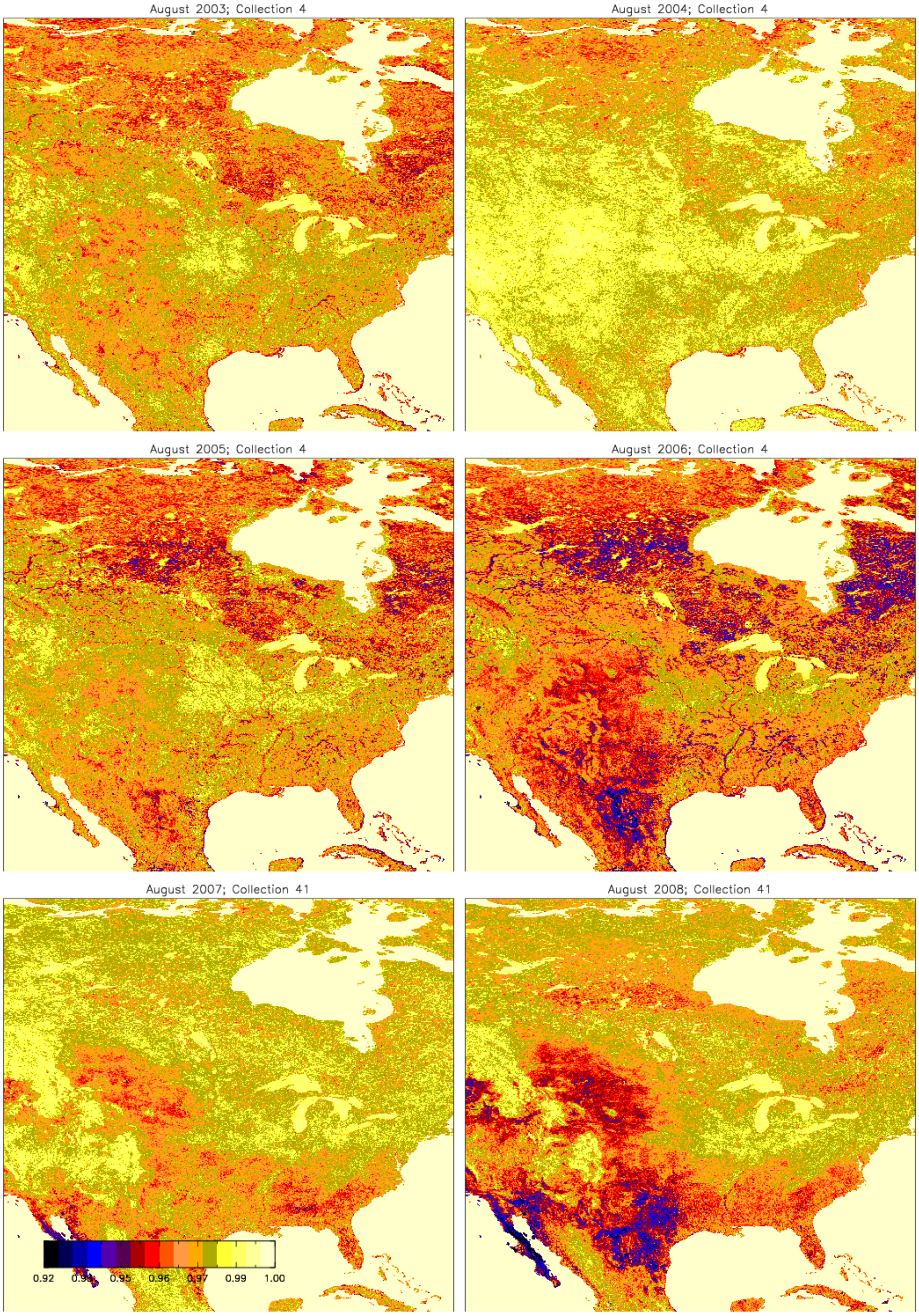

Figure 8: Time series of emissivities for successive Augusts from 2003 to 2008 in the UW database at 14.3μm over North America. The first four years are for Collection 4, the last two for Collection 4.1

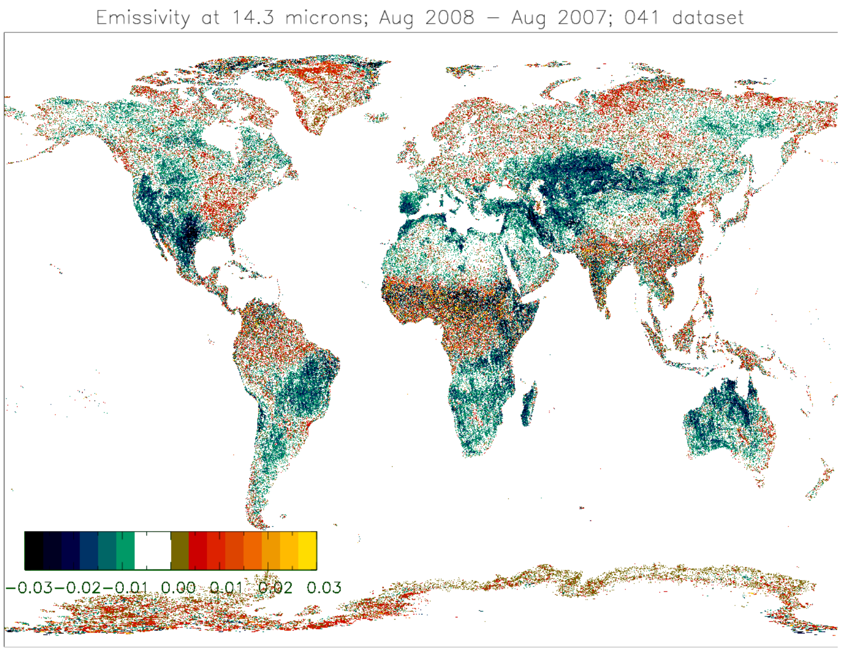

Figure 9: Map of the global distribution of land-surface emissivity differences at 14.3μm (excluding polar latitudes) between August 2007 and August 2008 for the Collection 41 MODIS land-surface emissivity product.

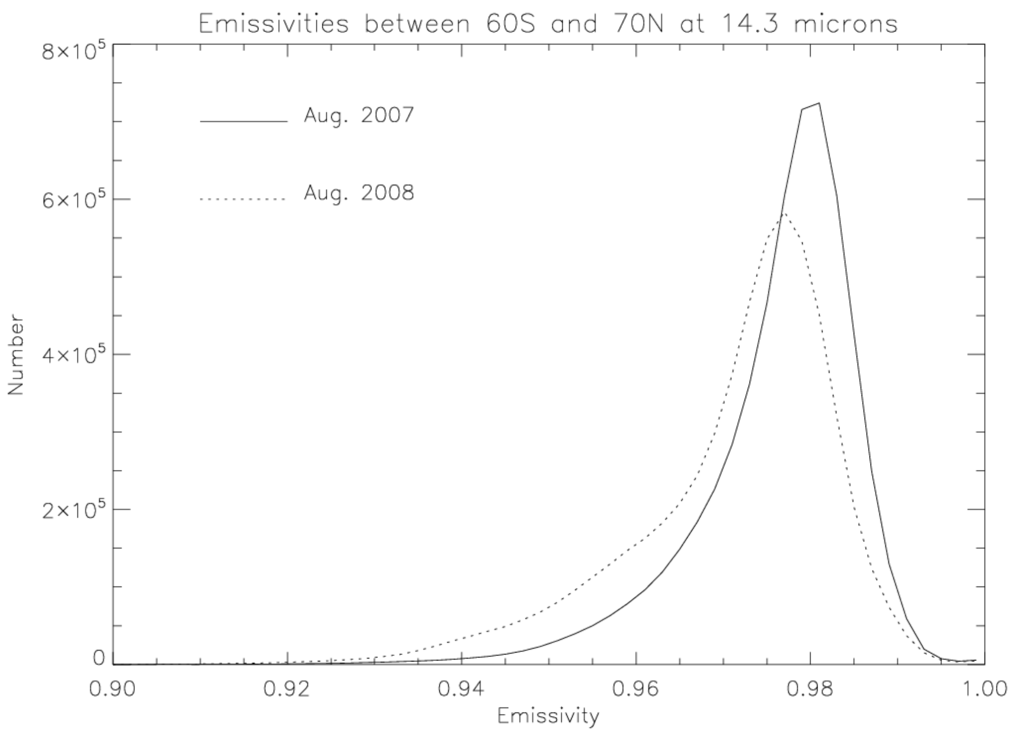

Figure 10: Histogram of the global distribution of land-surface emissivities at 14.3μm (excluding polar latitudes) for August 2007 and August 2008 for the Collection 4.1 MODIS land-surface emissivity product.

where the emissivity around 8.6μm can fall significantly below 0.9. This may be important even in the NAE model.

The general point about emissivity retrieval for complex terrain should be stressed. Situations where there are multiple surfaces within the IASI field of view are not suited to being described by a single emissivity value. The situation is further complicated by the fact that surfaces with different emissivities will tend to have different scene temperatures. In mountainous terrain the situation can be further exacerbated by sun-ward facing slopes being many degrees warmer than those in shadow. Therefore at least initially, emissivity retrievals should be attempted in regions with homogeneous surface types and relatively flat terrain.

3 Other Issues Surrounding Assimilation

In this section we explore the possibility of assimilating advanced infrared sounder data into the high-resolution 4km and UKVD models. As during the period of this study neither the UKVD nor the 4km models had stable test configurations suitable for assimilation trials, no such experiments were performed. Instead the suitability of using these data in these models is evaluated with the expectation of starting assimilation trials in the next few months.

The studies presented here have, mostly for reasons of simplicity, focused on IASI observations which select data for which the whole column is deemed to be clear by the English *et al.* (1999) cloud detection (“hole-hunting”). It is suggested that this form of data-screening be used in an initial evaluation rather than the more aggressive cloudy assimilation of Pavelin *et al.* (2008). This is primarily to mitigate possible errors in derived cloud properties that may arise when retrievals are performed over land. Eventually, however, it is expected that assimilation in the high-resolution models will include cloud so as to be consistent with the global model.

In the following sections, the IASI observations will be evaluated in terms of data coverage, quality control and first-guess departure statistics. Finally some areas requiring further work will be discussed.

3.1 Data Coverage

In Figure 11 the data coverage for IASI for twelve consecutive 3-hour assimilation windows is presented. This assumes that all observations are available when the analysis is being performed, but if locally-received data are used the delay is less than 15 minutes and this assumption is reasonable. The coverage for AIRS observations is not shown but would show a similar distribution in the 03Z and 15Z windows. CrIS — which is due to be launched in 2010 — will have similar orbital characteristics to AIRS. Therefore slightly more than half of the 3-hour assimilation windows will have high-spectral resolution data available. It should be noted that here the IASIHR dataset is used which contains the observation for all four IASI pixels; for the current operational system only

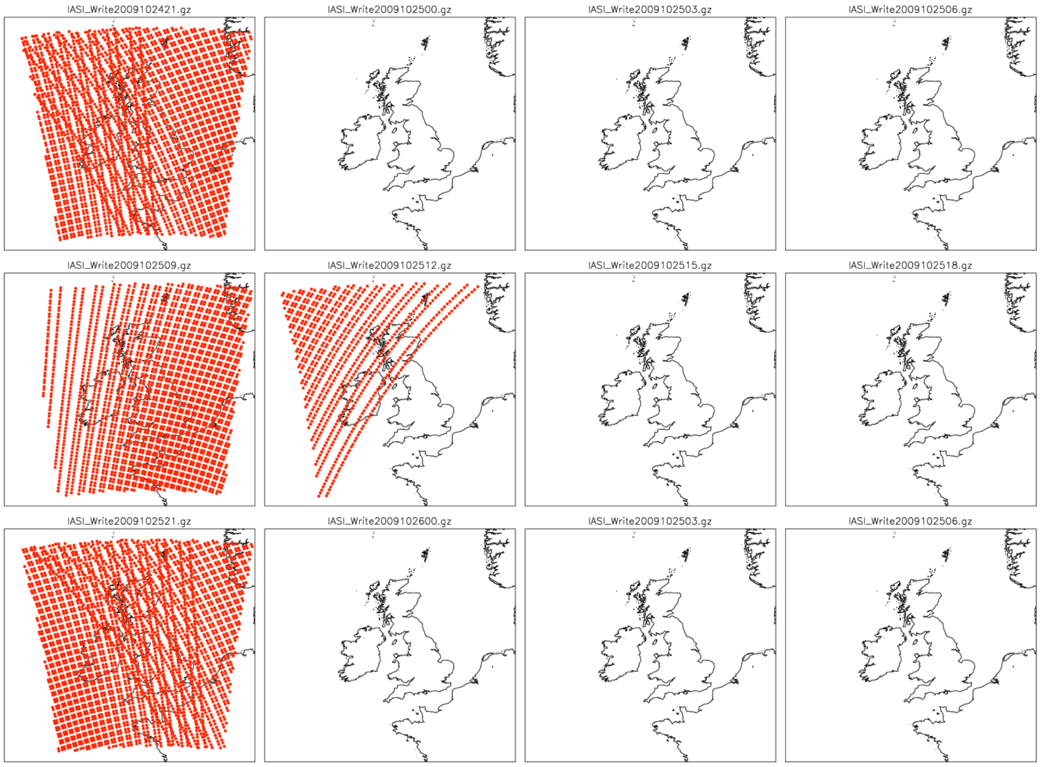

Figure 11: The position of IASI observations for twelve consecutive UKVD 3-hour assimilation cycles from 21Z on $24^{\rm th}$ October 2009 to 6Z on $24^{\rm th}$ October 2009. These assume all observation made within 1.5hours of the analysis time are available.

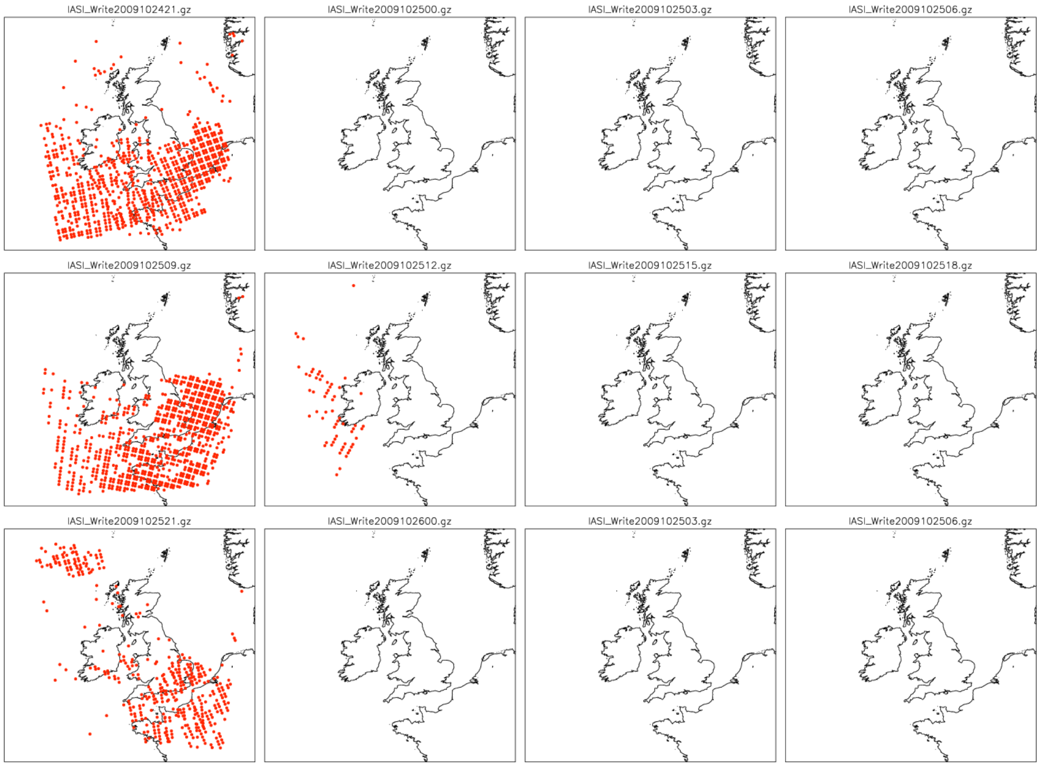

Figure 12: As Figure 11 but for observations passing the cloud-detection test.

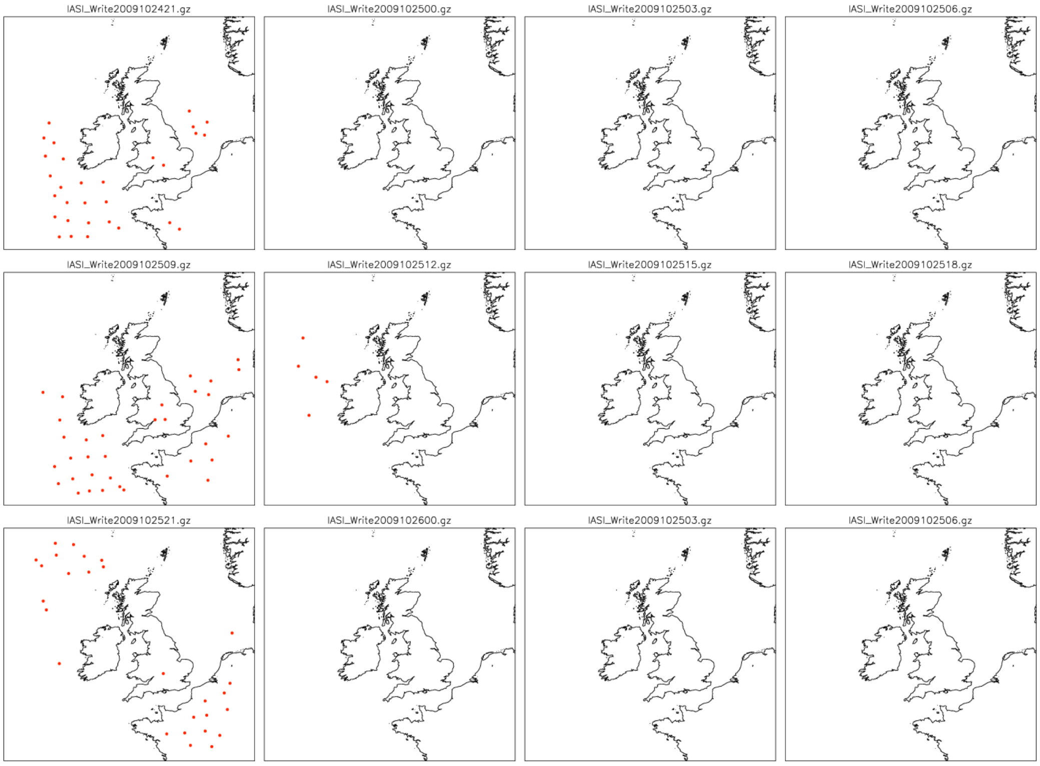

Figure 13: As Figure 11 but for observations passing the cloud-detection test and the default thinning algorithm.

one of the four pixels is available.

Figure 12 show the same period as Figure 11 but only those observations which are flagged as clear are plotted while Figure 13 thins the observations in Figure 12 in the manner currently used in the NAE model (this may, of course, be changed if need be for the UKVD and UK4 models). The number of observations available compares favourably with the data density from the radiosonde network. It therefore appears that advanced infrared sounder radiances will be available in the UKVD domain in sufficient numbers to make assimilation of these observations worthwhile.

3.2 Quality Control

With the UKVD domain having a relatively restricted aereal extent, excessive quality control can have major impact on the number of observations available for assimilation in a way that is not so important for global and regional models. An example is given in Figure 14 where the surface type flag generated by AAPP is shown. In the current IASI processing configuration, observations are not assimilated if flagged as coastal. Clearly in this case a conservative buffer has been applied to ensure that coastal scenes cannot encroach into the FOV, but in the process a large number of pure sea or pure land points have been rejected. This is actually limited by the size of the AMSU-A field of view when viewing off-nadir which is used in the cloud-detection algorithm. It may therefore be desirable to remove AMSU-A from the cloud detection algorithm and to revise the use of the AAPP

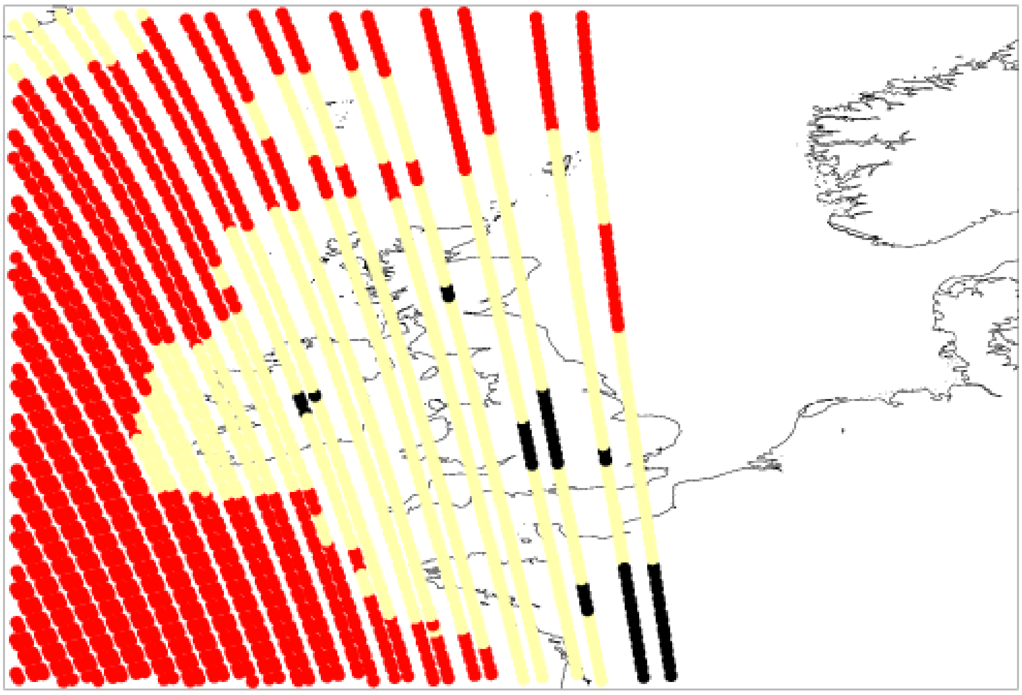

Figure 14: Distribution of surface type flags from AAPP for IASI. Black is land, red is sea and yellow is coast.

coastal flag to allow more points around the coastlines to be used.

Another issue with quality control is caused by the humidity fields in the background lying outside of the limits allowed by the RTTOV regression. Figure 15 shows maps of the minimum humidity value in the 650–880hPa pressure range with a log colour scale for eleven consecutive cycles of the UKVD where a significant number of IASI observations were available. A region of very low humidity can be seen. The humidity is exactly zero in some cases which implies that the value was actually negative but has been reset to a more physical value. These very low humidity regions can be seen to be advected between cycles.

Figure 16 shows the UKVD background humidity profiles at IASI observation locations (and presented on RTTOV levels) for the 21Z 24$^{\text{th}}$ October 2009 case. The very low humidity values can be seen to be confined to very thin layers in the vertical. Figures 17 and 18 show the same period for the 4km and global models. Very similar structures can be seen in the 4k model but the atmosphere gets much less dry in the global model. It should be noted that such low values can be seen in the global model at other times, however. It is not currently clear exactly why the high-resolution models have such low humidity values. As can be seen, these regions can cover a significant fraction of the total domain and are generally in the clear areas where one would hope to be able to use IASI. For the assimilation problem, it should be acceptable to simply replace the very low humidity values with the minimum value allowed by RTTOV in the RTTOV calculations and therefore allow assimilation in these regions, but detailed evaluation of this is required.

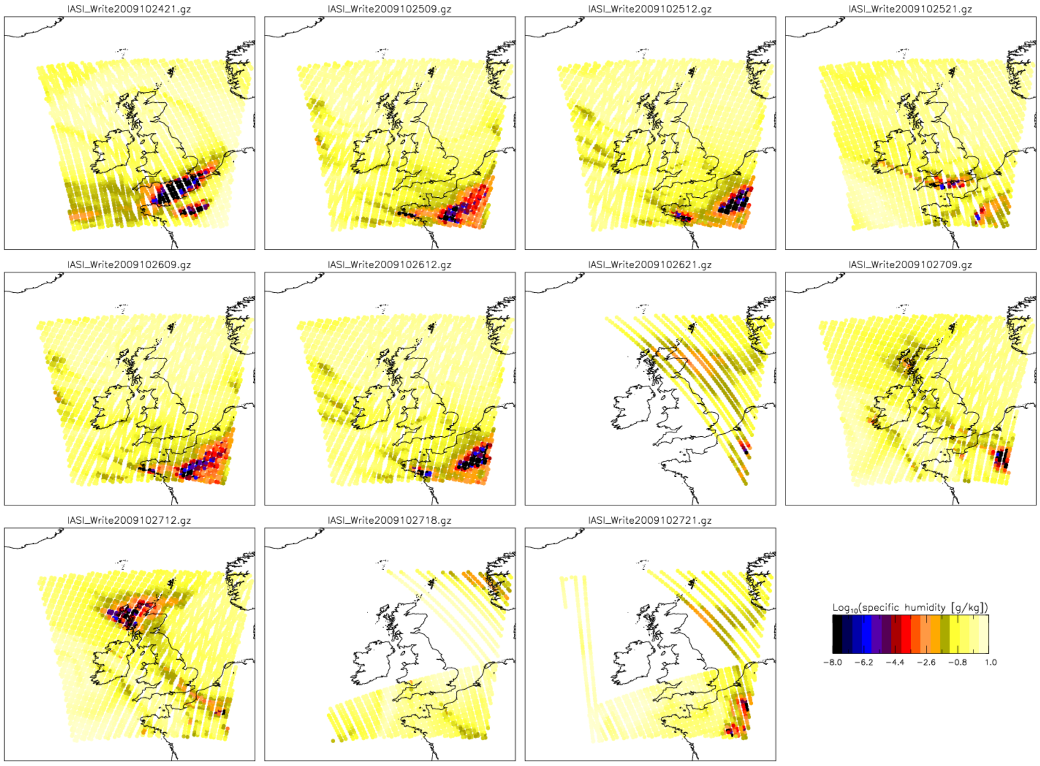

Figure 15: Maps of the minimum specific humidity in the 650–880hPa pressure range in the background fields for the UKVD model for a number of cycles with a significant number of IASI observations. Note the colour scale is logarithmic.

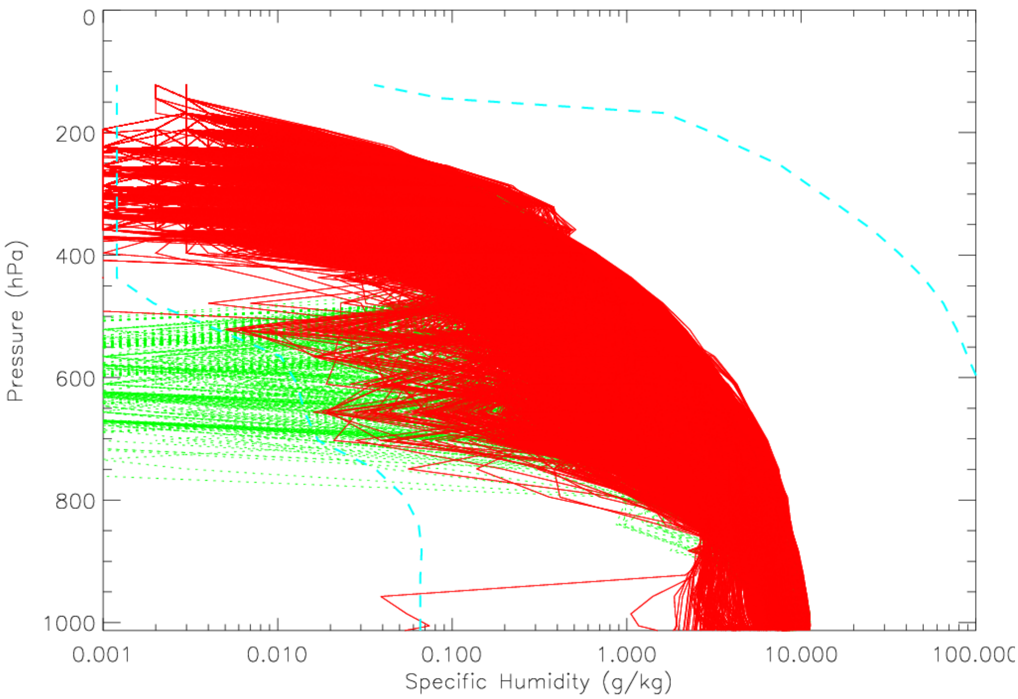

Figure 16: The UKVD background humidity profiles at IASI observation locations (and presented on RTTOV levels) for the 21Z 24th October 2009 case. The green curves are profiles where the RTTOV QC flag is set, the blue curves are the RTTOV limits.

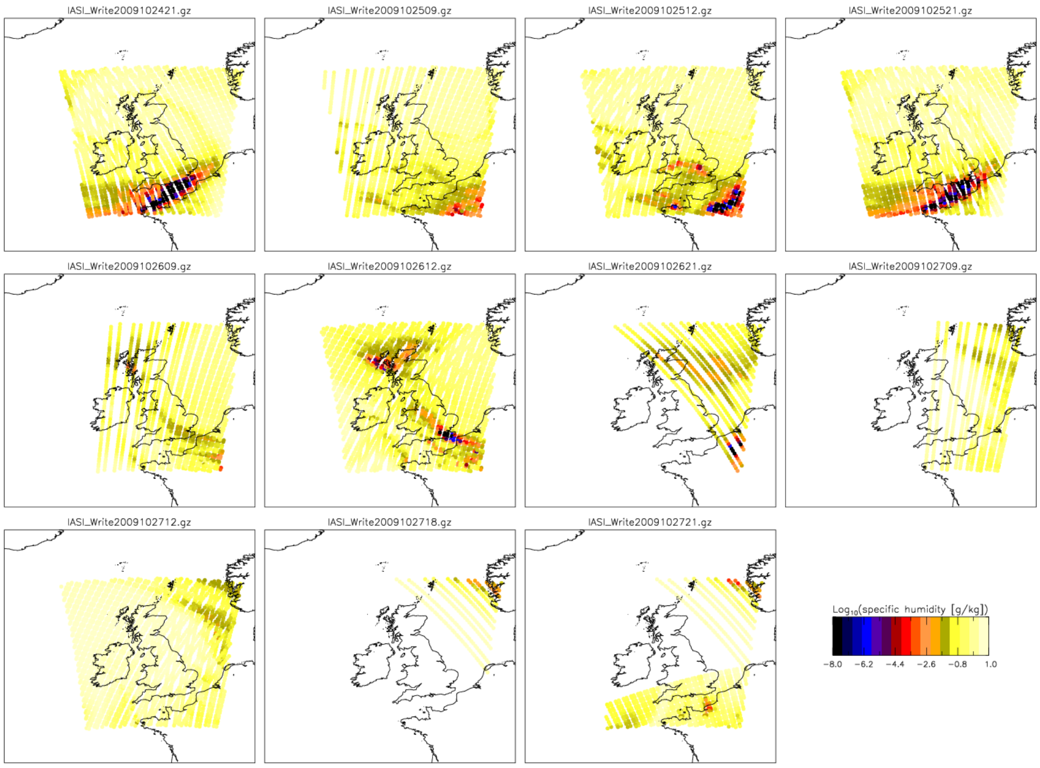

Figure 17: As Figure 16 but for the 4k model.

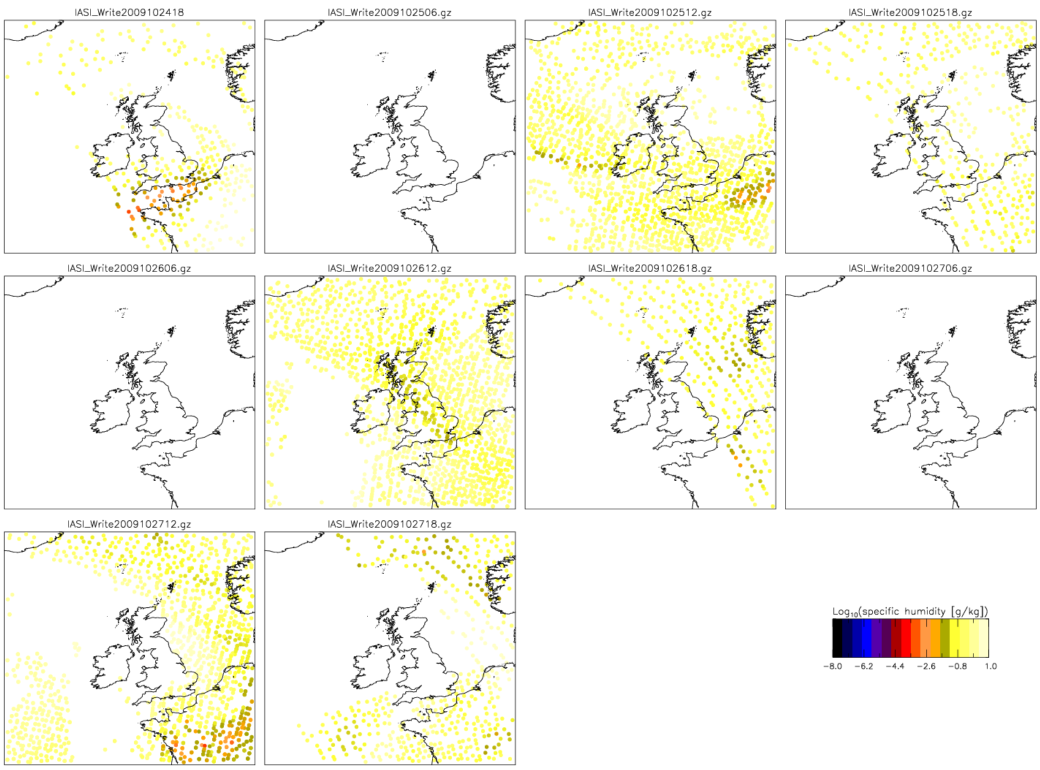

Figure 18: As Figure 16 but for the global model. Values for only 1-in-4 IASI observation locations are plotted.

3.3 First Guess Departure Statistics

Figures 19 to 22 show the comparison of first guess departure statistics for IASI in the UKVD, UK 4m and global models over the UKVD domain for the period 18^{th}– 27^{th} October 2009. In all cases the bias correction for the global model has been used.

The statistics for the three models in general compare well. The biggest differences are in the mean statistics for stratospheric channels (channel numbers less than about 70) and in the ozone band (channels 147-161). Stratospheric temperature differences probably account for the mean differences in the higher peaking humidity channels as well (approximately channels 200-270). Bias corrections for these channels derived from the global model will not account for the observed bias between observations and model calculated from the UK4 or UKVD models. The statistics are much better when bias corrected using coefficients derived from the limited area model itself.

Unfortunately, initial attempts to use bias correction files suitable for the UK4 model derived in the summer were not suitable for these experiments conducted in the autumn (when UKVD departures were available) and these results are therefore not shown. When calculating bias corrections from these very limited area models (which will not have the same range of meteorological situations in a given period as in the regional and global cases), it is difficult to ensure that all of the meteorological scenarios likely to be encountered are in the bias-correction training set. It is easier from this point of view to use bias corrections derived from the global model. There may also be scientific justification for this choice if we believe that the residual biases in channels sensitive to the stratosphere result from model bias.

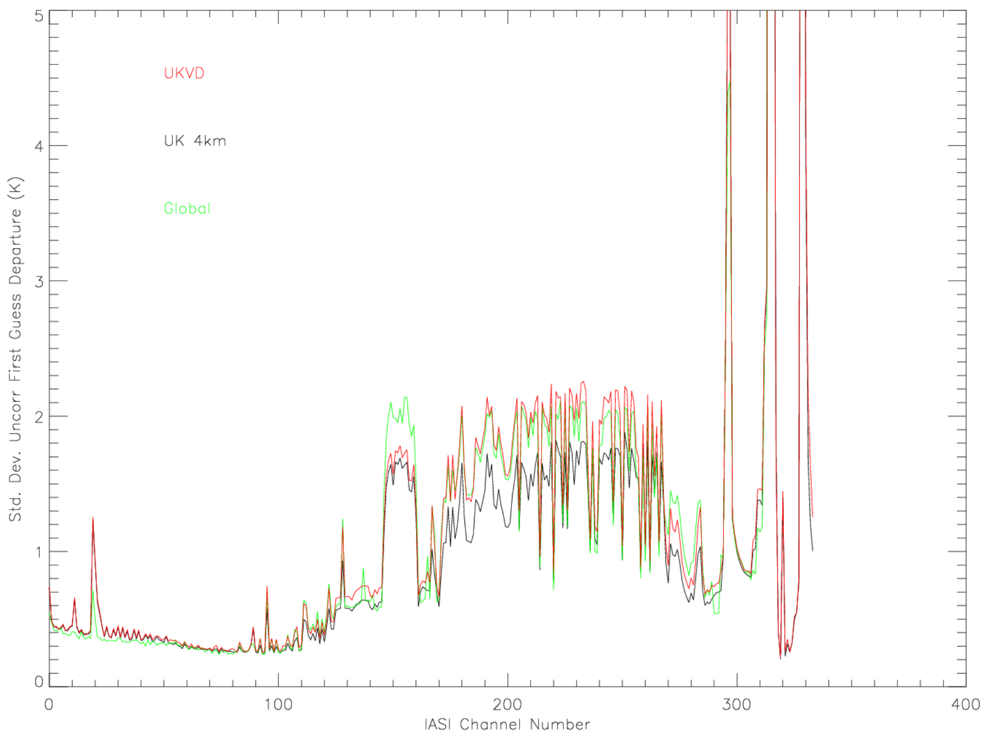

Figure 19: The standard deviation of the un-bias-corrected IASI clear-sky first-guess departures for the 18$^{\mathrm{th}}$– 27$^{\mathrm{th}}$ October 2009 for the UKVD, UK4 and global models in the UKVD domain.

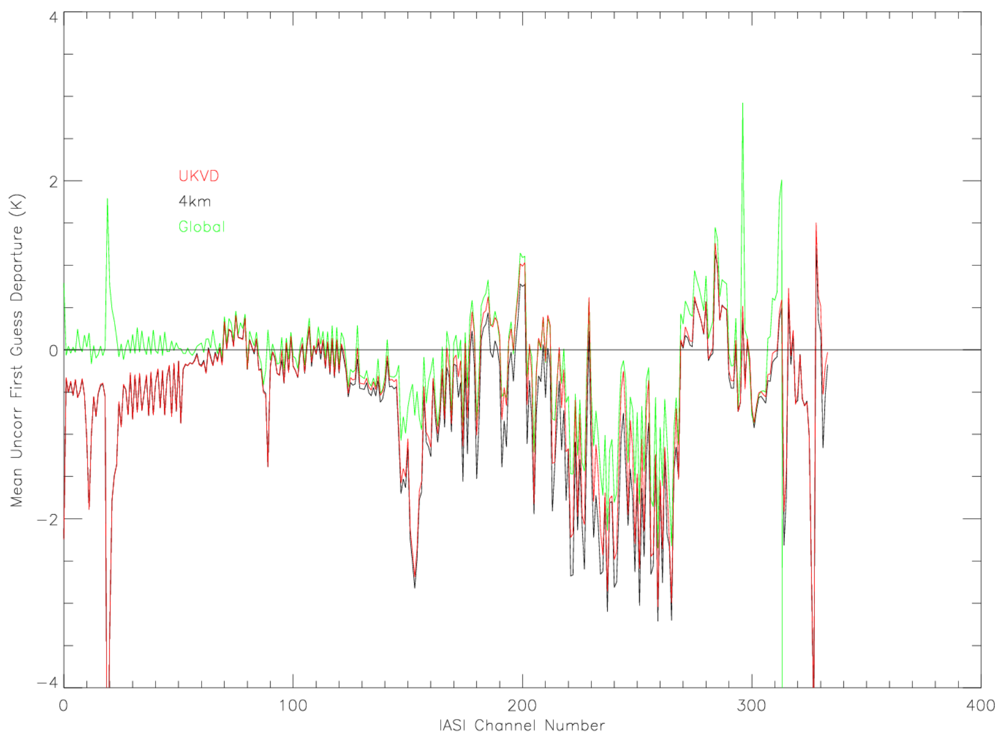

Figure 20: The mean un-bias-corrected IASI clear-sky first-guess departures for the 18$^{\mathrm{th}}$– 27$^{\mathrm{th}}$ October 2009 for the UKVD, UK4 and global models in the UKVD domain.

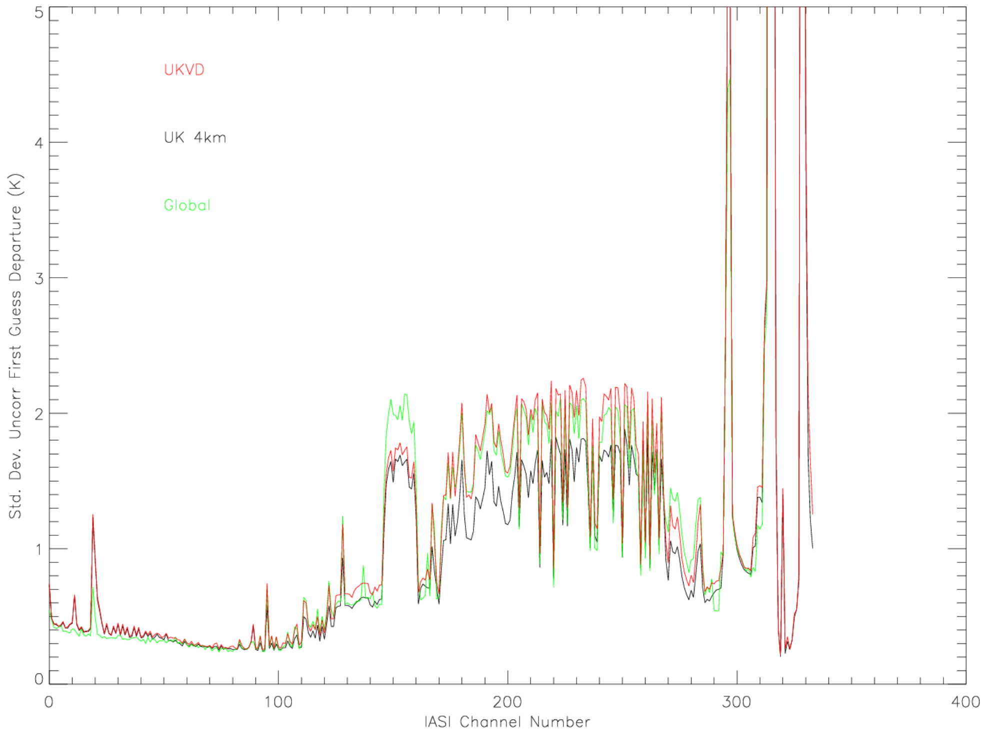

Figure 21: As Figure 19 but using after correction using the global bias correction.

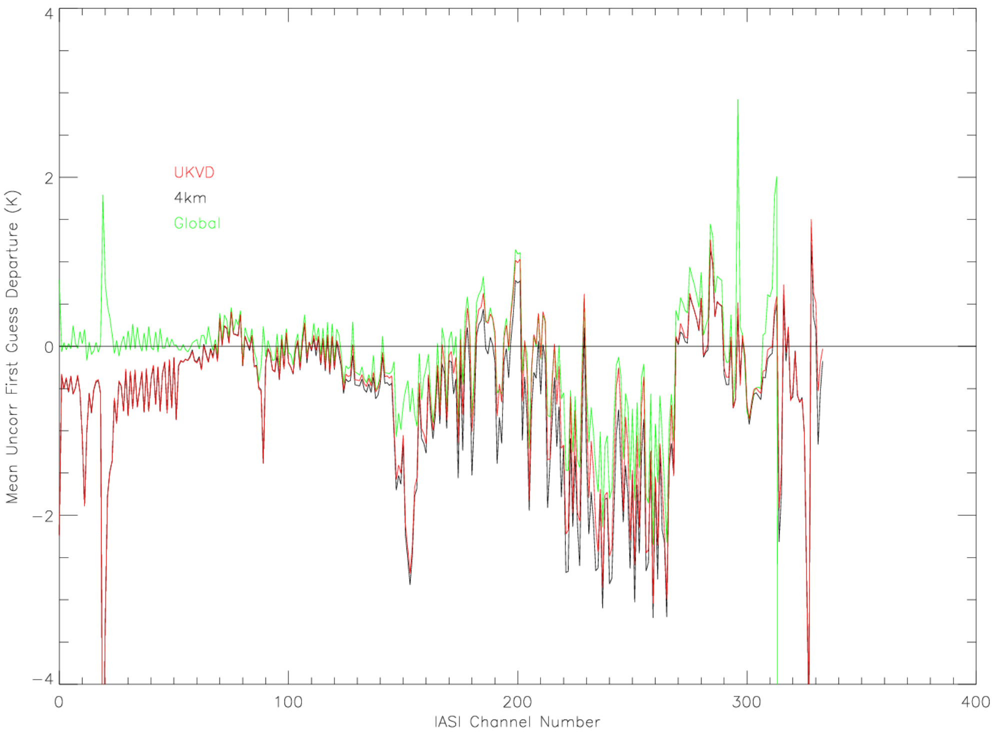

Figure 22: As Figure 20 but using after correction using the global bias correction.

4 Conclusions and Further Work

The prospects for successful assimilation of high-spectral resolution infrared radiances into the UK4 and UKVD models are good.

The data densities compare well with the radiosonde network and the first guess departures are reasonable when compared to the global model.

The use of the default land surface emissivity value of 0.98 appears to give reasonable results but a comparison with the University of Wisconsin emissivity product should be pursued now that a reasonable quality control mask is available. It is suggested that areas flagged by the UW quality control flag should not be assimilated inititially as these are regions where the surface emission is particularly complex at scales smaller than the instrument field of view.

The question of bias correction needs further research. It is imperative that the bias correction coefficients are trained with the full range of situations that may be encountered in the period that the bias correction is in use. Given the very limited spatial coverage of the UK4 and UKVD models this would tend to suggest that coefficients derived from the global model would be the best choice. However, there are large differences in bias in the stratosphere between the models, so global model coefficients would require careful testing.

An issue that has not been addressed here is the convolution of the 1.5km UKVD grid to the 12km IASI field of view. the calculations in this report assumes that the grid point nearest the centre of the IASI FOV is representative of the whole. A study by Duffourg *et al.* (2008) for Météo-France's AROME model indicates that this is acceptable for temperature channels but it can cause errors in the humidity band of over 1.5K in regions with high humidity gradients. It should be remembered, however, that even if the forward calculation is modified to allow for this variability within the field of view, the form of the analysis increments that result may not represent the difference between the true and background states (e.g., instead of the position of an airmass boundary being moved, a mean increment is applied — this will depend crucially how well background error structures in boundary regions can be represented by the background error model). Initially it may be advisable to use caution, and attempt to avoid assimilation in these regions through strict quality control based on first-guess departures in the water band.

One of the limiting factors in the assimilation of water vapour information from IASI and AIRS in the global model is representivity error. As explored by Stewart *et al.* (2009), this is due to the spatial resolution of the background field being too low to properly represent structures visible to infrared sounders with resolutions of around 10km. This is potentially mitigated in high-resolution models such as the UKVD (which has an analysis grid with a resolution around 3km). This would potentially be very interesting as it would give an opportunity to make greater use of observations in the humidity bands of these instruments. After initial implementation of an assimilation system for advanced infrared sounders in the UKVD, experiments reducing the assumed observation errors in VAR for the humidity channels from their current value of 4K should be performed.

Acknowledgements

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