

Identification of biases in the modelling of high peaking water vapour channels from IASI

S. M. Newman, F. Hilton and S. Clough

Met Office, FitzRoy Road, Exeter EX1 3PB, UK

A. D. Collard

European Centre for Medium-Range Weather Forecasts, Reading RG2 9AX, UK

International research aircraft campaigns have been used to validate radiances from the Infrared Atmospheric Sounding Interferometer (IASI) and identify sources of error in the radiative transfer modelling. This paper investigates the modelling of strong water vapour emission lines for three such case studies.

IASI observations are compared with coincident data from the aircraft campaigns combined with upper atmosphere forecasts from the Met Office and ECMWF global models, forward-modelled using a line-by-line radiative transfer model. The resulting biases identified in the research aircraft case studies for high-peaking water vapour lines are found to be consistent with operational biases from the Met Office and ECMWF assimilation schemes.

It is shown that in the models' current configuration ECMWF humidity fields are more successful in reproducing observed IASI radiances. Differences in the observed biases for the two centres are explored in relation to differing schemes for the treatment of upper atmospheric humidity in the 4D-Var assimilation scheme.

1. Airborne campaigns

This study uses data gathered by aircraft campaigns conducted during 2007 and 2008 dedicated to IASI calibration and validation. The underpinning strategy in airborne research studies for satellite cal/val is to characterise rigorously both the absolute upwelling atmospheric radiance and the state of the atmosphere (in particular temperature and humidity). Temporal and spatial collocation of these measurements is important, to minimise representivity errors. The UK Facility for Airborne Atmospheric Measurements (FAAM) BAe 146 aircraft is a well instrumented airborne research laboratory, suited to satellite cal/val exercises of this kind. The FAAM aircraft instruments used in this study include:

- Airborne Research Interferometer Evaluation System (ARIES) measuring upwelling and downwelling infrared radiances at 1 cm^{-1} spectral resolution;
- Heimann broadband infrared radiometer for mapping surface temperatures;
- AVAPS dropsonde system, allowing profiles of temperature and humidity below the aircraft to be sampled at high spatial resolution;

- Onboard temperature and humidity probes for measuring in situ atmospheric conditions, and aerosol and cloud probes for measuring particulates;
- Onboard chemistry probes for measuring in situ atmospheric concentrations of trace gases such as ozone and carbon monoxide.

Description of the case studies

For the three case studies described here, flights of the FAAM aircraft were coordinated with overpasses of IASI on the MetOp-A satellite. Only measurements within the same geographic area and small time window have been considered, to give maximum confidence that all measurements relate to the same atmospheric airmass. Exclusively clear sky fields of view for radiometric measurements have been analysed, as determined from onboard observations and MetOp AVHRR imagery.

The first campaign, the Joint Airborne IASI Validation Experiment (JAIVEx) was based in Houston, Texas during April and May 2007. The FAAM 146 was joined by the NASA WB-57 high altitude aircraft, carrying two additional airborne interferometers. This enabled collocated measurements of infrared nadir radiances from space, the stratosphere and the upper troposphere. Sorties were conducted over ocean (Gulf of Mexico) and over land (ARM Southern Great Plains facility, Oklahoma). This dataset is intended to be representative of warm, moist atmospheric conditions.

In order to sample contrasting climatic conditions, the FAAM 146 undertook a flight in December 2007 off the northwest coast of Scotland, timed to coincide with a MetOp overpass in predominantly clear sky conditions.

A further series of flights occurred during the Cold Land Processes Experiment (CLPX-II) based in Alaska in February 2008. Flights over sea ice and over the snow pack enabled measurements in cold, dry conditions.

Line-by-line simulations

The IASI observations are compared with brightness temperatures simulated by a line-by-line radiative transfer model. The atmospheric profiles for input into the radiative transfer code, representative of the observed radiances, were constructed in the following way:

1. The nearest collocated dropsonde profile was used for temperature and humidity below the FAAM 146 altitude (typically around 10 km);
2. Trace gas profiles for ozone and carbon monoxide were derived for this lower atmosphere range from in situ aircraft probes;
3. In the absence of closely coincident radiosonde observations, temperature and humidity for the upper atmosphere (above around 10 km) were derived from operational NWP model fields. Fields were available from both the Met Office and ECMWF global model forecast (run from the closest previous analysis with on

average three hours lead-time to the time of the overpass). Ozone was available as a variable parameter from the ECMWF model.

4. The surface skin temperature was derived from Heimann radiometer measurements, coupled with spot retrievals of temperature and emissivity using ARIES hyperspectral radiances.

GENLN2 (Edwards, 1992) was used as the line-by-line code. Recent updates to spectroscopic parameters (HITRAN 2004) and the water vapour continuum (MT_CKD_1.0) were implemented in the simulations. Comparisons with another line-by-line code (LBLRTM) show no significant differences in the strong water vapour band of interest in this paper.

This paper investigates differences in bias between the IASI measurement and the simulated observation when using Met Office and ECMWF forecasts. These can be attributed to differences in the upper atmospheric forecasts themselves since all other parts of the simulation are identical.

2. Operational biases

In order to verify whether the biases between the IASI observations and the simulated brightness temperatures identified in the case study are representative of the forecast model in general, they are compared with operational biases from the Met Office model for the same day over a wider region. Observations are taken from a latitude band spanning the area of the case study over a six hour assimilation cycle.

In addition, a comparison is made for a full day of operational bias statistics from the Met Office and ECMWF for 30 April 2007. The statistics are split into three latitude bands and represent all valid night time observations over the sea surface determined to be unaffected by cloud. This global comparison serves to reinforce the results of the case studies.

The operational processing of IASI data is described for the Met Office and ECMWF respectively in Hilton et al. (2008) and Collard et al (2008). Biases between IASI and the model forecast are calculated using the RTTOV radiative transfer model – RTTOV-7 at the Met Office (Saunders et al., 2002) and RTTOV-8 at ECMWF (Saunders et al., 2005). Both versions of RTTOV use coefficients derived from kCARTA (Strow et al., 1998) and there is not expected to be a difference in bias between the models.

3. Case study results

FAAM flight B290 on 30 April 2007 was conducted over the Gulf of Mexico, with a coincident MetOp overpass at 1529 UTC. Figure 1 below shows results from the strong water vapour band 1400-1800 cm^{-1} , where IASI observations are compared with line-by-line simulations.

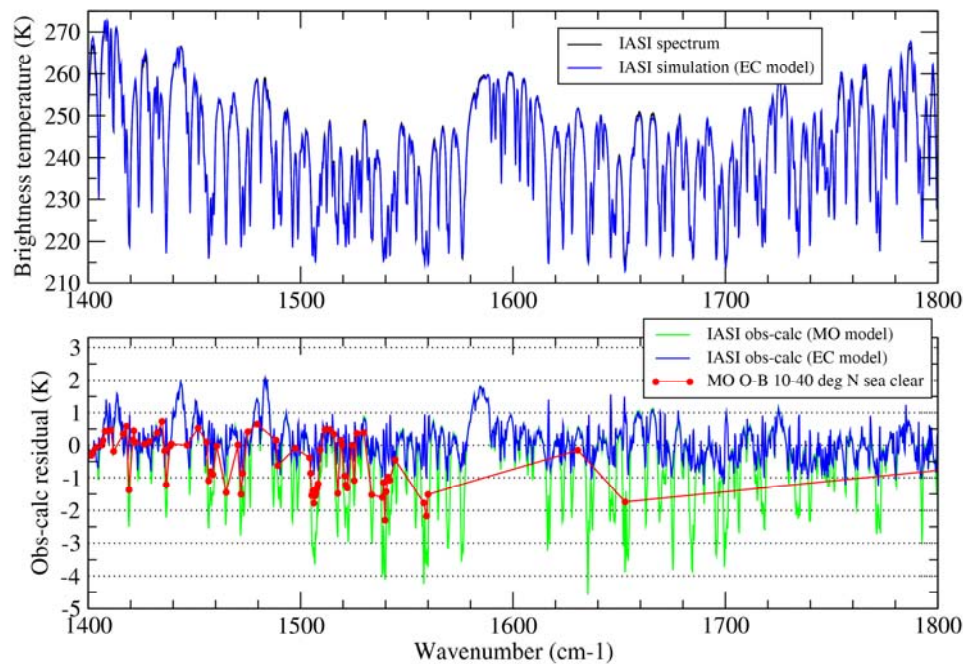


Figure 1: (Upper panel) IASI clear-sky brightness temperature spectrum recorded during JAIVEx flight B290, overlaid with simulation using ECMWF upper atmosphere fields. (Lower panel) residual differences (IASI observed – calculated GENLN2 spectrum) for both Met Office and ECMWF upper atmosphere fields, see legend. Overlaid as connected data points are Met Office operational observed – background biases for IASI data selected as clear over ocean between latitudes 10-40° N.

Comparisons for the averages of two sets of simulations are shown, where the upper atmosphere model field data comes respectively from the Met Office and ECMWF global NWP models. It is apparent that with ECMWF fields the residuals are limited to ± 1 K over much of the water vapour band. However, when Met Office fields are included in the simulation there are significant negative residuals, reaching -4 K at some frequencies. The latter is well matched by the observed-background (O-B) residual, generated from Met Office assimilated IASI fields of view over a much larger area (10-40° N clear sky over sea for 30 April 2007). The assimilated channels are limited to the channel selection for NWP described in Collard (2007).

Figure 2 below compares the average of the Met Office and ECMWF temperature and water vapour profiles, matched to the case study observations' location and time. The temperatures do not differ greatly, but the Met Office water vapour field exhibits a distinct dry bias relative to ECMWF, leading to the observed negative brightness temperature bias for IASI. Simulations combining ECMWF water vapour with Met Office temperature fields, and vice-

versa, (not shown) confirm that the water vapour profile differences are dominant in producing the differing radiance biases in the 1400-1800 cm^{-1} band.

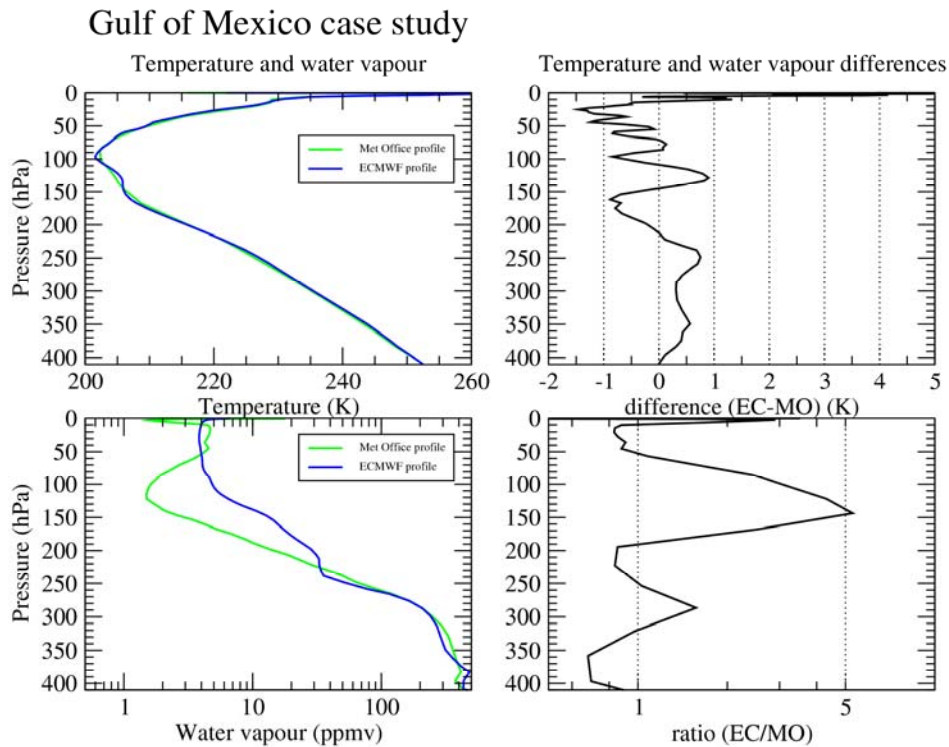


Figure 2: Comparison of temperature and water fields from JAIVEx on 30 April 2007. The left-hand panels compare the fields above 400 hPa, with the differences shown on the right.

Results for the mid-latitude UK flight on 12 December 2007 are shown in Figure 3. Here a slight positive bias for ECMWF fields is accompanied by a negative bias for Met Office fields. Once again the agreement between the latter and operational O-B biases for selected channels (and over a much wider geographic area) is striking.

Results for the Alaska case on 26 February 2008 are less clear-cut (Figure 4). The residuals for the Met Office and ECMWF fields do not differ greatly, with slightly negative residuals in both cases. However, the Met Office operational O-B bias remains consistent with that found for the case study.

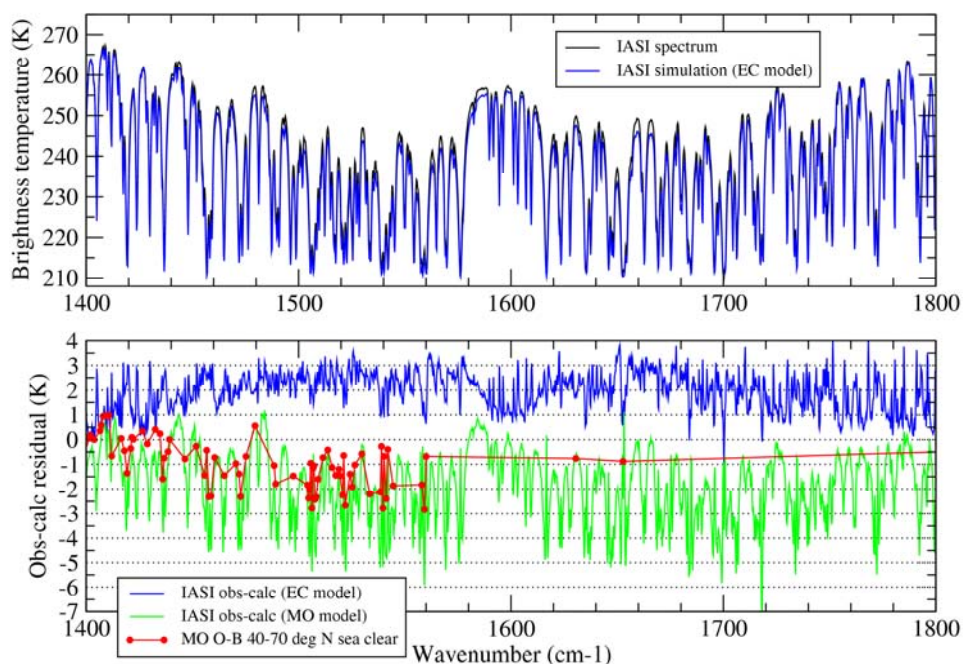


Figure 3: (Upper panel) IASI clear-sky brightness temperature spectrum recorded during flight B332, overlaid with simulation using ECMWF upper atmosphere fields. (Lower panel) residual differences (IASI observed – calculated GENLN2 spectrum) for both Met Office and ECMWF upper atmosphere fields, see legend. Overlaid as connected data points are Met Office operational observed – background biases for IASI data selected as clear over ocean between latitudes 40-70° N.

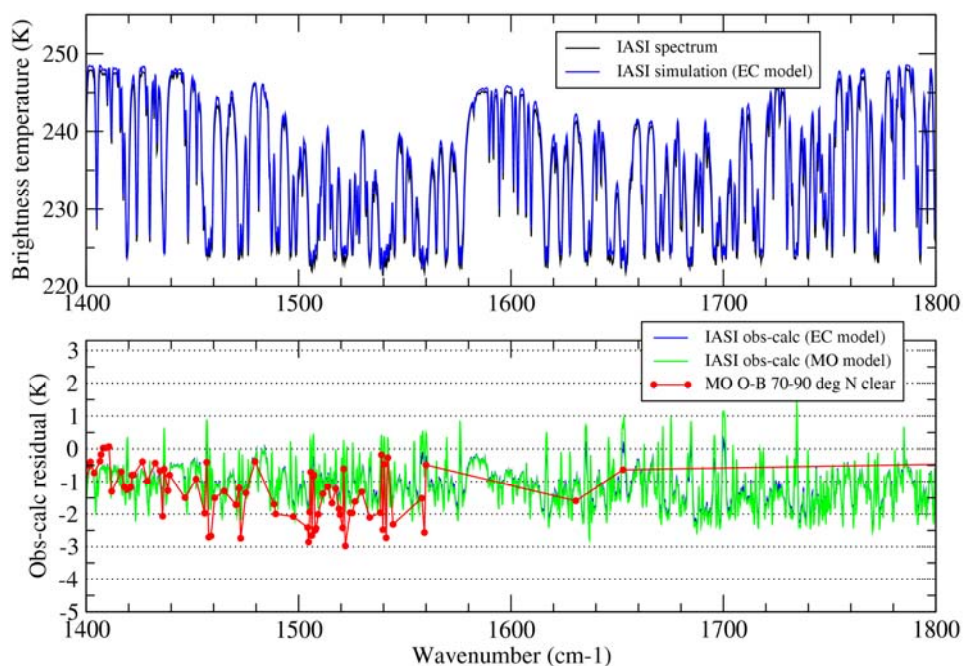


Figure 4: (Upper panel) IASI clear-sky brightness temperature spectrum recorded during flight B332, overlaid with simulation using ECMWF upper atmosphere fields. (Lower panel) residual differences for both Met Office and ECMWF upper atmosphere fields, see legend. Overlaid as connected data points are Met Office operational observed – background biases for IASI data selected as clear between latitudes 70-90° N.

A comparison of profiles from model fields for the mid-latitude and Alaska cases is shown in Figure 5. Although some details differ, there is broad agreement in all cases of a Met Office dry bias relative to ECMWF at the tropopause level (c.f. Figure 2).

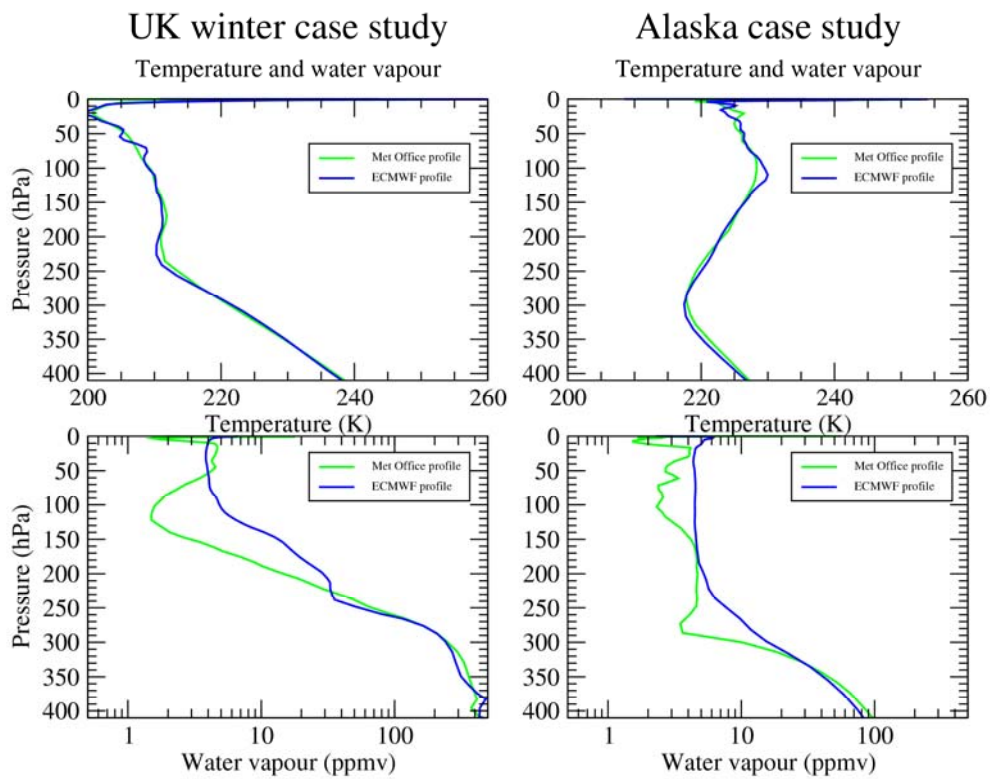


Figure 5: Comparison of temperature and water fields from cases on 12 December 2007 (UK winter) and 26 February 2008 (Alaska).

4. Assessment of whether case studies are representative

The case study results are remarkably consistent, given the wide variety of locations and different seasons covered by the three campaigns. The agreement of the bias found when using the Met Office fields for the upper atmosphere in the case studies, with the Met Office operational O-B statistics gives confidence that the results are representative over a wider area.

To confirm this, Figure 6 shows Met Office operational biases for a single channel sensitive to water vapour (channel 3168 at 1436.75 cm^{-1}) for 18 hours of data, and indicates that the JAIVEx case study area on 30 April 2007 is not atypical. The majority of global data points show a negative bias for the channel shown.

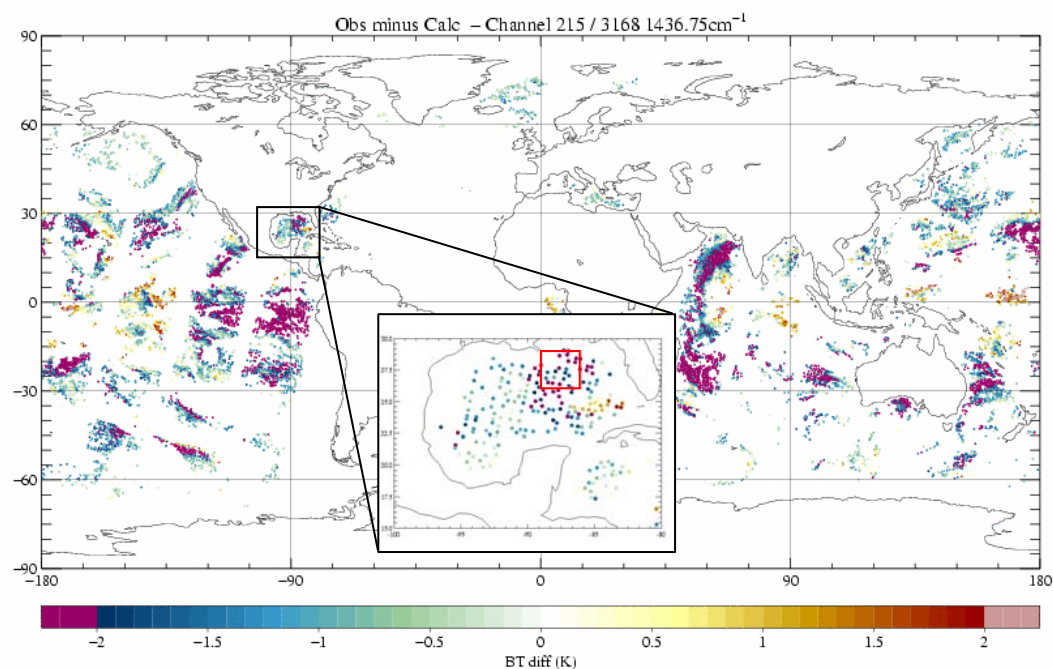


Figure 6: Global bias for IASI channel at 1436.75 cm^{-1} for the Met Office model (obs – calc) for 18 hours of data on 30 April 2007 (sea clear observations). The JAIVEx case study area is shown with a red box in the inset plot.

The difference between the operational bias statistics from the Met Office and ECMWF are also globally consistent. Figure 7 shows a comparison of Mean O-B values in the water vapour band between the Met Office and ECMWF for all valid clear, sea night-time observations on 30 April 2007. It is clear that the Met Office model has a large negative bias for high-peaking channels, and that this behaviour is seen for all latitude bands. The ECMWF bias is consistently slightly positive. Figures 6 and 7 therefore indicate that the negative radiance biases seen in the strong water vapour band are not restricted to the case study location.

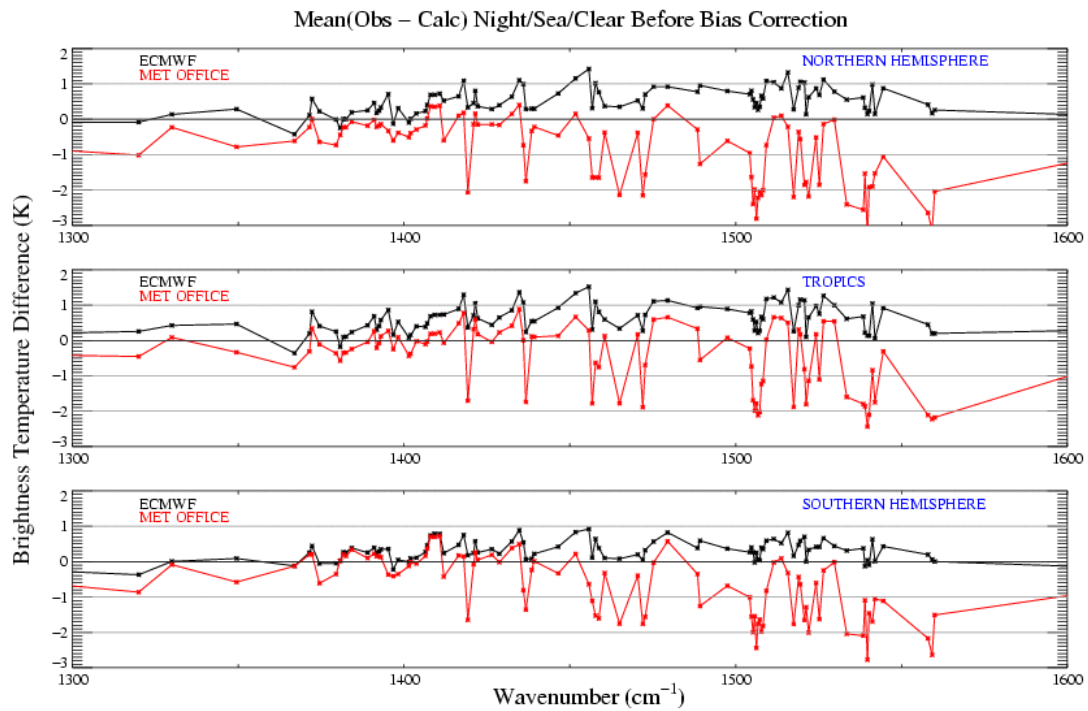


Figure 7: Observed – calculated biases for ECMWF and the Met Office for all clear, night-time, sea observations on 30 April 2007, showing strong water vapour band channels. The biases are discriminated by latitude (see legend).

5. Characteristics of channels showing largest biases

Typically the channels exhibiting the worst O-B biases are those closest to the centres of strong lines. The sensitivity of the strong water vapour lines to atmospheric water vapour can be seen by plotting Jacobians for selected channels, see Figure 9. These strongest lines are sensitive to water vapour throughout the stratosphere. Although assimilation of IASI data could help to correct the model bias, these channels cause problems for operational assimilation because a large model bias in the stratosphere leading to an observation-background difference can result in an erroneous humidity increment in the mid-troposphere.

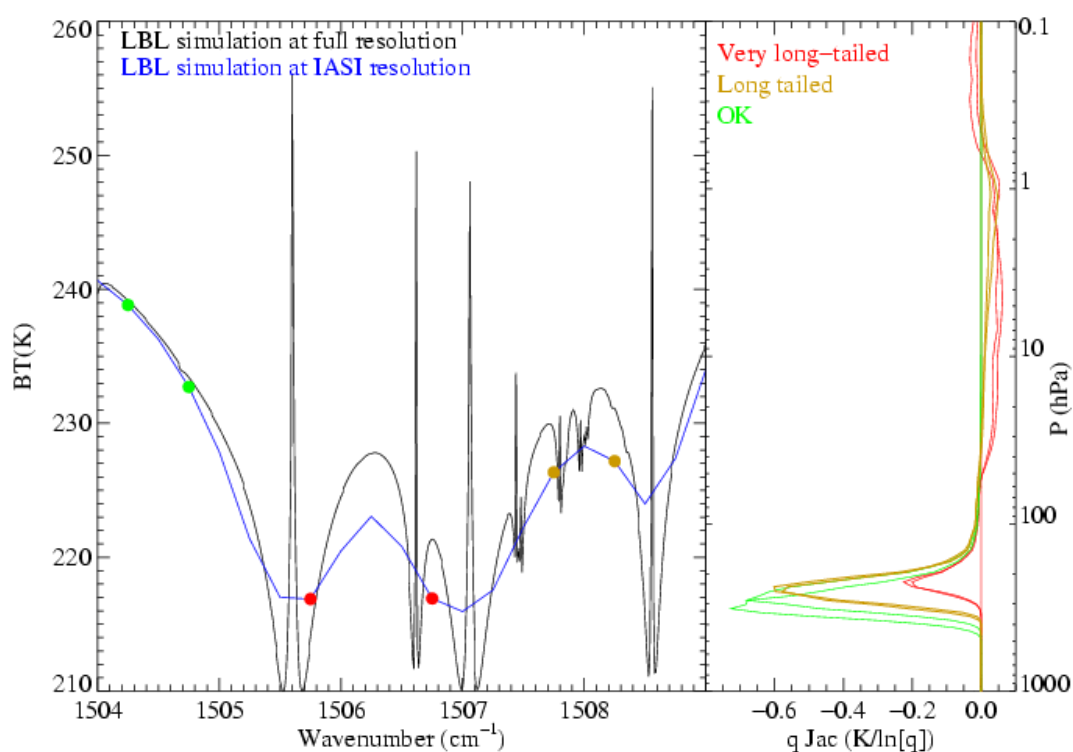


Figure 9: (Left panel) expanded section of water vapour band showing simulated brightness temperature at full resolution and at IASI resolution for JAIVEx case study. The coloured symbols refer to the Jacobian plot. (Right panel) RTTOV-7 Jacobians for six selected IASI channels, colour-coded as shown in the legend by sensitivity to water vapour above 100 hPa.

6. Assessment of model water vapour biases

The discrepancies between observed and calculated radiances in the strong water vapour band, when using Met Office model fields in the simulation, are indicative of a model bias in the treatment of water vapour. Comparing the model fields for April 2007 (Figure 8) it is clear that the Met Office Unified Model is extremely dry near the tropopause relative to ECMWF. Other monthly periods show similar behaviour.

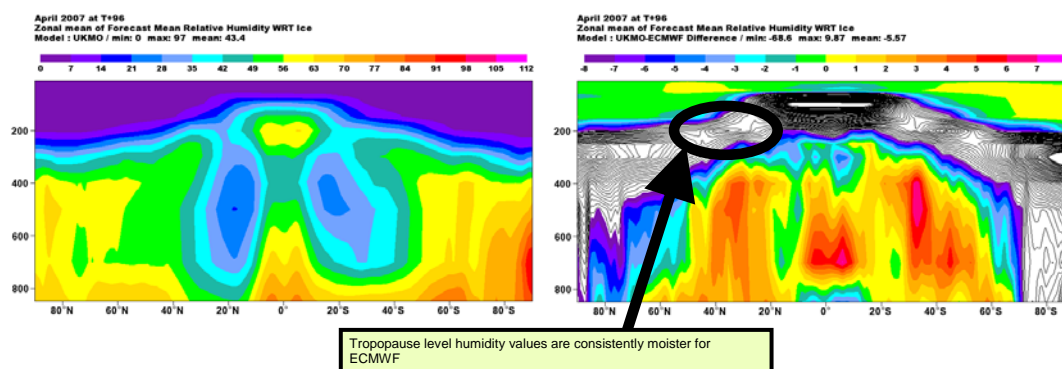


Figure 8: Zonal mean relative humidity field for April 2007. The left hand panel shows the Met Office field as a function of pressure, while the right hand panel show the difference (Met Office – ECMWF). The black contours at the tropopause level indicate a relative humidity difference more negative than –8%.

The reasons for the dry bias in the Met Office upper atmosphere are still under investigation. Climate runs of the Met Office unified model with no data assimilation which are allowed to relax towards climatology exhibit a smaller dry bias than the short-range forecasts and analyses (Sean Milton, 2008, pers. comm.) which is suggestive of the introduction of a bias at analysis time.

One possible contributory factor is that the data assimilation scheme constrains the stratospheric water vapour to be between 1 and 3 mg/kg. The stratosphere has a simple definition in the scheme, identified by a globally constant value of potential vorticity. This definition can lead to increments in the upper troposphere which tend to dry the model, particularly in the extra-tropics (David Jackson, 2008, pers. comm.).

Work is underway to investigate the impact of this constraint term on the analysis. In the longer term, a new project aims to address the upper-tropospheric/lower-stratospheric humidity increments by introducing a new moist control variable in 4D-Var which is normalised by the variance of the relative humidity at each model level.

7. Summary

Comparisons between IASI data and Met Office and ECMWF model profiles have helped to identify a large and as yet unresolved dry bias in the Met Office global model near the tropopause. This bias is present all year round and across all latitude ranges. In contrast, the ECMWF model tends to show a small moist bias. It is likely that this bias is introduced by the assimilation scheme. Work is now underway to understand the source of the bias and to correct for it. Verification of the model against observations such as IASI will play an important role in determining whether changes to the assimilation code have helped to improve the model forecast.

Acknowledgements

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