TECHNICAL MEMORANDUM

667

Evaluation of the microwave ocean surface emissivity model FASTEM-5 in the IFS

Niels Bormann, Alan Geer and Stephen English

Research Department

February 2012

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme

Series: ECMWF Technical Memoranda

A full list of ECMWF Publications can be found on our web site under:
http://www.ecmwf.int/publications/

Contact: library@ecmwf.int

European Centre for Medium-Range Weather Forecasts
Shinfield Park, Reading, RG2 9AX, England

Abstract

The latest version of FASTEM, the fast ocean surface emissivity model for microwave frequencies, is evaluated in the ECMWF system. The performance of FASTEM-5 is assessed through a comparison between observed and simulated brightness temperatures for a range of sensors, and the results are compared to similar characteristics for earlier versions of FASTEM.

FASTEM-5 shows significantly different bias characteristics compared to earlier versions. For the microwave imagers, the change in the foam cover parameterisation leads to an altered dependence of the biases on the 10m wind speed compared to FASTEM-4. At high 10m wind speeds, the behaviour is now closer to FASTEM-2, as expected from reverting the change to the foam cover model. For low wind speeds, the behaviour is similar to FASTEM-4 for vertically polarised channels, and similar to FASTEM-2 for horizontally polarised channels. At high wind-speeds, standard deviations of First-Guess departures suggest a small benefit from using FASTEM-4 rather than FASTEM-5, but overall the results do not clearly favour one parameterisation over the other. For the microwave sounders, FASTEM-5 leads to an overall reduction of biases compared to FASTEM-3 or -4, with a smaller dependence on the 10m wind speed. The impact on departure statistics is primarily confined to the window channels which are not assimilated in the ECMWF system, but used for quality control of the sounding channels. For these channels, a positive bias in terms of brightness temperatures remains.

The variational bias correction successfully removes the differences in the bias characteristics, leaving bias-corrected departure characteristics that are not significantly different with FASTEM-5 or FASTEM-4. The forecast impact of the move from FASTEM-4 to FASTEM-5 is neutral overall.

1 Introduction

This memorandum evaluates version 5 of the fast ocean surface emissivity model FASTEM (Liu et al. 2012) in ECMWF's data assimilation system. We will investigate the impact of FASTEM-5 on departure statistics between observed and simulated brightness temperatures, and compare the results with those obtained with earlier FASTEM versions, namely versions 2, 3, and 4.

The evolution of FASTEM and the differences between the versions considered here can be summarised as follows:

- FASTEM-1 calculated an effective surface emissivity, based on a fast fit to emissivities calculated from a geometric optics (GO) model. Foam cover was modelled as a function of 10m wind speed following Monahan and O'Muircheartaigh (1986). More details can be found in English and Hewison (1998).
- FASTEM-2 (Deblonde and English 2001) added a correction to the reflectivities, dependent on the surface-to-space transmittance. The fitting coefficients used the same underlying GO model as in FASTEM-1, but with a more sophisticated parameterisation.
- FASTEM-3 added a parameterization for the azimuthal variation of emissivity, and is otherwise identical to FASTEM-2.
- FASTEM-4 (Liu et al. 2011) provided a number of updates, including a new permittivity parameterisation, an altered foam cover model Tang (1974), an improved roughness parameterisation based on a two-scale emissivity model. In a two-scale model waves with length scales large compared to the wavelength of the observations are still treated using GO, but small-scale waves are assumed to modify the emissivity of each large-scale facet in the GO calculation based on scattering theory. FASTEM-4 was included in the RTTOV-10 release, as evaluated in Bormann et al. (2011).

- FASTEM-5 is a modified version of FASTEM-4. The change to the foam cover parameterisation introduced in FASTEM-4 is reverted from Tang (1974) to the model of Monahan and O'Muircheartaigh (1986) used in earlier FASTEM versions. Also, the regressions for the reflectance parameterisations are now constrained to give the same emissivity for vertical and horizontal polarisations at nadir. Furthermore, to reduce the fitting error, the user has the option to use a look-up-table for the large-scale correction part rather than the previously applied regressions. Further details on FASTEM-5 can be found in Liu et al. (2012).

2 Comparison of departure characteristics

In the following we will evaluate the impact of FASTEM-5 on observation departure statistics, that is on differences between observed and simulated brightness temperatures. The simulations are performed within ECMWF's data assimilation system from short-term forecasts using the fast radiative transfer model RTTOV-10 (Bormann et al. 2011). The statistics are derived over the period 5-25 July 2010 (unless indicated otherwise), with the short-term forecasts originating from a T511 ($\approx$ 40 km), 91 levels setup of the IFS. Different versions of FASTEM will be evaluated using the same short term forecasts, so there is no interaction between the different FASTEM versions and the data assimilation.

2.1 Microwave imagers

We first evaluate FASTEM-5 for the microwave imagers used in the ECMWF system. Microwave imagers such as TMI, AMSR-E, and SSMIS are assimilated through the all-sky route, that is they are used in cloudy/rainy as well as clear conditions. In this route, observations are averaged to a T255 Gaussian grid representation, and our statistics will be based on these super-obbed observations. As azimuth infor-

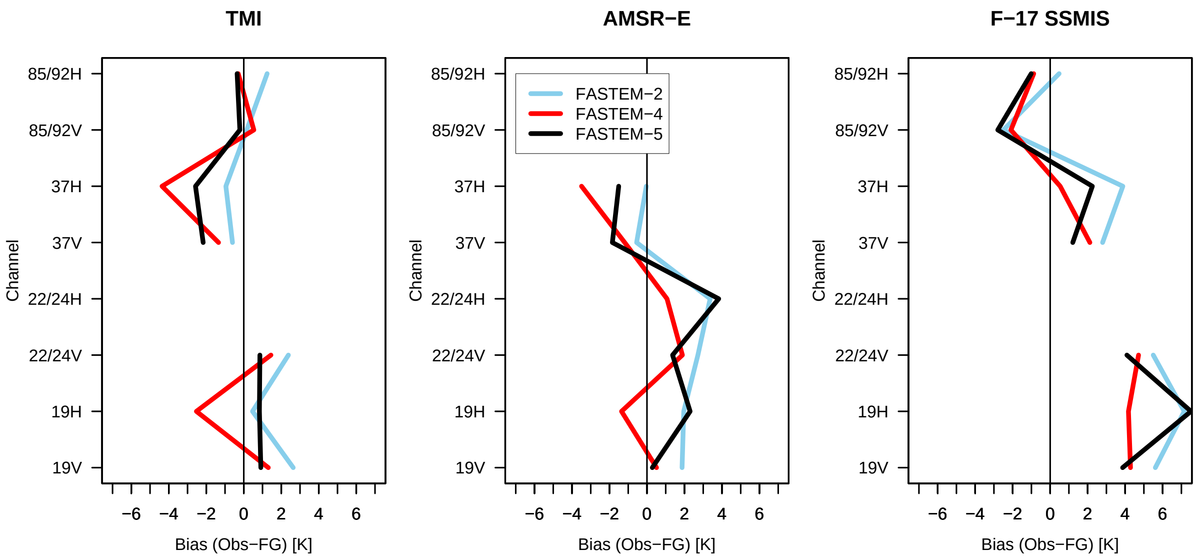

Figure 1: Mean biases (observation minus FG) for different FASTEM versions for the three microwave imagers considered here: TMI (left), AMSR-E (middle), and the F-17 SSMIS (right). Data are for a quality-controlled sub-sample for the period 5-31 January 2011.

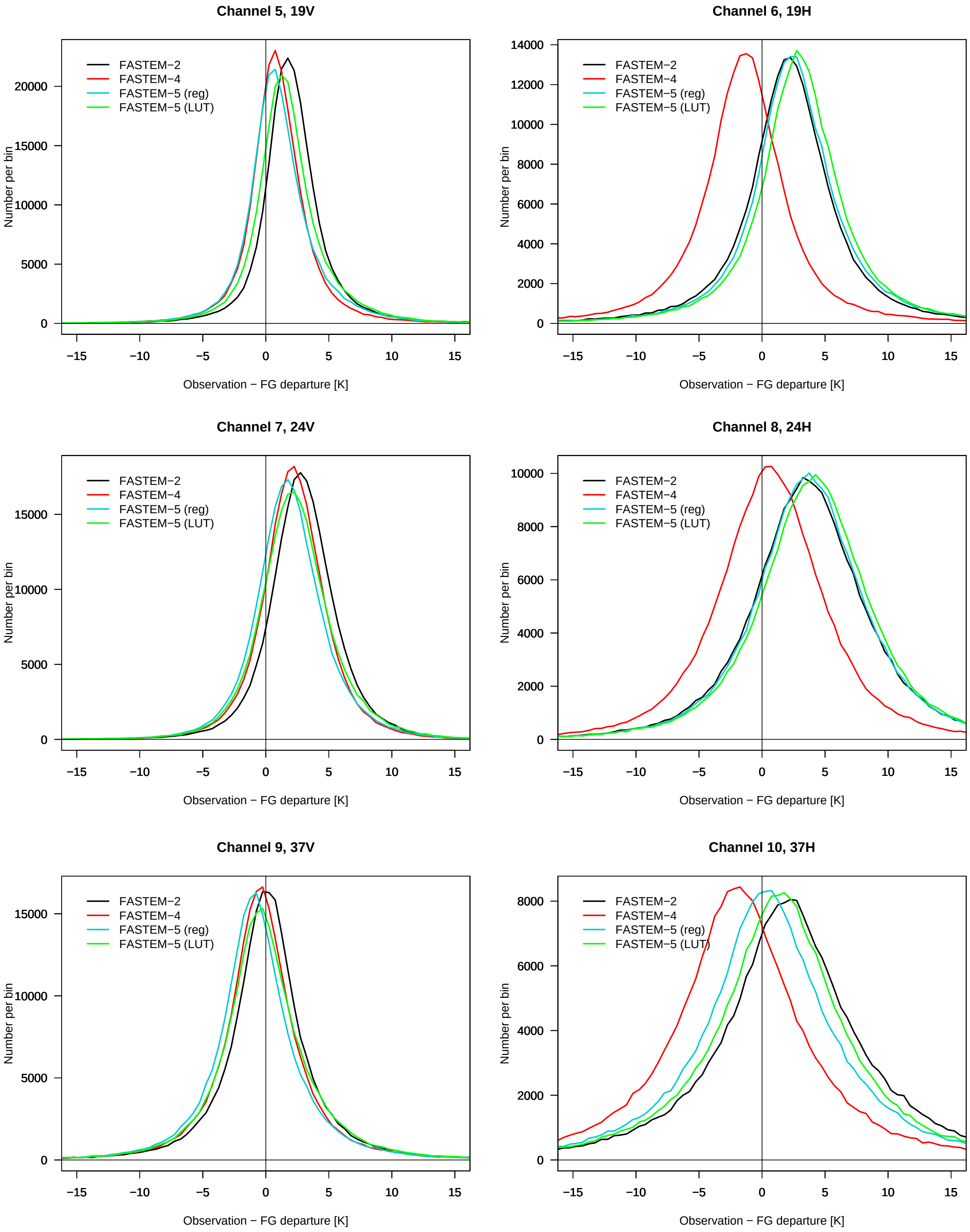

Figure 2: Histograms of FG departures before bias correction for AMSR-E channels 5-10 for different versions of FASTEM for all observations over sea over the period 5-25 July 2010. The versions shown are FASTEM-2 (black), FASTEM-4 (red), FASTEM-5 using regressions (blue) and FASTEM-5 using the LUT approach (green).

mation is not provided with the data for some of these sensors, the azimuthal component to the emissivity modelling is neglected. We will compare the performance of FASTEM-2, -4, and -5.

Mean biases for FASTEM-2, -4, and -5 for TMI, AMSR-E, and SSMIS are shown in Fig. 1. Several points are worth noting: firstly, there are considerable inter-instrument biases, and these biases are comparable to or larger than the differences between the biases in the different versions of FASTEM. This is a reflection of short-comings in the absolute calibration of these instruments. It means that it is difficult to say which version performs best, as one version might lead to smaller absolute biases for one channel on one instrument, but larger absolute biases for another. Secondly, the largest differences occur for the horizontally polarised channels which are most sensitive to the surface emissivity. For these channels, FASTEM-4 leads to significantly warmer brightness temperatures compared to FASTEM-2 or -5.

In the following, we will give a more detailed characterisation of the departure statistics, based on statistics for the AMSR-E instrument. While the instrument has now failed, its biases usually were between those of SSMIS and TMI (cf Fig. 1).

Figure 2 shows histograms of FG-departures for the AMSR-E instrument. They highlight how FASTEM-4 shows departures for the horizontally polarised channels that are notably different from those of the other versions. For channels 6 and 8 (19H and 24H, respectively) this means the peaks of the histograms are closest to zero for FASTEM-4. However, as shown in Fig. 1 this would not be the case for TMI. For the vertically polarised channels the differences between the versions are not as striking. Interestingly, the histograms suggest considerable differences between the regression and LUT-based versions of FASTEM-5, with differences between the two comparable to the differences between FASTEM-5 and FASTEM-2.

The change to the parameterisation of the foam cover in FASTEM-5 is expected to lead to a behaviour at high 10m wind speeds that is similar to that of FASTEM-2 for the microwave imager channels. Figure 3 shows that this is indeed the case. Whereas FASTEM-4 showed increasingly negative biases at high wind speeds, FASTEM-5 exhibits the considerably positive biases previously seen in FASTEM-2. Without an evaluation of the biases in the ECMWF 10 m wind speed it is difficult to say which bias behaviour is preferable; note that showing these characteristics as a function of the model wind speed introduces a negative sampling bias, providing a possible explanation of the negative biases see with FASTEM-4. The reversal of the foam cover model also means that the improvements in the standard deviations at high wind speeds for FASTEM-4 are not present for FASTEM-5 (Fig. 3). From this evaluation, the case for the reversal of the foam cover parameterisation is thus not clear. It appears that the model of Monahan and O'Muircheartaigh (1986) may under-estimate the foam cover or its variability for some conditions. Parameterisations for foam cover as a function of 10m wind speed show large spread (e.g., Anguelova et al. 2009), suggesting considerable uncertainty in this area. Furthermore, the parameterisation of foam cover as a function of 10m wind speed alone is rather simplistic, and in reality the foam cover will depend on a variety of factors, including the past evolution of the state of the ocean surface (Anguelova and Webster 2006; Jansen 2011, pers. communication). A more complex modelling of the foam cover used in FASTEM may well be beneficial.

For low 10m wind speeds, FASTEM-5 follows broadly the behaviour of FASTEM-4 for the vertically polarised channels and that of FASTEM-2 for the horizontally polarised channels (Fig. 3). This is likely the result of the combination of using an improved roughness model for the parameterisation of roughness effects in FASTEM-4 and -5 and the additional constraints imposed on the regressions in FASTEM-5.

FASTEM-5 allows the use of a LUT for the large-scale correction instead of the regression approach used in other FASTEM versions, and this has some effect on the wind-speed dependence of the bias characteristics (Fig. 4). As noted earlier, the differences between the biases for the regression-based model and

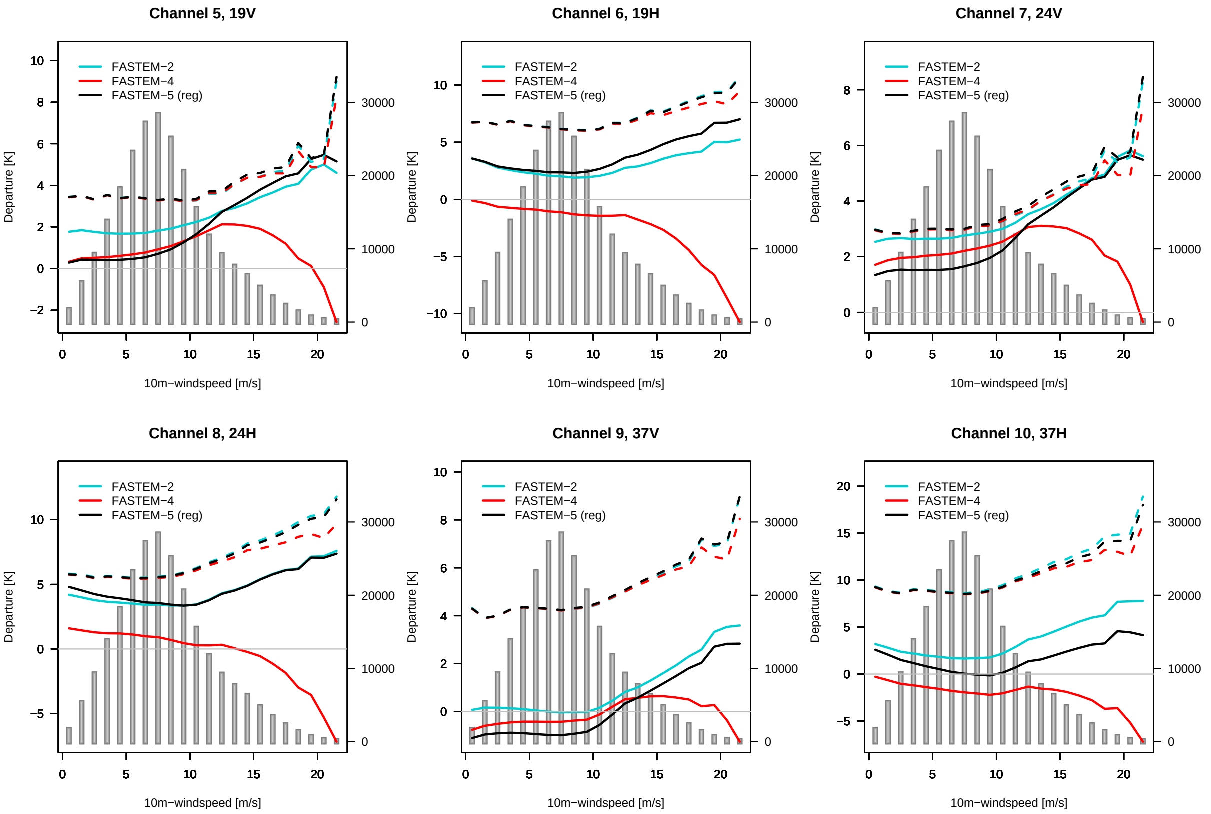

Figure 3: First Guess departure statistics before bias correction for AMSR-E channels 5-10 as a function of the model's 10m wind speed, calculated for the period 5-25 July 2010 and based on all observations over sea. Results obtained with FASTEM-2 are shown in cyan, FASTEM-4 in red and the regression-based FASTEM-5 in black, respectively. Biases (Obs - FG) are displayed in solid lines, standard deviations with dashed lines. Also shown in grey is the population of data considered in the statistics as grey bars (right-hand x-axis).

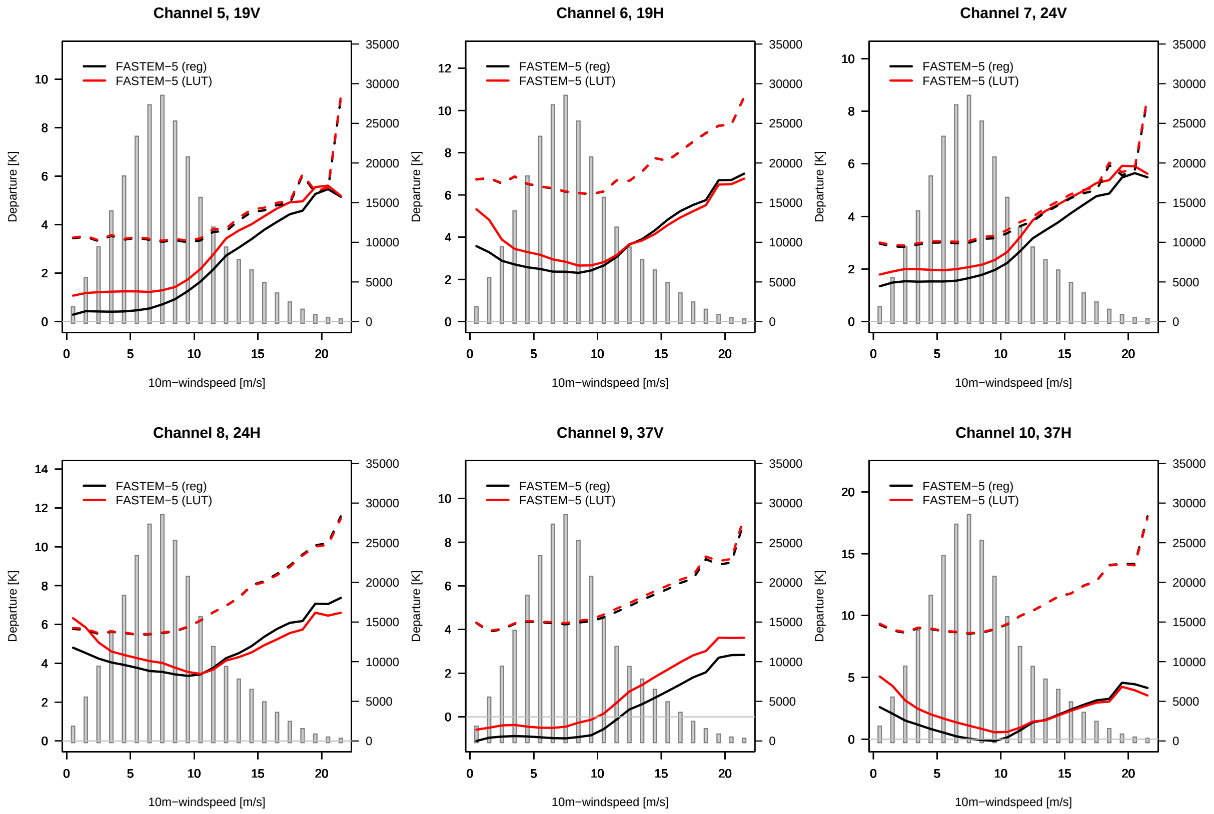

Figure 4: As Fig. 3, but for the regression based version of FASTEM-5 (black) and the LUT-based version of FASTEM-5 (red).

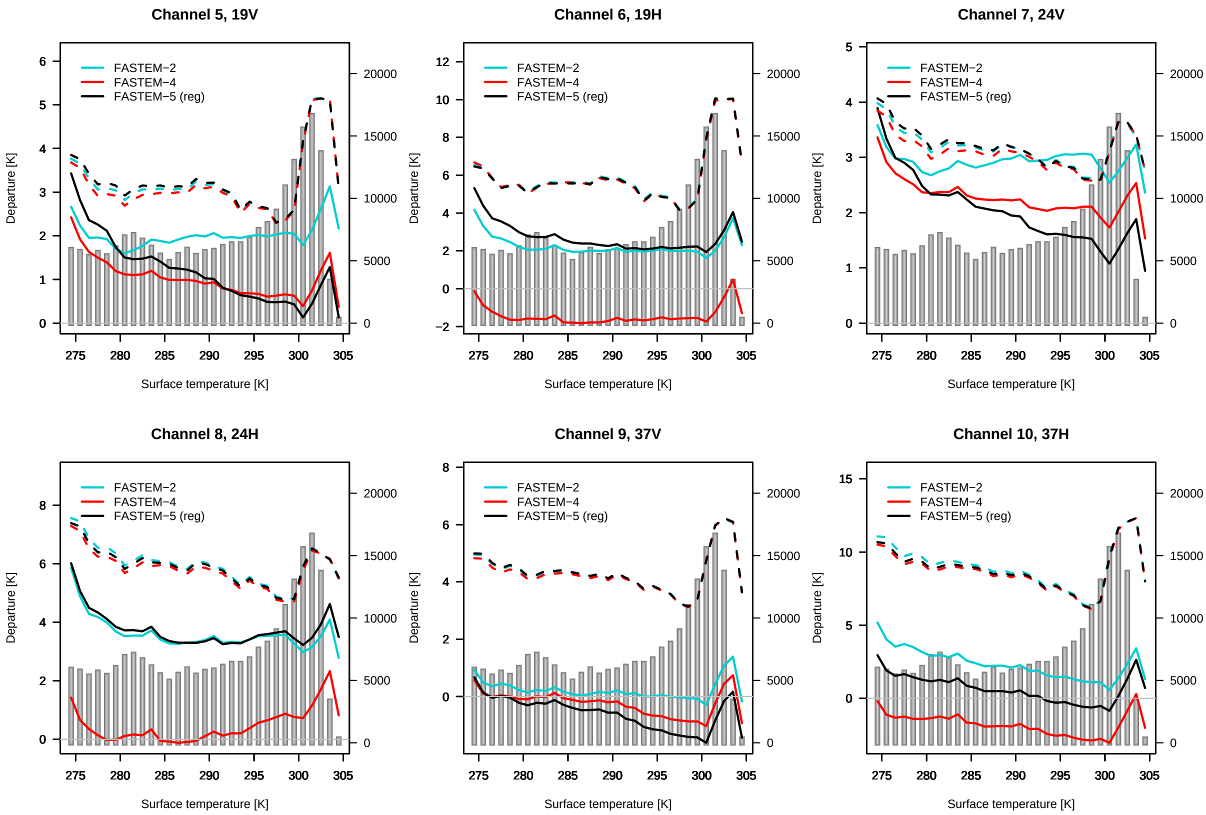

Figure 5: As Fig. 3, but for departure statistics as a function of surface temperature.

the LUT-based version are in places comparable to those between FASTEM-2 and the regression-based FASTEM-5, and a weak wind-speed dependence is apparent for the horizontally polarised channels.

Figure 5 shows the dependence of departure statistics on the surface temperature for the different FASTEM versions for AMSR-E. The Figure again shows that biases with FASTEM-5 broadly follow those with FASTEM-4 for vertically polarised channels and those with FASTEM-2 for horizontally polarised channels. For the vertically polarised channels, the bias with FASTEM-5 shows a somewhat stronger slope than that of FASTEM-4, the reasons of which are yet unclear.

2.2 Microwave sounders

We will now evaluate the impact of FASTEM-5 on departure statistics for the microwave sounders AMSU-A and MHS. These instruments are currently monitored and assimilated at ECMWF in a framework that assumes clear-sky conditions in the radiative transfer calculations.

FASTEM-5 leads to a significantly different wind-speed dependence compared to FASTEM-3 for the 50-89 GHz channels of AMSU-A (cf Fig. 7). For high 10m wind speeds, FASTEM-5 leads to brightness temperatures that are significantly warmer compared to FASTEM-3 for channels 3, 4, and 15, and the results are more similar to FASTEM-4 in this regard (cf Fig. 7). This behaviour is the opposite of that observed for the 19-37 GHz channels of the microwave imagers, and is likely related to the modifications to the roughness parameterisation in FASTEM-5. Low wind speeds also show a considerable warming in terms of brightness temperatures from using FASTEM-5 compared to FASTEM-3, of the order of 1-2 K for nadir as well as off-nadir viewing. For nadir-viewing, this is in contrast to the behviour with FASTEM-4 which showed little or no change for low wind speeds compared to FASTEM-3.

Due to the altered wind speed dependence, clear-sky brightness temperatures simulated with FASTEM-5 compare more favourably with observations than those simulated with FASTEM-4 or FASTEM-3, especially for channels 3 and 15 for nadir-viewing (cf Figures 8 to 10). In these comparisons, the mode of the FG-departure histograms is a better indicator of the true bias than the mean, as they are based on observations in clear as well as cloudy conditions, but only employ clear-sky simulations. Cloud contamination will therefore show up as positive biases. The mode is closer to zero with FASTEM-5, with, for instance, values of around 2 K for channel 3. While this channel is not currently assimilated in the ECMWF system, a check on bias-corrected FG departures for this channel is used to screen out cloud affected data over sea. Hence the changes are nevertheless of some relevance to the assimilation of AMSU-A data. It is worth pointing out that some positive bias still appears to exist, but the reduction

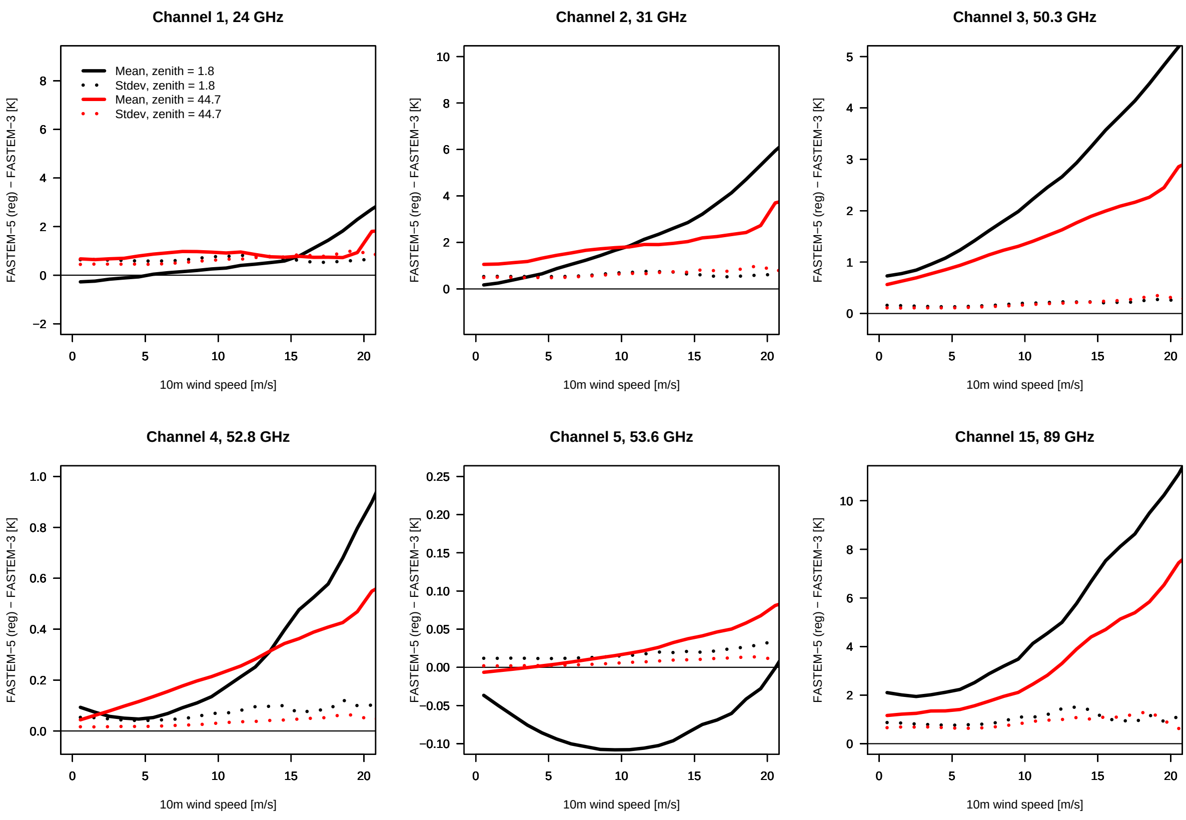

Figure 6: Differences between clear-sky brightness temperatures simulated with the regression-based FASTEM-5 and with FASTEM-3 for AMSU-A channels with sufficient sensitivity to the surface. The statistics are shown in terms of the mean difference (solid line) and the standard deviation (dotted line) as a function of the 10m wind speed used in the simulations. Black lines give statistics for scan positions 15 and 16 (ie close to nadir), whereas red lines show statistics for scan positions 4 and 27 (zenith angle around 44.7°). The latter are the outermost scan positions currently considered for assimilation. The statistics are based on just under 50,000 simulations over sea, and the input data for the two simulations was the same.

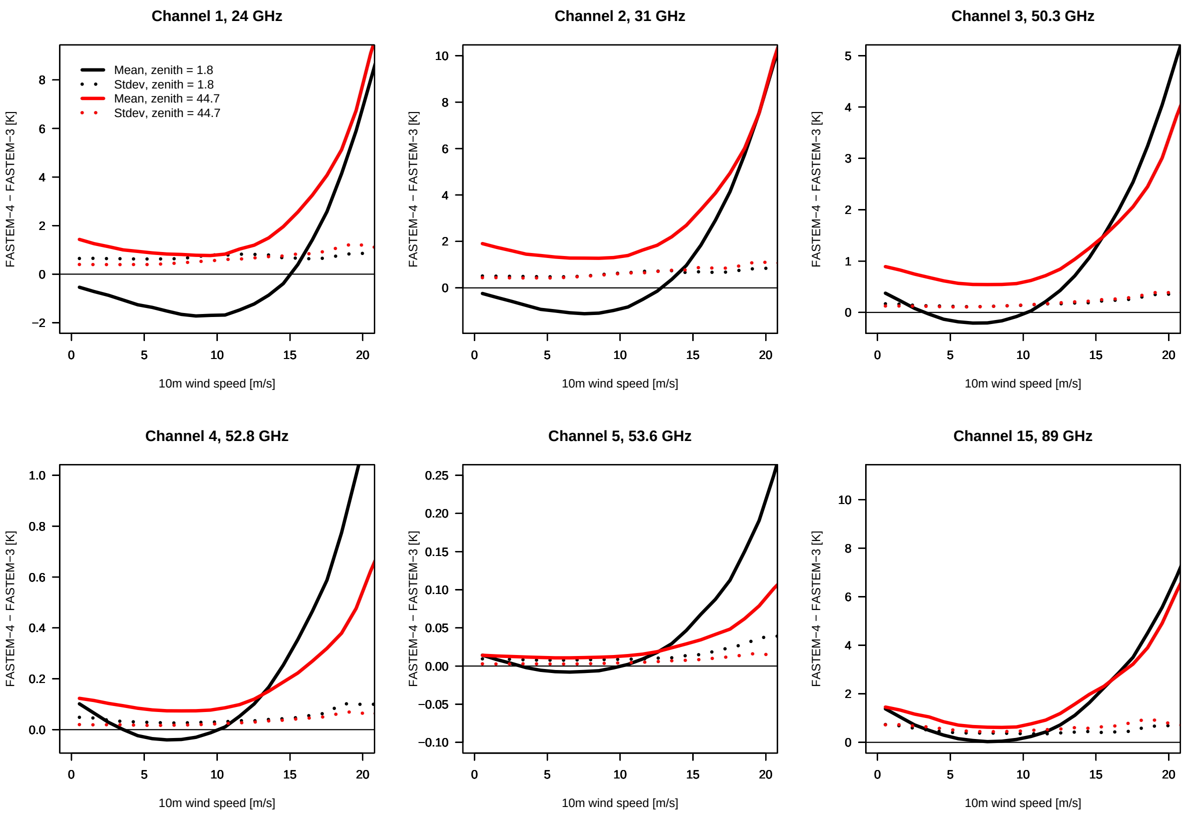

Figure 7: As Fig. 6, but for differences between clear-sky brightness temperatures simulated with FASTEM-4 and with FASTEM-3.

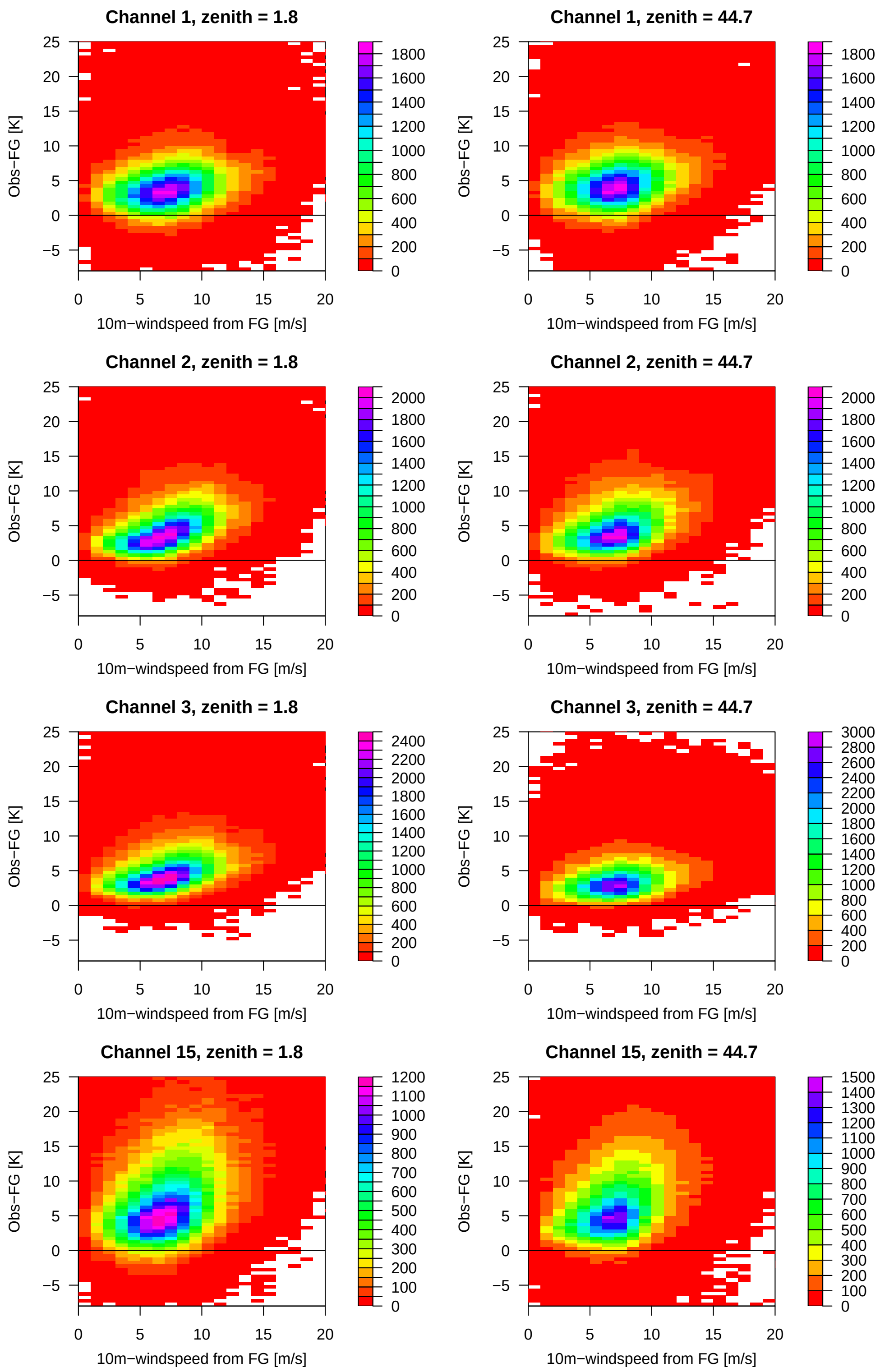

Figure 8: Two-dimensional histograms of the differences between observed and simulated brightness temperatures before bias correction for the window channels of NOAA-18 AMSU-A as a function of the 10m wind speed taken from the FG. The data is for the period 5-25 July 2010, over sea within +- 60°latitude, showing all data before quality control and thinning, and the microwave emissivity model is FASTEM-3. The left column shows data for the central scan positions (zenith angle around 1.8°), whereas the right column shows results for the outermost scan positions considered for assimilation at ECMWF (zenith angle around 44.7°).

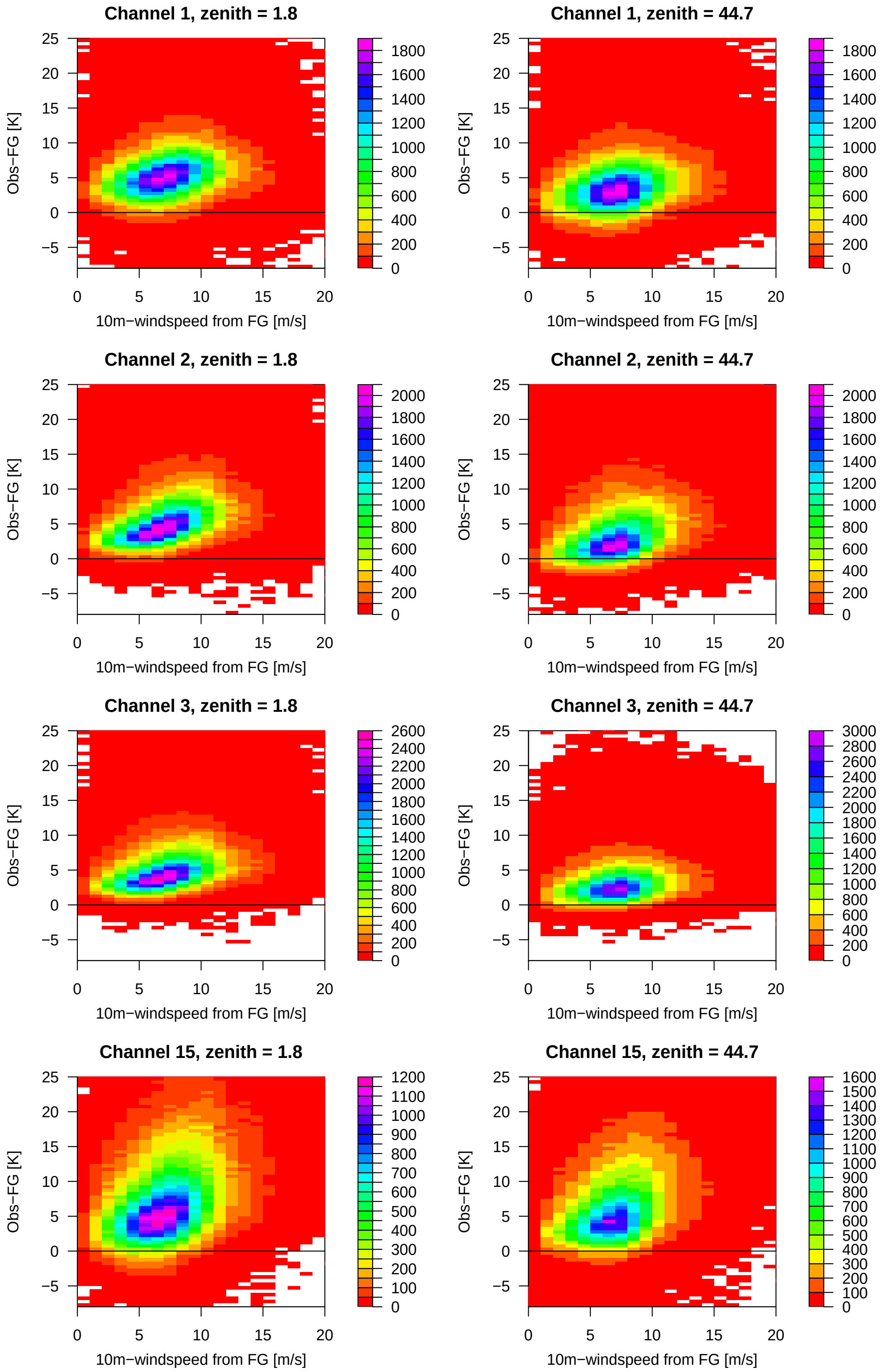

Figure 9: As Fig. 8, but for FASTEM-4.

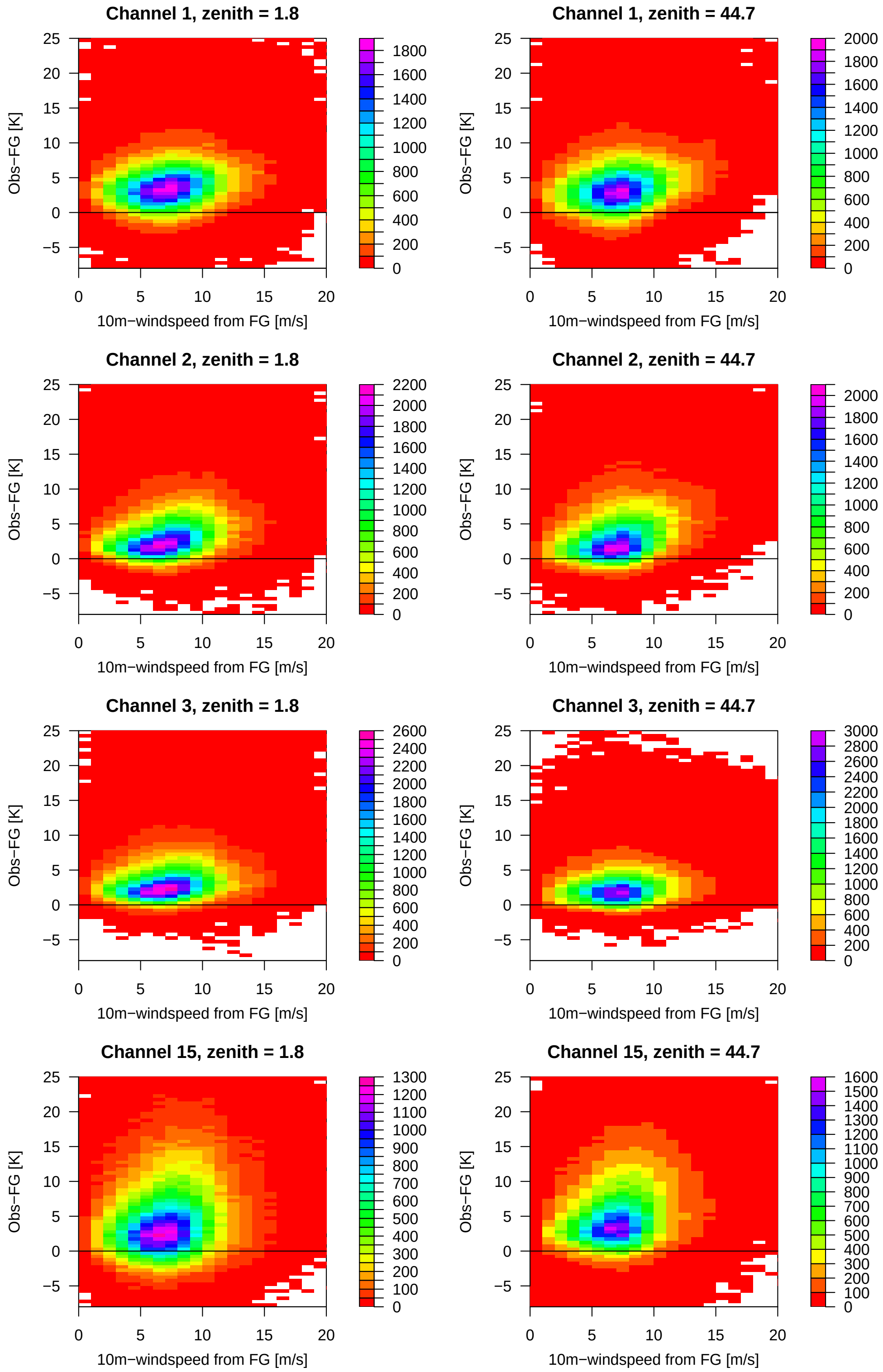

Figure 10: As Fig. 8, but for the regression-based FASTEM-5.

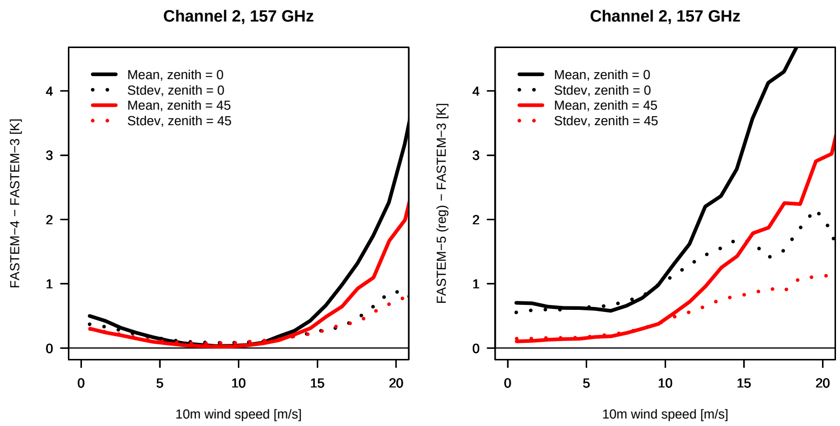

Figure 11: As Fig. 6, but for the difference between FASTEM-4 and FASTEM-3 on the left, and between the regression-based FASTEM-5 and FASTEM-3 on the right. Simulations are based on approximately 15,000 profiles.

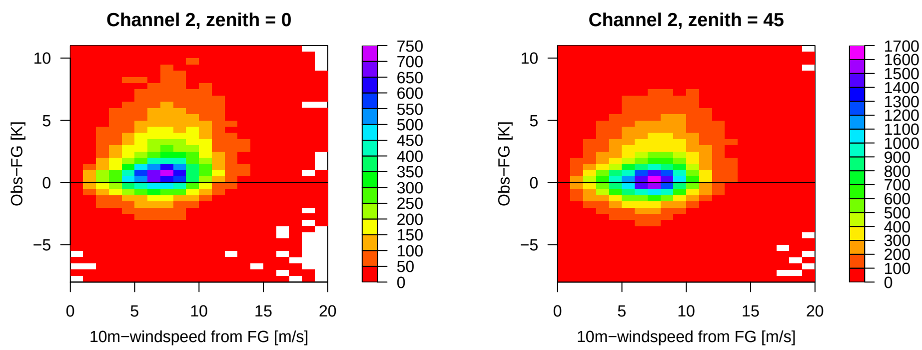

Figure 12: As Fig. 8, but for departures for channel 2 of the METOP-A MHS obtained with the regression-based FASTEM-5.

of the bias by roughly 1 K compared to FASTEM-3 is considered a positive aspect of FASTEM-5.

For AMSU-A, the differences between the regression-based version of FASTEM-5 and the LUT-based one are relatively small compared to the size of typical FG-departures or the differences between different versions of FASTEM, and are hence not shown here.

For MHS, significant differences are noticeable only for channels 1 and 2. Channel 1, the 89 GHz channel, behaves as the equivalent channel 15 on AMSU-A. For channel 2 at 157 GHz, the move from FASTEM-4 to FASTEM-5 again affects primarily the biases for the near-nadir viewing geometry, where FASTEM-5 leads to significantly warmer simulated brightness temperatures (Fig. 11). For high wind speeds, the simulated brightness temperatures are warmer by serveral Kelvin for both FASTEM-5 and FASTEM-4 compared to FASTEM-3. Overall, these changes act to reduce a positive bias between observed and simulated brightness temperatures for this channel, and now this bias is more constant with the 10m wind speed (Fig. 12). The channel is not actively assimilated in the ECMWF system, but its departures are used to screen for strong cloud contamination in the sounding channels, so the bias changes will affect the quality control for MHS data.

3 Impact in assimilation experiments

We will now discuss the impact of using the regression-based FASTEM-5 in data assimilation experiments. We chose the regression-based FASTEM-5 version here, as LUT-approaches can lead to discontinuities that are undesireable in tangent-linear or adjoint models. Also, the above analysis did not show any clear benefit from using the LUT-approach.

3.1 Experiments

The forecast impact of using FASTEM-5 is investigated through assimilation experiments over two seasons, using ECMWF's 12-hour 4DVAR system at a horizontal resolution of T511 ($\approx$ 40 km), with an incremental analysis resolution of T255 ($\approx$ 80 km) and 91 levels in the vertical. The experimentation is based on cycle 37R3, as implemented operationally at ECMWF in November 2011. The experiments make use of the full set of observations assimilated operationally. The periods covered are 1 January - 2 March 2011 and 1 June - 4 August 2011 (total of 126 days), and 10-day forecasts were performed for each 0Z cycle. The FASTEM-5 experiment is compared to a control experiment that uses FASTEM-4 as included in cycle 37r3 of ECMWF's assimilation system.

During the assimilation, observational biases are corrected using variational bias correction (e.g., Dee 2004). This will act to reduce the impact of the different biases seen as a result of using different versions of FASTEM. The sounding and the imaging instruments employ different bias correction models in the variational bias correction. The sounding instruments use a linear model with a global constant and four layer thicknesses as airmass predictors. Scan-biases are modelled through a 3rd order polynomial in the scan position. The model is modified to exclude the airmass predictors for the window channels used for quality control, and to allow a different global offset and scan-bias over land for channels 4 and 5 of AMSU-A. In contrast, the microwave imaging instruments/channels use a linear model with a global constant and the model's surface temperature, total column water vapour, and 10m wind speed as predictors. Scan-biases are again modelled through a polynomial in the scan position.

3.2 Analysis impact

For the microwave imagers, the variational bias correction is able to largely compensate for the bias differences discussed earlier, leaving departure statistics after bias correction that, on average, have only small changes between the FASTEM-5 and the FASTEM-4 experiment (Fig. 13). Mean bias corrections reflect the different bias characteristics discussed earlier, and it depends on the instrument and channel whether the bias corrections are smaller or larger in absolute terms with FASTEM-4 or FASTEM-5. Overall, FASTEM-5 tends to give smaller absolute bias corrections for TMI, especially for the 19H and 37H channels, whereas FASTEM-4 tends to produce smaller biases for these channels for SSMIS. As mentioned earlier, these differences are mainly due to the absolute accuracy of the calibration of the instruments. Note that over the tropics, the standard deviations of the bias corrections tend to be larger with FASTEM-5, suggesting that the biases show additional geographical variability. This is less apparent for the extra-tropics. After bias correction, there is a small increase in the standard deviations for the 19 GHz channels, and there are small changes in the number of used observations as a result of altered quality control decissions.

For AMSU-A, the main impact of the change to FASTEM-5 on assimilated channels is through the altered quality control. A check on bias-corrected departures for channel 3 is used to screen for strong

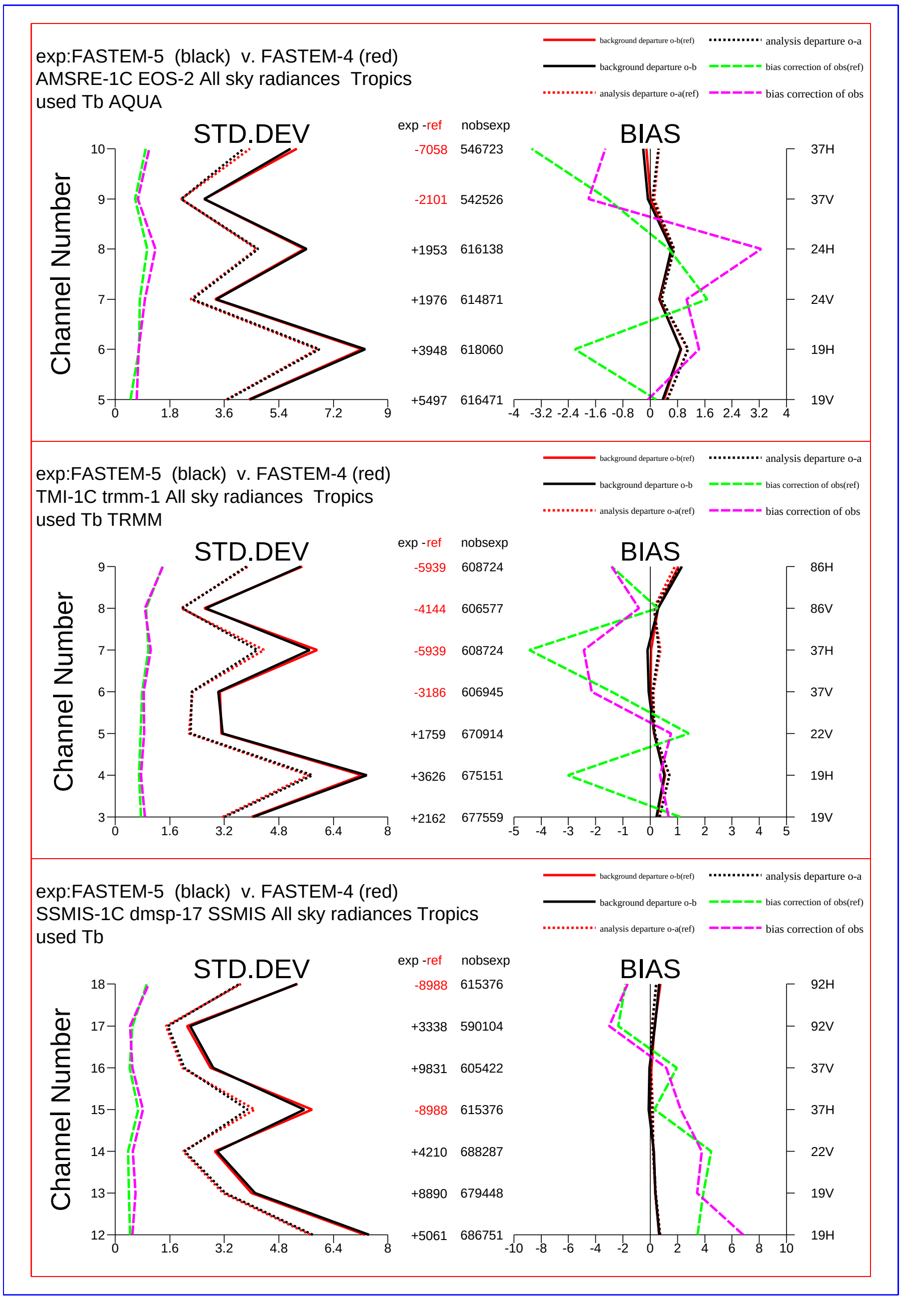

Figure 13: Departure statistics for microwave imager radiances over the tropics for the period 1 January - 2 March 2011 for AMSR-E (top), TMI (middle), and SSMIS on F-17 (bottom). Statistics for the FASTEM-5 experiment are shown in black, whereas statistics for the FASTEM-4 experiment are shown in red, with solid lines showing FG-departure statistics (observation minus FG) and dotted lines analysis departure statistics. Bias corrections are also shown, for the FASTEM-5 experiment in magenta and for the FASTEM-4 experiment in green. The number of observations for the FASTEM-5 experiment are given in the middle, including the difference between the FASTEM-5 and the FASTEM-4 experiment. The statistics are based on used observations; note that some channels are shown as used here, but effectively carry no weight in the assimilation due to very large observation errors (channel 10 for AMSR-E, 7 and 9 for TMI, and 15 and 18 for SSMIS).

cloud contamination. The differences in the bias characteristics for FASTEM-5 compared to FASTEM-4 for channel 3, particularly in slow 10m wind speed regions, mean that more lower tropospheric channels are now diagnosed as cloud-free. This leads to an increase of assimilated AMSU-A observations for these channels of up to 2 % over the Southern Hemisphere. Otherwise, after bias correction, there is little change in the departure statistics for the assimilated channels.

Similarly, the assimilation of MHS data is also primarily affected through the change in quality control, as FG-departures of channel 2 are used to screed for strong cloud contamination. This leads to an increase in the number of assimilated MHS observations of around 3 % over the Southern Hemisphere, especially in high wind speed regions. A marginal reduction in the standard deviation of FG-departures after bias correction can be reported for channel 4 over the extra-tropics, but otherwise the overall characteristics of the departures are unchanged (not shown).

For other assimilated observations, there is no significant impact on the departure statistics, suggesting no significant change to the quality of the First Guess or the analysis. Similarly, there are no significant changes to the mean analyses for the two seasons considered.

3.3 Forecast impact

The forecast impact of the move from FASTEM-4 to FASTEM-5 is overall neutral when verified against observations or analyses (e.g., Figures 14 and 15). This is consistent with the small changes in the departure statistics after bias correction for the microwave radiances and other assimilated observations mentioned earlier. For the Southern Hemisphere, there is a small positive impact from the day 4 forecast onwards for the June/July experiment, whereas a small negative impact for similar forecast ranges can

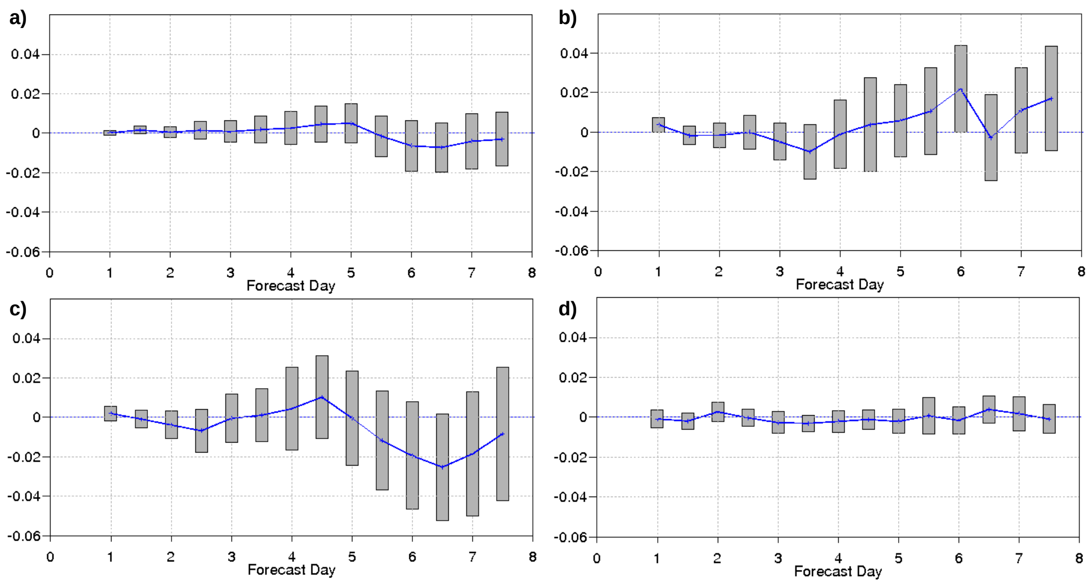

Figure 14: a) Normalised difference in the root mean square error (RMSE) of the 500 hPa geopotential between the FASTEM-5 and the FASTEM-4 experiment for the Northern Hemisphere as verified against radiosonde observations. Results for both periods are pooled together (126 cases). Negative values indicate a reduction in the forecast error from using FASTEM-5 compared to FASTEM-4. Error bars indicate 95% confidence intervals. b) As a), but for the Southern Hemisphere. c) As a), but for Europe. d) As a), but for the 850 hPa wind forecast over the tropics.

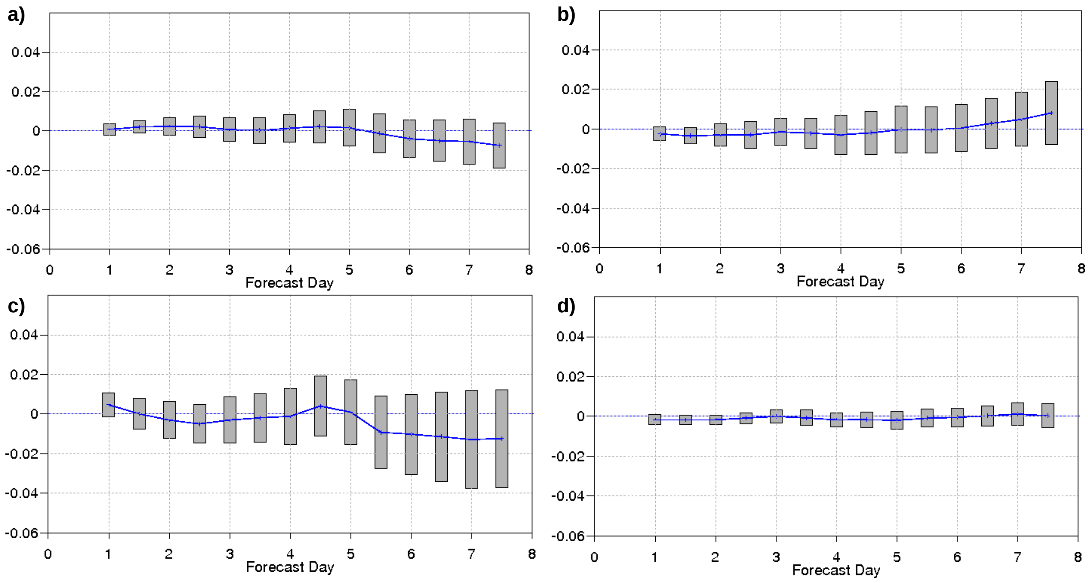

Figure 15: As Fig. 14, but for verification against the operational analysis.

be noted for the January/February experiment. For the latter, the negative impact beyond day 4 is not accompanied with any indication of a degradation at the short range, so it is likely a result of limited sampling.

4 Conclusions

This memorandum documents the introduction of FASTEM-5 in the ECMWF system. FASTEM-5 is a small update of the recently released FASTEM-4 which was introduced in the ECMWF system as part of the upgrade to RTTOV-10 (Bormann et al. 2011). FASTEM-5 has been assessed by comparing simulated surface-sensitive brightness temperatures against observed values. The forecast impact has also been described.

The main findings are:

- FASTEM-5 shows a different dependence on the 10m wind speed compared to FASTEM-4:
  - For the microwave imagers and high 10m wind speeds, the behaviour is now closer to FASTEM-2, as expected from reverting the change to the foam cover model. For low wind speeds, the behaviour is similar to FASTEM-4 for vertically polarised channels, and similar to FASTEM-2 for horizontally polarised channels. At high wind-speeds, standard deviations of FG-departures suggest a small benefit from using FASTEM-4 rather than FASTEM-5.
  - For the microwave sounders, FASTEM-5 leads to an overall reduction of biases compared to FASTEM-3 or -4, with a smaller dependence on the 10m wind speed. The impact on departure statistics is primarily confined to the window channels which are not assimilated, but used to quality control the sounding channels. For these channels, a positive bias in terms of brightness temperatures remains.

- For the micorwave imagers, the regression-based version of FASTEM-5 leads to considerable differences compared to the LUT-based one, but departure characteristics give little indication which version should be favoured.
- The variational bias correction successfully removes the differences in the bias characteristics, leaving bias-corrected departure characteristics that are, on average, not significantly different with FASTEM-5 or FASTEM-4.
- The forecast impact of the move to FASTEM-5 is neutral overall.

The change in the foam cover model from Monahan and O'Muircheartaigh (1986) to Tang (1974) in FASTEM-4 and its reversal in FASTEM-5 have highlighted the sensitivity of biases in high wind speed regions on the foam cover parameterisation. Our study does not find clear evidence that one parameterisation is preferred over the other for microwave imager channels. Given the large spread of models for foam cover as a function of 10m wind speed, and given that actual foam cover is dependent on many more factors than 10m wind speed, it appears worthwhile to enhance the sophistication of foam cover modelling in FASTEM. For instance, better information may be available directly in NWP systems that include a wave model.

FASTEM-5 will be introduced in the ECMWF operational system with cycle 38r1.

References

Anguelova, M., J. Bobak, W. Asher, D. Dowgiallo, B. Moat, R. Pascal, and . Y. M.J, 2009: Validation of satellite-based estimates of whitecap coverage: Approaches and initial results. In In proceedings of the 16th air-sea interaction conference, Phoenix, Arizona, AMS, 8.1.

Anguelova, M., and F. Webster, 2006: Whitecap coverage from satellite measurements: A first step towards modelling the variability of oceanic whitecaps. *J. Geophys. Res.*, **111**, C03017, doi:10.1029/2005JC003158.

Bormann, N., A. Geer, and T. Wilhelmsson, 2011: Operational implementation of RTTOV-10 in the IFS. Technical memorandum 650, ECMWF, 23pp.

Deblonde, G., and S. English, 2001: Evaluation of the fastem-2 fast microwave oceanic surface emissivity model. In Tech. Proc. ITSC-XI Budapest, 67–78.

Dee, D., 2004: Variational bias correction of radiance data in the ECMWF system. In ECMWF Workshop on Assimilation of High Spectral Resolution Sounders in NWP, ECMWF, Reading, UK, 97–112.

English, S., and T. Hewison, 1998: A fast generic millimeter-wave emissivity model. In Proceedings of SPIE, 3503, 288–300.

Liu, Q., S. English, and F. Weng, 2012: Fast microwave ocean emissivity model version 5 (FASTEM-5). *IEEE Trans. Geosci. Remote Sens.*, **50**, submitted.

Liu, Q., F. Weng, and S. English, 2011: An improved fast microwave water emissivity model. *IEEE Trans. Geosci. Remote Sens.*, **49**, 1238–1250.

Monahan, E., and I. O'Muircheartaigh, 1986: Whitecap and the passive remote sensing of the ocean surface. *Int. J. Remote Sensing*, **7**, 627–642.

Tang, C., 1974: The effect of droplets in the air-sea transition zone on the sea brightness temperature. *J. Phys. Oceanography*, **4**, 579–593.