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The Radiometric Sensitivity Requirements for Satellite Microwave Temperature Sounding Instruments for NWP

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Abstract

The sensitivity of NWP forecast accuracy with respect to the radiometric performance of microwave sounders is assessed through a series of observing system experiments at the Met Office and ECMWF. The observing system experiments compare the impact of normal data from a single AMSU with that from an AMSU where synthetic noise has been added. The results show a measurable reduction in forecast improvement in the southern hemisphere with improvements reduced by 11% for relatively small increases in radiometric noise (NEΔT increased from 0.1 to 0.2 K for remapped data). The impact of microwave sounding data is shown to be significantly less than was the case prior to the use of advanced infrared sounder data (AIRS and IASI) with microwave sounding data now reducing Southern Hemisphere forecast errors by approximately 10% compared to 40% in the pre-AIRS/IASI period.

1 Introduction

Microwave sounding data from polar orbiting satellites is an important component of operational Numerical Weather Prediction (NWP) systems. Of particular importance are measurements in the 50-60 GHz spectral range, covering absorption and emission from the O_2 rotational band, which contains information on atmospheric temperature. The Advanced Microwave Sounding Unit (AMSU) is a low noise cross-track scanning radiometer (Goodrum et al., 2000) and AMSUs onboard US and European meteorological satellites have provided continuous observations since 1998. These observations are directly assimilated at most NWP centres in the form of radiances.

Specification of the next generation of microwave sounders (MWS) is currently underway. In Europe the post-EUMETSAT Polar System (post-EPS) mission is expected to become operational around 2020. Within the US National Polar Orbiting Environmental Satellite System (NPOESS), with the first preparatory platform due for launch in 2010, MWS capability will be delivered by both cross-track and conically scanning microwave radiometers. The design of the cross-track instrument (the Advanced Technology Microwave Sounder - ATMS see (Muth et al., 2004)) has been finalised, however, the conical instrument (the Microwave Imager Sounder - MIS) is currently being specified. The radiometric performance of these instruments is a key factor in determining their impact in NWP systems. The purpose of this paper is to assess the sensitivity of NWP forecast accuracy to the radiometric performance of the 50 GHz temperature sounding channels in order to assist in the specification of future operational instruments. This has been tackled through a series of observing system experiments (OSEs) using both normal AMSU data and synthetically noise-degraded AMSU data within two operational NWP systems.

Recent OSEs have shown that MWS data has a very large positive impact on NWP forecast accuracy: for example, forecast errors in sea level pressure are reduced by approximately 40% for forecast days 1-4 in the southern hemisphere (English et al., 2004) through the introduction of microwave temperature sounding data from AMSU. Since these studies were carried out in 2003 the global satellite observing system has evolved, most notably with the successful launch of two advanced infrared sounding missions: AIRS (LeMarshall et al., 2006) and IASI (Challon et al., 2001). It is likely that the future global satellite observing system will include two or three advanced IR sounders in complementary orbits (Eyre, 2008). To estimate the likely impact of MWS data in the post-EPS era a secondary aim of this work has been to assess the current impact of microwave sounding data in observing systems which include both AIRS and IASI.

The specification of radiometric performance influences both the choice of scan geometry as well as the detailed design choices to be made for any given scan geometry. To date two scan geometries have been used for operational microwave sounders: cross track and conical scanning. Studies by (Rosenkranz et al., 1997) and (McMillin and Divakarla, 1999) have investigated the relative performance, for temperature and humidity sounding respectively, of both scan geometries using simulation studies. More recently, the launch of the Special Sensor Microwave Imager/Sounder (SSMIS) has permitted an assessment of the performance of conical scanners for NWP ((Swadley and Coauthors, 2008) and (Bell and Coauthors, 2008)) using on-orbit data. These studies showed that calibration problems can cause complex systematic errors in conical scanners that limit the impact of the temperature sounding data in NWP systems relative to that from AMSU-A, although the data still provides benefit. Another significant difference is that conical scanners, employing constant reflector rotation rates, typically have shorter integration times relative to cross-track scanners, where the smaller reflectors can be accelerated between Earth scenes and calibration views, hence increasing Earth scene integration time. Consequently conical scanners typically have higher radiometric noise levels, normally expressed as noise equivalent brightness temperature (NEΔT in Kelvin), than cross-track configurations. There are design options which could mitigate this limitation, for example the use of multiple 50 GHz feed-horns, but these options are untested on-orbit. The significance here is that if radiometric performance is critical then a cross-track design, with lower noise and better calibration performance, is a more optimal choice based on current evidence. Related to this, if a conical design is to be used for temperature sounding then particular attention has to be paid to the instrument design to ensure calibration stability and to optimise NEΔT as far as possible.

Section 2 describes the current use of AMSU data at the Met Office and ECMWF and the impact derived from the data in the Met Office global NWP model in both the pre- and post-advanced IR sounder era. Section 3 describes the OSEs carried out at both centres to assess the sensitivity of forecast accuracy to the radiometric performance for microwave sounders. Conclusions are drawn in Section 4, which includes some caveats on the interpretation of these results.

2 Current Use and Impact of Microwave Sounding Data in NWP

2.1 Use of Microwave Sounding Data

2.1.1 Met Office

Data from AMSUs onboard the NOAA Polar Orbiting Environmental System (POES) has been assimilated directly as brightness temperatures since 1999 and AMSU data from the first EUMETSAT polar platform (MetOp-A) has been assimilated since 2007. The Met Office currently use data from AMSUs onboard NOAA-16, NOAA-18 and MetOp-A, as well as data from F-16 SSMIS. Additional AMSU-A data are currently available from NOAA-15 and EOS-Aqua, however previous OSEs at the Met Office showed that the effect of successive additions diminishes so that the measured impact of a third microwave sounder is relatively small, reducing southern hemisphere (SH) forecast errors by 1% or less. The value of additional sounders therefore lies in adding increased robustness to the satellite observing system.

Prior to assimilation AMSU data is preprocessed by the ATOVS Advanced Pre-Processing Package (AAPP, (Atkinson et al., 2008)). As part of this step, the AMSU-A data is remapped to the grid of the High Resolution IR Sounder (HIRS) using bi-linear interpolation. This has the effect of reducing the effective noise of the AMSU data by approximately 32%. The NEΔT figures for the remapped data are shown in Table 1 for the tropospheric sounding channels (4-8). The noise for the remapped AMSU-A data is in the range 0.08-0.12 K for these channels.

Residual biases between observations and radiances modelled from forecast model fields are minimised using an off-line bias correction scheme (Harris and Kelly, 2001). These biases arise from a number of sources including forecast model error, radiative transfer modelling error as well as systematic errors in the radiometric calibration of the measured radiances. Bias corrections perform well when dealing with simple errors which show a high correlation with auxiliary data, for example scan angle, latitude or airmass. The widespread use and success of bias correction schemes at NWP centres partially alleviates the need for highly accurate absolute calibration, although for climate monitoring applications this issue remains important.

Observations are thinned to one observation every 154 km, an empirically tuned thinning distance aimed at minimising the detrimental effect of spatially correlated observation errors (Dando et al., 2007). The observation errors assumed for AMSU-A sounding channels, which determine the weight given to the observations in the 4D-Var analysis (Rawlins et al., 2007), are shown in Table 1. For channels 5-8, with weighting function peaks which span the troposphere and which have the largest impact on forecast accuracy, the assumed observation errors are 0.25K.

2.1.2 ECMWF

AMSU data from the NOAA POES platforms has been assimilated, in the form of brightness temperatures, since 1998. ECMWF currently use data from AMSUs onboard NOAA-15,-16,-18, MetOp-A and Aqua. F-16 SSMIS temperature sounding data is not currently used in the ECMWF system due to the persistence of local biases in the data, which remain after pre-processing and bias correction.

The data is not pre-processed and consequently the effective noise levels in the AMSU data are higher than those shown for the Met Office remapped data in Table 1. The noise levels, first guess departure statistics and assumed observation errors for the ECMWF AMSU data are shown in Table 2. The data is thinned to one observation every 120 km. For channels 5-8 the assumed observation errors are 0.35K.

Bias correction is carried out using a variational bias correction scheme (Auligné et al., 2007). In this approach a predictor-corrector scheme is used similar to that described above, however the bias coefficients in the correction scheme are part of the control variable in the variational analysis and are dynamically updated each analysis cycle.

2.2 Impact of Microwave Sounding Data

The impact of all microwave sounding data in the Met Office NWP system, as it stood in 2007, was assessed by a data denial OSE in which *all* microwave sounding data was withdrawn from an otherwise full operational data assimilation system. This full system included conventional data types (from sondes, surface stations, buoys and aircraft) as well as a range of satellite data types including: advanced IR sounder data from AIRS and IASI, data from a constellation of global positioning system radio occultation (GPSRO) sensors, scatterometer data from Quikscat and ERS-2, SSMI ocean surface windspeeds as well as Atmospheric Motion Vectors (AMVs) from geostationary satellites.

Forecasts were verified relative to observations from sondes and surface observing stations. Typically data from 20000-30000 global surface observations and 500-1000 sonde launches are used in the verification of each forecast day of the 30 day experiment which covered the period 24th May - 24th June 2007. Figure 1 shows the impact of removing microwave sounding data from NOAA-16, -18, MetOp-A and F-16 SSMIS. For comparison Figure 1 shows the impacts from a previous experiment carried out in 2003, before AIRS, IASI and GPSRO data was introduced.

The withdrawal of microwave sounding data increased forecast errors in the southern hemisphere by around 40% in 2003. In 2007 the impact is smaller, although still significant and important, at around 10-15%. The change is principally due to the introduction of AIRS and IASI data in the 2007 experiment. These results supported the inclusion of advanced IR sounding data in the Met Office control experiments for the OSEs aimed at establishing the sensitivity of forecast accuracy to radiometric performance, in order to represent the global observing system as it is likely to stand in 2020.

3 Observing System Experiments

3.1 Met Office

A series of OSEs were carried out to meet the primary aim of this work: to determine the sensitivity of forecast performance to the radiometric sensitivity of microwave sounding data. Ideally a number of OSEs should be run for various levels of noise and the forecast performance assessed in order to fully determine the relation between the two, however the computational expense of running OSEs for near-full operational resolutions using 4D-Var makes this impractical. The experiments were run for both a single AMSU and a single AMSU with degraded noise performance.

The Met Office OSEs covered the period 24th May - 24th June 2007 and are summarised in Table 3. The data denial experiment, described above, in which *all* MWS data was withdrawn from an otherwise full operational system was used as the control (CNTRL-UK) against which the other experiments were verified. In the first experiment (EXPT1-UK) data from MetOp-A AMSU (*normal* AMSU hereafter) was added on top of the control experiment. In the second experiment (EXPT2-UK) data from MetOp-A AMSU was used which had synthetic, unbiased and uncorrelated Gaussian noise added (*noisy* AMSU hereafter).

In determining the amplitude of the noise to be added several factors were borne in mind. Firstly, NEΔT figures were available from preliminary post-EPS instrument designs for both conical and cross-track scanners. These were in the range 0.1 - 0.6K for the 50 GHz channels, depending on channel bandwidth and scan geometry. Initially this supported the choice of a high value for the effective radiometric noise level (NEΔT′) for the noisy experiments, for example 0.5K. Inspection of the first guess departure (also known as innovation) statistics (Figure 2), however, shows that AMSU is normally correcting relatively small ($\sim$ 0.1K) errors in the background field. For most of the time innovations for AMSU channels 4-8 are in the range 0.1-0.2K. Errors of 0.3K or more are relatively infrequent. Adding synthetic noise to give NEΔT′ of 0.5K would make these errors difficult to correct. Indeed, over several assimilation cycles the quality of the background field would deteriorate. Anticipating that introducing synthetic noise to give NEΔT′ of 0.5K would have very dramatic negative effects on forecast quality, it was decided to add noise to achieve an NEΔT′ of 0.2K, as a test of a realistic relaxation of the radiometric specifications of a microwave sounder, relative to current AMSU-A performance. Synthetic noise was generated such that the quadrature addition of the new noise and the noise of the remapped AMSU data was approximately 0.2K for the key 50GHz channels (5-9). This amounted to adding noise with a standard deviation of 0.17K. This noise was added to all AMSU channels.

3.2 ECMWF

The ECMWF observing system experiments also covered the period 24th May - 24th June 2007. Following previous practise at ECMWF the control experiment (CNTRL-ECMWF) used conventional observations and a very limited set of satellite data (including only AMVs) (Kelly et al., 2007). Notably, no data from AIRS and IASI was used in the control experiment. Following the convention above the first experiment (EXPT1-ECMWF) used data from a single AMSU-A (from NOAA-18) and the second experiment (EXPT2-ECMWF) data from a noise degraded NOAA-18 AMSU was introduced.

For consistency with the Met Office experiments, the noise amplitude was such that the resulting effective noise (NEΔT′), if the data was remapped to the HIRS grid, would be 0.2K. For the ECMWF data this meant achieving

$NE\Delta T' \approx 0.29$ K for the unmapped data, necessitating the addition of random noise with a standard deviation of 0.26 K. The bias corrected innovations for normal and noise degraded AMSU-A data in channels 1-15 are shown in Figure 2.

3.3 Results - Analysis Impacts

It was anticipated that the addition of unbiased random noise to the measured radiances would not result in any systematic difference in the resulting analysis, compared to the analysis where normal radiances were used. Figure 3 shows the mean difference in analysis fields for temperature at 200 hPa, 500 hPa and 850 hPa for normal and noisy experiments at ECMWF (EXPT1-EC and EXPT2-EC respectively). The differences are generally below 0.3K. There are several areas where systematic differences over large areas are evident. In the polar regions, differences of 0.2 - 0.25K are evident. Systematic differences are also evident in the north east Pacific and in the southern Atlantic. Elsewhere the differences between normal and noisy experiments appear small scale and random.

The addition of noise would, however, be expected to make the resulting analysis more noisy. The increase in analysis noise was estimated by evaluating RMS errors for the normal and noisy analysis, using the analysis produced from the full system (EXPT3-EC) as a proxy for truth. Zonal mean RMS errors in temperature at six pressure levels in the range 10hPa to 850hPa, spanning the mid stratosphere to lower troposphere, are shown in Figure 4 for normal and noisy experiments. At all levels the analysis degradation is most evident in the southern hemisphere. The difference in analysis error between normal and noisy experiments increases southwards of 20 degrees, reaching a maximum of 50/20/50mK at the 200/500/850 hPa levels in the latitude range 60-80 degrees south where analysis errors for the normal experiment are 0.5/0.4/0.65K respectively. Analysis errors in the southern hemisphere are typically twice the magnitude of the analysis errors in the northern hemisphere for the tropospheric levels. Analysis errors are larger in the stratosphere and the inter-hemispheric differences larger, with southern hemisphere errors typically 2-4 times larger than the northern hemisphere values. Analysis degradations resulting from noise addition are smaller in magnitude in the tropics and northern hemisphere but are detectable.

The analysis errors estimated in this way are necessarily an underestimate of the true errors, as the proxy for truth (the analyses from the full system) itself has non-zero errors. The analysis errors reported here are therefore a lower limit to the true errors. Any approximate estimates of forecast sensitivity to analysis errors derived from this study would therefore represent upper limits to true sensitivity.

3.4 Results - Forecast Impacts

For the Met Office OSEs forecast fields were verified against radiosonde observations for temperature, relative humidity, geopotential height and winds, and relative to surface based observations for mean sea level pressure. As summarised in Table 4 the verification was carried out at forecast ranges from day 1 to day 6 and for a range of pressure levels. The root mean square (RMS) observed minus forecast differences were then used to compute changes in the mean RMS errors (RMSE) for each experiment relative to the specified control experiment. The ECMWF OSE were verified against analysis fields from a reference experiment which included a full set of observations, sampled on a 2.5 degree grid. The verification measures used matched those of the Met Office with a few minor exceptions: (i) for technical reasons 300 hPa pressure level scores were used instead of the 250 hPa scores used by the Met Office and (ii) relative humidity scores were also verified for the 300, 100 and 50 hPa pressure levels, and also for days 4-6. Neither of these differences are expected to significantly change the results reported below. Verification statistics were computed for the northern hemisphere (NH), the tropics and the southern hemisphere (SH).

Figure 5 shows the forecast improvement for NH, the tropics and SH for the Met Office OSEs for both *normal* and *noisy* AMSU experiments. Each circle represents a verification measure averaged over the period of the OSEs. The impact of the AMSU data is greatest for the mass related fields (temperature, geopotential height and mean sea level pressure) and is smaller for winds and humidity. The impacts are also largest in the SH, for which the analysis is constrained by a relatively sparse network of conventional observations.

The changes in mean forecast RMSEs, averaged over all 123 verification measures listed in Table 4, are summarised in Table 5. For the Met Office OSEs the impacts of the data are small in the NH, generally less than 5% (with an overall mean RMSE reduction of 1.13% for the normal data), due to the abundance of conventional observations available for the analysis, as well as the presence of both AIRS and IASI data. The impact of the data in the tropics is similarly small, at less than 5% (overall mean RMSE reduction of 0.03 %), which has been observed in previous OSEs and is attributed to tropical meteorology being governed less by geostrophic balance (which benefits from accurate analyses of mass fields from temperature sounders) and more by convection (less well analysed by microwave sounding measurements). In the SH the impact of the data is significant with mean forecast errors, averaged over all verification measures, reduced by 5.4% for the *normal* AMSU data. The mean reduction in forecast error for the *noisy* AMSU experiment was 4.8%, representing a relative reduction in forecast improvement of 11%.

Figure 6 shows the forecast improvement for the ECMWF OSEs for both *normal* and *noisy* AMSU experiments. The impacts in the NH and the tropics are smaller than in the SH, but still statistically significant (at the 95% confidence level) at -4.6% and -4.8% respectively for the normal AMSU data, reducing to -3.3% and -3.6% respectively for the noisy data. The impact in the SH is larger. For the *normal* AMSU experiments, mean forecast errors are reduced by 22.3%. The *noisy* AMSU experiment shows a reduction of 19.7%, representing a relative reduction in forecast accuracy of 11%. This value is close to the value obtained in the Met Office experiments and indicates the robustness of the results. The ECMWF OSEs show a significant degradation of forecast quality in all three regions, at a similar level of significance.

Figures 5 and 6 show the same qualitative behaviour in that the largest forecast improvements are found for mass fields (temperature, geopotential height and mean sea level pressure) with less impact on wind fields and less impact still for humidity fields. This holds true for both tropics and extra-tropics but with the largest impacts found for the SH.

Figures 5 and 6 represent overall summary plots of the impact of noisy radiance data on a range of verification measures, and address the central aim of this study. Examining the verification data in more detail yields useful insights into the design of similar experiments in future. Figure 7 shows the verification for geopotential height for 200 hPa, 500 hPa and 850 hPa for forecast ranges from T+12 hours to T+6 days in the southern hemisphere. The error bars represent the standard error on the mean RMSE reduction (at 1σ) for both normal and noisy experiments and indicate the significance of departures from the 45 degree line. Figure 7 shows that the largest forecast impacts are obtained at shortest range and the impact decreases monotonically to the longest forecast range. Absolute forecast impacts are still significant at T+6 days. The significance of the *differences* in forecast impact becomes marginal beyond T+4 days as the statistical uncertainties in the verification measures becomes larger at longer range. Very similar results are obtained for temperature and wind.

Forecast verification for geopotential height at 10, 50 and 100 hPa is shown in Figure 8. Error bars are not shown if they lie within the marker circle. Consistent with the results obtained for the tropospheric levels the forecast impact is largest (and larger than for the tropospheric levels) for the shortest range, decreasing monotonically with forecast range. The uncertainties in the verification are smaller than for the tropospheric levels, enabling the detection of significant degradation at all forecast ranges to T+6 days.

The impact on troposheric relative humidity in the southern hemisphere is shown in Figure 9. The impact of the MWS on humidity scores is smaller, at 20% for the normal data at T+12 hours. The absolute impacts decrease with time for both normal and noisy experiments, but are still significant at T+6 days. The degradation in the impact resulting from the noisy data is most evident at 500hPa where the degradation is significant to forecast day 4. Significant degradations are evident to Day 3 at 850 hPa, but the degradations at 200hPa are more marginal in significance.

Figure 10 show the impact of normal and noisy data on the analyses and forecast fields for vector winds in the Tropics (20N-20S). In this case the analyses and forecast fields have been verified against radiosonde observations. The impact of the MWS at 850 hPa small, at around 1% or less, and of marginal significance. Forecast impacts are larger at 500hPa and 200 hPa at up to 3% for both normal and noisy data, with the largest impacts at short range (T+24 and T+48 hours). There is some indication overall that the noisy data reduce the forecast improvement relative to the noisy data, with the most significant results at T+24 hours for 200 hPa and 500 hPa.

The difference in absolute SH impacts of a single AMSU in the Met Office (5.4%) and ECMWF (22.3%) OSEs is explained by the presence of AIRS and IASI in the Met Office control experiment, and is broadly consistent with the Met Office pre- and post-advanced IR sounder MWS data denial experiments, which show a factor of four reduction in the relative importance of MWS data. This is a significant result which highlights the high value of the infrared data in NWP.

4 Summary and Conclusions

This work was prompted by the requirement to specify the radiometric performance of microwave sounders for future meteorological satellite missions. The approach involved assessing the sensitivity of NWP forecast accuracy to the noise level (NEΔT) for AMSU data through a series of OSEs at the Met Office and ECMWF. *Normal* AMSU data and *noisy* AMSU data, in which synthetic noise was added, were introduced into global 4D-Var NWP systems at both the Met Office and ECMWF.

This study has two main conclusions. Firstly it has been confirmed that forecast improvements are measurably reduced (by $\sim$ 11%) for relatively small degradations (increasing NEΔT from 0.1K to 0.2K for remapped AMSU-A data) in the radiometric performance of microwave temperature sounding data. Secondly the impact of MWS data in the post-advanced IR sounder era, although still very significant at around 10% in most SH forecast scores, is significantly less than the impact during the pre-advanced IR sounder era, when the impact was around 40%.

It would appear therefore that if the continued steady improvement in NWP forecast accuracy is to be maintained then any degradation in forecast performance resulting from the choice of a lower specification MWS instrument, relative to the current operational baseline, would have to be offset by improvements elsewhere in the system. This statement, however, needs to be qualified and the limitations of this work should be made clear.

This study aimed to establish forecast sensitivity to radiometric sensitivity in experiments which used AMSU data in the same way the data is currently exploited at operational NWP centres. In particular the data is not averaged (other than the averaging achieved through remapping) and is spatially thinned. No account has been taken of the possibilities for spatially averaging high noise raw data to achieve acceptable radiometric noise levels. Experience in spatially averaging microwave sounding data is limited. In the operational exploitation of SSMIS data the Met Office and the Naval Research Laboratory spatially averaged the radiance data to achieve noise levels below 0.1K for the 50 GHz channels, but no systematic study was undertaken to compare the impacts of averaged versus unaveraged data. Data from ATMS, due for first launch in 2009, is oversampled at relatively high noise (NEΔT = 0.75K at 54.4 GHz) and spatial averaging will be a necessary step in the pre-processing of the data for NWP applications (Atkinson et al., 2008).

A second qualification relates to other potential improvements in the exploitation of satellite data which could modify the sensitivities derived here. Likely developments by 2020 include greater use of sounding data over land, greater use of data from cloudy and precipitating regions, improvements in the definition of observation and background errors (including better treatment of observation error correlations) as well as the implementation of more intelligent thinning schemes.

Regarding the design of similar observing system experiments in the future, significant differences in the key tropospheric verification scores resulting from the addition of noise are only detectable to forecast day 4 for a 30 day sample period. The expense of future experiments could therefore be reduced by reducing the forecast range to 4 days.

Finally, this study assesses the cost of degrading radiometric performance of a MWS mission. It should also be possible in future to assess the potential benefits to be achieved through improving radiometric noise performance, by averaging data and increasing the weight given to observations in the analysis.

Acknowledgments

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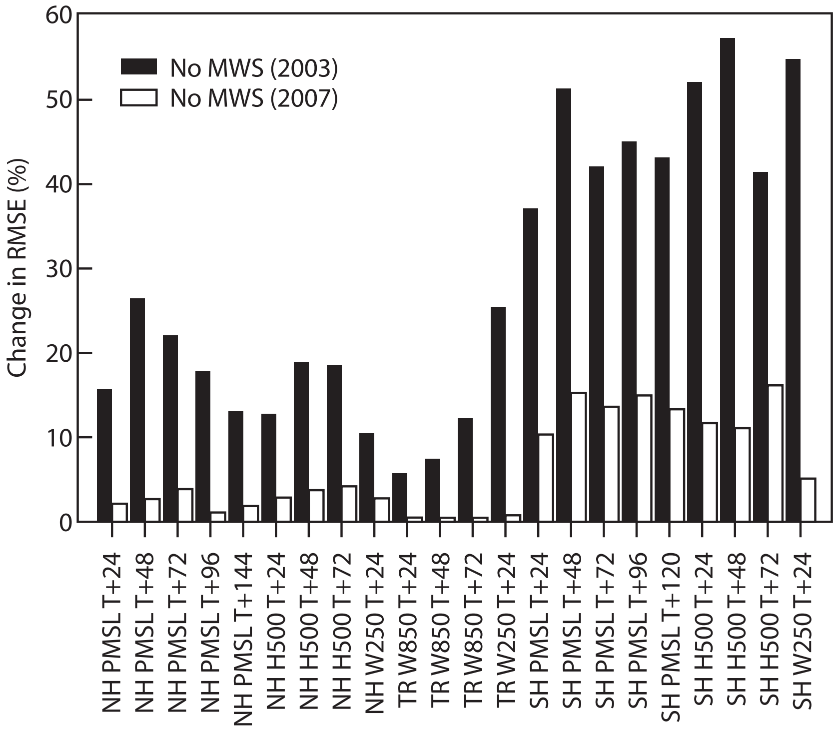

Figure 1: Met Office data denial OSEs in which MWS data was withdrawn from an otherwise full observing system which contained advanced IR sounder data (AIRS and IASI) in 2007, but not in 2003.

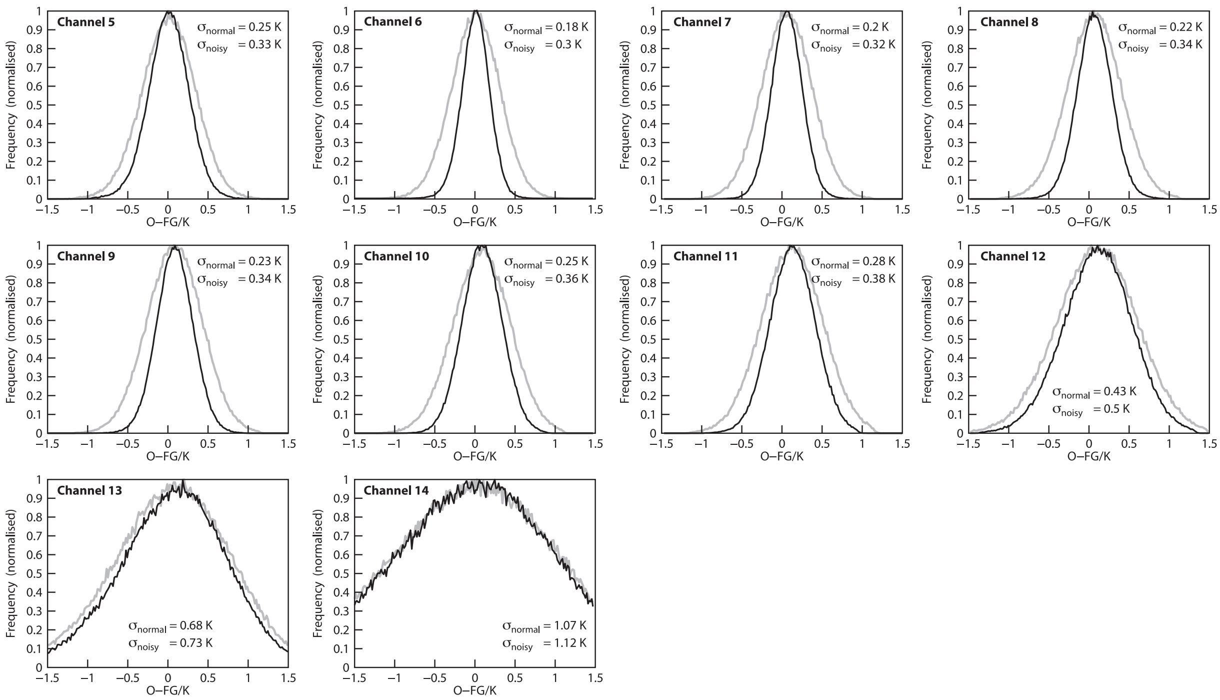

Figure 2: First guess departures for AMSU-A channels 5-14 for normal (black) and noisy (grey) data used in the ECMWF OSEs.

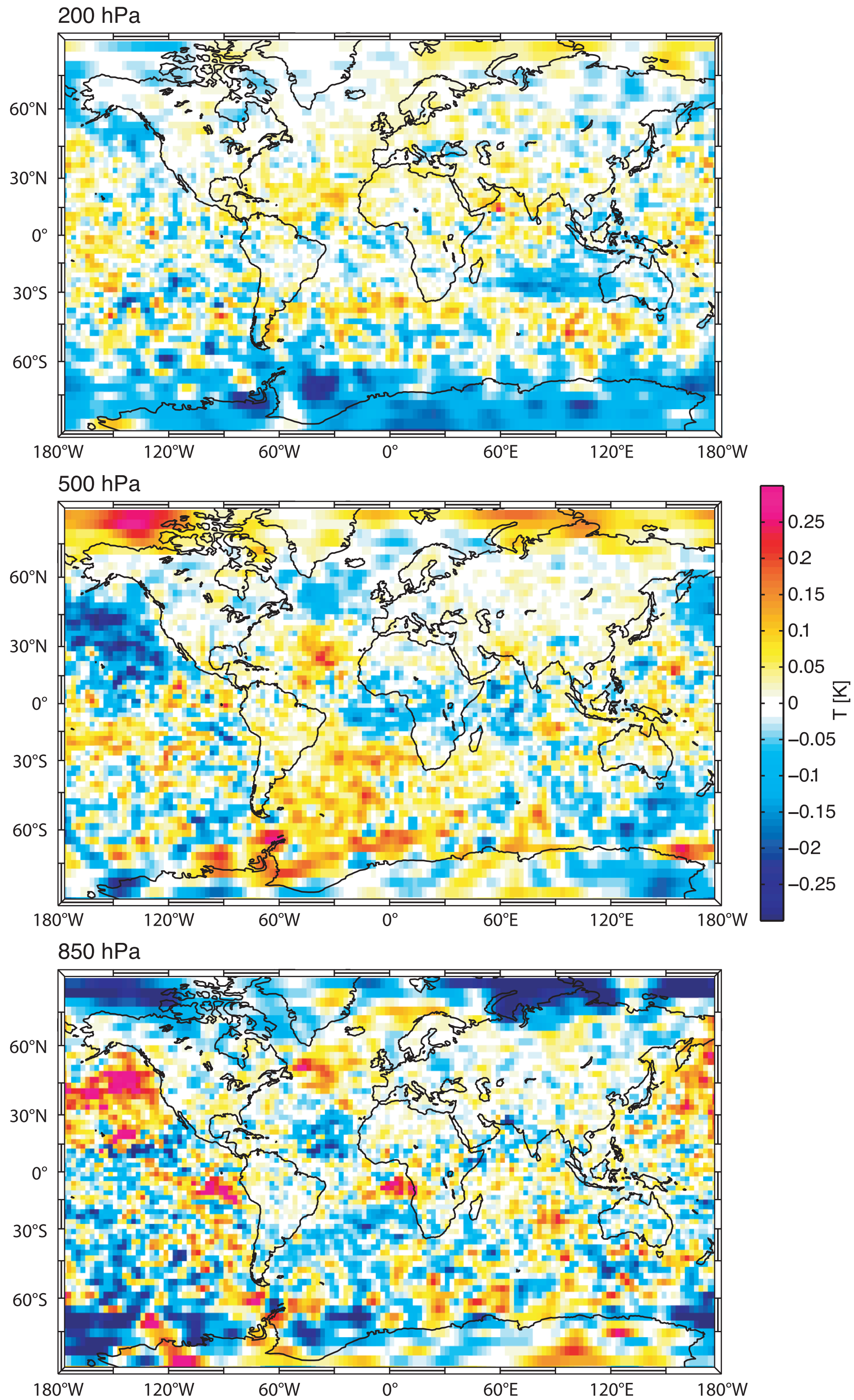

Figure 3: The mean difference in analysis temperature fields at 200, 500 and 850 hPa for normal and noisy AMSU experiments.

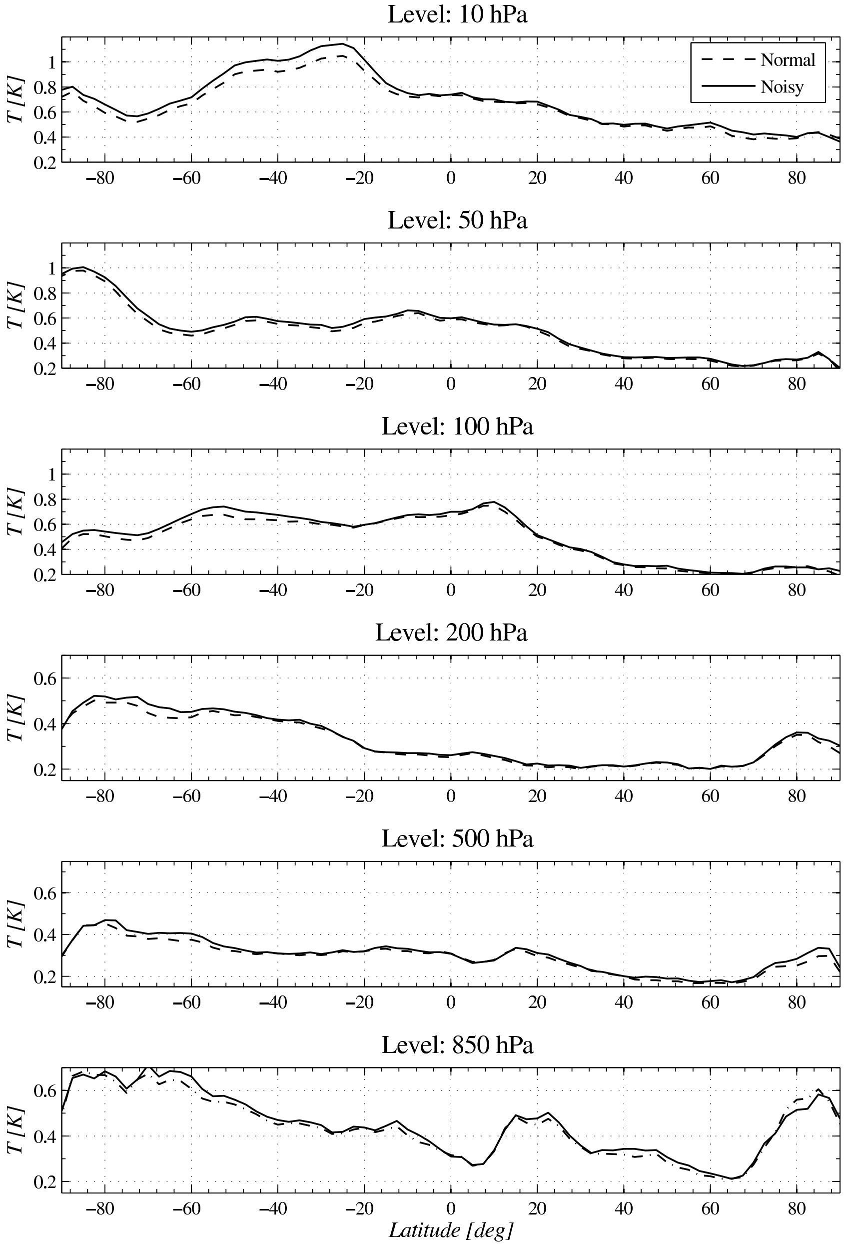

Figure 4: Estimated analysis accuracy, expressed as a zonal mean RMSE, for temperature at (top to bottom) 10, 50, 100, 200, 500 and 850hPa for normal (dotted line) and noisy (solid line) AMSU data OSEs.

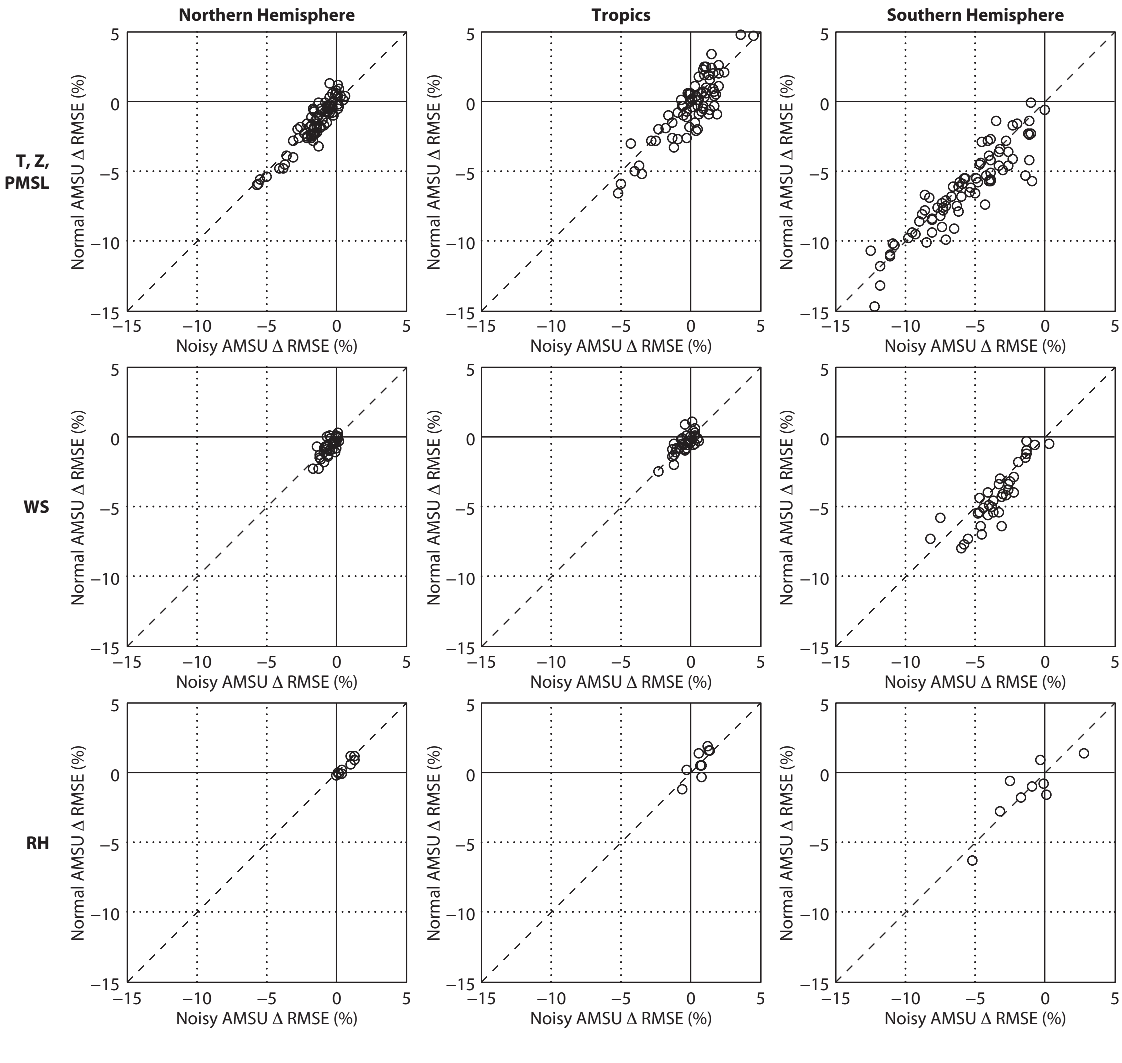

Figure 5: Met Office OSEs: The impact on forecast quality, in terms of RMSE reductions for all verification measures listed in Table 4, resulting from the addition of normal and noisy AMSU-A data to a baseline experiment (CNTRL-UK) in which all microwave sounding data has been withdrawn.

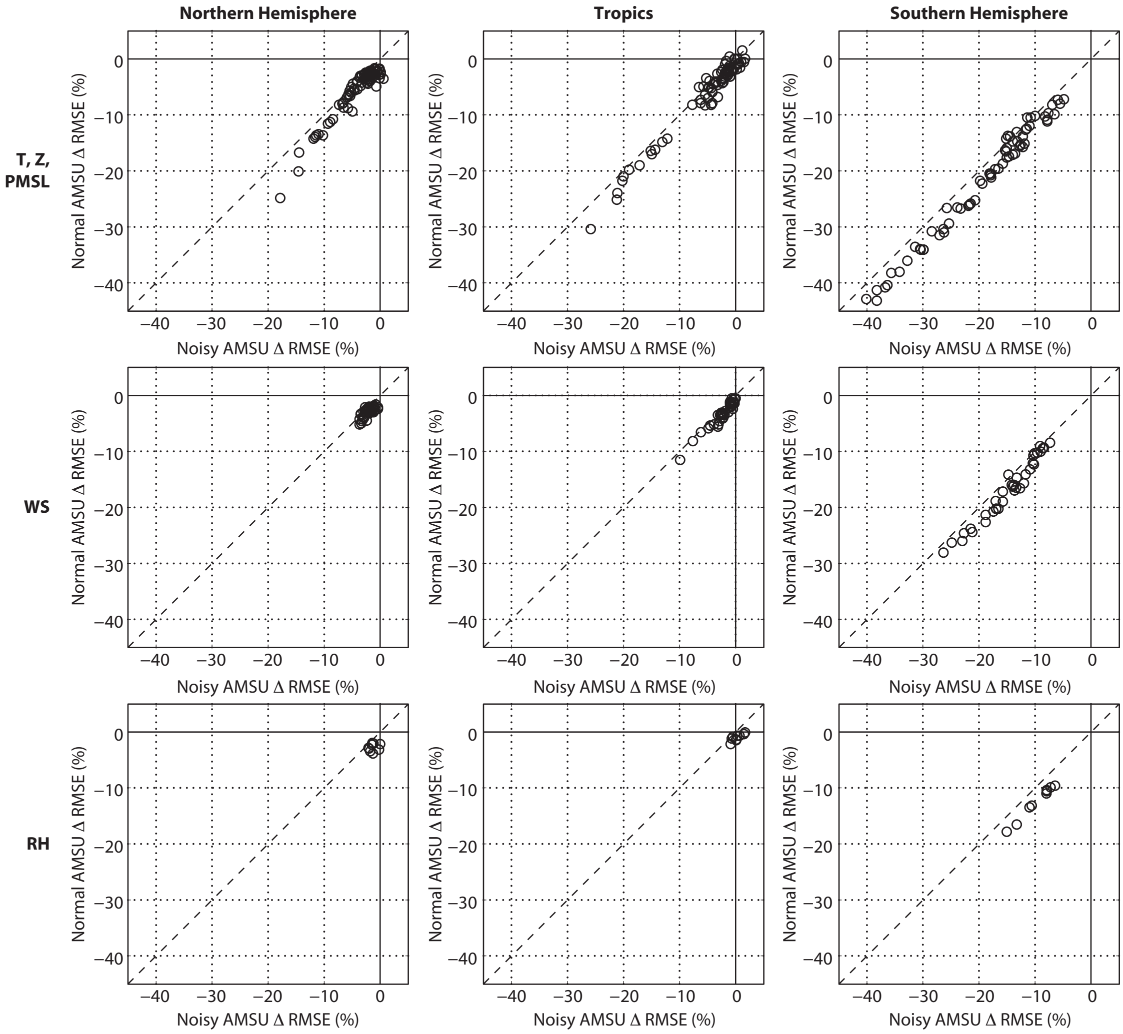

Figure 6: ECMWF OSEs: The impact on forecast quality, in terms of RMSE reductions for all verification measures listed in Table 4, resulting from the addition of normal and noisy AMSU-A data to a baseline experiment (CNTRL-EC) in which all satellite data (except AMV data) has been withdrawn.

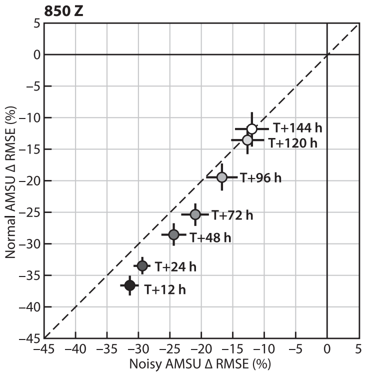

Figure 7: The effect of adding normal and noisy AMSU data on geopotential height forecast accuracy (RMSE) at 850, 500 and 200 hPa for forecast ranges 12 hours - 144 hours in the SH for the ECMWF OSEs. The x and y coordinates of each point represent the change in forecast error (RMSE) relative to a no MWS baseline experiment (CNTRL-EC) for noisy and normal AMSU experiments respectively. For example points in the lower left quadrant indicate both normal and noisy experiments reduce forecast errors but points below the dotted 45° line indicate the noisy data reduce errors less than the normal data. The error bars represent the standard error on the mean (at 1σ) forecast error change over the 30 day experiment.

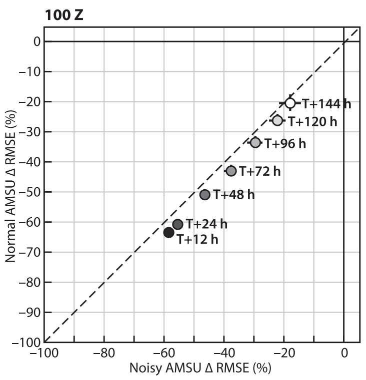

Figure 8: The effect of adding normal and noisy AMSU data on geopotential height forecast accuracy (RMSE) at 100, 50 and 10 hPa for forecast ranges 12 hours - 144 hours in the SH for the ECMWF OSEs. Error bars as described for Figure 7.

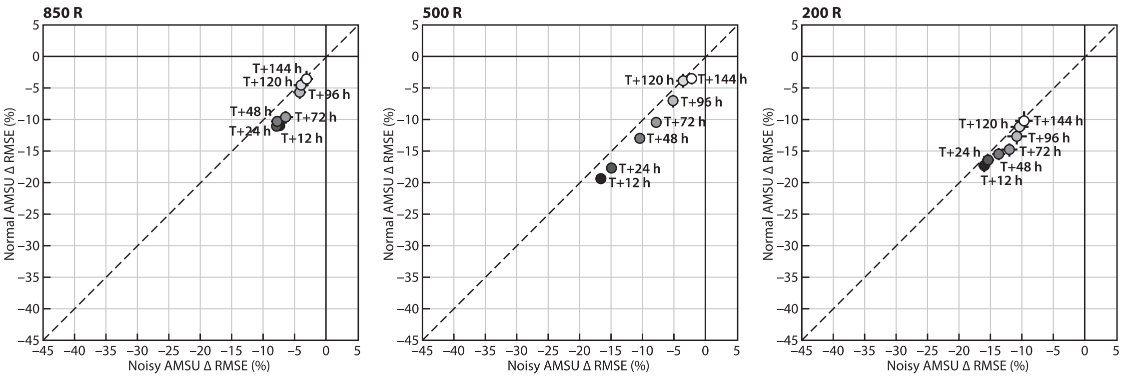

Figure 9: The effect of adding normal and noisy AMSU data on relative humidity forecast accuracy (RMSE) at 850, 500 and 200 hPa for forecast ranges 12 hours - 144 hours in the SH for the ECMWF OSEs. Error bars as described for Figure 7.

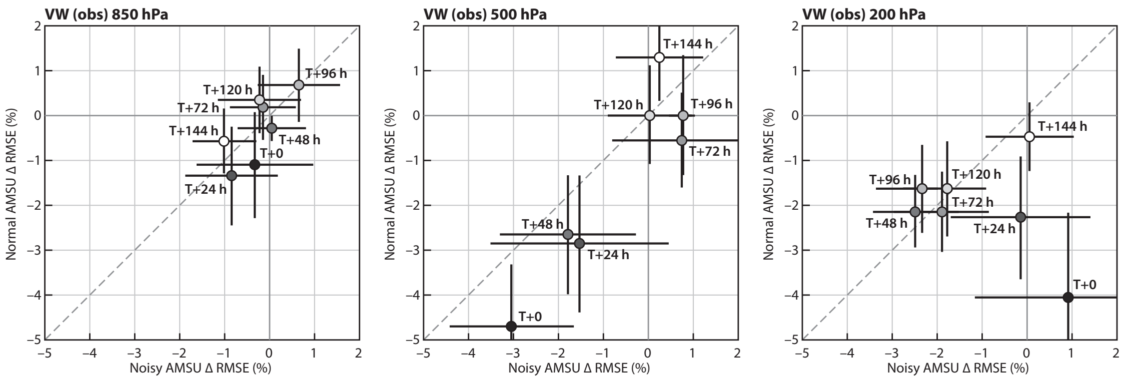

Figure 10: The effect of adding normal and noisy AMSU data on vector wind forecast accuracy (RMSE) at 850, 500 and 200 hPa, verified using radiosondes, for analysis time (T+0) and forecast ranges from 24 hours - 144 hours in the the Tropics for the ECMWF OSEs. Error bars as described for Figure 7.

Table 1: Met Office: AMSU-A channel characteristics, first guess departure (O-FG) statistics and assumed observation errors (R).

Channel number	Frequency /GHz	Bandwidth /MHz	NEΔT (re-mapped) /K	std(O-FG) (normal) /K	std(O-FG) (noisy) /K	R (normal) /K	R (noisy) /K
4	52.8	400	0.09	0.30	0.39	1.25	2.50
5	53.6	170	0.12	0.17	0.26	0.25	0.50
6	54.4	400	0.09	0.12	0.23	0.25	0.50
7	54.9	400	0.08	0.13	0.22	0.25	0.50
8	55.5	330	0.12	0.15	0.24	0.25	0.50

Table 2: ECMWF: AMSU-A channel characteristics, first guess departure (O-FG) statistics and assumed observation errors (R).

Channel number	Frequency /GHz	Bandwidth /MHz	NEΔT (un-mapped) /K	std(O-FG) (normal) /K	std(O-FG) (noisy) /K	R (normal) /K	R (noisy) /K
4	52.8	400	0.13	0.31	0.30	-	-
5	53.6	170	0.18	0.25	0.33	0.35	0.44
6	54.4	400	0.13	0.18	0.30	0.35	0.44
7	54.9	400	0.12	0.20	0.32	0.35	0.44
8	55.5	330	0.18	0.22	0.34	0.35	0.44

Table 3: OSEs at the Met Office and ECMWF

Experiment ID	Observations included
CNTRL-UK	Full system *without* MWS data. Including AIRS and IASI IR radiances, SSMI ocean wind-speed, AMVs, Scatterometer winds from Quikscat and ERS-2, GPSRO data
EXPT1-UK	CNTRL-UKMO + MetOp-A AMSU/MHS data (nominal noise, NEΔT$\approx$0.1K) for AMSU-A channels 4-8
EXPT2-UK	CNTRL-UKMO + MetOp-A AMSU/MHS data + synthetic noise (NEΔT$' \approx$ 0.2K)
EXPT3-UK	Reference experiment. Full set of observations
CNTRL-EC	Baseline experiment. Conventional observations + AMVs only
EXPT1-EC	CNTRL-ECMWF + NOAA-18 AMSU-A/-B data (nominal noise, NEΔT $\approx$ 0.13K)
EXPT2-EC	CNTRL-ECMWF + NOAA-18 AMSU-A/-B data + synthetic noise (NEΔT$' \approx$ 0.29K)
EXPT3-EC	Reference experiment. Full set of observations

Table 4: Verification measures used to assess forecast accuracy

Variable	Pressure levels / hPa	Forecast range / days
Mean Sea level Pressure	surface	T+1 - T+6
Geopotential Height	850,700,500,250,100,50	T+1 - T+6
Temperature	850,700,500,250,100,50	T+1 - T+6
Wind	850,700,500,250,100,50	T+1 - T+6
Relative Humidity	850,700,500	T+1 - T+3

Table 5: A summary of the impact of increased MWS radiometric noise on NWP forecast accuracy.

NWP Centre	Region	Mean % Change in forecast RMSE (**A**) (± 95% confidence) (normal data)	Mean % Change in forecast RMSE (**B**) (± 95% confidence) (noisy data)	Relative Change ((**B-A**)/**A**) (± standard error) / %
ECMWF	NH	-4.55 ± 0.69	-3.28 ± 0.58	-27.9 ± 10.1
	TR	-4.76 ± 1.02	-3.62 ± 0.95	-24.0 ± 14.9
	SH	-22.27 ± 2.35	-19.74 ± 2.21	-11.4 ± 7.3
Met Office	NH	-1.13 ± 0.27	-1.01 ± 0.24	-10.6 ± 16.0
	TR	-0.03 ± 0.38	-0.21 ± 0.33	600 ± 3891
	SH	-5.36 ± 0.55	-4.77 ± 0.55	-11.0 ± 7.3

References

Atkinson, N., P. Brunel, P. Marguinaud, and T. Labrot (2008). Aapp developments and experiences with processing metop data. In *Proceedings of International TOVS Study Conference*, Agra Dos Reis, Brazil.

Auligné, T., A. P. McNally, and D. P. Dee (2007). Adaptive bias correction for satellite data in a numerical weather prediction system. *Q. J. R. Met. Soc. 133*, 631–642.

Bell, W. and Coauthors (2008). The assimilation of ssmis radiances in numerical weather prediction models. *IEEE Transactions on Geoscience and Remote Sensing 46*, 884–900.

Challon, G., F. Cayla, and D. Diebel (2001). Iasi: An advanced sounder for operational meteorology. In *Proceedings of the 52nd Congress of IAF*, Toulouse France.

Dando, M. L., A. J. Thorpe, and J. R. Eyre (2007). The optimal density of atmospheric sounder observations in the met office nwp system. *Q. J. R. Met. Soc. 133*, 1933–1943.

English, S. J., R. Saunders, B. Candy, M. Forsythe, and A. Collard (2004). Met office satellite data observing system experiments. In *3rd WMO Workshop on the Impact of Various Observing Systems in Numerical Weather Prediction*, Alpbach, Austria. WMO.

Eyre, J. R. (2008). A vision for the global observing system in 2025. Available from WMO.

Goodrum, G., k. B. Kidwell, and W. Winston (2000). Noaa klm users guide. [Available online at http://www2.ncdc.noaa.gov/docs/klm].

Harris, B. A. and G. Kelly (2001). A satellite radiance bias correction scheme for data assimilation. *Q. J. R. Met. Soc. 127*, 1453–1468.

Kelly, G., J.-N. Thépaut, R. Buizza, and C. Cardinali (2007). The value of targeted observations - part i: Data denial experiments for the atlantic and the pacific. In *ECMWF Technical Memoranda Number 511*, ECMWF, Shinfield Park, Reading, UK. ECMWF.

LeMarshall, J., J. Jung, J. Derber, M. Chahine, R. Treadon, S. J. Lord, M. Goldberg, W. Wolf, H. C. L. J. Joiner, J. Woollen, R. Toddling, P. V. Delst, and Y. Tahara (2006). Improving global analysis and forecasting with airs. *Bulletin of the American Meteorological Society 87*, 891–894.

McMillin, L. and M. G. Divakarla (1999). Effects of possible scan geometries on the accuracy of satellite measurements of water vapour. *J.Atmospheric and Oceanic Technology 16*, 1710–1720.

Muth, C., P. S. Lee, S. Krimchansky, and W. A. Webb (2004). Advanced technology microwave sounder on npoess and npp.

Rawlins, F., S. P. Ballard, K. J. Bovis, A. M. . Clayton, D. Li, G. W. Inverarity, A.C.Lorenc, and T. J. Payne (2007). The met office global four dimensional variational assimilation scheme. *Q. J. R. Met. Soc. 133*, 347–362.

Rosenkranz, P. W., K. D. Hutchison, K. R. Hardy, and M. S. Davis (1997). An assessment of the impact of satellite microwave sounder incidence angle and scan geometry on the accuracy of atmospheric temperature profile retrievals. *J. Atmospheric and Oceanic Technology 14*, 488–494.

Swadley, S. and Coauthors (2008). Analysis and characterisation of the ssmis upper atmospheric sounding channel radiances. *IEEE Transactions on Geoscience and Remote Sensing 46*, 962–983.