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Harmonisation of the usage of microwave sounder data over land, coasts, sea ice and snow: First year report

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Abstract

The usage of microwave sounder data from different instruments has been made more consistent by harmonising the use of similar channels over land, sea ice and snow. This includes the introduction of MHS channel 4 over snow-covered land, ATMS channels 7, 8, 20, 21 and 22 over sea ice, ATMS channels 6, 18 and 19 over cold sea. In addition, the 118GHz channels of MWHS2 (channels 2 to 6) have been activated over land. Corresponding channels on other instruments are already used in these areas with a dynamic emissivity retrieval used to improve the accuracy of the observation operator for surface sensitive channels.

Results show small improvements to the first guess fits to independent observations including lower peaking temperature sounding channels from AMSU-A. This indicates the change is improving the accuracy of short range temperature forecasts in the troposphere. Also, geopotential height analysis increments are smaller and there are some significant benefits to forecasts out to 3 days, especially at high latitudes.

In addition, the usage of microwave sounder data in the all sky system has been extended to near coastal regions. Currently there is a strict quality control check which rejects all microwave sounder data in near coastal areas (land-sea mask value between 0 and 0.95) resulting in $\sim$14% of available MW sounder data not being assimilated in the all sky system. Relaxing this check results in significantly improved first guess fits to independent humidity sensitive and wind observations as well as modest improvements to geopotential height forecasts out to 5 days.

1 Introduction

In recent years at ECMWF the use of surface sensitive microwave sounder data has moved from being predominantly over ocean to gradually being extended over land, sea ice and snow-covered land (Di Tomaso et al., 2013; Bormann et al., 2017). Surface emissivity models over ocean are very accurate. Over land, sea ice and snow-covered land, however, the first guess skin temperature and surface emissivities are prone to large errors due to the heterogeneity of the surface properties and the diurnal cycle amongst other reasons. This has meant that the assimilation of microwave radiances over these surfaces has traditionally been more challenging due to the requirement for accurate skin temperature and surface emissivity as inputs to the radiative transfer model. Recently, the development of a dynamic emissivity retrieval (Karbou et al., 2006; Baordo and Geer, 2016) has enabled the use of the data over these surfaces and recent data denial experiments have shown that the data assimilated in these areas results in significant improvements to forecast accuracy (Bormann et al., 2017). Bearing in mind that the introduction of these data has been gradual there are now some inconsistencies in how similar channels from different instruments are used. The work presented here aims to address these inconsistencies and harmonise the usage of surface sensitive microwave sounding channels over these surfaces.

The assimilation of a selection of microwave humidity sounding channels over snow-covered land was introduced in March 2016 including SSMIS channels 10 and 11 as well as MHS channel 3. MHS channel 4 measures at the same frequency as SSMIS channel 10 but its use was unintentionally not introduced at the same time. Therefore the introduction of the assimilation of MHS channel 4 over snow-covered land will be tested here.

Recently the use of AMSU-A lower peaking temperature sounding channels 5-7 has been introduced over cold sea (defined conservatively as open sea with a skin temperature of less than 278K) and sea ice (Di Tomaso et al., 2013). The corresponding ATMS channels are currently not used in these areas. Therefore the introduction of ATMS temperature sounding channels 7 and 8 over sea ice and channel 6 over cold sea will be tested. In addition the use of MHS channels 3-5 has also been introduced over cold sea and sea ice (Di Tomaso et al., 2013). Again, the corresponding ATMS channels are not used in these areas. Therefore the introduction of ATMS humidity sounding channels 20, 21 and 22 over sea ice and channels 18 and 19 over cold sea will be tested.

The assimilation of MWHS2 data from the Chinese FY-3C satellite was implemented operationally in April 2016 (Lawrence et al., 2015b). This instrument is unique as it has 118GHz channels, the first time these channels have been flown in space. These channels are nominally temperature sounding channels but do have some sensitivity to cloud and humidity too, hence they were introduced in the all sky system. The initial implementation was conservative so these channels were only assimilated over ocean. Therefore the introduction of MWHS2 118GHz channels 2, 3, 4, 5 and 6 over land will be tested.

The assimilation of 183GHz channels from MHS, SSMIS, MWHS2 and SAPHIR is performed over ocean and land as detailed in Geer et al. (2014). However, there is currently very strict quality control of these observations over coastal areas or regions with mixed ocean and land which results in up to $\sim$14% of available observations being rejected. This check was introduced to avoid inaccurate emissivity retrievals affecting the first guess departures in these regions. In this report the first guess departure statistics are assessed and the assimilation of the higher peaking humidity sounding channels in these areas is tested.

The report is organised as follows: the results of the channel harmonisation experiments are discussed in section 2; the results of introducing the assimilation of all sky sounding channels over coasts are presented in section 3; and future planned work is summarised in section 4.

2 Harmonisation of the usage of MW channels over land, sea ice and snow

The changes to the use of MHS channel 4 and ATMS channels 6 to 8 and 18 to 22 are motivated by making the usage of these channels consistent with the use of corresponding channels on other instruments. The introduction of the assimilation of the 118GHz channels on the MWHS2 instrument over land represents the first time such channels have been assimilated over land. Therefore there are several details of the assimilation configuration that will be explored in section 2.1.

Channels	Areas blacklisted (current)	Areas blacklisted (proposed)	Extra data
MHS-4	Snow-covered land and orography>1000m	Orography>1000m	5%
ATMS-6	Sea ice, cold sea and orography>500m	Sea ice and orography>500m	9%
ATMS-7	Sea ice and orography>1500m	Orography>1500m	14%
ATMS-8	Sea ice	Nowhere	13%
ATMS-18, 19	Sea ice, cold sea and orography>800m	Sea ice, latitudes>60 °and orography>800m	5.5%
ATMS-20, 21	Sea ice and orography>1000m	Orography>1000m	17%
ATMS-22	Sea ice and orography>1500m	Orography>1500m	17%
MWHS2-2, 3, 4	Land and sea ice	Sea ice	51%
MWHS2-5	Land and sea ice	Orography>1500m and sea ice	33%
MWHS2-6	Land and sea ice	Orography>500m and sea ice	33%

Table 1: Areas where channels whose usage has been changed are blacklisted before and after the changes

Table 1 details the changes in data usage proposed. Surface classifications can be found in appendix A.

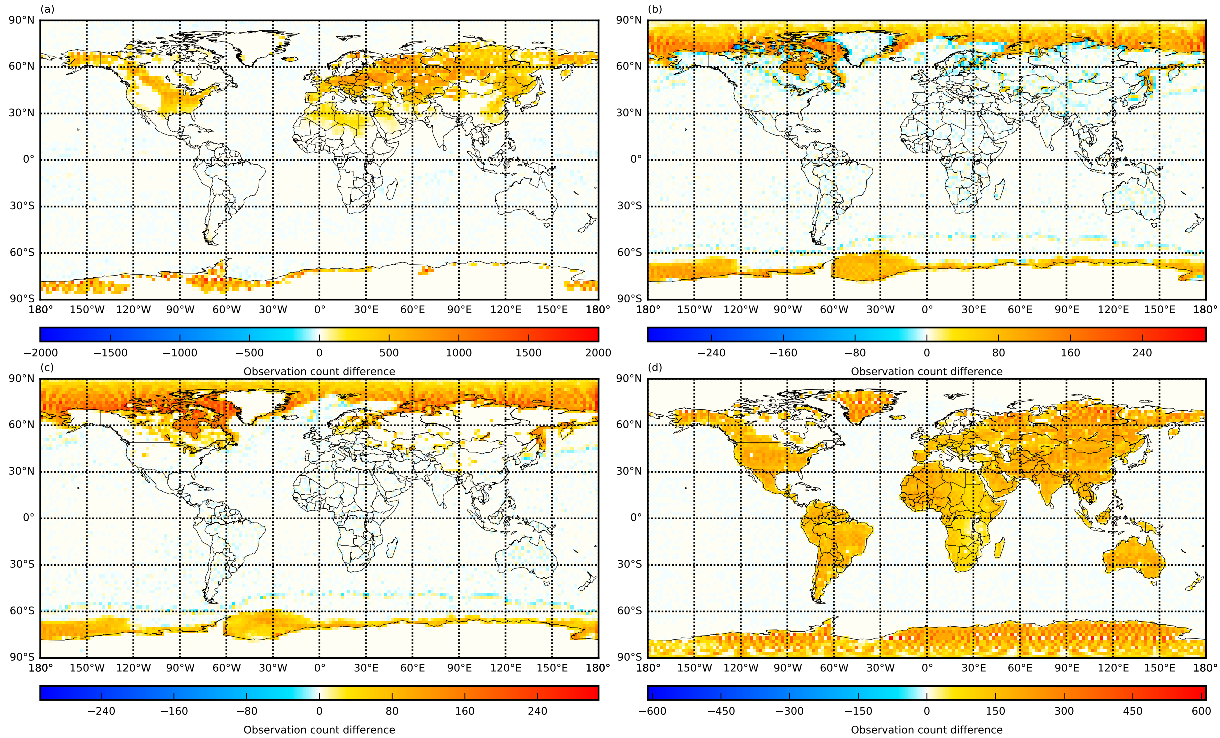

Figure 1: Maps showing the additional data assimilated in January 2015 for each change: (a) MHS channel 4; (b) ATMS channel 8; (c) ATMS channel 20; (d) MWHS2 channel 2

Figure 1a shows that more MHS channel 4 data are assimilated over Northern Europe, Russia, Northern China, Alaska, Canada, Northern United States and on the coast of Antarctica in the Northern hemisphere winter. In the Northern hemisphere summer extra observations are limited to the far North of Russia, Alaska and Canada and the far South of South America as well as the coastal areas of Antarctica (not shown).

Figures 1b and c show the extra ATMS data assimilated over sea ice. The distribution of this extra data obviously changes throughout the year as the areas covered by sea ice change but the overall increase in data is reasonably constant.

Figure 1d shows that the extra MWHS2 data assimilated covers all land surfaces away from coastal or mixed land-sea areas. There is additional orography screening implemented for the lowest peaking channel 5 and 6 as indicated in table 1.

2.1 MWHS2 118GHz channels over land

MWHS2 has 8 channels measuring close to the oxygen absorption line at 118GHz of which 6 are currently assimilated over ocean only. The instrument also has 5 channels measuring close to the water vapour absorption line at 183GHz of which 3 are currently assimilated. There are also 2 window channels, measuring at 89 and 150GHz. More details on the channel characteristics can be found in Lawrence et al. (2015b).

Over land the surface emissivity used in the forward calculations for the first guess in observation space

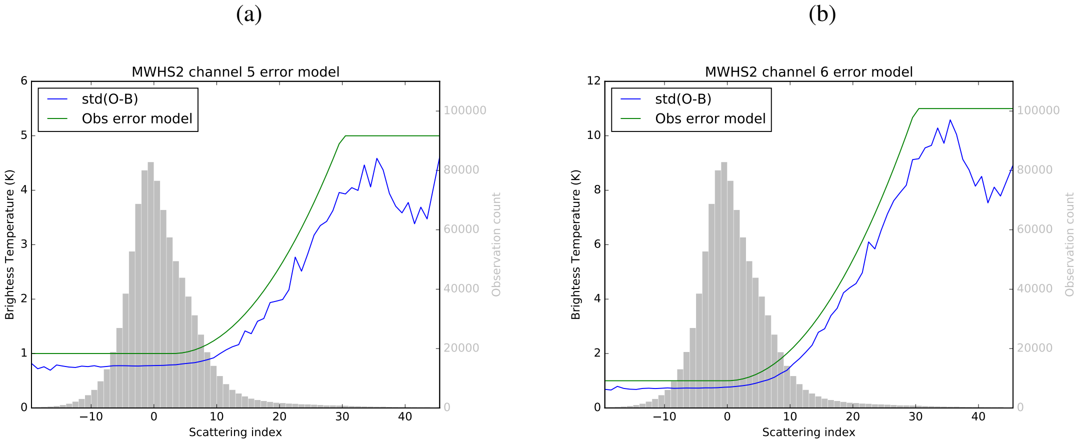

Figure 2: Observation error model (blue) and standard deviation of first guess departures (green) binned by scattering index for MWHS2 channels 5 (a) and 6 (b). Statistics are calculated from all MWHS2 observations over land (excluding scan positions 1 to 5 due to larger biases in observations from these scan positions as found by Lawrence et al. (2015b)) for a 2 month period: December 2015 and June 2016 merged together

is less accurate than over ocean. Therefore dynamic surface emissivity retrievals (Karbou et al., 2006; Baordo and Geer, 2016) are used to provide a more accurate estimate of this quantity resulting in smaller biases and random errors in the first guess departure statistics over land. For the existing assimilation of the MWHS2 183GHz channels the surface emissivity over land is retrieved from the 89GHz channel. For the assimilation of the 118GHz channels over land the surface emissivity could be retrieved from either the 89GHz channel or one of the two 118GHz window channels. It was decided to use the 89GHz channel as this channel has a stronger surface sensitivity than the 118GHz window channels.

As detailed in Lawrence et al. (2015b) a variational bias correction scheme is used to correct systematic biases in the MWHS2 data prior to the assimilation. The predictors used for the 118GHz channels are the same as for corresponding AMSU-A channels: a globally constant term; four layer thicknesses as airmass predictors; and a third order polynomial as a scan angle predictor. These same predictors will be used for the assimilation of the 118GHz channels over land.

The existing assimilation of MWHS2 is done within the all sky framework (Geer et al., 2014) which requires an observation error model to account for larger representation errors where cloud is present in either the model or observations. Lawrence et al. (2015b) provide details of the observation error model for the 183GHz channels which uses the difference between the brightness temperatures from the 89 and 150GHz channels (scattering index) as a cloud predictor. To account for situations when there is cloud in the model and not in the observation, and vice versa, the symmetric scattering index (average of the first guess and observations) is used.

For the assimilation of the 118GHz channels over land a quadratic observation error model based on the same symmetric scattering index is used. Figure 2 shows that this model matches the shape of the standard deviation of first guess departures when binned against the symmetric scattering index. The assumed error model is chosen conservatively as shown by the larger values of the error model compared to the standard deviation of first guess departures. This conservative approach is consistent with the error model applied to MHS data over land (Geer et al., 2014).

2.2 First guess departure statistics

Overall, the first guess departure statistics of the new data to be assimilated are similar to those of the corresponding data from other instruments which are already successfully assimilated. Therefore, judging by the first guess departure statistics, there should be no cause for concern when assimilating these new data.

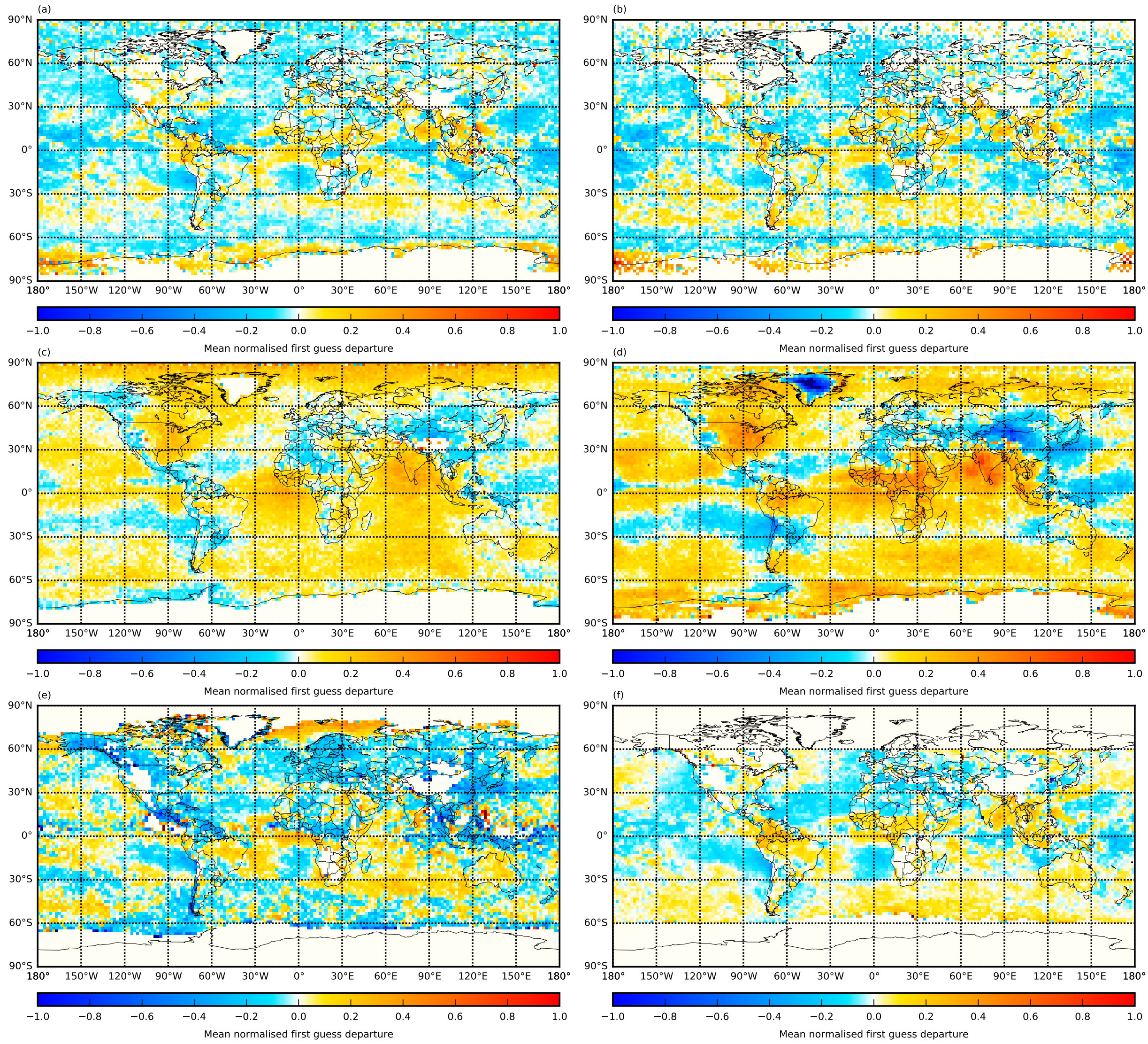

Figure 3: Maps showing the mean normalised first guess departures in June 2014 for selected channels whose usage has been changed (left column) and corresponding channels from other instruments (right column) for comparison: (a) MHS channel 4; (b) SSMIS channel 10; (c) ATMS channel 7; (d) AMSU-A channel 6; (e) ATMS channel 18; (f) MHS channel 5

Figure 3a shows that there are small residual biases for MHS channel 4 over snow-covered land which are very similar to the corresponding SSMIS channel 10 over the same regions (Figure 3b). The normalised residual biases in these areas are significantly smaller than those in the tropics.

Figure 3c shows that there is a slight warm bias in the ATMS lower peaking temperature sounding

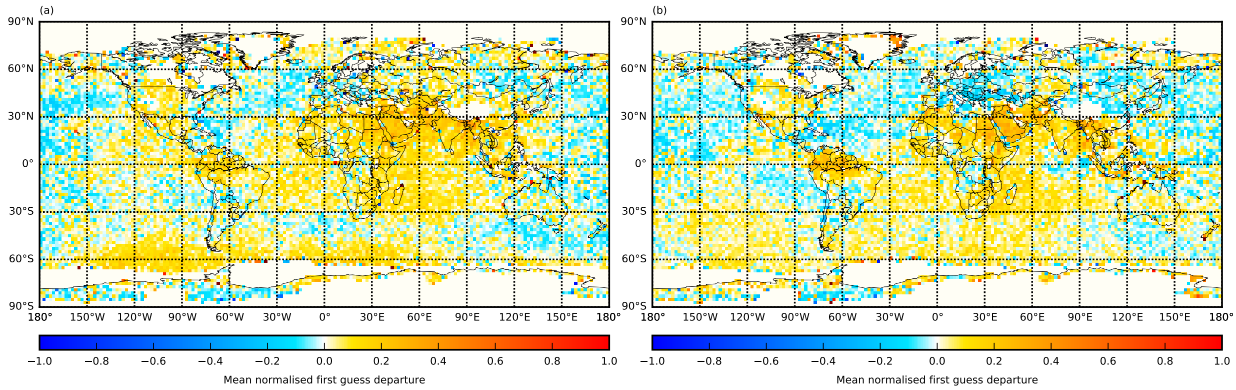

Figure 4: Map showing the mean normalised first guess departures in June 2014 for: (a) MWHS2 channel 5; (b) MWHS2 channel 6

channels over sea ice in the Northern polar regions but this is similar to the corresponding AMSU-A lower peaking temperature sounding channels (Figure 3d) which are successfully assimilated in these areas (Di Tomaso et al., 2013). Bormann et al. (2017) investigated the source of this bias and found it to be at least partially caused by the incorrect use of the specular reflection assumption in the radiative transfer calculations. Figures 3c and d also show slight differences in the data coverage between ATMS channel 7 and AMSU-A channel 6, e.g. over Greenland, Himalayas and Antarctica. This is due to the relaxed screening and variable observation error model described by Lawrence et al. (2015a) which is applied to AMSU-A but not ATMS.

Figure 3e shows that there are relatively large residual biases for ATMS channels 18 and 19 at high latitudes where the data is introduced over ocean and the sea surface temperature is less than 278K. Figure 3e shows this bias manifesting in the Northern high latitudes in the Northern hemisphere summer and a similar bias appears in the Southern high latitudes in the Southern hemisphere summer (not shown). The corresponding MHS channel 5 (and SSMIS channel 9) have some additional screening applied in the all sky system which rejects any data poleward of 60 °N and 60 °S, indicated in figure 3f. Therefore ATMS channels 18 and 19 were similarly blacklisted in these areas. There are also some other differences in the residual biases between ATMS channel 18 and MHS channel 5 and these are primarily caused by MHS being assimilated in the all sky framework and ATMS being assimilated through the clear sky framework. This means there are areas where the observations are clear and corresponding model points are cloudy for ATMS causing cold biases in the humidity sounding channels particularly around the ITCZ.

Figure 4 shows that the largest residual biases for MWHS2 channels 5 and 6 over land are over South America and the Middle East but these are similar in magnitude to the corresponding AMSU-A temperature sounding channels with similar weighting function peaks (e.g. figure 3d).

2.3 Experiments

Initial experiments were run over two periods of three months each: 2nd June 2014 to 1st September 2014 and 2nd December 2014 to 1st March 2015. The experiments used the configuration of cycle 42r1 of the IFS and ran at $T_{CO}639$ (18km) forecast resolution with the first, second and third inner loops of the assimilation minimisation run at T_L159 (120km), T_L191 (100km) and T_L255 (80km) resolutions

Seasons	Cycle	Description
Initial experiments		
Summer & Winter 2014	42r1	Control
Summer & Winter 2014	42r1	Above + MHS-4 over snow
Summer & Winter 2014	42r1	Above + ATMS temperature sounding channels over sea ice
Summer & Winter 2014	42r1	Above + MWHS2 118GHz channels over land
Summer & Winter 2014	42r1	Above + ATMS humidity sounding channels over sea ice
Final experiments		
Summer & Winter 2015/6	43r1	Control
Summer & Winter 2015/6	43r1	Above + all channel harmonisation changes combined

Table 2: Summary of experiments to incrementally test the channel harmonisation changes

respectively.

Final experiments were run over two periods of four months each: 2nd November 2015 to 28th February 2016 and 2nd May 2016 to 31st August 2016. The experiments used the configuration of cycle 43r1 of the IFS and ran at $T_{CO}399$ (55km) forecast resolution with the first, second and third inner loops of the assimilation minimisation run at T_L95 (170km), T_L159 (120km) and T_L255 (80km) resolutions respectively. Table 2 shows the exact configurations run for both the initial and final experiments.

2.4 Results

To assess whether the changes in data usage are resulting in an improvement or degradation the change in standard deviation of first guess departures of independent observations can be investigated. The independent observations are used as a proxy for the truth as their usage remains unchanged between experiments and controls. In contrast, the background forecasts used to produce the first guess departures will have changed due to the extra data being assimilated in the analysis. Therefore a decrease in standard deviation of first guess departures suggests that the extra data is improving the accuracy of the background forecasts and vice versa. For example a decrease in the standard deviation of first guess departures of AMSU-A channel 5 indicates improved lower/mid tropospheric temperature forecasts.

Results from the individual changes show very small differences in the standard deviations of first guess departures which are almost always not statistically significant. However, when combined together there are some significant results. Figure 5 shows that the combination of channel usage changes results in a small (up to 0.05%) but significant reduction in the standard deviation of first guess departures of AMSU-A channels 5 to 9, indicating slightly improved background forecasts of tropospheric and lower stratospheric temperature. The largest improvement appears to come from the addition of the ATMS temperature sounding channels over cold sea and sea ice.

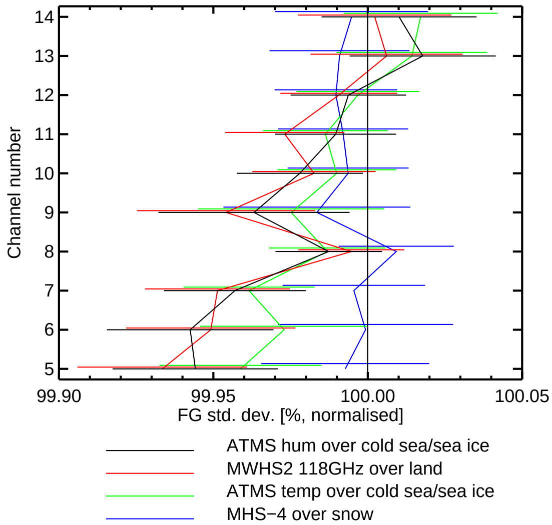

Figure 5: Change in global standard deviation of first guess departures for AMSU-A when each of the channel harmonisation changes are incrementally added to the control experiment

Figure 6a shows that the statistically significant improved first guess fits to AMSU-A channels 5 to 9 are similar in the final experiments as they were in the initial combined experiments (figure 5). Ignoring the changes for the channels whose usage has been changed (ATMS channels 6 to 8 and 18 to 22 and MHS channel 4), figures 6b and c show that the first guess fits to ATMS channels 9 and 10 and MHS channel 3 are also slightly improved. Finally, figure 6d shows that the first guess fit to MWHS channel 5 is also slightly improved. These improved fits indicate improved background forecasts of tropospheric and lower stratospheric temperature and upper tropospheric humidity resulting from the assimilation of the additional data. There is also a small (up to 0.1%) but significant improvement to the standard deviations of first guess departures of SSMIS channel 11 indicating improved upper tropospheric humidity forecasts (not shown).

To assess the effect of the data usage changes on longer range forecasts the forecast scores can be analysed. Forecast scores are the root mean square error (RMSE) difference between forecasts at various lead times and the analysis valid at the same time. A reduction in these errors in the experiment compared to the control indicates that the change is improving the accuracy of the forecasts and vice versa.

As with the change in standard deviation of first guess departures the majority of the changes in forecast scores resulting from the individual changes are small enough to not be statistically significant. However, when considering the channel harmonisation changes as a whole there are some significant areas of improvement to the forecast scores.

Figure 7 shows that the RMSE of geopotential height forecasts is reduced in both the Northern and Southern high latitudes at T+12. This indicates smaller analysis increments so the short range forecasts in these areas are more accurate and the analysis is having to make less of an adjustment. The benefits in these areas are also carried forward into the T+24 forecasts. There are also small areas of significant improvements in the stratosphere in the Northern mid latitudes between T+72 and T+120. There are apparent small improvements to forecasts all the way out to T+216 in the Northern high latitudes although these changes are not statistically significant. The apparent degradation to the upper troposphere in the tropics between T+48 and T+96 does not appear in the corresponding plot showing the difference in forecast error standard deviations (not shown).

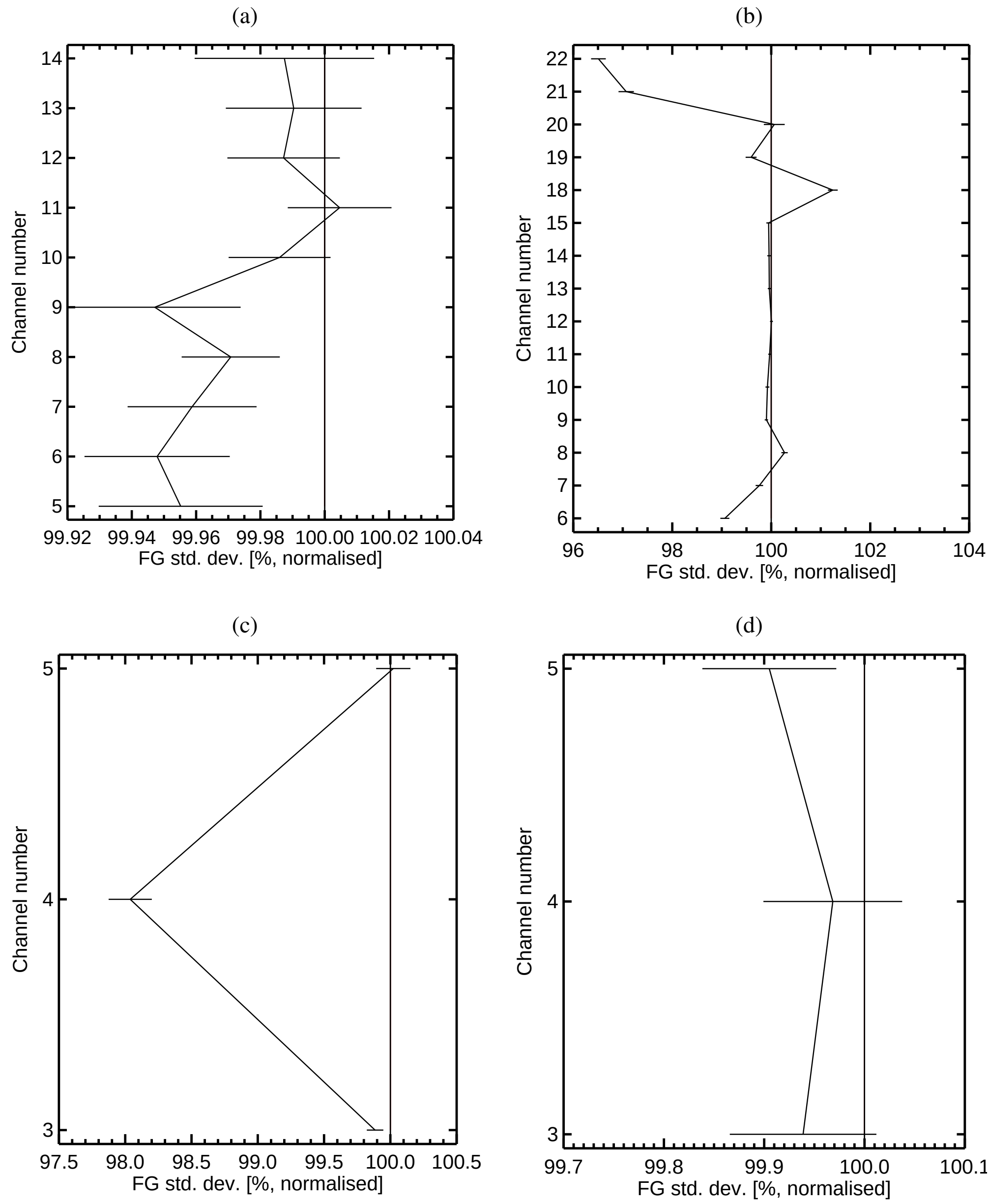

Figure 6: Change in standard deviation of first guess departures for AMSU-A (upper left), ATMS (upper right), MHS (lower left) and MWHS (lower right) for the final channel harmonisation configuration against the control experiment

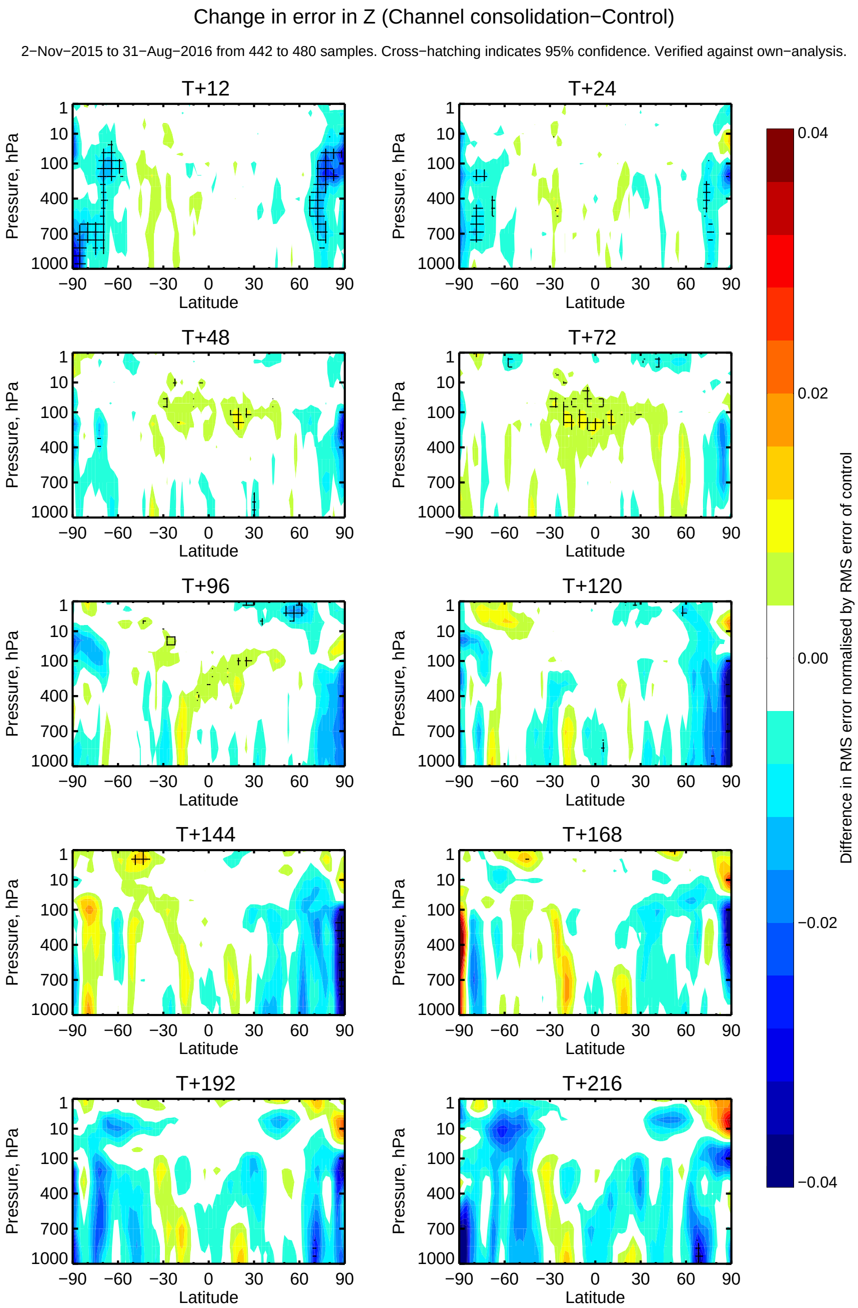

Figure 7: Zonal plots of change in root mean square error of geopotential height forecasts against own analysis for the final channel harmonisation configuration against the control experiments

From the studies of Di Michele and Bauer (2005) it was expected that the assimilation of the MWHS2 118GHz channels may lead to a positive impact on precipitation forecasts over land. However, the change in background fits to NEXRAD data over the US was assessed in the experiments to introduce these channels and there was no significant improvement or degradation. In these tests channels 2 to 6 are assimilated over land whereas there may be more benefit to precipitation forecasts from using channels 7 to 9 (118GHz $\pm$ 2.5/3.0/5.0) which are in the wings of the 118GHz oxygen absorption line and hence are sensitive lower down in the troposphere. However, the use of these channels over land is more challenging as they have much stronger sensitivity to the surface and hence any errors in the retrieved surface emissivity or skin temperature will lead to larger biases in the first guess departures.

2.5 Summary

In this section the usage of microwave sounding channels has been harmonised for a number of instruments and channels. The changes result in improved first guess fits to low peaking AMSU-A channels and upper tropospheric humidity sensitive channels. This indicates improved background temperature forecasts in the troposphere and improved background humidity forecasts in the upper troposphere. The change also results in smaller geopotential height analysis increments in the high latitudes where the majority of extra data is added. There are also small areas of significant improvements to geopotential height forecasts from T+24 to T+120 forecasts, particularly at high and mid latitudes in the stratosphere.

In light of these results the channel harmonisation changes were recommended for operational implementation and will be included with cycle 43r3.

3 All sky sounding channels over coastal areas

In the all sky system channels are classified into four different types of channel depending on where in the atmosphere they are sensitive to. These categories are imaging channels, lower tropospheric sounding channels, upper tropospheric sounding channels and stratospheric channels. This classification affects how the channel is treated in the assimilation, for example the stratospheric channels use a fixed observation error as they are not sensitive to cloud and precipitation. Also, the imaging channels are not used over land due to their large sensitivity to surface parameters such as skin temperature and surface emissivity which are less accurate over land. In this report sounding channels are defined as all channels other than imaging channels. The lowest peaking of these channels still have some sensitivity to the surface but the surface to space transmittance is generally below 0.2. For humidity sounding channels, the combination of the low surface to space transmittance and the use of a dynamic emissivity retrieval (Baordo and Geer, 2016) means that errors resulting from the inaccurate skin temperature and surface emissivity in the forward calculations are not significant compared to other error sources. This has allowed the introduction of the active assimilation of these channels over land at ECMWF in recent years.

Currently any all sky observations near coasts or in mixed land and sea areas, defined as having a model land-sea mask value of between 0.01 and 0.95, are rejected. The exact proportion of data rejected due to this check therefore depends on the model resolution. At operational resolution ($T_{CO}1279$) between 8% and 16% of all sky MW sounding channel observations are rejected. At the lower resolutions ($T_{CO}399$) used for experiments and testing between 13% and 30% of these observations are rejected. The difference is due to the lower resolution land-sea mask having more points with mixed land and sea values (between 0.01 and 0.95). Figure 8 shows that these areas surround all of the continents but also cover many small islands and areas of inland lakes and seas. For example very little all sky data is currently assimilated over

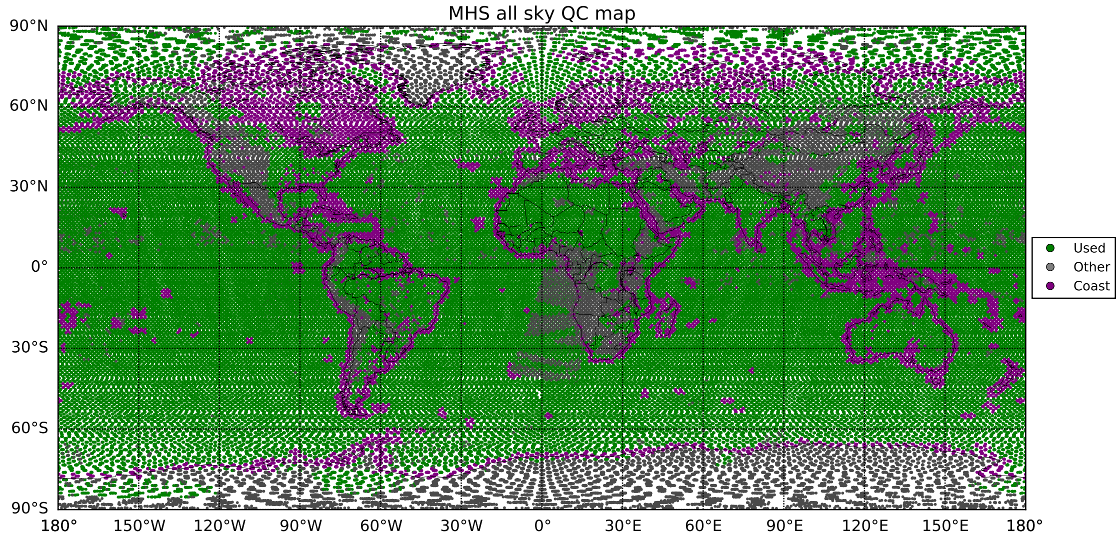

Figure 8: Map showing used observations (green), observations rejected due to coast check (purple) and observations rejected for other reasons (grey) for MHS channel 4 observations from a single DA cycle at 00z on 1st November 2016

Northern Canada, Scandinavia and the maritime continent. This conservative check was implemented at a time when all sky microwave data was only assimilated over ocean to avoid any unwanted land contamination.

The all sky assimilation of MW sounding channels has resulted in significant improvements to forecast accuracy (Geer et al., 2014) in recent years so, providing the first guess departure statistics of observations in coastal areas are broadly similar to those over ocean and land, there should be some benefit to be gained from additionally assimilating these channels in coastal regions.

3.1 First guess departure statistics

Before relaxing the coastal quality control the first guess departure statistics should be assessed in these areas. The emissivity used in the first guess calculations over coastal areas uses the same methodology as over land, i.e. it is dynamically retrieved from a window channel using the model first guess surface skin temperature. This method should account for any heterogeneity of the surface classification within the field of view of the instrument. Figure 9 shows that there is very little variability in the mean and standard deviation of first guess departures of MHS channel 4 when binned by the land-sea mask value in the tropics, mid latitudes or high latitudes. In fact, for the majority of land-sea mask values between 0 and 1 the standard deviation of first guess departures is actually less than the values over land (land-sea mask equal to 1). The exception is for land-sea mask values around 0.9 in high latitudes the standard deviation of first guess departures is slightly larger than for a land-sea mask value of 1. However, this could just be sampling noise.

The first guess departure statistics for other all sky MW sounding channels with little surface sensitivity are similar. Given the data in coastal regions looks of a similar quality to the data over ocean and land the assimilation of these channels in coastal areas will be tested. The observation error model used in coastal areas is the same as the one currently used over land, i.e. using the scattering index as a cloud predictor. A full list of the channels to be introduced over coasts is given below:

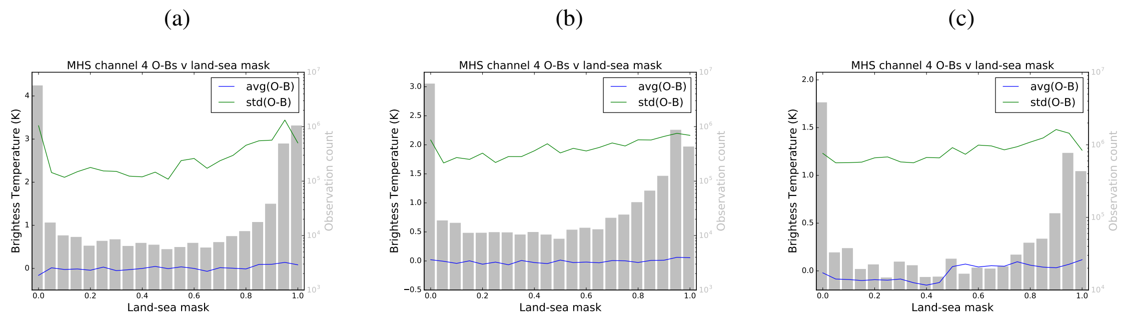

Figure 9: Mean (blue) and standard deviation (green) of first guess departures for MHS channel 4 binned by land-sea mask value for the: (a) tropics; (b) mid latitudes; (c) high latitudes. Data sample is 2 months: June and November 2016 merged together

- MHS: Channels 3 and 4 on MetOp-A & B, NOAA-18 and channel 4 on NOAA-19
- MWHS2: Channels 2, 3, 4, 5, 6, 11 and 12 on FY-3C
- SSMIS: Channels 10 and 11 on F-17
- SAPHIR: Channels 1, 2 and 3 on Megha-Tropiques

This means there will be data from a total of 19 channels added over coastal areas.

3.2 Experiments

Experiments were run over two periods of four months each: 1st June 2016 to 30th September 2016 and 1st November 2016 to 28th February 2017. The experiments used the configuration of cycle 43r3 of the IFS and ran at $T_{CO}399$ (55km) forecast resolution with the first, second and third inner loops of the assimilation minimisation run at T_L95 (170km), T_L159 (120km) and T_L255 (80km) resolutions respectively. The full set of experiments run is summarised in table 3.

Seasons	Cycle	Description
Summer & Winter 2016/17	43r3	Control
Summer & Winter 2016/17	43r3	Control + all sky sounding channels over coasts
Summer & Winter 2016/17	43r3	Control + all sky sounding channels over coasts (not over snow/sea ice)
Summer & Winter 2016/17	43r3	Control + all sky sounding channels over coasts (not in the tropics)

Table 3: Summary of experiments to test the all sky over coasts changes

3.3 Results

Adding the microwave sounding data over coasts (second row of table 3) results in improved first guess fits to AMSU-A channels 5 to 11 as shown by figure 10a indicating improved tropospheric and lower stratospheric temperature background forecasts. Figure 10b shows improved first guess fits to ATMS channels 6 to 9 and 18 to 22 indicating improved tropospheric temperature and humidity background forecasts. Figure 10c shows improved first guess fits to CrIS humidity sounding channels indicating improved tropospheric humidity background forecasts. Finally, figure 10d shows improved fits to conventional wind observations between 150hPa and 70hPa indicating improved upper tropospheric and lower stratospheric wind forecasts, particularly in the tropics (not shown). The majority of other humidity sensitive observations also show improved fits and upper tropospheric fits to AMVs are also improved (not shown). This gives confidence that the signals shown are indicating real benefits to short range forecasts of temperature, humidity and wind.

Figure 11 shows that the change results in improved tropospheric geopotential height forecasts in the Northern hemisphere with statistical significance to day 2. There are also longer lasting improvements in the Northern hemisphere stratosphere out to day 4. These improvements are also visible for vector wind and there is also a significant improvement to short range vector wind at $\sim$100hPa in the tropics which is consistent with the improved first guess fits to conventional wind and AMV observations.

However, at longer ranges there are significant degradations in the Northern hemisphere at days 5 to 7, particularly at day 6. These degradations affect 500hPa to 100hPa geopotential height, vector wind and temperature forecasts. Figure 12 shows that these degradations are centred over North America at day 5, spreading into the North Atlantic at day 6 and Europe at day 7. Before day 5 it is hard to track the errors back to find the source but there are two possible areas where a significant amount of extra data has been added. Firstly, the extra data over snow and sea ice could be the cause with the errors propagating South and taking 5 days to amplify into a significant signal over North America. Larger residual biases in ATMS humidity channels were seen in these areas in section 2.2, suggesting short-comings in the surface emissivity treatment in these areas. Di Tomaso et al. (2013) showed that assimilating additional microwave temperature and humidity sounding data over the high latitudes caused significant moistening and warming of the atmosphere which is also seen in the experiments reported on here. At short range this appears to be correcting a dry and cold model bias when verified against radiosonde observations but it may be that it adding even more data leads to forecast degradations at longer lead times. On the other hand, the first guess fits to AMSR2 are slightly degraded in the tropics indicating that the change may be degrading the forecasts of convective rain in the tropics. This potentially indicates a second possible source of the extra data in the tropics (especially the maritime continent) where these errors could propagate across the Pacific to North America to affect day 5 forecast scores in these areas.

To test these hypotheses two further sets of experiments were run where: firstly data over coasts where the land was classified as snow or the ocean was classified as sea ice were removed (third row of table 3); secondly data over coasts in the tropics (latitudes between 20 °S and 20 °N) were removed (fourth row of table 3). The results of these experiments show that the degradation was still present when the data in the tropics was removed but became much weaker when the data over snow and sea ice was removed. Therefore, it would appear that the source of the degradations is the extra data over mixed snow and sea ice areas in the high latitudes.

Rejecting coastal data over snow and sea ice means that the overall increase in data assimilated for the sounding channels decreases from $\sim$13-30% to $\sim$10-20%. Consequently, figure 13 shows that the improvements to first guess fits with the final configuration are slightly weaker than with the original configuration. However, the majority of significant improvements from the initial experiments are still

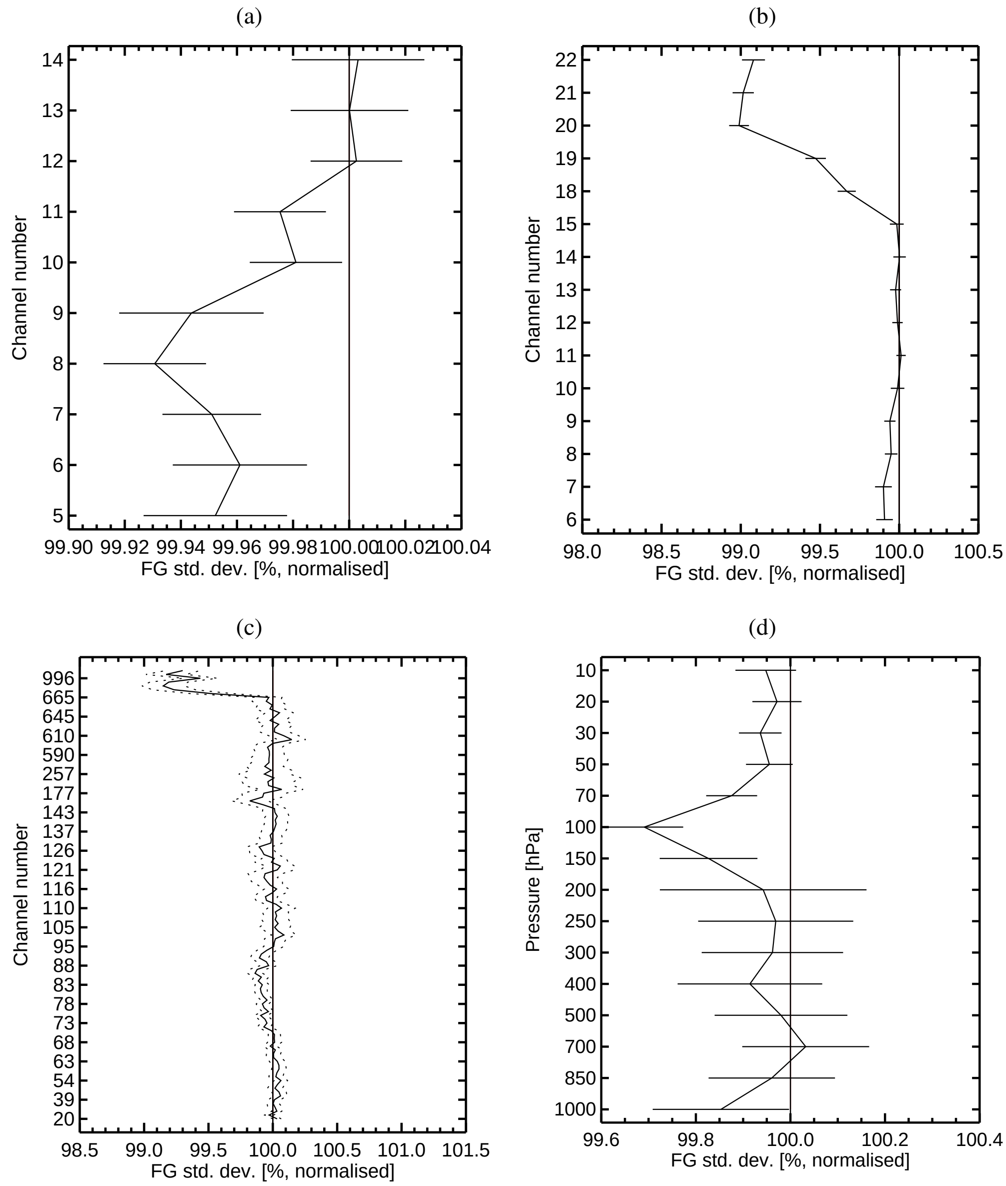

Figure 10: Change in standard deviation of first guess departures for AMSU-A (upper left), ATMS (upper right), CrIS (lower left) and conventional wind observations (lower right) for the initial all sky sounding channels over coasts experiments against the controls

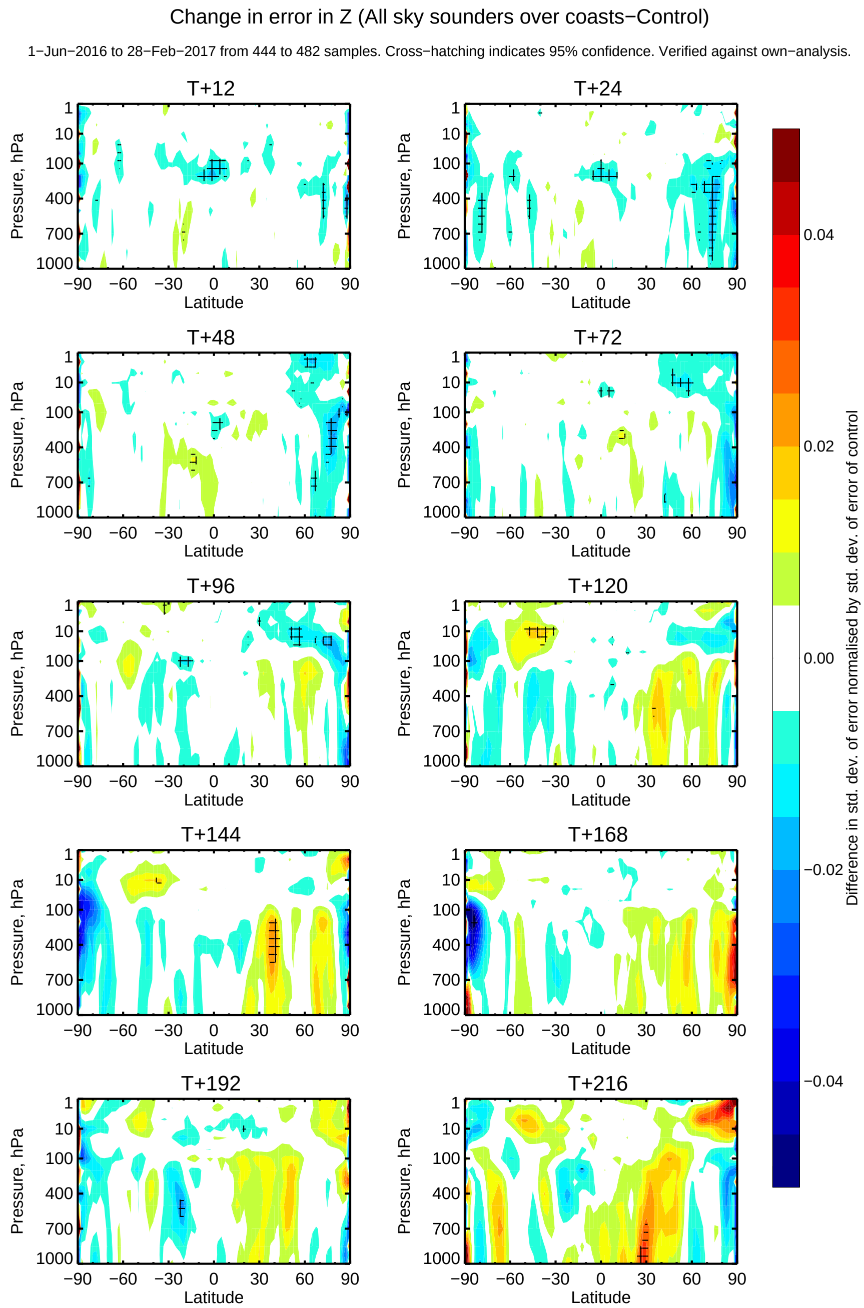

Figure 11: Zonal plots of change in standard deviation of geopotential height forecasts against own analysis for the initial all sky over coasts experiments against the control

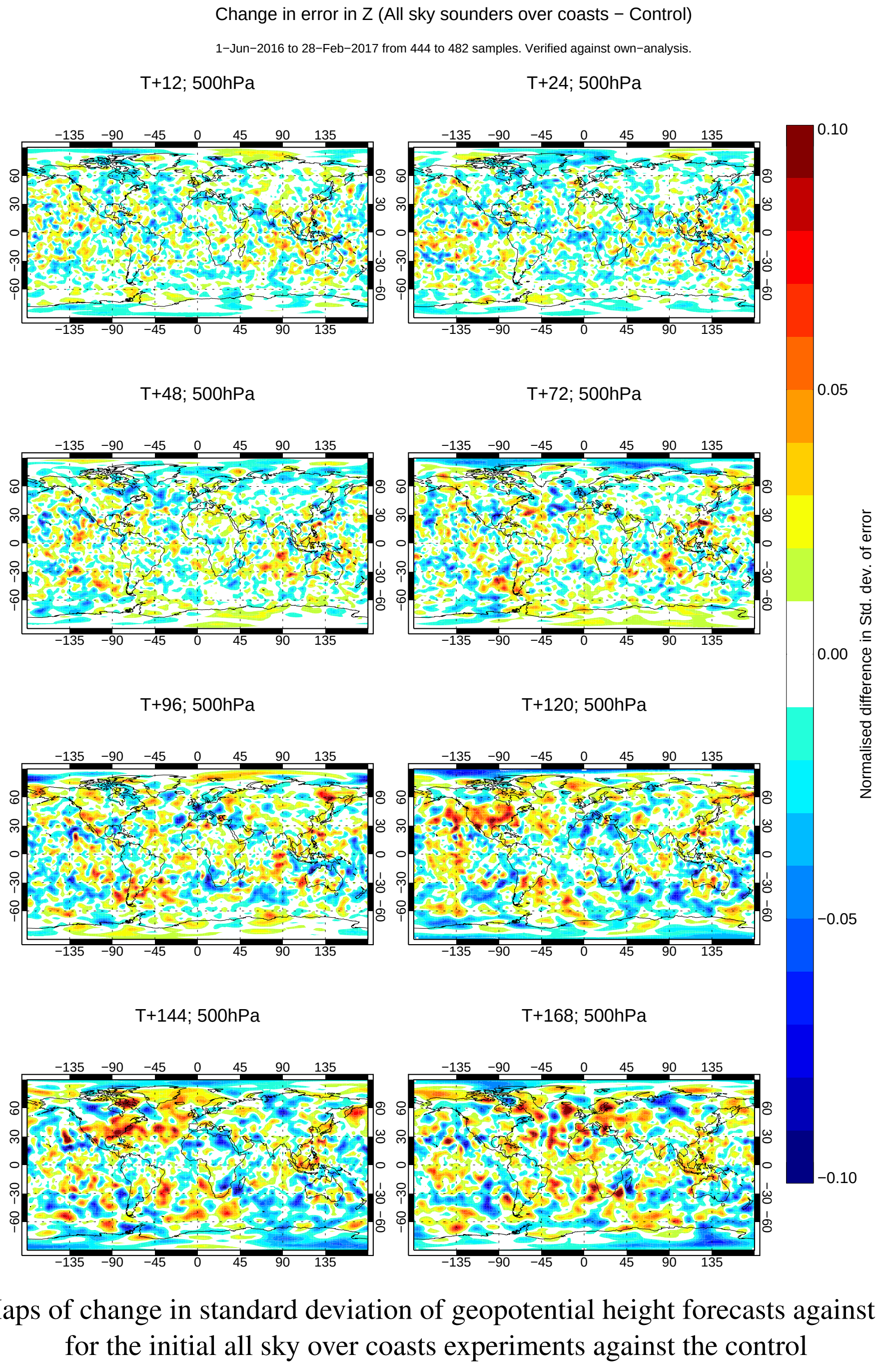

Figure 12: Maps of change in standard deviation of geopotential height forecasts against own analysis for the initial all sky over coasts experiments against the control

significant in the final experiments. In particular, improvements to first guess fits to AMSU-A and ATMS temperature sounding channels are reduced by ∼20-50%, ATMS and CrIS humidity sounding channels are reduced by ∼30-40% whereas the improved fits to conventional wind and AMV observations are unaffected as most of this impact is coming from the extra observations over coasts in the tropics. This still indicates improved background forecasts of tropospheric and lower stratospheric temperature, tropospheric humidity and upper tropospheric and lower stratospheric tropical winds.

Comparing figure 14 with figure 11 shows that the degradations in the Northern hemisphere at days 5 to 7 are not present with the final configuration. However, some of the improvements in the day 1 to 4 Northern hemisphere forecasts are also weakened by rejecting the coastal snow and sea ice data. Nonetheless there are still areas of significant improvements which mean that the extra data still represents a useful addition to the system. Therefore, this configuration, with all sky sounding channel data added over coasts except in areas of mixed snow and sea ice, makes a good candidate for operational implementation.

In previous work it has been identified that the assimilation of microwave sounding data in areas covered by snow and sea ice could be improved upon (Baordo and Geer, 2015; Bormann et al., 2017). This is outside the scope of the present study but could be revisited in future work.

3.4 Summary

In this section the additional assimilation of all sky microwave sounding channels over coastal areas has been tested. The change results in improved first guess fits to tropospheric and lower stratospheric temperature observations (e.g. AMSU-A, ATMS), humidity sensitive observations (e.g. ATMS, CrIS) and wind observations (e.g. AMVs and conventional wind observations). These results indicate improved background temperature forecasts in the troposphere and lower stratosphere, humidity forecasts in the troposphere and wind forecasts in the upper troposphere and lower stratosphere. The change also results in small but significant improvements to geopotential height, vector wind and, to a smaller extent, temperature forecasts in the Northern hemisphere out to day 5. There is also a significant improvement to tropical upper tropospheric wind forecasts at T+12 and T+24.

In light of these results the assimilation of microwave sounding data in near-coastal areas has been recommended for operational implementation and is planned to be included with cycle 45r1.

4 Future work

There are a couple of possible avenues to explore in order to extend the work summarised in this report. It would be good to understand the mechanisms behind the poor results from adding the all sky sounding data over coasts at high latitudes where there is snow-covered land and sea ice. One potential cause is the assumption within the radiative transfer of specular reflection of radiation over snow and sea ice surfaces. In reality, the radiation is more likely to undergo diffuse (or Lambertian) reflection. This effect is quantified in Bormann et al. (2017) and could be explored further. In addition, the emissivity over sea ice and snow is highly variable and it may be useful to extend the study of Baordo and Geer (2015) to attempt to obtain more accurate estimates of emissivity over snow and sea ice.

The assimilation of two GMI humidity sounding channels over ocean has recently been tested and will be implemented at cycle 43r3 (Lean et al., 2017). In the future the assimilation of these channels could be extended to land surfaces and, for the least surface sensitive of the channels, could also be extended to

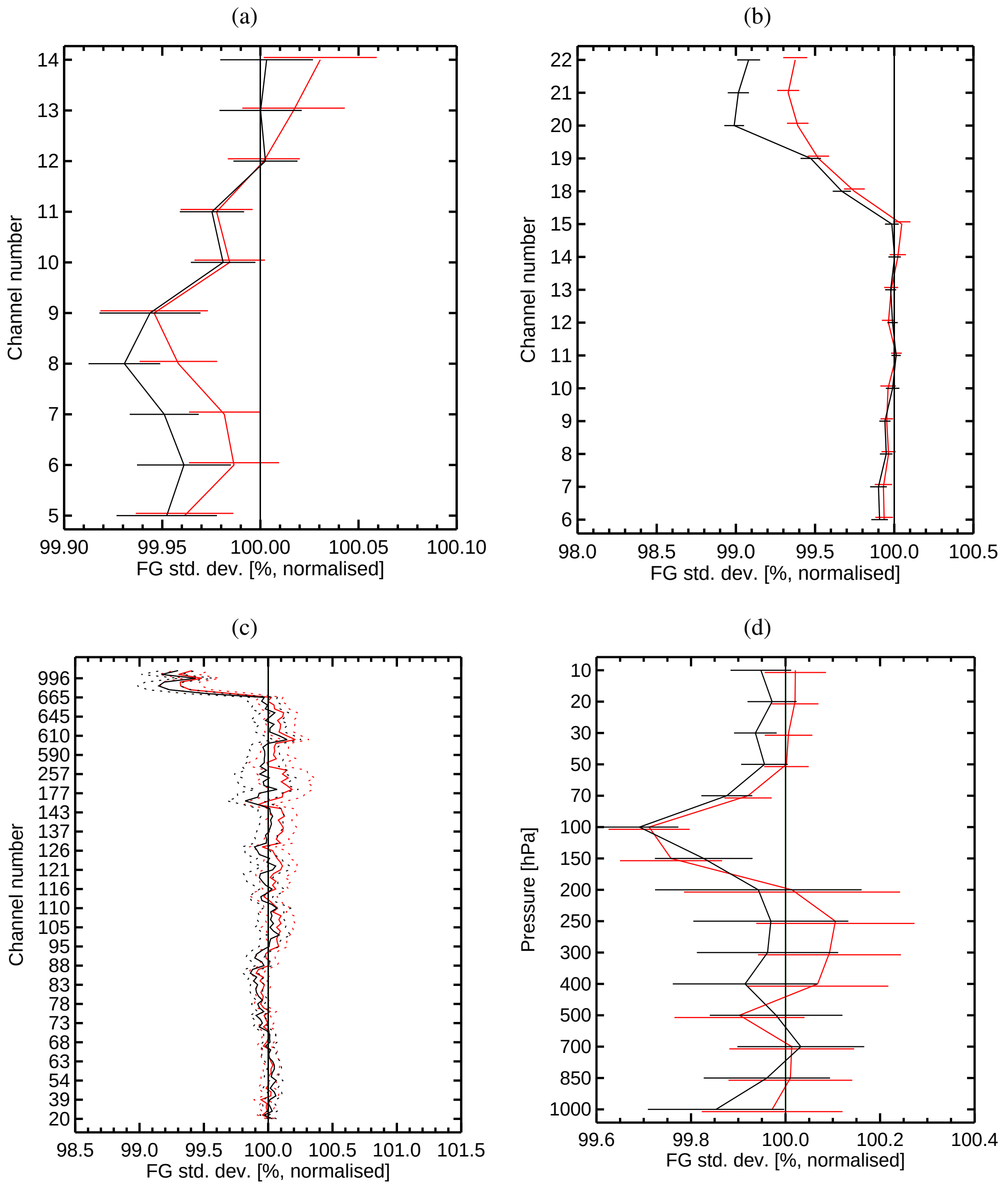

Figure 13: Change in standard deviation of first guess departures for AMSU-A (upper left), ATMS (upper right), CrIS (lower left) and conventional wind observations (lower right) for the initial (black) and final (red) all sky sounding channels over coasts experiments against the controls

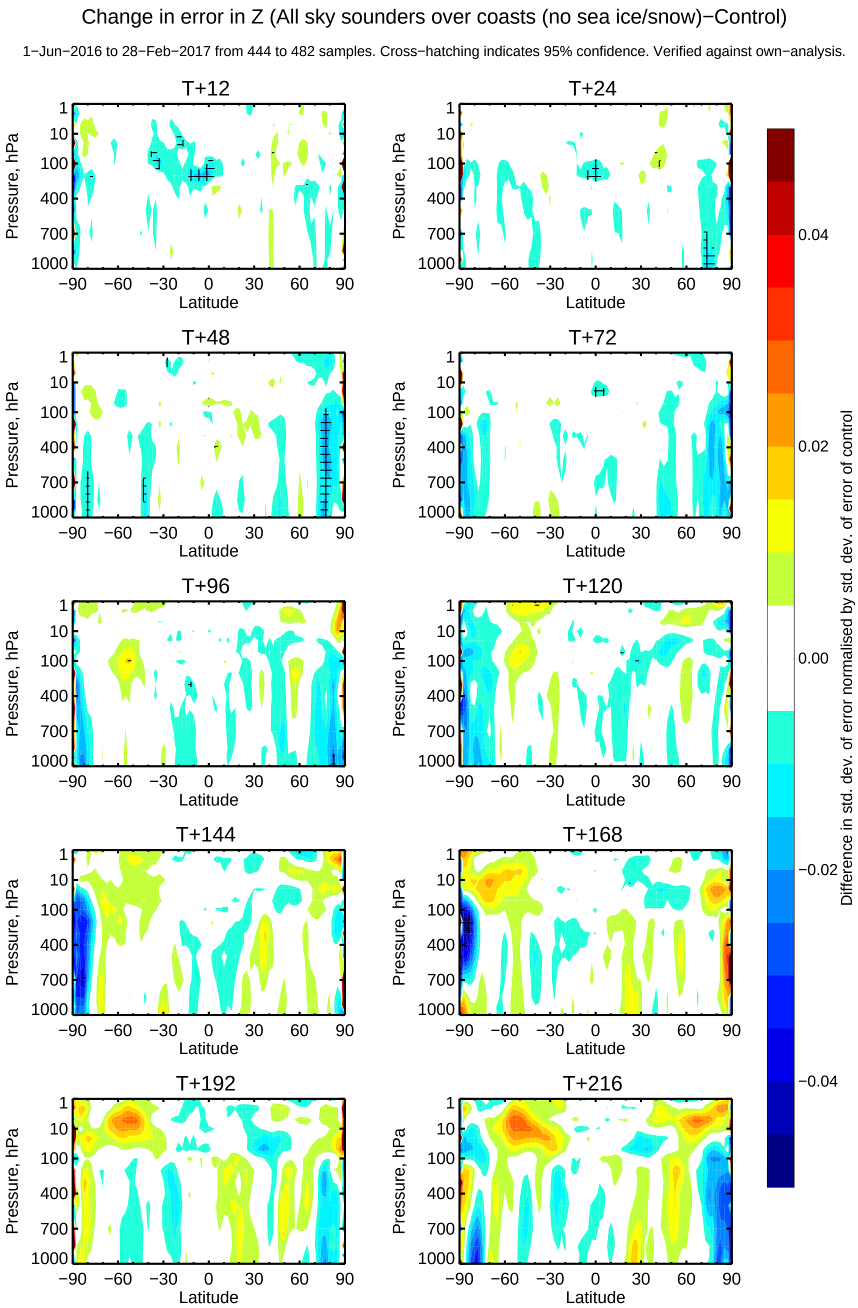

Figure 14: Zonal plots of change in standard deviation of geopotential height forecasts against own analysis for the final all sky over coasts experiments against the control

coastal regions. This would follow the existing methodology for the other humidity sounding channels using a dynamic emissivity retrieval and would make the usage of all humidity sounding channels in the all sky system consistent across instruments.

Another significant ongoing project is to test moving the assimilation of the AMSU-A temperature sounding channels from the currently operational clear sky assimilation methodology to the all sky system. This builds on previous work (Geer et al., 2012) to develop the framework for processing AMSU-A through the all sky system.

Currently, cloud affected AMSU-A radiances are identified using checks on the first guess departures and cloud liquid water retrievals from AMSU-A window channels. Where cloud is detected the lowest peaking channels 5 to 8 are rejected and not assimilated. This results in up to 25% of the available data not being assimilated. The aim is to relax the cloud screening and assimilate AMSU-A radiances in both clear and cloudy conditions through the all sky system. The expected benefits would come from the additional temperature information in meteorologically active areas as well as direct constraints on cloud liquid water and frozen hydrometeors. The main challenge associated with this work is to separate the increments to temperature from those to the cloud hydrometeors which is tricky when the observations in question are sensitive to both simultaneously.

Later in 2017 the first JPSS satellite is planned for launch which will carry an ATMS instrument onboard, amongst others. Once launched the data quality of this instrument will be assessed and, if satisfactory, assimilation experiments will be run to test the impact of additionally assimilating this new instrument. This will be the second ATMS instrument in orbit but with both temperature and humidity sounding channels it is hoped that assimilating a second ATMS will still lead to improved forecast accuracy on top of just assimilating one ATMS.

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Appendices

A Surface classifications

In the IFS blacklisting procedures surfaces are classified as follows:

- Ocean: any observation field of view (FOV) where the model land-sea mask value is less than 0.01 and the sea ice mask value is less than 0.01 i.e. the FOV is covered by less than 1% land and 1% sea ice

- Land: any observation FOV where the model land-sea mask value is greater than 0.01. N.B. There are some additional conditions for some observation types in coastal areas where the land-sea mask value lies between 0.01 and 0.95

- Sea ice: any observation FOV where the land-sea mask value is less than 0.01 and the sea ice mask value is greater than 0.01
- Cold sea: any observation FOV where the land-sea mask value is less than 0.01 and the surface temperature is less than 278K
- Snow-covered land: any observation FOV where the land-sea mask value is greater than 0.01 and the surface temperature is less than 278K

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