Assessment of FY-3C microwave sounding data

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Contents

Abstract

Microwave sounding instruments were launched on China's FY-3C platform in Sept 2013 and data have been operationally received since October 2014. The early operational data have been assessed using comparisons to Numerical Weather Prediction (NWP) fields and to the performance of similar instruments. The MicroWave Temperature Sounder - 2 (MWTS-2) exhibits features such as large scale negative biases, striping and an unexplained surface sensitivity in channels whose peak sensitivity should be high in the atmosphere. The MicroWave Humidity Sounder - 2 (MWHS-2) shows some promising results in a new suite of 118GHz channels, while data from the 183GHz channels are comparable in quality to equivalent channels on instruments already used successfully in NWP, reanalysis and climate applications. Results of assimilation experiments including data from MWHS-2 183GHz channels are discussed. While overall impacts on forecast accuracies are mostly neutral, improved fits to the model are seen in other humidity sensitive channels on independent instruments, indicating the MWHS-2 data improves the analysis.

1. Introduction

Microwave sounding satellite instruments form an important part of the Met Office observing system where, in recent years, a combination of several microwave sounders has had a consistently large impact on reducing analysis and forecast errors (Joo et al. 2013). The Advanced Microwave Sounding Unit (AMSU) A and B, the Microwave Humidity Sounder (MHS) and, recently, the Advanced Technology Microwave Sounder (ATMS), have provided microwave sounding data for operational Numerical Weather Prediction (NWP) and reanalysis systems since the late 1990s. Until now, data has predominantly been from missions sponsored by the US and Europe. **Figure 1** shows a timeline of the operational sounding satellites launched since 1978 and current plans for future missions until 2040. It shows that the Chinese FengYun (FY) series will become a significant source of sounding data in the next decade. It is therefore important to assess the FY-3 data quality and the potential benefit for NWP and reanalysis applications. In addition, a timely evaluation of the earlier instruments in the series (FY3-A, -B and -C) will also influence the design and pre-launch testing of future satellites, the primary aim being to minimise the risk of sub-optimal performance in subsequent missions. The first two satellites in the sounding series, FY-3A and FY-3B, launched in May 2008 and November 2012 respectively, were considered experimental missions. FY-3C, launched in September 2013, is the first operational mission and features more advanced versions of some of the instruments on previous platforms, as well as the addition of a radio occultation instrument. In particular, the microwave sounding instruments, MicroWave Temperature Sounder - 2 (MWTS-2) and MicroWave Humidity Sounder - 2 (MWHS-2), have been developed with extra channels with respect to their experimental predecessors. These instruments will be deployed on future platforms and will potentially become an important source of microwave sounding observations in the Met Office NWP system as well as supporting global and regional reanalysis efforts.

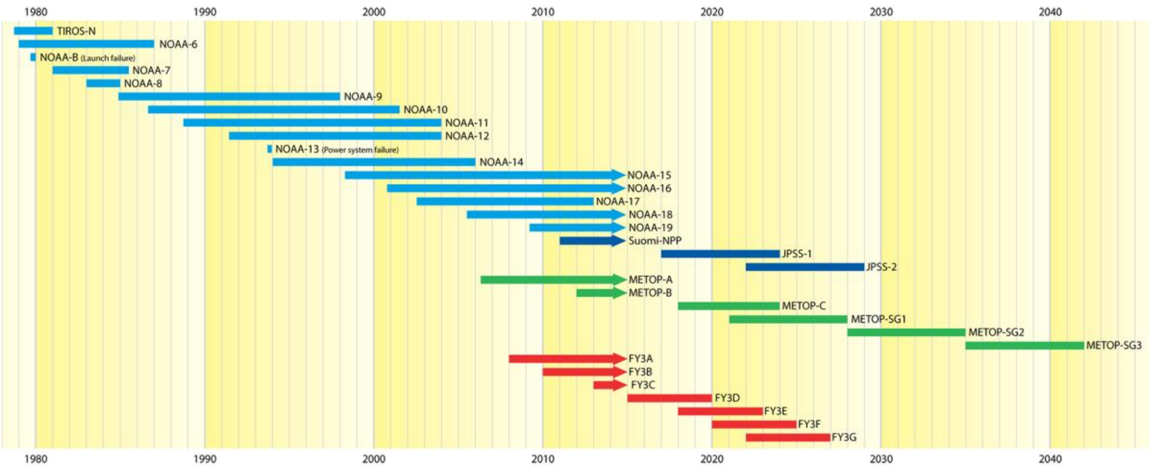


Figure 1 Operational sounding missions from 1978 to 2040. US funded missions (light and dark blues), Europe funded mission (green), China funded missions (red).

In this report, an assessment of MWTS-2 and MWHS-2 data is presented. A significant part of the evaluation is the comparison with NWP model fields. The accuracy of the NWP model, particularly in atmospheric temperature fields, allows an effective way to diagnose instrument problems. Assessment of satellite observations using NWP fields has already been used successfully for several instruments such as FY-3A (Lu et al. 2011) and ATMS (Doherty et al. 2012). Further to this, results can be compared to the behaviour of equivalent channels on AMSU-A, AMSU-B, MHS and ATMS instruments. Much of this research has also been conducted alongside a similar evaluation carried out at ECMWF allowing two independent NWP models to be used, therefore giving indications where problems are model based and increasing our confidence in any conclusions drawn. A report on the combined assessment of the data at ECWMF and the Met Office can be found in Lu et al. (2015).

The evaluation presented here focuses on the work carried out at the Met Office. In section 2, the data used and details of the instruments are discussed. Section 3 considers the quality assessment using comparison of observations and model fields output from the Met Office Observation Processing System (OPS). The impact of the addition of FY-3C data to the forecast system is examined in section 4. Section 5 summarises the results, makes recommendations on use of the data in NWP and considers future work.

2. Data source and processing details

The FY-3C satellite has a local equator crossing time of 10.00am (descending) and is in a sun synchronous orbit. Data from MWTS-2 and MWHS-2 are received from a global broadcast (via EUMETCAST) and also directly at the Met Office via a direct broadcast stream. The timeliness of the data is sufficient for operational NWP use. Data were operationally received and archived from late October 2014, although some sample data taken from summer 2014 were available for testing. MWTS-2 has experienced an initial failure in Feb 2015 and, although data were received again in May 2015, the instrument has been turned off due to a failure of the platform power system in April 2015. A subset of the FY-3C instruments, including MWHS-2, were powered up again in July 2015 and a global data stream established later that month. Significant modifications to the processing of the data before dissemination were also made during Jan 2015, particularly affecting MWTS-2 (see section 3), and to a lesser extent, MWHS-2. November and December 2014 were generally a more stable period for the data so the evaluation presented here has primarily focused on these two months.

2.1 Channel characteristics

Both MWTS-2 and MWHS-2 are cross scanning radiometers with 13 and 15 channels respectively. Details of the channels are given in **Table 1** for MWTS-2 and

Table 2 for MWHS-2. MWTS-2 has several channels equivalent to those of ATMS and AMSU-A with the majority around the 57GHz oxygen absorption band. On MWHS-2, while a suite of 183GHz channels is present (as on ATMS), there are also eight channels in the oxygen absorption band at 118GHz. These channels have never been available before on a satellite sounding instrument. The 118GHz channels can be roughly divided up as:

- the highest peaking (MWHS-2, channels 2-4) behave like pure temperature sounding channels, with little sensitivity to humidity;
- Lower peaking channels (MWHS-2, channels 5-7) have greater sensitivity to water vapour and therefore behave more as combined humidity and temperature sounding channels;
- MWHS-2 channels 8 and 9 have higher surface sensitivity and could be considered similar to window channels.

It is worth noting that there was some initial confusion in the interpretation of 'horizontal' and 'vertical' polarisation between the instrument manufacturer and the convention adopted in the radiative transfer model (RTTOV). Comparison of the surface sensitive channels with NWP-based simulations manifested this issue as large cross-scan biases evident over ocean, but not over land, which were removed when using the opposite polarisation. Over ocean, microwave emission is strongly polarised and hence view angle dependent. Discussion with CMA confirmed that an exactly opposite definition was being used.

Table 1 Summary of the channel characteristics of MWTS-2 and the equivalent channel numbers for AMSU-A and ATMS.

Channel No.	Central Freq (GHz)	Polarisation	Main absorbing gas	NEDT (K)	AMSU-A channel no.	ATMS channel no.
1	50.30	H	Window	1.2	3	3
2	51.76	H	Window	0.75	-	4
3	52.8	H	O_2	0.75	4	5
4	53.596	H	O_2	0.75	5	6
5	54.40	H	O_2	0.75	6	7
6	54.94	H	O_2	0.75	7	8
7	55.50	H	O_2	0.75	8	9
8	57.290	H	O_2	0.75	9	10
9	57.290±0.217	H	O_2	1.2	10	11
10	57.290±0.322±0.048	H	O_2	1.2	11	12
11	57.290±0.322±0.022	H	O_2	1.7	12	13
12	57.290±0.322±0.010	H	O_2	2.4	13	14
13	57.290±0.322±0.0045	H	O_2	3.6	14	15

Table 2 Summary of the channel characteristics of MWHS-2 and the equivalent channel numbers for AMSU-B/MHS and ATMS.

Channel No.	Central Freq (GHz)	Polarisation	Main absorbing gas	NEDT (K)	AMSU-B/ MHS channel no.	ATMS channel no.
1	89	H	Window	1	1	16
2	118.75±0.08	V	O_2	1	-	-
3	118.75±0.2	V	O_2	1	-	-
4	118.75±0.3	V	O_2	1.6	-	-
5	118.75±0.8	V	O_2	1.6	-	-
6	118.75±1.1	V	O_2	1.6	-	-
7	118.75±2.5	V	O_2	1.6	-	-
8	118.75±3	V	O_2	2	-	-
9	118.75±5	V	O_2	2.6	-	-
10	150	H	H_2O	1	2	-
11	183±1	V	H_2O	1	3	22
12	183±1.8	V	H_2O	1	-	21
13	183±3	V	H_2O	1	4	20
14	183±4.5	V	H_2O	1	-	19
15	183±7	V	H_2O	1	5	18

2.2 Pre-processing

MWTS-2 has 90 cross scan positions while MWHS-2 has 98 cross scan positions. In order to avoid oversampling, averaging is applied (a simple mean of each three adjacent positions) to obtain an average value over three scan positions. A similar averaging has also been used for ATMS in the Met Office system although ATMS is also averaged along-orbit. This acts to further reduce noise for ATMS. MWHS-2 observation locations were mapped onto MWTS-2 resulting in 30 cross scan positions for both instruments. However, since the failure of MWTS-2, this re-mapping was stopped. Having coincident locations allows the two instruments to be processed as one system through the OPS and 4D-Variational scheme (VAR) in a similar approach to AMSU-A and AMSU-B/MHS. This allows, for example, cloud screening from the humidity sounder to be used to quality control the temperature sounder.

2.3. Processing in OPS

The main functions of the OPS are to quality control the observations, perform a bias correction and derive additional parameters required by the main assimilation system, such as cloud and surface parameters. Many of the quality control steps are applied generally across all satellite instruments and include error checks in the radiative transfer calculations, convergence in 1D-Var, and gross limit checks on latitude/longitude etc. Instrument specific tests are also carried out, cloud detection in particular can be tailored to the channels available. Through the use of auxiliary files, it is also possible to declare channel specific screening relating to surface type, the presence of cloud, health of the instrument, or the ability to model the channel. The system was modified to process a composite 'instrument' called MWSFY3C (MicroWave Sounders - FY-3C) which was formed from the combination and remapping of channels from MWTS-2 and MWHS-2.

2.3.1 Cloud detection and channel selection

As well as OPS quality control used across all observations, two complementary cloud detection methods are applied:

- Bennartz rain test ('bennartzrain' flag) – which uses the 89GHz and 150GHz channels from MWHS-2 in the calculation of a scattering index;
- Cirrus cloud cost test ('mwbcloudy' flag) – in which channels at 183±7GHz, 183±3GHz and 183±1GHz are used in the calculation of a cost function, in combination with imposing a threshold on the magnitude of the observed - model background difference at 183±7GHz.

These have been adapted from methodologies successfully applied to ATMS and AMSU-A/AMSU-B/MHS (further details in Doherty et al. 2012). **Table 3** summarises the selection of channels over different surface types and when clouds are detected from either of the tests above. Due to difficulties in modelling window channels, MWTS-2 1 and MWHS-2 1 and 10 have been deactivated such that they can be used for cloud detection but are not included elsewhere in the processing. For MWSFY3C, VAR uses the same channel selection criteria as OPS.

Table 3 Summary of channel rejections for different surface types and in the presence of cloud.

Surface/cloud type	Rejected channels	
	MWTS-2	MWHS-2
Sea	None	None
Land	1,2,3,4 (5 in the tropics only)	1,5,6,7,8,9,10,11,12,13,14,15
Sea ice	1,2,3	1,5,6,7,8,9,10,11,12,13,14,15
Highland (land point above 1km)	1,2,3,4,5	1,5,6,7,8,9,10,11,12,13,14,15
Bennartz Rain	4,5,6,7	2,3,4,11,12,5,6,7,8,9,13,14,15
Mwbcloudy	3	5,6,7,8,9,13,14,15

2.3.2 Thinning

There are three rounds of spatial and temporal thinning applied to the MWSFY3C data within OPS - these are commonly used for other satellite instruments. The first, where data is thinned to 25 km and one hour in time, is applied after checking pre-processing flags. Round two occurs before 1D-Var and thins data to 80km and one hour intervals. Finally, prior to the main 4D-Var analysis, a third round is completed in which the thinning remains at one observation in every 80km in both the tropics and extra-tropics. This makes more aggressive use of the MWSFY3C data than, for example, ATMS where the distance is 154km in the tropics and 125km in the extra-tropics.

2.3.3 Observation errors

Tables 4 and **5** show the MWTS-2 and MWHS-2 observation errors, respectively, in OPS and VAR. Observation errors were derived based on the method used for ATMS where the existing errors of equivalent channels on another similar instrument are scaled using the ratio of Noise Equivalent Delta Temperature (NEDT) (Doherty et al. 2012). ATMS was used as the reference instrument and the ratio of the NEDT from data that had already received scan position averaging was used. The same technique was used for the observation errors specified in both OPS and VAR. Each channel for which there was an equivalent channel, was scaled by this ratio, apart from the 183GHz channels. For these humidity channels, the same errors (4K) were used without scaling.

For the 118GHz channels, reasonable values have been chosen as a starting point, but these are likely to require revision in the future as the use of these channels is refined. The most surface sensitive channels (MWHS-2 8-9) have been given large errors roughly consistent with other window channels on the instrument. For MWHS-2 5-7, which act predominantly as humidity sounding channels, similar errors have been assigned as those used for the 183GHz channels (4K). For the MWHS-2 3-4 temperature sounding channels, peaking higher in the atmosphere, slightly smaller errors have been chosen (although still significantly higher than other temperature sounding channels) while MWHS-2 2 has been given a slightly higher error value due to its elevated NEDT compared to the other two highest peaking 118GHz channels. For the window channel, 150GHz (where there is no equivalent on ATMS) the error given for MHS on MetOp B was instead used. This value was also not scaled but the size of the error is not too much concern at present because the channel is not activated in OPS apart from in cloud detection.

Table 4 MWTS-2 observation errors in OPS and VAR.

Channel number	1	2	3	4	5	6	7	8	9	10	11	12	13
Error in OPS (K)	3.16	2.09	1.225	0.44	0.51	0.44	0.5	1.47	1.11	1.57	1.23	1.14	1.2
Error in VAR (K)	2.9	2.5	2.2	0.47	0.54	0.43	0.93	1.47	0.73	1.31	1.37	2.32	4.79

Table 5 MWHS-2 observation errors attributed in OPS and VAR.

Channel number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Error in OPS (K)	7.67	4.0	3.0	3.0	4.0	4.0	4.0	6.0	6.0	5.0	4.5	4.0	4.0	4.0	4.0
Error in VAR (K)	7.67	4.0	3.0	3.0	4.0	4.0	4.0	6.0	6.0	4.33	4.5	4.0	4.0	4.0	4.0

2.3.4 Bias correction coefficients

The bias correction scheme used for MWSFY3C is the same scheme commonly used for sounding data at the Met Office. Bias correction coefficients consist of two atmospheric thickness components (for two different pressure level intervals, 850-300hPa and 200-50 hPa) and a component for each scan position. There is also a constant offset that can be applied. The bias correction coefficients were calculated using data from November 2014. The coefficients were initially set to zero and a first guess generated using 10 days of data. This first iteration of coefficients was then used to collect statistics for the whole month. This second iteration was used to process data from 1st to 20th November again, to determine final values used in the analysis of departure statistics for this period. The highest peaking temperature sounding channel, MWTS-2 13, has a scan position dependent correction only. This is also the case for equivalent channels on AMSU-A and ATMS. This approach is required as a result of the lower confidence in the accuracy at upper levels in the model (above 40km).

One feature in the treatment of MWSFY3C is that the bias coefficients have been calculated using data over land and sea. For ATMS and AMSU-A/AMSU-B/MHS, all surface types - land, sea and sea ice - are included in the estimation of biases while for other satellite instruments, only observations over sea are used regardless of whether a channel is used over other surfaces. For MWSFY3C, the addition of sea ice should have little effect due to the comparatively small volume of data involved. In the case of channels at 183GHz, the effect is smaller still as data over sea ice are screened out and the impact would be a slight difference in the weighting of observations in different latitude bands during the calculation (the weighting is calculated from the channel with the highest data volume and then applied across all channels). The Met Office will be implementing a variational bias correction scheme early in 2016, in which observations over all surface types will be included in the bias correction estimate for radiance datasets.

3. Initial assessment from OPS statistics

To understand the quality of the new microwave sounding data, an assessment using NWP model fields was carried out. As there are equivalent channels on both ATMS and AMSU-A/AMSU-B/MHS, it is also possible to make a comparison with their performance. Many of the features revealed in this analysis were confirmed as present in the ECMWF evaluation, suggesting that these are instrument based problems rather than model based, particularly for MWTS-2, where the confidence in the model temperature fields is high (the errors mid-troposphere mapped into observation space are typically in the range 50-100 mK). Throughout this section, data from 1st - 30th Nov 2014 were used in the calculation of the statistics for both instruments unless otherwise stated.

3.1 MWTS-2

Figure 2 (a) and (c) show the mean observed - background brightness temperature (O-B) and mean corrected - background brightness temperature (C-B) respectively for each MWTS-2 channel. There is a large negative offset for most of the channels ranging between -2K and -4K. Nevertheless, the bias correction deals with this offset quite well and produces mean C-B values comparable to ATMS. Work at ECMWF/CMA established that a new antenna pattern correction and non-linearity correction was required to reduce the large bias. Modifications were made to the processing in January 2015 which resulted in a reduction of the offset.

The standard deviation of O-B (**Figure 2** (b)) for each channel appears slightly reduced once bias-corrected (**Figure 2** (d)). However, in the comparison to ATMS, it seems that MWTS-2 consistently shows a higher standard deviation. As noted in section 2.2, more spatial averaging is applied to ATMS which may account for some of this difference. For channel 8, an anomalously large standard deviation of the corrected departures is observed, which is not apparent for ATMS nor in the uncorrected departures. This channel also exhibits a large jump in NEDT value which is likely to be the underlying cause of this feature. Considering the mean global O-B throughout Nov 2014, the values are quite stable with little drift and no apparent step changes during the month.

The dependence of O-B and C-B on scan position was also evaluated (not shown). The O-B values varied smoothly across the scan indicating that there are no significant problems with the scan edges, for instance caused by intrusion of part of the satellite into the field of view. The bias correction scheme, which has a specific scan dependent set of coefficients, is also performing well in reducing the cross scan bias.

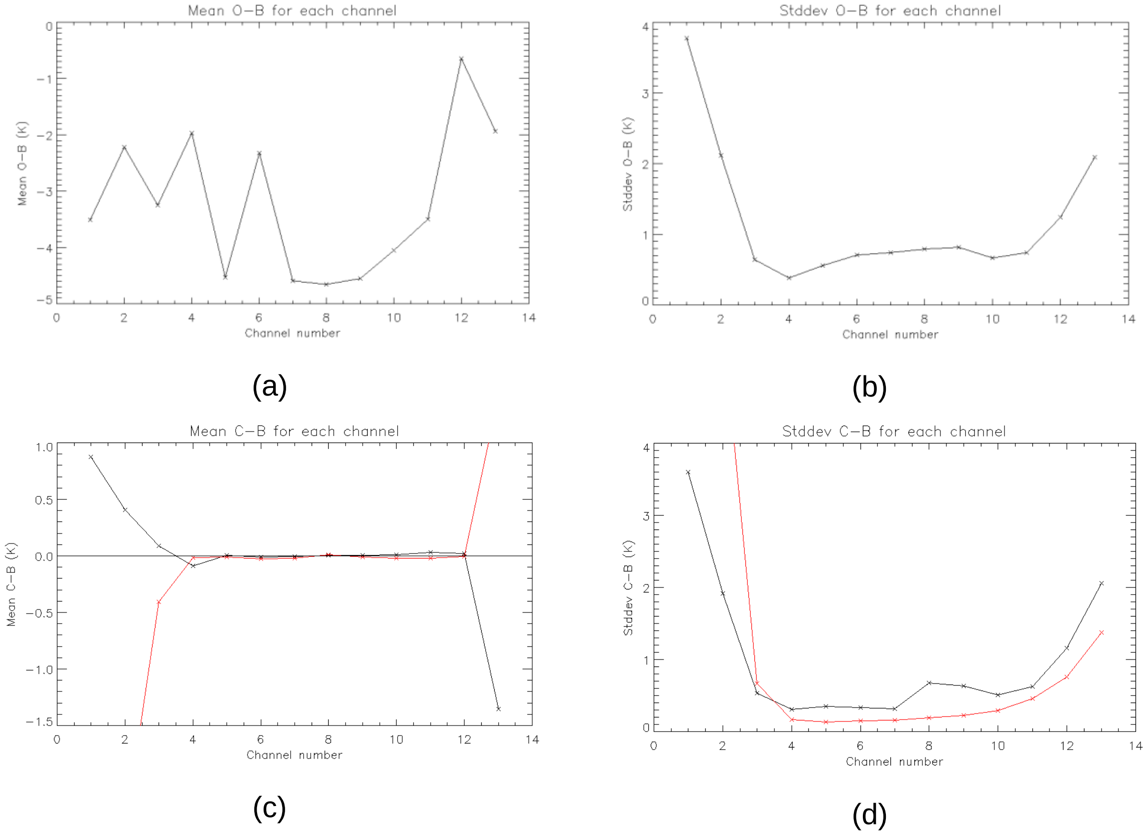


Figure 2 (a) Average O-B, **(b)** Standard deviation of O-B, **(c)** Average C-B and **(d)** Standard deviation of C-B. MWTS-2 data from Nov 2014 (black), ATMS C-B from Nov 2014 (red).

An unusual feature in MWTS-2 data is an apparent surface sensitivity in channels where the peak sensitivity is high is the atmosphere. **Figure 3** illustrates the case for MWTS-2 channel 6 which has a peak in sensitivity at around 250hPa yet there is a discernable land/sea contrast with a magnitude of 0.5-1K. This is not observed in AMSU-A or ATMS and it also present in the raw MWTS-2 brightness temperatures, so this is not a feature caused by the model or an artefact of the radiative transfer calculation. This spurious sensitivity is apparent in MWTS-2 channels 5-8 however it is difficult to determine whether other channels have been affected, albeit to a lesser extent. It was noticed that there was an anti-correlation in raw brightness temperature between the affected channels and the window channel, MWTS-2 1. This allows an empirical correction to be derived which successfully removes the contrast. However, although some ideas have been suggested, there is currently no confirmation of the likely underlying cause. Despite the uncertainty in the underlying physical mechanism, modifications to the processing of the data in Jan 2015 included this empirical correction.

A better understanding of the source and extent of the impact is desirable for the data to be used reliably in the NWP and reanalysis systems.

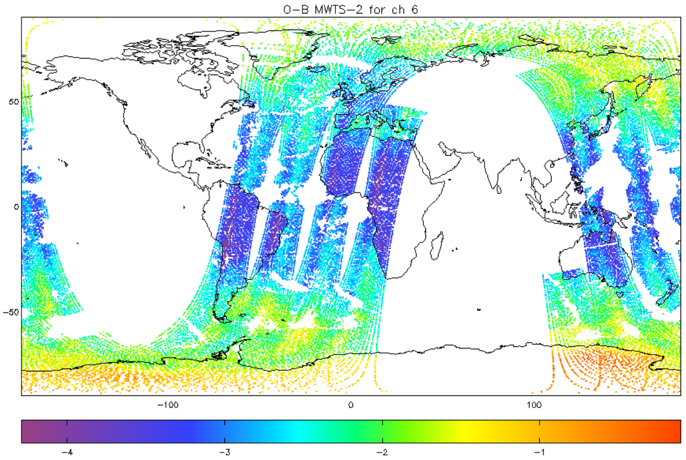


Figure 3 Map of O-B for MWTS-2 channel 6 illustrating the apparent surface sensitivity for a channel with peak sensitivity at around 250 hPa.

Comparison with NWP also revealed that striping was present in some of the higher peaking channels (**Figure 4**). This is most likely due to introduction of a flicker noise in the low noise amplifier in the instrument, similar to that found in ATMS (Doherty et al. 2012). Although the magnitude appears larger in MWTS-2 than ATMS, data affected by striping on ATMS has still provided benefit, so even without correction these channels could still be useful.

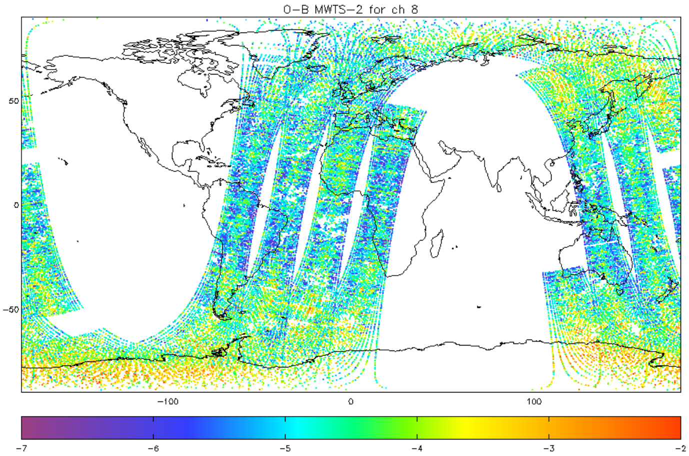
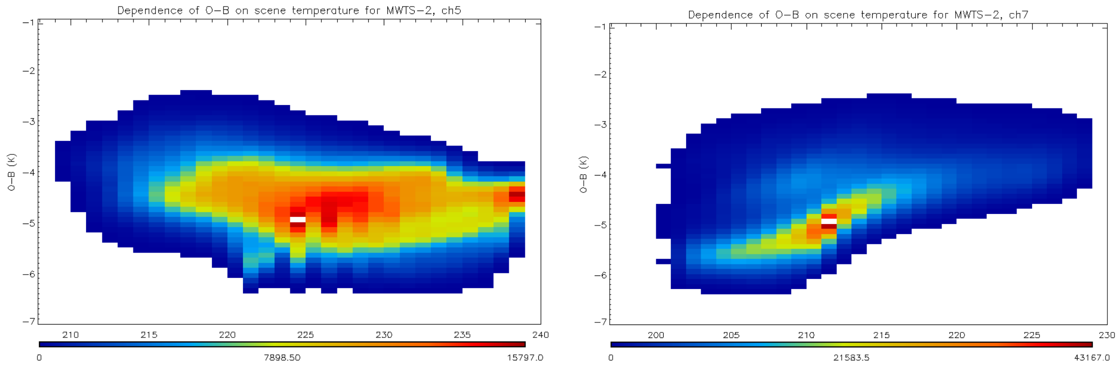


Figure 4 Map of O-B for MWTS-2 channel 8 for 12Z on 01/11/2014 illustrating the striping present in the data.

In order to assess the non-linearity of the instrument, the dependence of O-B on scene temperature was inspected. When converting between digital counts and temperature, a linear interpolation is used between cold space and the warm calibration target, followed by a non-linearity correction if necessary. For real data, deviations from this linear assumption result in a brightness temperature error that varies with scene temperature. For MWTS-2 there is generally no obvious dependence on scene temperature, as illustrated, by example, for channel 5 in **Figure 5** (a). The only possible exception was MWTS-2 7 (**Figure 5** (b)) which appears to show more negative O-B differences for decreasing scene temperature. The cause of the effect, influencing one channel in isolation, is not obvious.



(a) (b)

Figure 5 Dependence of MWTS-2 O-B on scene temperature for **(a)** MWTS-2 5 and **(b)** MWTS-2 7. Colours indicate the density of observations.

The presence of orbital biases was also investigated by calculating the dependence of O-B on the angle, Φ, which is the angle of the satellite orbital vector relative to the vector pointing to the intersection of the ascending node of the satellite with the ecliptic plane (in the earth coordinate frame). This orbital angle varies from 0-360º with ~0-90º corresponding to the satellite travelling from the equator to the North Pole and ~90-270º from the North pole, back through the tropical region and on to the South pole. The final ~270-360º is returning from the South pole to the tropics again. Analysing this dependence confirms whether there is a shift in O-B between the ascending and descending parts of the orbit. No obvious orbital bias (expected to be manifested as a single bias 'cycel') was observed in MWTS-2 channels, however, there are air mass dependent biases illustrated by the double peak in
Figure 6. For MWTS-2 7, affected by the spurious surface sensitivity, there is also a slight difference in the magnitude of the peaks between the northern and southern hemisphere as the larger land mass of the north is depressing the O-B.

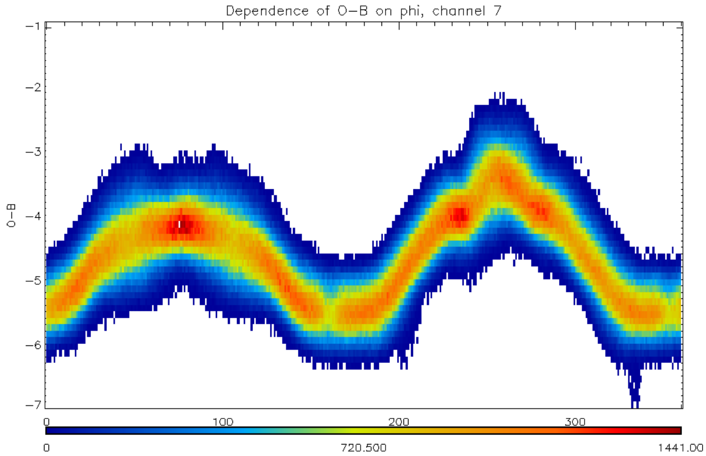


Figure 6 2D histogram of O-B dependence on orbital angle, Φ, for MWTS-2 channel 7 from 0 to 360º in latitude. Colours indicate the density of observations.

3.2 MWHS-2

The mean O-B for each channel (**Figure 7** (a)) does not show the large negative biases observed in MWTS-2 and instead shows a cluster of values closer to zero. **Figure 7** (c) shows that with the application of the bias correction, the C-B values are smaller in magnitude, as required, and close to the ATMS values for the 183GHz channels. For surface sensitive channels some larger biases persist, as expected as a result of the larger uncertainties involved in modelling the surface emission.

There is also a reduction in standard deviation from the uncorrected (O-B) values (**Figure 7** (b)) to the corrected (C-B) values (**Figure 7** (d)). For the 183GHz channels, the C-B values are close to the equivalent ATMS channels although they appear consistently slightly higher. This may be due to the difference in spatial averaging described in section 2.2. For the 118GHz channels, the standard deviation of the departures for the highest peaking temperature sounding channels is higher than the values typically required of temperature sounding channels (0.1 - 0.25K). This is due to the position of the channels on the wings of a single narrow oxygen absorption line requiring small channel bandwidths, which therefore introduces higher noise. As expected, the values of the lowest peaking 118GHz channels sharply rise as their surface sensitivity increases.

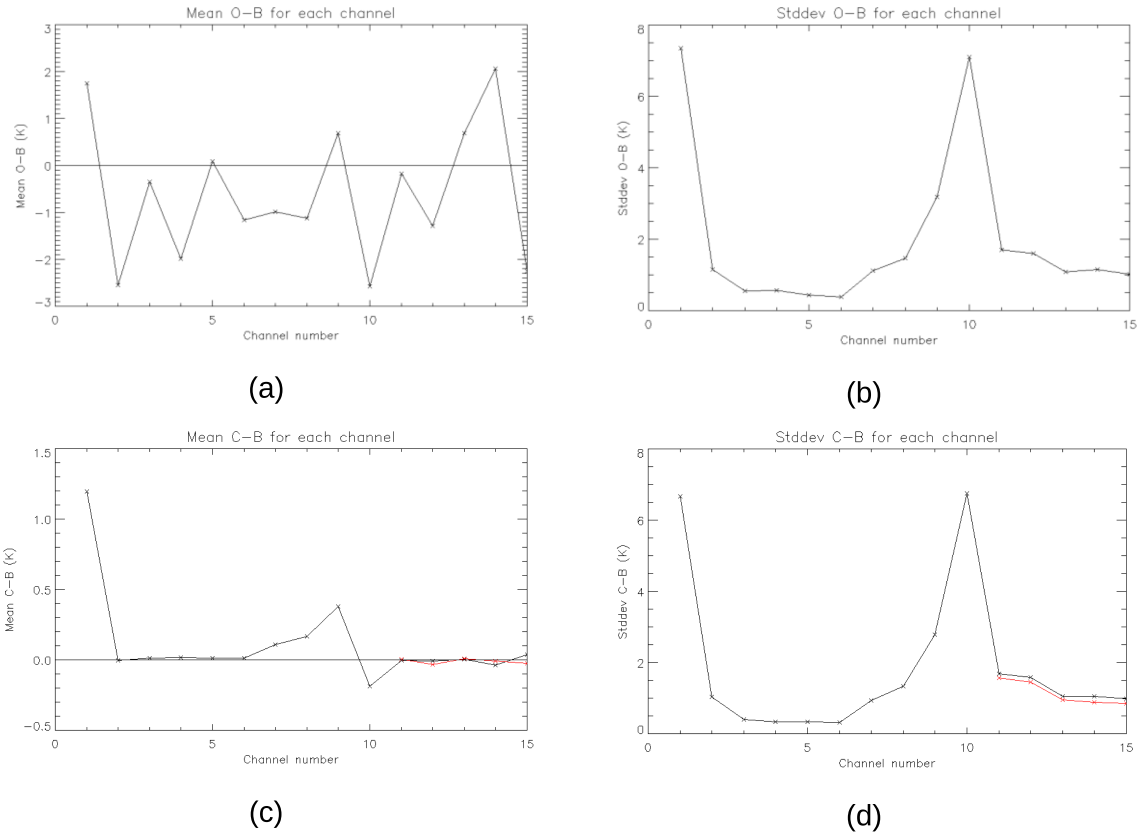


Figure 7 (a) Average O-B, **(b)** Standard deviation of O-B, **(c)** Average C-B and **(d)** Standard deviation of C-B. MWHS-2 data from Nov 2014 (black), ATMS C-B from Nov 2014 (red).

As for MWTS-2, the dependence of O-B on scan position confirmed no significant issues at the scan edges (not shown). Again, the bias correction performs well in reducing the cross scan biases as required. Similar to MWTS-2, there are also striping effects observed in some of the channels but, as discussed earlier, it is still possible to realise benefit from the data as has been done for ATMS. The scene temperature dependence was investigated but the noisier humidity sounding channels made it more difficult to discern any trends (not shown). Nonetheless, it appeared that there was no consistent, obvious, dependence present.

The presence of orbital biases was also investigated for MWHS-2 and while no ascending/descending bias was found, an interesting pattern in the air mass dependent biases for the 118GHz channels was observed. **Figure 8** shows the dependence of O-B on Φ for four channels with peak sensitivity descending in height (**Figure 8** (a) highest and **Figure 8** (d) lowest). The amplitude of the air mass dependent bias decreases until MWHS-2 6 where there is virtually no dependence and then the amplitude increases again when sensing the lowermost atmosphere. At present it is not clear what the underlying cause of this pattern is. A frequency shift would be unlikely to produce this effect as the channels are constructed of two side bands which are symmetrical about the absorption line centre. Any shift would result in compensating effects from one side band experiencing increased absorption while the other experiences a decrease. The problem may lie in the spectroscopy which is complicated by the uncertainty in the contribution from the water vapour continuum. A firm conclusion has not been reached but discussion of the relevant spectroscopy can be found in Lu et al. (2015).

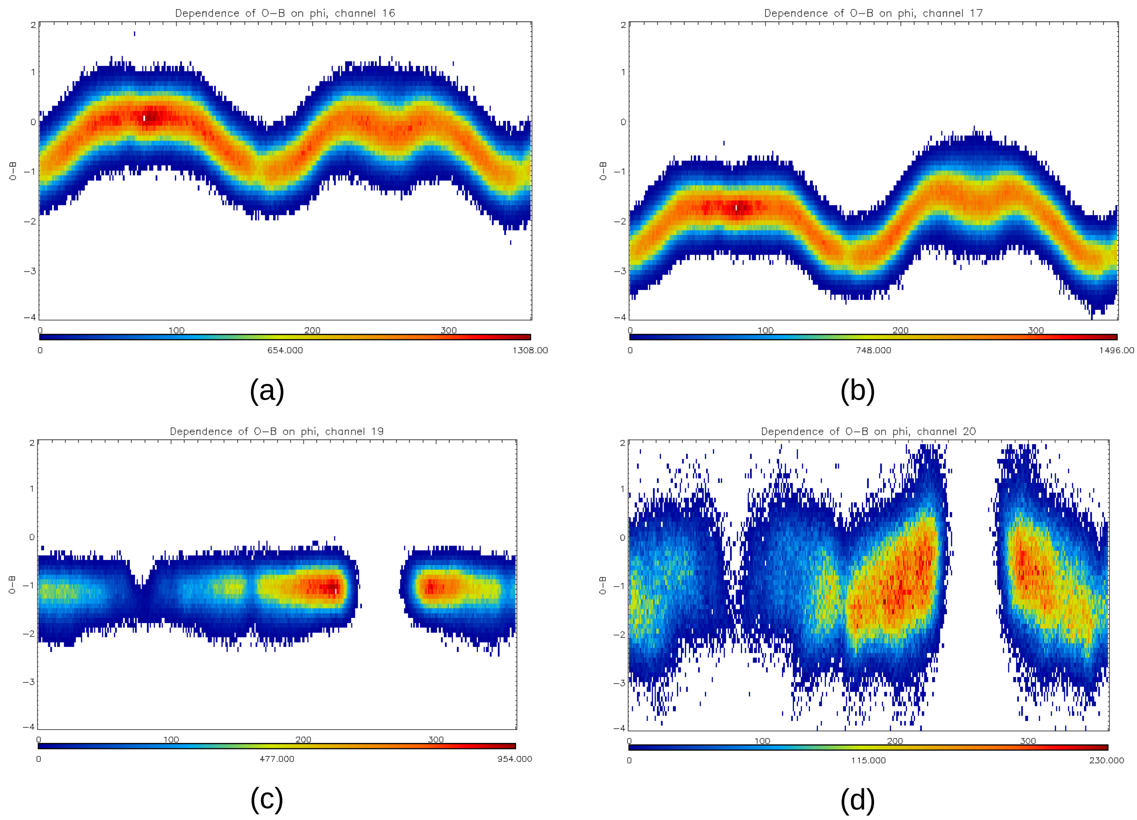


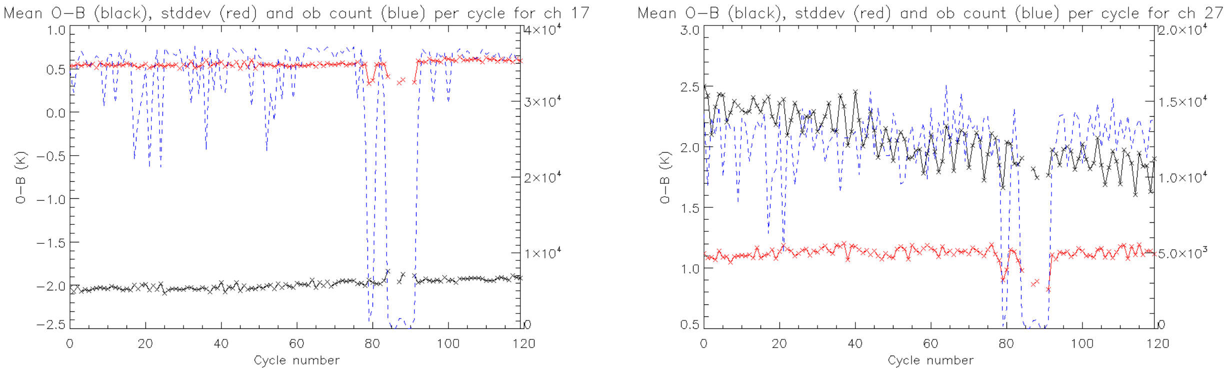
Figure 8 O-B dependence on orbital angle, phi for **(a)** MWHS-2 3, **(b)** MWHS-2 4, **(c)** MWHS-2 6 and **(d)** MWHS-2 7.

The monitoring of O-B and C-B throughout Nov 2014 revealed reasonable stability in most channels (see **Figure 9** (a)). However, 183 GHz channels 13 and 14 stood out with a 0.2-0.5 K downward trend (see **Figure 9** (b)), while similar drifts were not observed in equivalent ATMS and MHS channels.

A longer experiment, processing data through OPS only, was conducted over a 7-month period to investigate longer term stability. The drift observed in channels 13 and 14 was found to persist until January 2015 when the data processing modifications made by CMA reversed it to an upward trend. **Figure 10** (b) shows the channel 14 mean O-B after having being processed in OPS (i.e. C-B) from Nov 2014 to May 2015. The post-January upward trend is ~0.8 K (~0.4 K for channel 13, not shown) between January and April 2015, before an apparent stabilisation in May 2015. The static correction scheme does not deal well with such a drift (since it is observed both in O-B and C-B with similar magnitude), but it is expected that the new variational bias correction (VarBC), due to become operational in early 2016, will efficiently remove most of these trends.

It is worth noting that the January change in the data processing also caused a large shift in the mean O-B of several channels, from -0.4 K in channel 11 (**Figure 10** (a)) to 0.2-0.4 K across channels 3 to 8.

Another visible feature is a 1 K jump in the mean O-B during the first half of March 2015, probably caused by further CMA changes to the pre-processing of the data. Although O-B returned to normal values after this event, the channel 14 standard deviation, which experienced a simultaneous increase, returned to slightly larger values (by ~0.1 K) than before (see **Figure 10** (d)). The March 2015 event also caused sharp temporary variations in channels 3-6 and 13 (not shown).



(a) (b)

Figure 9 O-B (black), standard deviation (red), and observation number (blue) statistics for each cycle throughout Nov 2014 for **(a)** MWHS-2 4 and **(b)** MWHS-2 14.

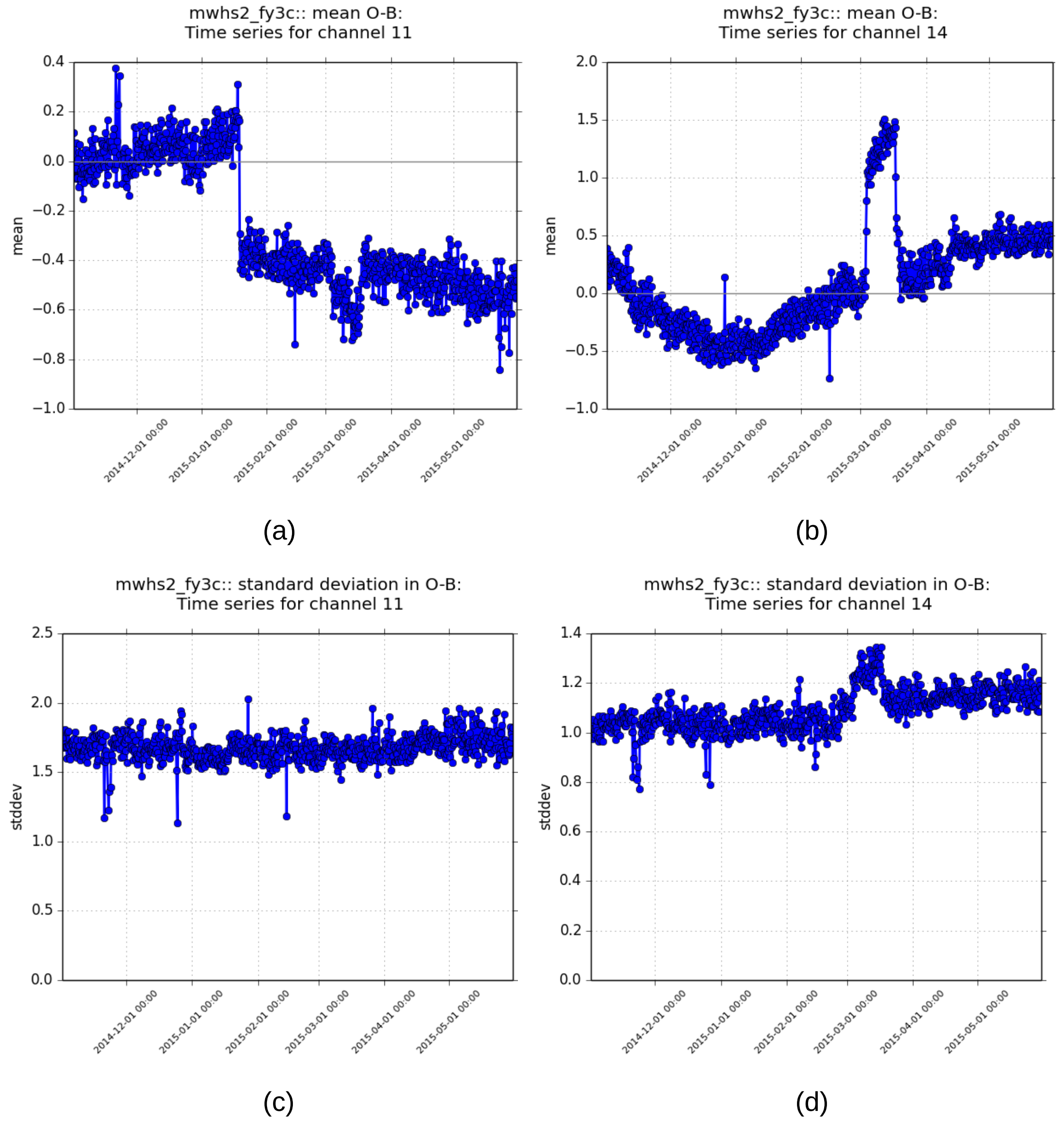


Figure 10 Mean post-processed O-B for channels 11 (a) and 14 (b) from Nov 2014 to May 2015. Associated standard deviations for channels 11 (c) and 14 (d).

4. NWP trials

The initial assessment presented in section 3 shows that MWTS-2 data contain features that are challenging to understand. Until a satisfactory explanation for these issues can be found and the appropriate corrective measures in place, the data are not suitable for further testing in the NWP system. Regarding MWHS-2, making best use of the 118 GHz channels is also currently an area requiring further development at the Met Office. It is expected that useful information on cloud might be derived from these channels.

Therefore, for these first assimilation experiments using FY-3C microwave sounding data, we focus initial testing on the use of the suite of 183GHz channels and two window channels (150 GHz and 89 GHz), in a similar way to AMSU-B/MHS. This subset of MWHS-2 channels is being added to a mature observing system which already contains five instruments (four AMSU-B/MHS and ATMS) with similar capabilities. It may therefore be expected that the impact will be manifested as an incremental improvement to humidity fields. However, it is clear that microwave sounding instruments provide a valuable contribution to the NWP system so even if relatively small, an incremental increase in accuracy can still be important.

As data from FY-3C was operationally stored and received from late October 2014 and due to certain key input files for the NWP system only being available after 11th Nov 2014, a trial period was chosen to begin on 12th Nov 2014. The suite used for testing was a modified copy of a control suite (created for general use) for the period of summer 2014. This had a parallel suite 35 (PS35) baseline configuration but with reduced resolution (N320 Unified Model resolution and VAR at N108 and N216 resolutions). The trial was to run to the end of December 2014 to provide a good length of time from which reliable results could be calculated.

After creating a control suite, the only modification made to produce the experiment suite was the addition of FY-3C. It was found in later analysis, that an error had been introduced into the channel selection of the first experiment started (note that this is not present in the data used for the analysis in section 3). The two window channels should have been deactivated in addition to the MWTS-2 channels and 118GHz channels in OPS. This would allow the window channels to be used for the cloud detection but as they are difficult to model, they would not be part of the processing, e.g. in 1D-Var. Their inclusion causes a larger number of observations to fail the quality control screening. The impact of rejecting these channels is to increase the number of good observations allowed for the 183GHz channels and also the retrieved surface parameters in 1D-Var would not contain the influence of these channels in the calculation. It is expected that, where the addition of the 183GHz is having an effect, the correct use of the window channels should allow the larger data volume to have a greater impact. It is difficult to quantify the effect on the surface parameters - it is not anticipated to have a large influence but it is likely that some degradation due to less accurate values would occur. A second trial was initiated with the correction to the channel selection. **Table 5** summarises the different NWP suites used.

Table 5 Summary of NWP experiments run for the time period 12th Nov - 31st Dec 2014

Experiment number	Suite ID	Details
Control	mi-ae636	Control
1	mi-ae555	Addition of MWHS-2 183GHz channels with window channels used throughout OPS
2	mi-ae714	Addition of MWHS-2 183GHz channels with window channels deactivated in OPS

The trials were analysed through two methods – analysing the impact on background fits to independent observations, and the impact on the NWP index. Normally, a summer and winter season would be analysed however, at the time of testing, data were only available for a winter period. This single, longer trial still provides good understanding about the areas of improvement or degradation and the magnitude of the effect.

4.1 VAR statistics

The VAR statistics allow a comparison of the observations for a particular cycle with the six hour forecast from the previous cycle (the model *background*). With the introduction of MWHS-2, it is important to confirm that no degradation has been caused in the fit of the model to other observations. While little effect is expected for temperature sounding instruments, humidity sensitive channels are more likely to show some changes as the humidity field is being more directly influenced by the addition of 183GHz information.

4.1.1 Experiment 1 vs. control

A key metric in evaluating the change in background fit to observations is the change in standard deviation of the departures. **Figure** (a)-(d) show the percentage change in standard deviation for AIRS, MHS on Metop A and NOAA-19, and ATMS. For AIRS (**Figure** (a)) the temperature sounding channels on the instrument appear to show virtually no change, however for the water vapour channels there are small improvements. Unexpectedly, in the lower numbers of the water vapour channels the impact is relatively insignificant, with standard deviation clustered within ±0.2 %. For channel ≥ 200, the improvement is significant and results in around 0.6% reduction in standard deviation. It is not clear why this pattern should occur however it is encouraging that generally either a neutral or positive impact is observed. In considering the fit to MHS/AMSU-B, it was found that the instruments on Metop A and B showed a neutral change (-0.4 to 0%) while NOAA-18 and 19 showed more consistent reduction in standard deviation across the channels (-0.9 to -0.5%). Interestingly, Metop A and B are in morning orbits while NOAA-18 and -19 are in afternoon orbits.

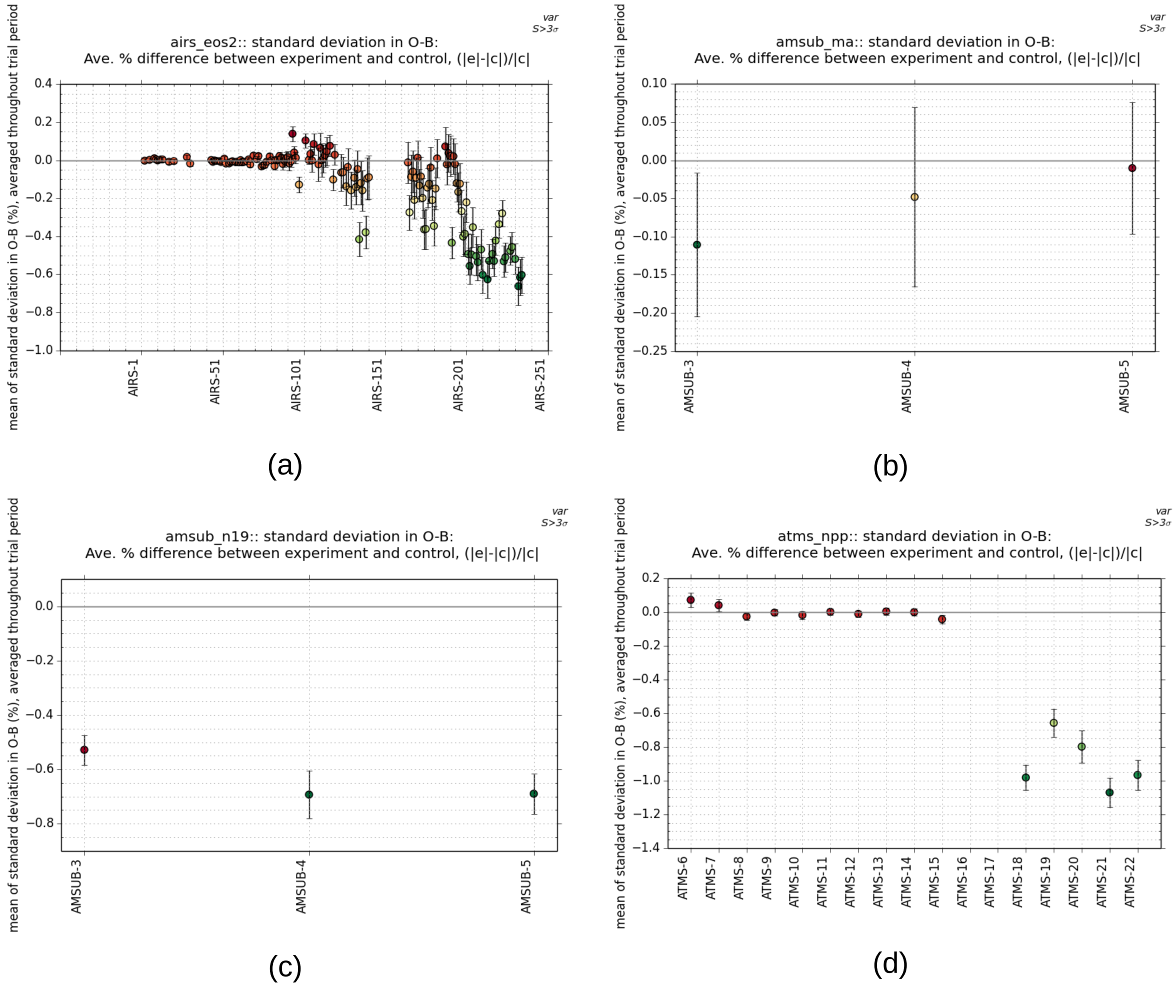
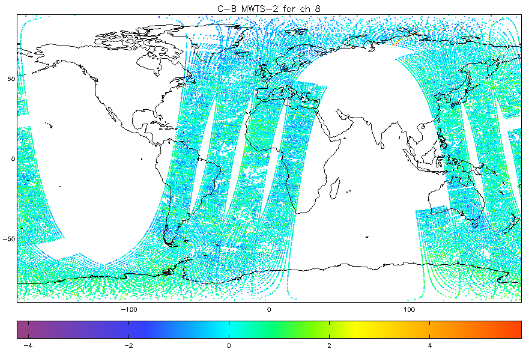


Figure 11 Percentage change in standard deviation in observed - background brightness temperature for experiment 1 compared to control for **(a)** AIRS, **(b)**, MHS on Metop A, **(c)** MHS on NOAA-19 and **(d)** ATMS.

Looking more closely across all the instruments containing water vapour sensitive channels, it seems a general pattern that the morning orbit instruments show neutral changes (both IASI instruments as well as MHS) while those in afternoon orbits showed more positive impact. The VAR statistics are a comparison between observation and a background which is the six hour forecast from the previous model cycle. **Figure 12** (a) illustrates the global coverage for MWTS-2 (and by extension, MWHS-2) which is in a morning orbit for a 12Z model cycle. The coverage for ATMS is shown in **Figure 12** (b) (an afternoon orbit) and AMSU-B/MHS on Metop B is given in **Figure 12** (c) (in a morning orbit). It appears that the location of the MWTS-2 observations, where most impact will be derived, provide more overlap with the location of the observations for instruments in afternoon orbits than for morning orbits in the subsequent model cycle six hours later. This likely explains the variation in impact seen according to the different equator crossing times and suggests that for a six hour period, impact from MWHS-2 is still relatively localised to the observations. Continuing with this hypothesis, **Figure** (d) shows the reduction in standard deviation for ATMS where all five equivalent channels to MWHS-2 are available. Encouragingly, a positive impact is seen across all of those channels (-1 to -0.7%). It is also worth noting that for these observed changes in standard deviation, across all of the instruments there is virtually no change to the observation count so this will not be influencing any apparent reductions.

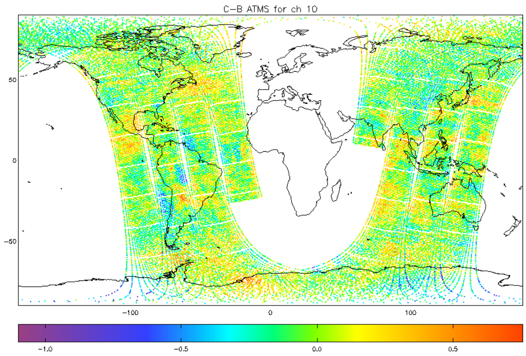
For the temperature sounding channels across various instruments there is a neutral impact on the standard deviation which confirms that MWHS-2 is not having an adverse impact where it was not expected. Generally, the change in the mean O-B in the VAR statistics has been relatively small as well.

MWTS-2 8



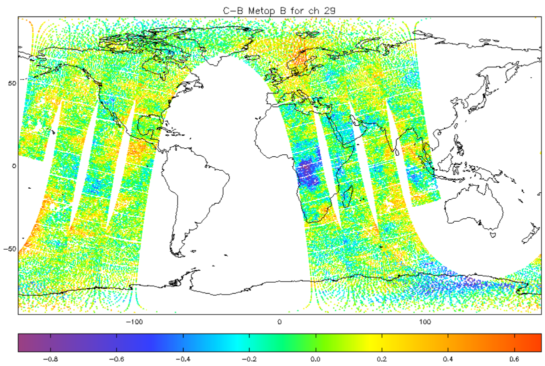
(a)

ATMS 10



(b)

Metop B AMSU-A 9



(c)

Figure 12 Data coverage for a single cycle for **(a)** MWTS-2 8 for 12Z on 01/11/2014 **(b)** ATMS 10 for 18Z on 01/11/2014 and **(c)** AMSU-A 9 on Metop B for 18Z on 01/11/2014.

4.1.2 Experiment 2 vs. control

The VAR statistics for experiment 2, where the window channels have been correctly used in OPS, appear broadly similar to those discussed above for experiment 1. The changes in standard deviation for O-B, where the impact was positive for experiment 1, are similar or slightly larger in experiment 2. This is likely due to the increased data volume of the 183GHz channels (with observations not being rejected due to the incorrect use of the window channels) allowing more impact and more benefit in this case. Again, it also appears that instruments on satellites in afternoon orbits are showing a larger improvement than those in morning orbits. **Figure** (a) shows the percentage reduction in the standard deviation of O-B for AIRS which, as in experiment 1, reveals that most of the lower numbered water vapour channels have a neutral impact before showing a slightly positive change of about 0.5-0.8% for high numbered water vapour channels. Metop A (**Figure** (b)) and Metop B are showing a more positive impact than experiment 1 although percentage changes are still under 0.5% improvement. NOAA-19 (**Figure** (c)) also continues to display a reduction of around 0.5-0.6%.

For ATMS (**Figure** (d)), the standard deviation for channels 18-22 is reduced by 0.7-1.2%. As mentioned in section 3.2, MWHS-2 13 and 14 (the corresponding channels to ATMS 20 and 19 respectively) display a trend in bias throughout the month. This residual bias may be reducing the positive impact for the equivalent ATMS channels. In experiment 2, where the observation count is higher for MWHS-2 by just over 10%, the effect has been amplified. Once again, changes in observation numbers for other instruments are extremely small and neutral impact is observed in the temperature sounding channels across the instruments.

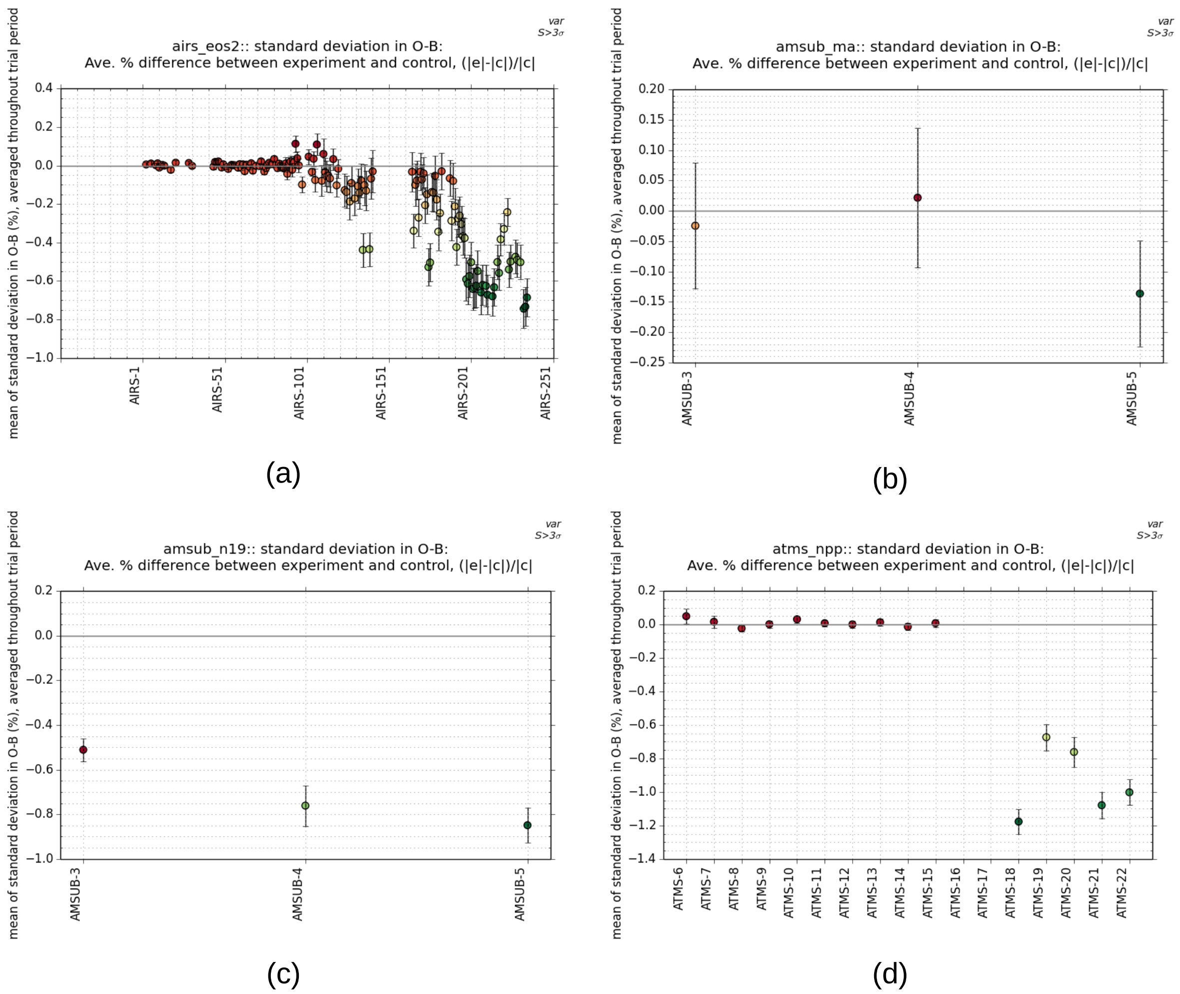


Figure 13 Percentage change in standard deviation in observed - background brightness temperature for experiment 2 compared to control for **(a)** AIRS, **(b)**, MHS on Metop A, **(c)** MHS on NOAA-19 and **(d)** ATMS.

4.2 NWP index impact

The experiments have been analysed using both the new NWP index calculation, which verifies improvements in the forecast against observations, and older index which verifies against both observations and analysis. As only a short time period has been processed, the old NWP index is perhaps more relevant due to higher weighting assigned to the shorter forecast ranges. For trials of this time period (less than one month - six weeks), verification of longer forecast periods such as four or five days is less reliable.

Table 6 summarises the impacts for each experiment against the control and the impact from the correction to the use of the window channels in OPS. These overall changes in index show a neutral impact for both experiments against the control with experiment 1 performing slightly better using the old index when verifying against observations. It appears that the addition of extra data and avoiding potential degradation in the surface parameters is not significant enough to affect the global index. This would agree with the small difference in VAR statistics seen between the two experiments.

Table 6 Summary of the impact on new and old NWP index through addition of MWHS-2 channels.

Experiments verified	Verification vs. observations		Verification vs. analysis (old index)
	New NWP index	Old NWP index	
Add MWHS-2 (window channels used) vs. control	+0.235	-0.012	+0.154
Add MWHS-2 (corrected channel use) vs. control	+0.185	+0.137	+0.005

As noted earlier, while the addition of the humidity channels on MWHS-2 was unlikely to have a significant impact on the overall system (reflected in these neutral scores) it is also important to confirm that no degradation is introduced. However, to gain more confidence in the result it is useful to look more closely at impacts to individual atmospheric variables at different forecast ranges. This also allows the separation of the statistically insignificant longer forecast ranges due to the shorter length of trial. **Figure 8** shows percentage reduction in forecast RMS error for experiment 1 compared to the control for verification against observations. Neglecting the changes at five or six days, the changes are generally close to neutral. For the northern hemisphere, changes are very small while for the tropics there are a few small positive impacts with reductions of RMS errors of around 0.5% or higher in some of the shorter range forecasts. In the southern hemisphere, again many of the changes are near neutral although several of the short range forecasts show a reduced error. Notably, in all three cases, the relative humidity fields (which should be most affected by the addition of MWHS-2) are not degraded.

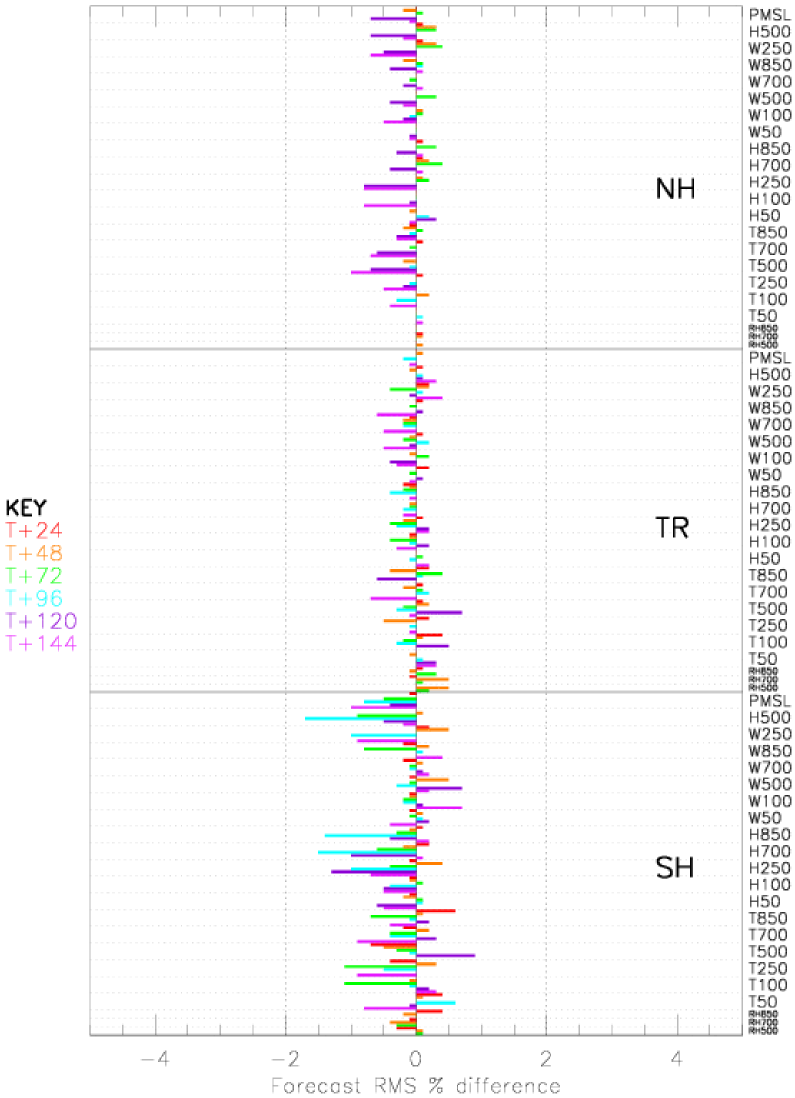


Figure 8 Forecast RMS error percentage difference against observations for different atmospheric variables after the addition of MWHS-2 with window channels used in OPS (experiment 1) compared to the control.

Figure 9 shows the reductions in forecast error verified against observations for the addition of MWHS-2 where the window channels have been correctly used in OPS (experiment 2). Again neglecting the longer range forecasts, the impact is generally neutral with the northern hemisphere showing only very small changes. There are similar neutral features to the comparison for experiment 1 in the tropics. Also in agreement with experiment 1, the southern hemisphere in experiment 2 shows a reduction in the short range forecast errors. Generally, the relative humidity appears neutral or slightly improved across most of the short ranges. The only exception is a ~1% degradation of RH500 at T+72.

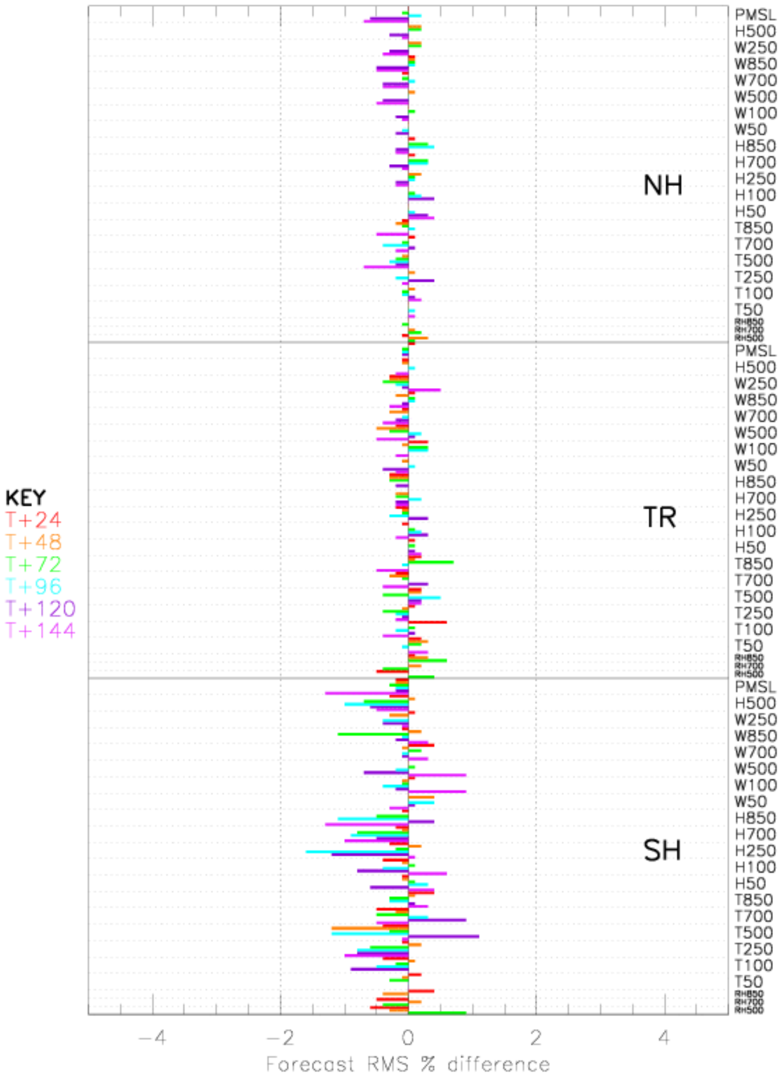
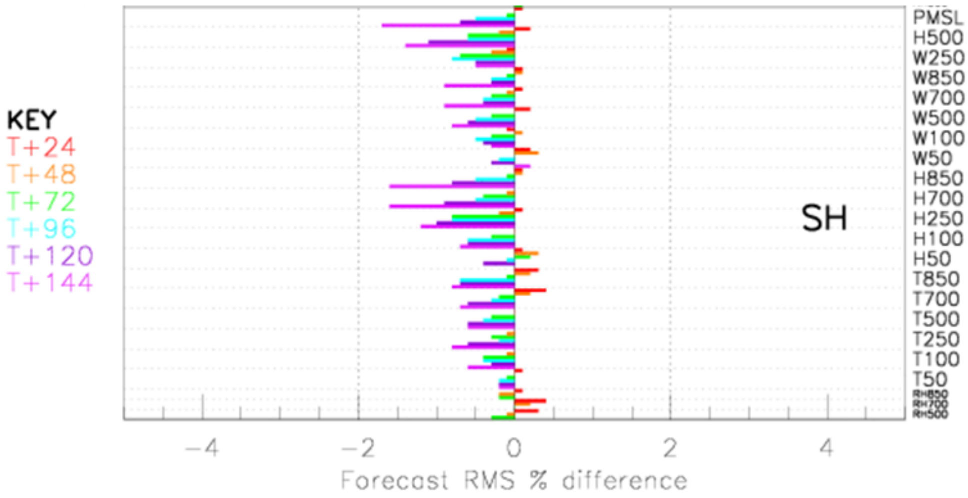
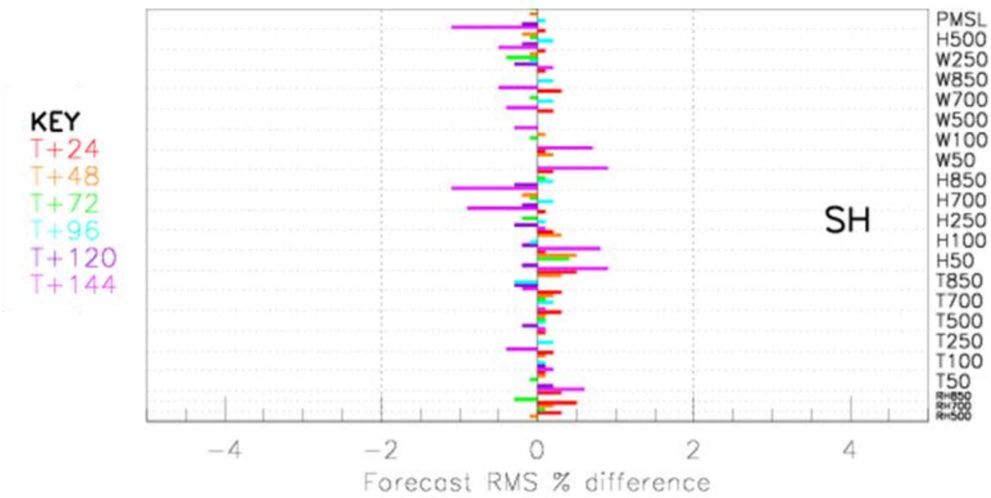


Figure 9 Forecast RMS error percentage difference against observations for different atmospheric variables after the addition of MWHS-2 with correct use of window channels in OPS (experiment 2) compared to the control.

Figure 16 shows the forecast RMS error for experiments 1 (a) and 2 (b) in the southern hemisphere when compared to analysis. Features are similar to those observed when compared to observations, except that relative humidity only degrades by 0.5% in experiment 2.



(a)



(b)

Figure 16 Forecast RMS error percentage difference against analysis in the southern hemisphere for experiment 1 (a) and 2 (b) compared to the control.

4.3 VarBC

MWHS-2 183 GHz channels 11-15 were also tested in a short experiment (mi-af461) adapted from a trial control suite (mi-ae802), which uses the parallel suite 36 (v31.1.0) as a base-line configuration. The main difference with the mi-ae555 and mi-ae714 experiments described in the previous sections is the use of the VarBC scheme (Cameron, 2015). VarBC is aimed to be operationally implemented in PS37 and was shown to yield greater benefits to the NWP system than the static scheme.

The trial covers the period from April 5 to May 7, 2015. It was expected to cover 2 months time, but technical issues caused it to stop half way. A 10-day spin-up time has been excluded from the analysis, so that the subsequent varstats and NWP index were obtained for a 23-day time period.

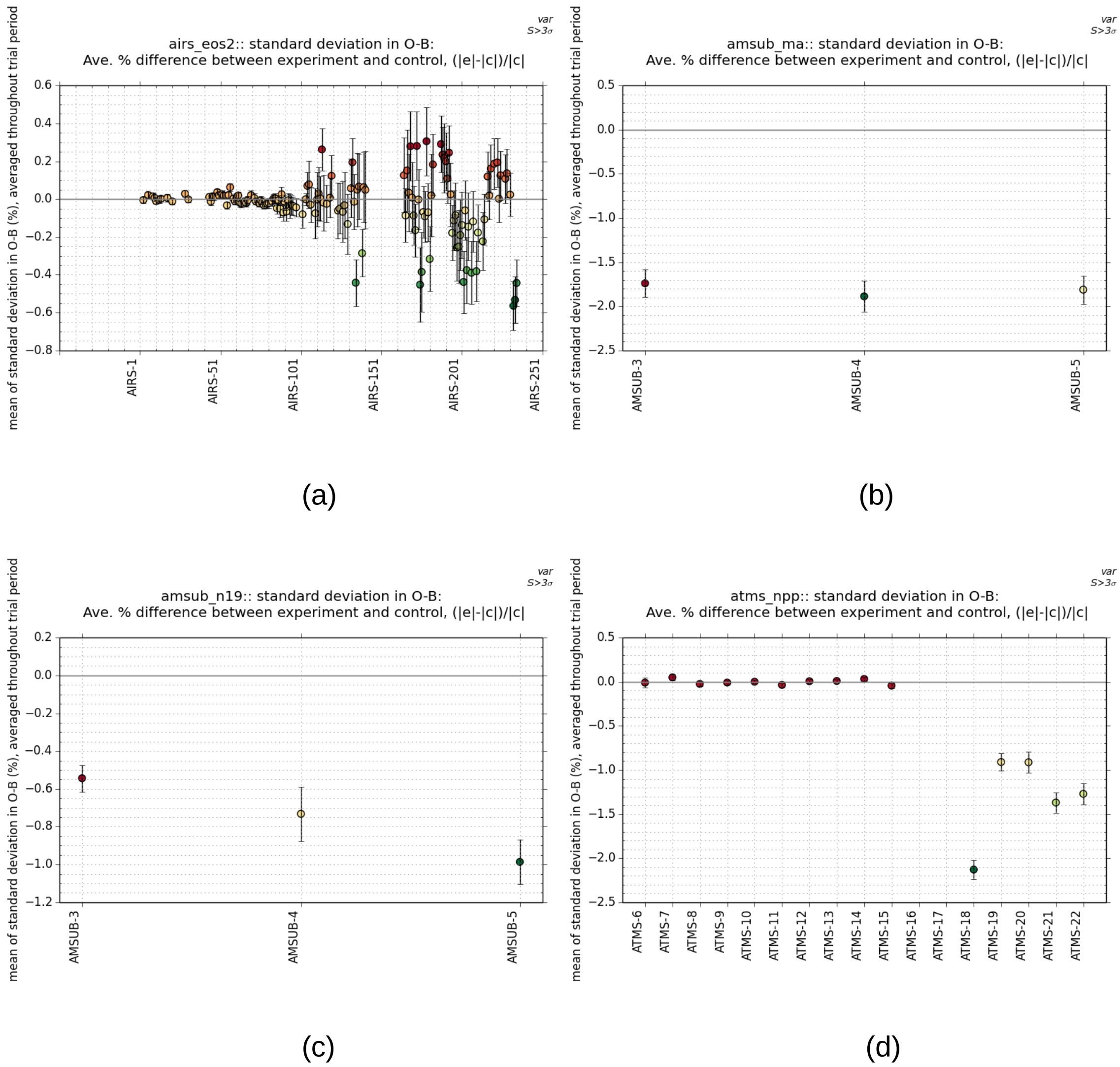


Figure 17 Percentage change in standard deviation in observed - background brightness temperature for mi-af461 compared to control for **(a)** AIRS, **(b)**, MHS on Metop A, **(c)** MHS on NOAA-19 and **(d)** ATMS.

Figure 17 shows the percentage change in standard deviation in O-B for AIRS (a), MHS/MetOp-A (b), MHS/NOAA-19 (c), and ATMS (d). Although this trial yields more neutral results for AIRS (-0.6 to 0.4%) compared to mi-ae555 and mi-ae714, the standard deviation for MHS (-1.6 to -1.9% on MetOp-A, -2.4 to -3% on MetOp-B, and -0.5 to -1% on NOAA19) and ATMS (-0.9 to -2.1%) present significant improvements. No significant change is observed for the other instruments. MHWS-2 mean O-Bs range for this experiment between 0.006 and 0.03 K, which represents an improvement of one order of magnitude with respect to the trials with static bias correction.

All the NWP indexes yield neutral results (-0.317 for new index, and -0.068 vs Obs and -0.241 vs Ana in old index). None of the atmospheric variables presents a change in RMS forecast error at a significant level considering the 23-day long trial period.

5. Conclusions

5.1 Summary

Two new microwave sounding instruments launched on the Chinese FY-3C satellite have been evaluated in order to assess their suitability for assimilation in the Met Office global NWP system. When comparing the observations with NWP model data, it was found that MWTS-2 data required further investigation before being ready for assimilation tests. As well as striping, large scale biases, up to -4K compared to the model, were found in many of the channels. While the bias correction scheme has been able to reduce this offset, it would be useful to determine the origin. At present, it is understood from work carried out at ECMWF/CMA that there is a need for an improved antenna pattern correction and non-linearity correction which greatly reduces the offset. This will likely be applied to the data as part of the initial processing in the future so a re-evaluation may be required when this occurs. Generally, it was shown that the standard deviation of C-B was also slightly higher than the equivalent channels on ATMS, especially for the higher peaking channels. However, an explanation is still required for the apparent surface sensitivity for channels that should have virtually no contribution from the surface. Despite recent modifications made by CMA, further aspects of the calibration scheme still need to be addressed, such as the form of the non-linearity correction, before considering further assessment and assimilation tests of the MWTS-2 data.

For MWHS-2 the results were more encouraging with comparable means of C-B to ATMS while the standard deviation was slightly higher. Some of the channels exhibited striping, although the magnitude is not a significant concern for assimilation. Also, further work is needed to understand the apparent pattern in air mass bias across the 118GHz channels. For the 183GHz channels, their behaviour was very similar to ATMS although they appeared to be subject to a trend in the bias, predominant in channels 13 and 14. Providing the channels reach a stable bias, the risk of any degradation from residual bias can be reduced and the new variational bias correction scheme, due to be implemented in early 2016, will deal with slowly changing biases. Hence, the data appeared to be suitable in its current state for testing in NWP.

The assimilation experiments for the suite of 183GHz channels show an overall neutral impact on the MO NWP index but closer inspection of the VAR statistics reveals that the addition of MWHS-2 has improved the fit of the model background to other humidity sounding channels. No significant issues were found with these channels that would prevent their use in an operational system. For the addition of such a suite of channels, where benefits are mostly confined to humidity fields, this impact was as expected.

5.2 Future work

The FY-3C MWHS-2 data has been shown to be of sufficient quality to provide useful benefit in the Met Office global data assimilation and forecast system. The data should therefore be introduced into the operational model at the earliest opportunity. This is likely to be the Autumn 2015 (PS37) upgrade, which should become operational early in 2016.

As the FY-3C microwave sounding data for the area around the UK is also received by direct broadcast at the Met Office, with timeliness suitable for regional models, the data may also be considered for assimilation in the UKV model.

Further benefit could be gained from use of the 118GHz channels on MWHS-2. This requires an investigation into the cloud information that can be. Realising this benefit is dependent on progress in the development and testing of the cloud incrementing operator, which partitions moisture between vapour and liquid in the Met Office 4D-Var system.

Finally, the microwave imager (MWRI) onboard the FY-3C satellite potentially offers benefit in both the Met Office global and UKV models, and in global and regional reanalysis systems. In the case of the UKV this is dependent on the receipt of direct broadcast data to meet the timeliness demands of the UKV assimilation system.

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