

Assimilation of observations from the Microwave Humidity Sounders on board China’s FY-3B and FY-3C Meteorological Satellites.

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Abstract. China’s FengYun 3 (FY-3) platforms are a series of polar orbiting satellites which will become a major source of data for numerical weather prediction (NWP) and climate monitoring over the next two decades. The Microwave Humidity Sounder (MWS) -1 on board FY-3B and the MWS-2 on board FY-3C both have humidity sounding channels in the 183 GHz band that have been shown to have comparable first guess departures to equivalent channels on well established operational instruments such as AMSU-B, MHS, or ATMS. Therefore, assimilation experiments in the Met Office NWP model have been conducted for MWS-1 and -2 independently. Results show a neutral impact on both short and long range forecasts. Nonetheless, improvements are observed in the fit of observations to the model for independent humidity sensors. Although a beneficial impact from the addition of MWS-1 to the global system has not been clearly established to date and requires further investigations, MWS-2 improves the fit to the model background in the humidity channels of most infrared and microwave sounders with benefits ranging from 0.2 to 2%.

1 Introduction

Space-borne microwave sounding instruments form an important part of the Met Office observing system. The combination of several microwave sounders has provided a consistently large reduction of analysis and forecast errors over the recent years (Joo et al., 2013).

Although data has predominantly been made available by US and European missions, China’s FengYun (FY) 3 program will become a significant source of sounding data in

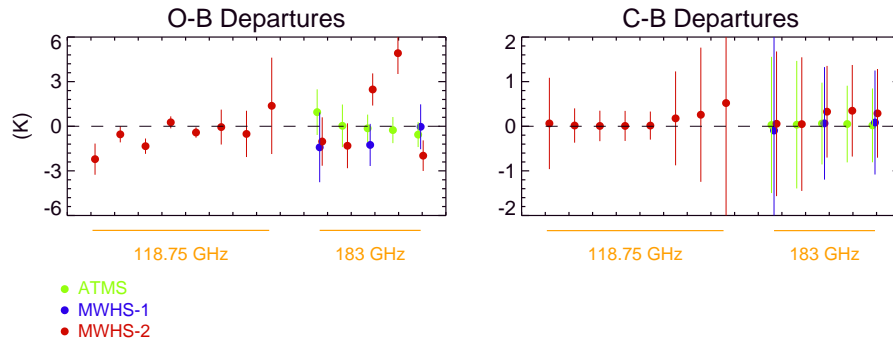
the next decade. It is therefore important to assess the potential benefits of assimilating those observations in the Met Office numerical weather prediction (NWP) model.

FY-3A and FY-3B, launched in May 2008 and November 2012 respectively, are considered experimental missions. FY-3C, launched in September 2013, is the first operational mission and features advanced versions of several instruments from the previous platforms. This study focuses on the implementation and assessment through assimilation experiments of the Microwave Humidity Sounder (MWS) -1 on board FY-3B and its advanced version MWS-2 on board FY-3C.

In the same vein as well established microwave sounders such as the NASA’s ATMS or EUMETSAT’s MHS, MWS-1 and MWS-2 are cross-track scanning radiometers with sounding capability in the 183 GHz water vapor band as well as window channels. MWS-2 also has a new set of 118 GHz channels in the oxygen band, never used before by a space-borne radiometer. Table 1 summarizes MWS-1 and MWS-2 channels characteristics, as well as ATMS’ for comparison purposes.

MWS-1 and MWS-2 have been thoroughly assessed both at the Met Office (Lean et al., 2015; Carminati et al., 2015) and at ECMWF (Lu et al., 2011a; Chen et al., 2014; Lawrence et al., 2015; Lu et al., 2015) using comparison methods against NWP fields, which has been shown to be an effective way to diagnose biases in observations (Lu et al., 2011b; Bell et al., 2008; Doherty et al., 2012). Although MWS-1 is affected by a scene temperature dependency and both instruments (MWS-1 and MWS-2) suffer a scanning-angle bias, static and variational bias corrections used by the two centers efficiently remove those

Figure 1. August 2015 average first guess departure from raw observations (left) and corrected observations (right) for MWHS-1 (blue), MWHS-2 (red), and ATMS (green). Vertical bars show the 1σ standard deviation. Departures are derived in 1D-Var OPS and the Met Office static bias correction is used for corrected observations.



features. Corrected observations from the 183 GHz channels for both instruments exhibit background departures comparable to those found for ATMS. Standard deviations in departures also appear either similar or slightly larger compared to other instruments with similar sounding capabilities. Figure 1 shows an example of comparison between MWHS-1 (blue), MWHS-2 (red), and ATMS (green), where mean first guess departures from raw and corrected observations, and standard deviations are computed in the Met Office 1D-Var observation processing system for the month of August 2015.

Note that abrupt changes in bias are occasionally observed for MWHS-2, either caused by instrument re-tuning or a change in platform temperature. It is clear that greater stability is desirable for operational assimilation. Nevertheless, MWHS-1 and MWHS-2 data quality was estimated to match the required standards to pursue their evaluation through assimilation experiment in NWP models.

Assimilation experiments conducted at ECMWF resulted in neutral to slightly positive impact on NWP forecasts scores accompanied by a reduction of the short range forecast errors and an improved the fit to the model for other sounders when MWHS-1 183 GHz channels were assimilated into the integrated forecasting system (Chen et al., 2014). Similarly, all-sky assimilation of MWHS-2 183 GHz channels in the full ECMWF observing system improved wind, temperature, and humidity forecasts, and the fit to independent sounders, while yielding a neutral impact on forecast scores (Lawrence et al., 2015). As a result, ECMWF has been assimilating FY-3B MWHS-1 in operations since September 2014, and FY-3C MWHS-2 183 GHz channels are operationally monitored since December 2015.

The present document highlights the outcomes of assimilation experiments involving MWHS-1 and MWHS-2 at the Met Office.

Table 1. MWHS-1, MWHS-2, and ATMS channels frequencies and polarization at nadir.

Channel Number			Frequency (GHz)		
MWHS-1	MWHS-2	ATMS	MWHS-1	MWHS-2	ATMS
-	1	16	-	89 (H)	88.2 (V)
-	2	-	-	118.75 ± 0.08 (V)	-
-	3	-	-	118.75 ± 0.2 (V)	-
-	4	-	-	118.75 ± 0.3 (V)	-
-	5	-	-	118.75 ± 0.8 (V)	-
-	6	-	-	118.75 ± 1.1 (V)	-
-	7	-	-	118.75 ± 2.5 (V)	-
-	8	-	-	118.75 ± 3.0 (V)	-
-	9	-	-	118.75 ± 5.0 (V)	-
1-2	10	17	150 (V-H)	150 (H)	165.5 (H)
3	11	22	183 ± 1.0 (V)	183 ± 1.0 (V)	183 ± 1.0 (H)
-	12	21	-	183 ± 1.8 (V)	183 ± 1.8 (H)
4	13	20	183 ± 3.0 (V)	183 ± 3.0 (V)	183 ± 3.0 (H)
-	14	19	-	183 ± 4.5 (V)	183 ± 4.5 (H)
5	15	18	183 ± 7.0 (V)	183 ± 7.0 (V)	183 ± 7.0 (H)

2 Assimilation experiment set up

MWHS-1 and MWHS-2 have been independently integrated into a low resolution (N320L70 UM, N108/N216 4D-VAR uncoupled hybrid assimilation) full system in three different assimilation experiments in the Met Office global model.

2.1 Experiment 1

The trial covers the period from November 12 to December 31, 2014 (49 days), and uses a parallel suite 35 (PS35) base-line configuration. Unlike ECMWF, MWHS-2 is used at the Met Office in clear sky only. The 183 GHz channels are assimilated over oceanic surface, while the 150 and 89 GHz window channels are passively used for quality control purposes.

Prior to their introduction into the system, MWHS-2 98 cross-scan positions are averaged every three adjacent positions, in order to avoid oversampling, in a comparable way to ATMS (Doherty et al., 2015).

Observations then pass to the Observation Processing System (OPS) where quality controls, bias correction, and 1D-

Table 2. MWHS-1 and MWHS-2 observation errors (K), assimilated channels in function of surface type, and cloud screening as used in Exp1, 2, and 3. Note that Bennartz rain only applies to MWHS-2.

Channel number		Observation errors (K)		Assimilated channels			Cloud screening	
MWHS-1	MWHS-2	MWHS-1	MWHS-2	Sea	Sea-ice	Land	Bennartz rain*	Cirrus cost
-	1	-	7.67	NO	NO	NO	-	-
-	2-9	-	3-6	NO	NO	NO	-	-
1	-	5	-	NO	NO	NO	-	-
2	5	5	-	NO	NO	NO	-	-
3	11	4.5	4.5	YES	NO	NO	Rejected	-
-	12	-	4	YES	NO	NO	Rejected	-
4	13	4	4	YES	NO	NO	Rejected	Rejected
-	14	-	4	YES	NO	NO	Rejected	Rejected
5	15	4	4	YES	NO	NO	Rejected	Rejected

Var retrieval of physical parameters such as cloud and surface parameters, required by the main assimilation system, are carried out in a similar way across all the instruments. Screening for errors in the radiative transfer calculations (RTTOV 9) and gross limit checks on latitude and longitude are also applied. Instrument-specific tests, channel selection, or thinning can also be carried out. MWHS-2 benefits of two complementary cloud detection tests, bennartz rain and cirrus cloud cost, which have been adapted from methodologies discussed in Doherty et al. (2015). The bennartz rain test (hereafter bennartzrain) uses the 89 GHz and 150 GHz MWHS-2 channels for the calculation of a scattering index, while the cirrus cloud cost test (hereafter mwbcloody) uses the 183 ± 7 GHz, 183 ± 3 GHz and 183 ± 1 GHz channels for the calculation of a cost function, in combination with an imposed threshold on the magnitude of the departure at 183 ± 7 GHz.

Three rounds of thinning are applied across all spaceborne instruments in OPS. For MWHS-2, it consists in 25 km thinning in a 1-hour window after the observation pre-processing, 80 km thinning in a 1-hour window prior to the 1D-Var calculations, and again 80 km thinning in a 1-hour window prior to the main 4D-Var analysis. For this experiment, the Met Office static bias correction, based on Harris and Kelly (2001), was applied. The correction relies on coefficients relating the bias to atmospheric thickness values at two pressure intervals (850-300 hPa and 200-50 hPa) and to individual scan position. A constant offset can also be applied. Coefficients are updated periodically.

MWHS-2 characteristics applying for this trial are summarized in table 2.

2.2 Experiment 2

MWHS-2 183 GHz channels were also tested in a shorter experiment, which uses the parallel suite 36 (PS36) as a baseline configuration. The main difference with Exp1, described in the previous section, is the use of the new Met Office variational bias correction (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 05 to May 07, 2015 (23 days).

MWHS-2 was processed using the same configuration as described in table 2.

2.3 Experiment 3

A third experiment was set up to evaluate the assimilation of MWHS-1 183 GHz channels in clear sky conditions over ocean in the Met Office global model. This experiment also uses the PS36 baseline configuration with the Met Office VarBC scheme. The two MWHS-1 150 GHz window channels are passively used for quality control purposes. The trial covers the period from April 22, although MWHS-1 observations were effectively assimilated only by April 24, to July 01, 2015 (62 days).

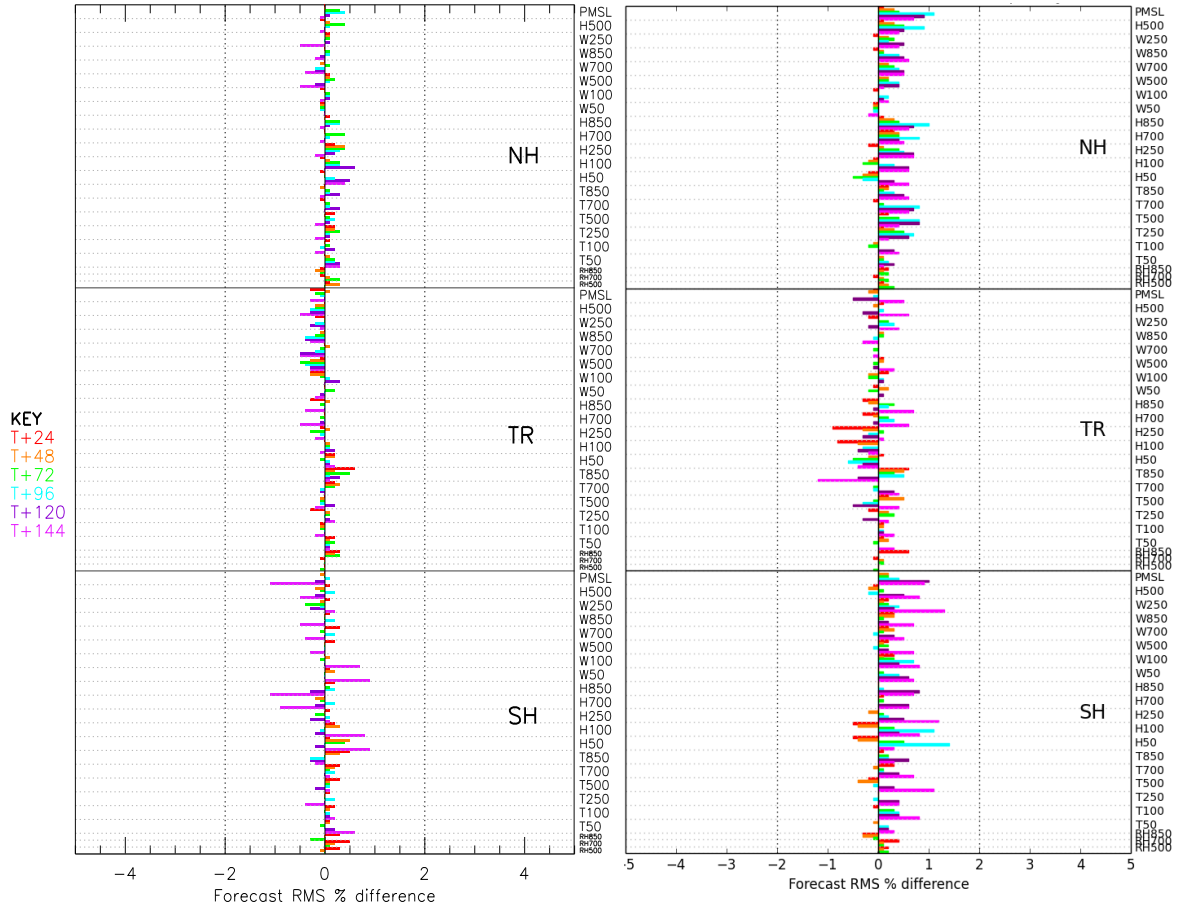
MWHS-1 benefits from the mwbcloody test described in Exp1 but not bennartzrain. Any other processing details are similar to those described for Exp1. MWHS-1 characteristics applying for this trial are summarized in table 2.

3 Results

Trials are analyzed through the examination of the impact on background fits to independent observations, and the impact on NWP scores. The latter verifies improvements in the forecast against observations and analysis. In that context, it is important to note that MWHS-1 and MWHS-2 are independently integrated to a body of five operationally-used microwave instruments of similar capability composed by AMSU-B/MHS and ATMS. Therefore, the addition of a new instrument is expected to result in a small incremental improvement to humidity fields. This is unlikely to have a significant impact on the overall system, which would be reflected by neutral scores. Nevertheless, it is also important to confirm that no degradation is introduced.

NWP scores reflecting the addition of MWHS-2 in Exp1 and Exp2 returned, as expected, neutral results with values

Figure 2. (Left) Changes in pressure at mean sea level (PSML), height (H), wind (W), temperature (T) and relative humidity (RH) RMS forecast errors (%) verified against analysis for Exp1 at forecast time ranging from T+24 to T+144 hours, in the northern hemisphere (top), tropics (middle), and southern hemisphere (bottom). (Right) Same as left but for Exp2.



below the 95% confidence interval relative to the trial length, when verified against both observations and analysis. However, it is possible to look more closely at verification for individual atmospheric variables at different forecast ranges. This allows the separation of the statistically insignificant longer forecast ranges due to the relatively short length of the trials.

Figure 2 shows the changes in forecast error verified against analysis for Exp1 (left) and Exp2 (right). Neglecting the longer range forecasts, the impact is mostly neutral in both hemispheres, and in the tropics. A few small positive impacts with reductions of RMS errors of 0.5% or higher in some of the shorter range height forecasts are present in the tropics and southern hemisphere. The relative humidity appears neutral across most of short ranges. The only exception is a $\sim 0.5\%$ degradation of the 700 hPa relative humidity (RH700) at T+24 in the southern hemisphere in Exp1. RH500 also degrades by $\sim 1\%$ when Exp1 is compared to observations at T+72 (not shown).

The addition of MWHS-1 in Exp3 produced, however, a neutral to slightly negative NWP scores.

Figure 3 shows the changes in forecast error verified against analysis for Exp3. Forecast errors in the northern hemisphere increase, but mostly at an insignificant level, below the 95% confidence interval. Again, the shortness of the assimilation period makes the analysis of the longest forecast time inconclusive. The Tropics present in both verifications a reduction in short-range forecast errors for the 500 and 50 hPa height (H500 and H50, respectively), but also an increase of stratospheric temperature (T50) errors. In the Southern hemisphere, the verification against analysis presents a mixed picture with significant impact, either positive and negative, on several parameters including wind, height and temperature. A noteworthy and concerning feature is the large increase of short-range RH500 errors (7, 5, and 4% at T+24, +48, and +72, respectively). This feature is also present in the verification against observations, although to a much lesser extent (not shown).

Figure 3. Same as Fig. 2 but for Exp3.

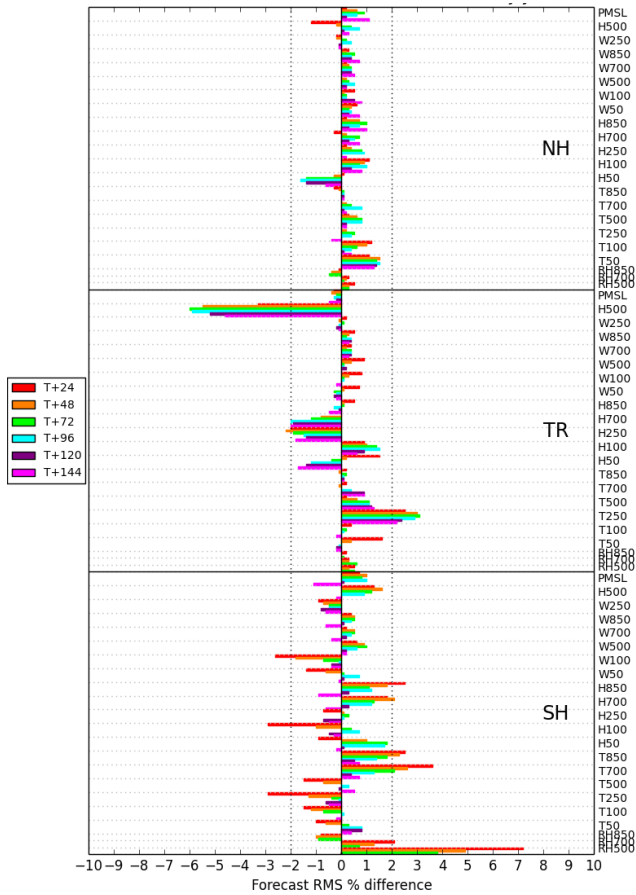


Figure 4 provides the vertical structure of the relative humidity absolute forecast errors verified against analysis at T+24. Errors in the mid-tropospheric 700-400 hPa pressure domain appear to be the most affected (consistent with the major degradation in RH500 shown in Fig. 3), and, to a lesser extent in the lowermost troposphere at pressure greater or equal to 950 hPa.

Met Office model forecasts are generated in 6-hour cycles, the model background is provided by the six hour forecast from the previous cycle. Statistics generated during the 4D-Var process allow a comparison of a given set of observations for a particular cycle with the six hour forecast from the previous cycle. A key metric in the estimation of alterations induced by the assimilation of a new instrument is the change in standard deviation of the fit of the background to independent sounder observations. A significant reduction of standard deviation would be considered as an improvement, while an increase would be synonymous of degradation.

With the introduction of MWHS-1 and MWHS-2, although little effect is expected for temperature sounding instruments, humidity sensitive channels are likely to show

some changes as the humidity field is being more directly influenced by the addition of 183 GHz information.

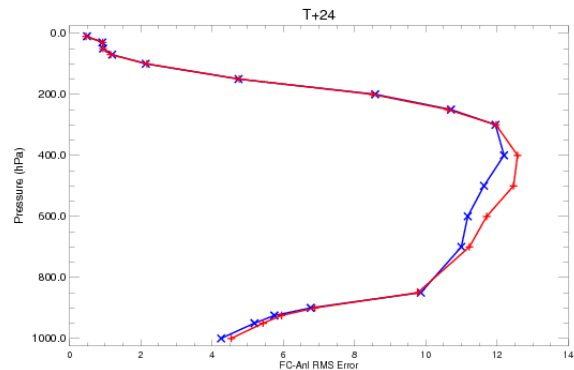
Figure 5 shows the percentage change in standard deviation in first guess departure from corrected observations for AIRS, MHS (MetOp A and NOAA-19), and ATMS in Exp1.

AIRS changes in standard deviation present the best improvements for high peaking water vapor channels with a reduction of 0.8%, and, to a lesser extent, the low peaking water vapor channels where the reduction is limited to 0.2%. All five ATMS equivalent channels to MWHS-2 also exhibit a 0.7-1.2% reduction in standard deviation. The addition of MWHS-2 has a neutral impact on the MHS/AMSU-B instruments on board MetOp A (and B, not shown), while the standard deviation for the instruments on board NOAA-19 (and 18, not shown) results in more consistent reduction (0.5-0.6%). Interestingly, it seems a general pattern that the morning orbit instruments show neutral changes, while those in afternoon orbits experience more positive impact. It appears that the location of the MWHS-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.

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.

Figure 4. Vertical profile of the absolute changes in RMS forecast errors of relative humidity (%) at T+24 in the southern hemisphere for Exp3. Control is shown in blue and Exp3 is shown in red.



The change in standard deviation obtained after the addition of MWHS-2 processed with VarBC in Exp2 (not shown) yields more neutral results for AIRS ($\pm 0.4\%$), but significantly improves for MHS (reduction down to 1.9%, 3%, and

Figure 5. (Clockwise from top left) Mean standard deviation in the Exp1 departures (%) averaged throughout the trial period for AIRS, AMSU-B (MetOp-A), ATMS, and MHS (NOAA-19).

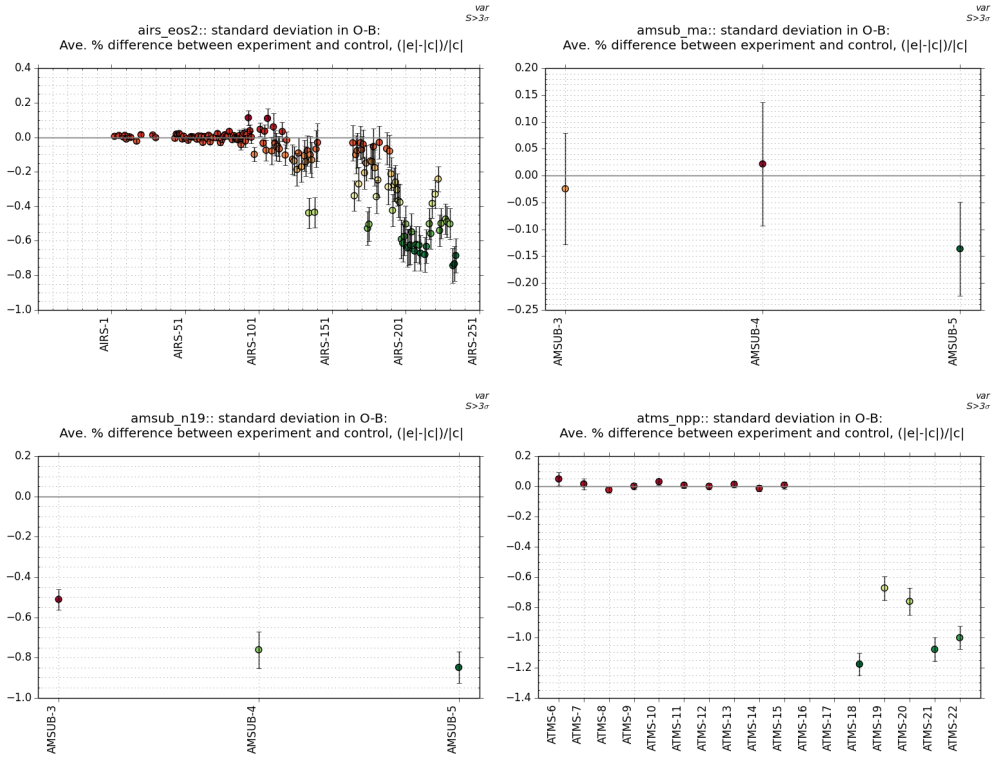


Figure 6. Same as Fig. 5 but for Exp3.

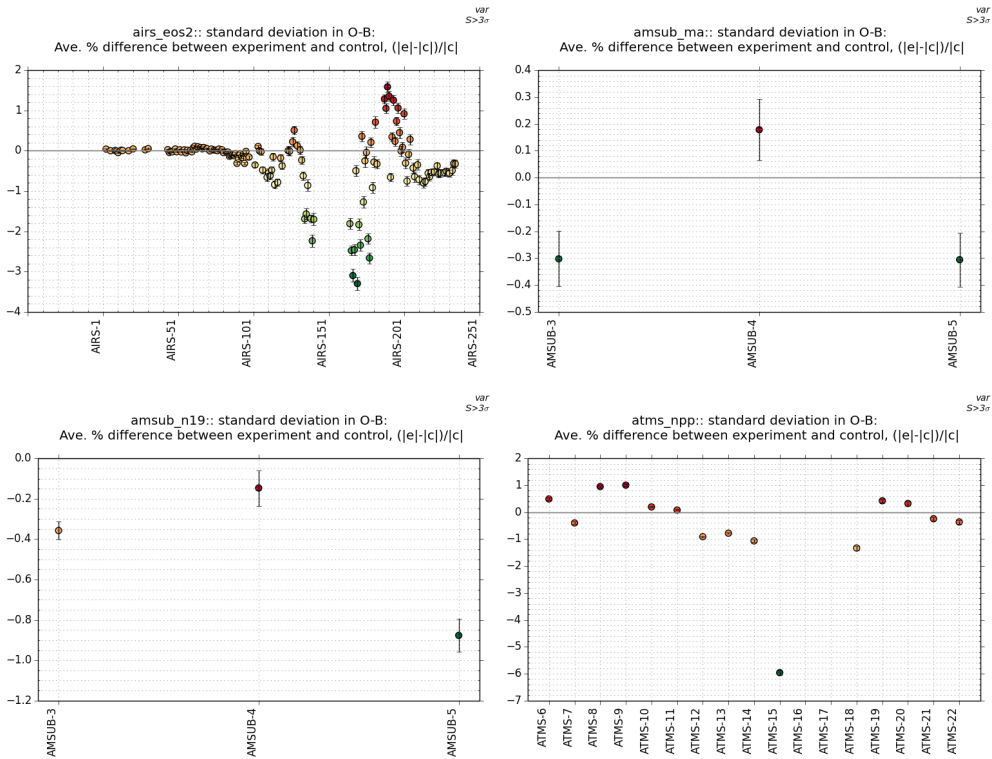
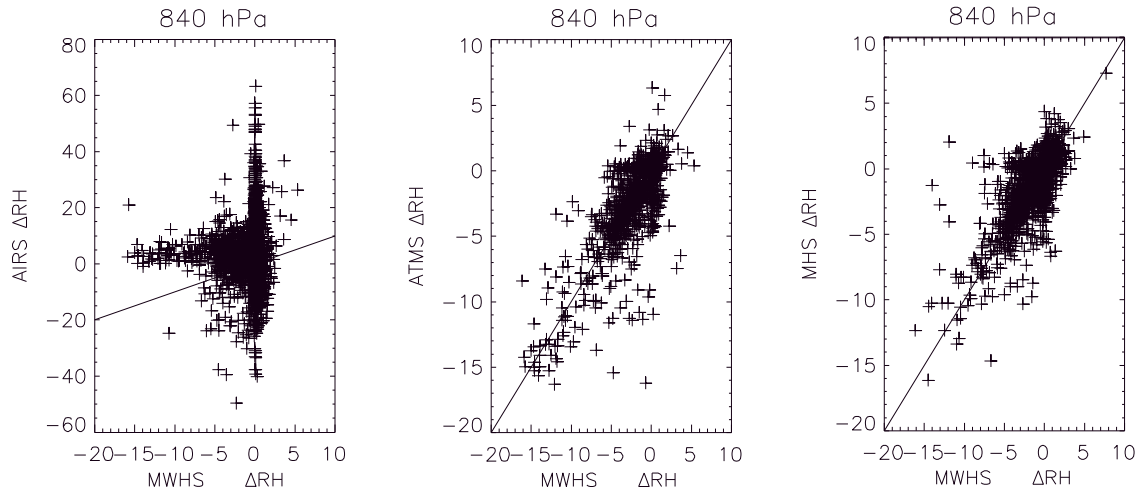


Figure 7. (From left to right) 1D-Var relative humidity departures (RH – model background RH) in the lower troposphere (840 hPa) for MWHS-1 versus AIRS, ATMS, and MHS (NOAA-19) for collocated observations. The solid black line shows the $x=y$ axis.



1% on MetOp-A, MetOp-B, and NOAA-19, respectively) and ATMS (reduction down to 2.1%). No significant change is observed for the other instruments.

Also noteworthy, MWHS-2 mean departures 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.

Figure 6 is similar to Fig. 5 but for the addition of MWHS-1 in Exp3.

The humidity sensitive channels across all the instruments respond in a mostly neutral way or with slight benefits from the addition of MWHS-1. One exception however affects AIRS lower peaking water vapor channels, which yield significant degradation over 1% in standard deviation. Surprisingly, AIRS window sensitive channels experience a significant reduction of the standard deviation (consistent for all hyperspectral infrared instruments). However, it must be noted that this reduction in standard deviation is systematically accompanied by an increase of the observation counts, and therefore do not necessarily signify an improved fit to the model.

Again, temperature sounding channels across all the instruments have a mostly neutral for response to the addition of MWHS-1.

In order to investigate the origin of the lower and mid-tropospheric relative humidity forecast error increase, and whether a possible link with the increased standard deviation in AIRS lower peaking humidity channels exists or not, the relative humidity retrieved from MWHS-1 observations

in the 1D-Var analysis in OPS is compared to that of AIRS, ATMS, and MHS (NOAA-19). Figure 7 shows scatter plots of relative humidity analysis increments (RH – model background RH) in the lower troposphere (840 hPa) for MWHS-1 versus (from left to right, respectively) AIRS, ATMS, and MHS (NOAA-19) for collocated observations. Collocation criteria are set to select the closest profile to each MWHS-1 profile within a 1 degree radius and 3600 seconds temporal window. MWHS-1 relative humidity seems to be consistent with that of ATMS (middle) and MHS (right) with a scattering roughly following the 1-to-1 line, indicative of a good correlation. However, the comparison between MWHS-1 and AIRS RH departures produces a cross-like pattern (no correlation) that betrayed a possible issue with AIRS lower tropospheric relative humidity.

Because AIRS is operationally used and no such behavior have been detected in experiments unrelated to MWHS-1, it is plausible that the addition of MWHS-1 observations to the global system allows spurious AIRS observations from low peaking humidity channels to pass quality controls that they would failed otherwise. This hypothesis is supported by the 5-20% increase in observation counts in VAR statistics for AIRS low peaking humidity channels (channels 188-201) in Exp3 (not observed in Exp 1 and 2).

At the time of writing, further experiments are ongoing with the aim to better understand the inter-connectivity between AIRS and MWHS-1, and how this affects global relative humidity fields.

4 Conclusions

FY-3B MWHS-1 and FY-3C MWHS-2 observations have been received at the Met Office since 2012 and 2014, respectively. Since then, both instruments have been subject of several validation studies conducted internally at the Met Office and in cross-collaboration with ECMWF. It resulted that observations from MWHS-1 and MWHS-2 were, once appropriately bias corrected, of matching quality with well established operational instruments of similar sounding capability. Therefore, and in light of encouraging assimilation experiments conducted at ECMWF, MWHS-1 and MWHS-2 have been independently integrated to the Met Office global model in a set of assimilation experiments with the aim of testing their impact on the system for possible operational use.

The analysis of a 62-day long assimilation experiment with MWHS-1 183 GHz channels returned overall neutral to slightly negative NWP scores. The further examination of different key parameters revealed a significant degradation of the lower and mid-tropospheric relative humidity, mostly located in the southern hemisphere. The increase in forecast errors appears to be tightly linked to an increase in standard deviation in the departure and in observation counts of AIRS lower peaking humidity channels. MWHS-1 operational use has been postponed pending results of further investigations under way.

The assimilation of MWHS-2 183 GHz channels in two separate experiments yielded an overall neutral impact on NWP scores. Nevertheless, it was shown to improve the fit of the model background for humidity sounding channels of independent instruments. Benefits, mostly impacting the standard deviation in first guess departures, range from 0.2 to 2% reduction across most instruments. As a result, MWHS-2 observations have been introduced in November 2015 to the Met Office parallel suite 37, which is planned to become operational in March 2016.

Work is currently under way at the Met Office to test the assimilation of MWHS-2 183 GHz channels over land. The addition of land observations is expected to have an incremental benefit and further reduce forecast errors. Pending positive results, the implementation of the assimilation of observations above land will be part of the parallel suite 38, early 2016.

Finally, further benefit could be gained from use of the 118 GHz channels on MWHS-2. Realizing this benefit is dependent on progress in the development and testing of the cloud incremental operator, which partitions moisture between vapor and liquid in the Met Office 4D-Var system.

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References

- Bell, W., Candy, B., Atkinson, N., Hilton, F., Baker, N., Bormann, N., Kelly, G., Kazumori, M., Campbell, W. F., and Swadley, S. D.: The assimilation of SSMIS radiances in numerical weather prediction models, *Geoscience and Remote Sensing, IEEE Transactions on*, 46, 884–900, 2008.
- Cameron, J.: Options for the development of varbc at the met office and recommendations for operational implementation at PS37, *Satellite Applications Technical Memo*, Met Office, 25, 2015.
- Carminati, F., Bell, W., Lean, K., and Atkinson, N.: FY3-B Assessment Report, *Met Office Satellite Applications Technical Memo*, 38, 2015.
- Chen, K., English, S., Bormann, N., and Zhu, J.: Assessment of FY-3A and FY-3B MWHS observations, *ECMWF Tech. Memo.*, 734, 2014.
- Doherty, A., Atkinson, N., Bell, W., Candy, B., Keogh, S., and Cooper, C.: An initial assessment of data from the Advanced Technology Microwave Sounder, *Met Office Forecasting R&D Technical Report*, 569, 2012.
- Doherty, A., Atkinson, N., Bell, W., and Smith, A.: An Assessment of Data from the Advanced Technology Microwave Sounder at the Met Office, *Advances in Meteorology*, 956920, <http://www.hindawi.com/journals/amete/aa/956920/>, 2015.
- Harris, B. and Kelly, G.: A satellite radiance-bias correction scheme for data assimilation, *Quarterly Journal of the Royal Meteorological Society*, 127, 1453–1468, 2001.
- Joo, S., Eyre, J., and Marriott, R.: The impact of Metop and other satellite data within the Met Office global NWP system using an adjoint-based sensitivity method, *Monthly Weather Review*, 141, 3331–3342, 2013.
- Lawrence, H., Bormann, N., Lu, Q., Geer, A., and English, S.: An Evaluation of FY-3C MWHS-2 at ECMWF, *EUMETSAT/ECMWF Fellowship Programme Research Report*, 37, 2015.
- Lean, K., Bell, W., Atkinson, N., and Carminati, F.: Assessment of FY-3C microwave sounding data, *Met Office Satellite Applications Technical Memo*, 35, 2015.
- Lu, Q., Bell, W., Bauer, P., Bormann, N., and Peubey, C.: Characterizing the FY-3A microwave temperature sounder using the ECMWF model, *Journal of Atmospheric and Oceanic Technology*, 28, 1373–1389, 2011a.
- Lu, Q., Bell, W., Bauer, P., Bormann, N., and Peubey, C.: An evaluation of FY-3A satellite data for numerical weather prediction, *Quarterly Journal of the Royal Meteorological Society*, 137, 1298–1311, 2011b.
- Lu, Q., Lawrence, H., Bormann, N., English, S., Lean, K., Atkinson, N., Bell, W., and Carminati, F.: An evaluation of FY-3C satellite data quality at ECMWF and the Met Office, *ECMWF Tech. Memo.*, 767, 2015.