Assessment of FY-3A and FY-3B MWHS Observations

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ABSTRACT

The Fengyun-3 series of satellites (FY-3) began in May 2008 with the launch of FY-3A. The onboard Microwave Humidity Sounders (MWHSs) provide vertical information about water vapor, which is important for numerical weather prediction (NWP). The noise equivalent delta temperature (NEDT) of the MWHS is higher than that of the Microwave Humidity Sounder (MHS) instrument (e.g., on board MetOp-B) but lower than that of the older AMSU-B instruments (on board NOAA-15, NOAA-16, and NOAA-17). Assimilation of MWHS observations into the ECMWF Integrated Forecast System (IFS) improved the fit of short-range forecasts to other observations, notably MHS, and also slightly improved the longer-range forecast scores verified against analyses. Also, assimilating the MWHS on board both FY-3A and FY-3B gave a larger impact than either instrument alone. Furthermore, when MWHS and MHS were added separately to a baseline using neither, the impact of MWHS was found to be comparable to that of MHS. Consequently, ECMWF has been assimilating the FY-3B MWHS data in the operational forecasting system since 24 September 2014. This is the first operational use of Chinese polar-orbiting satellite data by an NWP center outside of China.

1. Introduction

China launched the first of the Fengyun-3 series of satellites (FY-3) in May 2008. This is the second generation of these Chinese polar-orbiting satellites, carrying significantly more sophisticated sensors for operational meteorology than did the first generation. The first two satellites in the series, FY-3A and FY-3B, were classed as research satellites, and they carry two microwave sounding instruments: the four-channel Microwave Temperature Sounder (MWTS) and the five-channel Microwave Humidity Sounder (MWHS). In September 2013, the third satellite (FY-3C) was launched as the first operational satellite. The microwave instruments on board have the potential to play an important role in numerical weather prediction (NWP). Therefore, a detailed assessment of the data quality and the forecast impact of these microwave radiometers on the preparatory FY-3 is required.

Since FY-3 is expected to become an important data source for NWP, reanalysis, and climate sciences, this assessment has already begun. Lu et al. (2011a,b) assessed MWTS and MWHS on board FY-3A against a baseline of the operational ECMWF NWP short-range forecast, using the Radiative Transfer for TOVS (RTTOV) model (Saunders et al. 1999). Significant biases were found for MWTS and it was suggested that these were related both to shifts in the frequency of the channel pass bands and to radiometer nonlinearity. After these effects were properly accounted for, the data quality of the FY-3A MWTS and MWHS was found to be broadly comparable with that of AMSU-A and Microwave Humidity Sounder (MHS) in terms of bias.
(Zou et al. 2011). Noise figures for MWHS were found to be slightly larger than those for MHS. Initial observing system experiments suggested that the impacts were from neutral to slightly positive, which was encouraging and built confidence that the instruments could be used in NWP data assimilation systems (Lu et al. 2011b).

The present study provides a detailed assessment of the MWHS instruments on board both FY-3A and FY-3B, and reports on trials that led to the operational use of MWHS data in the ECWMF system. The data quality is first evaluated through a comparison of observations with equivalents derived from short-term forecasts, followed by assimilation trials that make use of the data from the two instruments. Of particular interest is how the forecast impact of the MWHS instrument, with its higher noise, compares to that of MHS when used in a comparable way.

The structure of the paper is as follows. In section 2, the MWHSs from FY-3 and MetOp-B are described and compared, followed by a description of the experiments used to evaluate the data. Section 4 presents the data quality assessment based on statistical analysis of the first-guess departures, whereas section 5 discusses the forecast impacts from assimilating MWHS data within the context of a full observing system. In section 6, a more detailed comparison of the impacts of the MWHS on board FY-3A and FY-3B and the MHS on board MetOp-B is presented. Finally, the conclusions are presented in the last section.

2. Microwave Humidity Sounders

a. MWHS data

The FY-3 MWHS is a five-channel cross-track scanning instrument able to provide vertical humidity information to NWP data assimilation systems. The vertical resolution is relatively poor, but similar observations have proven valuable in NWP in the past. The central frequencies of MWHS are shown in Table 1. The sounding channels (3–5) are sensitive to the water vapor around 400, 600, and 800 hPa, respectively. The nominal spatial resolution is 15 km at nadir, and the swath width is 2700 km with a total of 98 fields of view (FOVs) along each scan line. The MWHS instrument is flown on the FY-3A with an equatorial crossing time (ECT) of 1015 LT (all ECTs are local time; all other times in this article are UTC) (descending) and on the FY-3B with an ECT of 1340 (ascending).

b. MHS data

The MHS instrument is flying on the NOAA satellite series as well as on the MetOp satellites. MHS is a cross-track scanning microwave radiometer. It also has five channels, but with slightly different frequencies than those of the MWHS (Table 1). The nominal spatial resolution is the same as MWHS at nadir, but the swath width is smaller than that of MWHS, only 2250 km, with a total of 90 FOVs along each scan line. This means that in the tropics MWHS has smaller gaps between consecutive orbits than does MHS and consequently MWHS provides more observations globally.

3. Experiments and assimilation settings

The MWHS data have been experimentally assimilated into the ECMWF Integrated Forecast System (IFS) to investigate the data quality and forecast impact. We only consider observations from clear-sky regions, and radiative transfer effects resulting from cloud or rain are ignored. We only consider data over the sea, as the estimation of surface emissivity over land and sea ice has higher uncertainty. The quality control and other assimilation settings follow the operational use of clear-sky MHS data. To remove observations strongly affected by ice cloud and precipitation, we require that the absolute values of the first-guess departure of channel 1 be below 5 K. This dataset is referred to as the “clear data.” Variational bias correction (VarBC; Dee 2004) is applied to the observations, as is done for all microwave radiances in the IFS, and the bias predictors are the same as for equivalent MHS channels, including air mass as well as scan bias predictors (Bormann and Bauer 2010). This accounts for possible systematic errors in selected observations and/or observation operators. To remove redundant satellite observations and to reduce the

<table>
<thead>
<tr>
<th>Channel No.</th>
<th>Frequency (GHz)</th>
<th>Bandwidth (MHz)</th>
</tr>
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<tbody>
<tr>
<td>MHS</td>
<td>MWHS</td>
<td>MHS</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>89 (V)</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>157 (V)</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>183.31 ± 1 (H)</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>183.31 ± 3 (H)</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>190.31 (V)</td>
</tr>
</tbody>
</table>
impact of spatial error correlations, spatial thinning is performed and the best quality data are retained. An average distance of about 140 km is applied.

One control and three experiments were run to test the data quality and the impact of MWHS assimilation. All experiments used ECMWF’s 12-h four-dimensional variational data assimilation (4DVAR) with a model resolution of T511 spectral truncation (corresponding to a spatial resolution of around 40 km), a final incremental analysis resolution of T255 (about 80 km), and 91 levels in the vertical. To save computational cost, this is a lower resolution than is used in the current operational ECMWF system, but is the normal resolution for component testing (e.g., adding a new satellite data type). The control was run from 10 July to 7 September 2013, and 10-day forecasts were run at 0000 and 1200 UTC each day, which provides 120 forecast samples in total. The control run assimilates the same observations used operationally by ECMWF on these dates (i.e., excluding MWHS). The FY-3A experiment added the MWHS on FY-3A and the FY-3B experiment added the MWHS on FY-3B, separately. In a third experiment, the MWHS instruments from both satellites were added to the assimilation system. All of the experiments are performed over the same period as the control run. In addition, the same three experiments were repeated for the Northern Hemisphere winter from 1 December 2013 to 28 February 2014.

All the experiments mentioned above use the full observing system assimilated operationally at ECMWF at the time. This includes conventional data as well as radiance observations that are sensitive to humidity from four MHS instruments, two High Resolution Infrared Radiation Sounder (HIRS) instruments, the Advanced Technology Microwave Sounder (ATMS), as well as from the Atmospheric Infrared Sounder (AIRS), the Infrared Atmospheric Sounding Interferometer (IASI) on MetOp-A, and the Cross-track Infrared Sounder (CrIS). In particular, MHS and ATMS already provide similar microwave humidity sounding data in this system, with data from the MetOp-A and MetOp-B satellites in an orbit similar to FY-3A, and NOAA-18, NOAA-19, and the Suomi–National Polar-Orbiting Partnership (Suomi-NPP) satellite in an orbit similar to FY-3B. The assimilation system uses RTTOV, version 11, for all radiance simulations (Saunders et al. 1999; Hocking et al. 2012).

4. Data quality

We will now assess the quality of the MWHS data from the two satellites by comparing the observations with simulations calculated from short-term forecasts. This provides an evaluation of the data against a reference with stable characteristics, allows an assessment within the context of other similar observations, and is an important part of the calibration-validation of the instruments (e.g., Bell et al. 2008; Lu et al. 2011a,b; Bormann et al. 2013).

Figure 1 compares the overall characteristics of first-guess departures for clear data from MWHS against

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**Fig. 1.** Departure statistics of observation minus first guess for clear data from MWHS and MHS from 10 Jul to 7 Sep 2013. Only data over seas and within ±60° latitude are considered. Shown are (a) std dev after bias correction, (b) mean residual bias (after bias correction), and (c) mean bias correction, for the FY-3A MWHS (black solid), FY-3B MWHS (black dashed), and MetOp-B MHS (gray solid).
those of the MetOp-B MHS, to give an initial impression of the data quality. The standard deviations of first-guess departures of the MWHS instruments are larger than those of the MetOp-B MHS. This is likely to be a result of larger instrument noise, as previously pointed out by Lu et al. (2011a). Mean bias corrections are in the range from −3 to 0 K, compared to −1 to 1 K for MHS. However, as expected, after bias correction the overall bias is similarly close to zero for the three instruments shown.

The departure characteristics for the clear data appear to be mostly stable in time, with the exception of occasional spikes in the standard deviations of the first-guess departures for MWHS (Fig. 2a). One such spike occurred on 10 July for the FY-3A MWHS, while no spike appears for the FY-3B MWHS or for the MetOp-B MHS at the same time. This spike clearly relates to an anomaly in the FY-3A MWHS data. On this day, the first-guess departures exceed the absolute values of 15 K for a small number of scan lines. Further investigations suggest that this is due to an error in the calibration, possibly linked to a data outage that occurred around the same time (not shown). However, Fig. 2b indicates that the quality control (QC) employed in the IFS
removes the badly calibrated scan lines identified above and makes the first-guess departures of FY-3A and FY-3B MWHS broadly comparable with the MetOp-B MHS. This is mainly achieved by the “first guess” check that rejects outliers that deviate too much from the first guess. Though smaller standard deviation values are shown than those in Fig. 2a for MWHS, the absolute values and the variation with time are still larger than for MHS.

Histograms of first-guess departures (differences between observations and model simulations; \( O - B \)) for the MWHS and MHS data selected for assimilation suggest that the errors in both datasets are predominantly Gaussian, with larger noise for MWHS (Fig. 3). To quantify the difference in noise, artificial random noise has been added to each channel of MHS (not shown). The two curves fit each other after 0.8 and 1 K of random noise are added separately to channel 3 of MHS in order to compare with MWHS from FY-3A and FY-3B, respectively. The values for the added random noise are broadly consistent with the differences in noise equivalent delta temperature (NEDT) between the two instruments mentioned in the previous studies (Zou et al. 2011; Lu et al. 2011a).

Given the larger noise found in Figs. 1 and 3, we decided to assign larger observation errors to MWHS data during the assimilation compared to MHS (Table 2). The assigned observation errors for both instruments are larger than the standard deviations of the first-guess departures shown in Fig. 1, so they are an overestimate of the true observation errors. Such error inflation has been found to be necessary in previous studies, in order to counteract the effects of neglected error correlations.

The MWHS instruments on both satellites exhibit relatively complex scan-position-dependent biases, which are not resolved well by our current approach to bias correction. Similar results have been reported by Lu et al. (2011a) for the FY-3A MWHS. As illustrated in Fig. 4, the mean first-guess departures of MHS of each scan position are very smooth after bias correction, while the MWHS mean first-guess departures vary with scan position. The scan bias variation of the FY-3A MWHS (Fig. 4a) is much larger than that of the FY-3B MWHS (Fig. 4b), and an analysis over different periods suggests that the patterns do not change with time (not shown). The first-guess departures of channel 5 from both MWHS instruments vary the most compared with the other two channels. Scan biases in the ECMWF system are modeled as part of the variational bias correction through a third-order polynomial in the scan angle, and it is clear that this polynomial is not able to fully correct for the complex scan-position dependence of the bias for MWHS. It would be possible

| Table 2. Assigned observation errors of MWHS and MHS. |
|---------------------------------|-----------------|-----------------|
|                                 | MWHS observation errors (K) | MHS observation errors (K) |
| Channel 3 | Channel 4 | Channel 5 | Channel 3 | Channel 4 | Channel 5 |
| 2.3       | 2.5       | 2.4       | 2           | 2           | 2           |
to reduce the residual scan biases by introducing a separate offset for each scan position in the bias correction. However, given the size of the residual biases, this was not considered a priority. The first-guess departure standard deviation of each scan position of MWHS is also larger than that of MHS, which is consistent with our study mentioned above. This also shows that the residual scan-position-dependent biases are not sufficient to explain the larger standard deviations over all scan positions.

5. Assimilation results for a full observing system

We will now discuss the impact of adding MWHS data within the context of the full observing system used operationally at ECMWF at the time. As noted earlier, this system already assimilated data from five microwave humidity sounding instruments, so this provides a very stringent test of the data.

Departure statistics for other assimilated observations are mostly unchanged, showing that the assimilation of MWHS data is consistent with the rest of the observing system (not shown). Globally, the assimilation of MWHS decreases the standard deviations of the first-guess and analysis departures of MHS (Fig. 5). Similar improvements are found over the Northern Hemisphere, Southern Hemisphere, and tropics (not shown). Even better results are obtained by assimilating FY-3A MWHS and FY-3B MWHS together, providing further evidence of good consistency between the MWHS and MHS data. While the reductions in the standard deviations of background departures are relatively small, they nevertheless suggest a notable reduction in the short-term forecast error.

The overall impact of assimilating MWHS data on medium-range forecasts is from neutral to slightly positive. For example, a statistically significant reduction in root-mean-square error for wind vectors is achieved in
the Northern Hemisphere for both the FY-3B MWHS and the combined FY-3A and FY-3B experiments (Fig. 6). A more neutral change over the Southern Hemisphere and tropics was found. The scores are verified against both the ECMWF operational analyses and radiosonde observations with similar results. The main impact was on vector wind, which is as expected as one of the key forecast variables known to have sensitivity to humidity assimilation in 4DVAR (e.g., Geer et al. 2014). No difference in impact was found when results for boreal summers and winters were analyzed separately (not shown). Even though the improvements are not statistically significant at all forecast ranges, the neutral to slightly positive impact is an encouraging result, given

**Fig. 5.** Std dev of (left) analysis and (right) first-guess departures of the MHS data used, normalized by values for the control experiment. Horizontal bars indicate 95% confidence intervals. (a),(b) Assimilation of FY-3A MWHS and FY-3B MWHS (black) vs FY-3A MWHS (gray). (c),(d) Assimilation of FY-3A MWHS and FY-3B MWHS (black) vs FY-3B MWHS (gray).
the number of similar MWHSs in comparable orbits already assimilated in our control run.

6. Assimilation results for depleted observing system

To further characterize the impact of MWHS in comparison to MHS, we now compare their impacts when they are added separately to a baseline experiment that uses all operational observations except MHS and MWHS. Four experiments are set up to compare the impact of MWHS and MHS on forecast skill. In the first experiment, MWHS data from FY-3A and FY-3B are added to the baseline, whereas in the second experiment MHS data from MetOp-B and NOAA-18 are added instead. In the third and fourth experiments, only data from a single instrument are added, the FY-3B MWHS data and the NOAA-18 MHS data, respectively. These experiments were run for the period from 1 December 2013 to 23 February 2014. In all four experiments, only clear data over sea are assimilated from MWHS or MHS. Table 3 shows the ECT of the FY-3 and LEO satellites. MetOp-B and NOAA-18 were chosen for the MHS experiments, as the ECT of MetOp-B is closest to that of FY-3A and NOAA-18 has the closest ECT for a satellite carrying a fully functional MHS instrument.

Forecast scores and errors are evaluated by verifying against operational analyses. Overall, the forecast scores from the assimilation of the FY-3 MWHS series and the assimilation of MetOp-B MHS and NOAA-18 are comparable for most geophysical parameters (Fig. 7; only the forecast scores of vector wind are shown here). The forecast error change of the vector wind at a given range of forecast times, latitudes, and altitudes is shown in Fig. 8 with improvement displayed in blue. Forecast errors are reduced globally with the assimilation of the FY-3 MWHS series, which is comparable to the improvement from the assimilation of the two MHSs for the day-2 forecasts and beyond. For the short-range forecasts, MHS appears to give better results, although some of this apparent advantage for MHS may be due to MHS being included in the operational analyses used here for verification. The results verified against radiosonde observations further show that the assimilation of the FY-3 MWHS series results brings positive impacts on the baseline as well as the assimilation of MHS instruments does (not shown). As for the performance of a single instrument, similar conclusions can be drawn by comparing the assimilation of FY-3B MWHS and NOAA-18 MHS separately (not shown).

The results suggest that MWHS achieves an overall comparable impact in the assimilation system when
compared with MHS, despite the larger instrument noise noted earlier. This indicates that noise performance is currently not a limiting factor for the forecast impact for MWHSs.

7. Conclusions

Data from the microwave humidity sounding instruments on board FY-3 have been tested in the ECMWF Integrated Forecast System (IFS). This permits both an assessment of data quality through an analysis of first-guess departure statistics compared with the equivalent MetOp-B instruments, and an investigation of the potential impacts on operational forecasts through data assimilation experiments. The first-guess departure statistics indicate that MWHS data have higher noise than do MHS data. There are also occasional calibration issues seen in first-guess departures that in the period studied here were removed successfully by quality control. Although the quality control applied was successful, it is desirable to understand and remove calibration errors at the source through careful characterization of the instrument. Averaged first-guess departures show relatively complex bias characteristics as a function of scan position and those are not fully removed when a polynomial function is used to model the scan bias. However, it is not possible to say from this study how much these residual biases are degrading the impact of MWHS. The data quality assessment by the assimilation experiments and operational forecasts provides valuable information on the impacts of the data on numerical weather prediction analysis and forecast scores. In the experiments presented here, the MWHS instruments were able to produce from neutral to slightly positive impacts not only on humidity but also on the forecasts of vector winds. Improvements are larger when two MWHSs are assimilated (FY-3A and FY-3B) than when only one is used.

TABLE 3. Current satellites with microwave humidity sounding capabilities and their ECTs (local time).

<table>
<thead>
<tr>
<th>Satellite</th>
<th>ECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY-3</td>
<td></td>
</tr>
<tr>
<td>FY-3A</td>
<td>1015, descending</td>
</tr>
<tr>
<td>FY-3B</td>
<td>1340, ascending</td>
</tr>
<tr>
<td>FY-3C</td>
<td>1000, descending</td>
</tr>
<tr>
<td>LEO</td>
<td></td>
</tr>
<tr>
<td>MetOp-B</td>
<td>0930, descending</td>
</tr>
<tr>
<td>NOAA-18</td>
<td>1523, ascending</td>
</tr>
<tr>
<td>MetOp-A</td>
<td>0930, descending</td>
</tr>
<tr>
<td>NOAA-19</td>
<td>1339, ascending</td>
</tr>
<tr>
<td>Suomi-NPP</td>
<td>1325, ascending</td>
</tr>
</tbody>
</table>

FIG. 7. Normalized difference in the rms vector wind error at (top) 500 and (bottom) 850 hPa as a function of forecast range (days) over the (left) Southern Hemisphere, (middle) tropics, and (right) Northern Hemisphere for the experiments in the depleted observing system. Gray lines show results from the assimilation of the FY-3 MWHS series data, whereas black lines show the results for the assimilation of MHS data from MetOp-B and NOAA-18. Negative normalized differences indicate an improvement in forecast quality. Vertical bars show the 95% confidence intervals. Statistics are based on a sample of 169 forecasts over the study period and verified against the ECMWF operational analysis.
When added to a baseline system with neither MHS nor MWHS data, MWHS can achieve a large proportion of the impacts of adding a similar number of MHS instruments in similar orbits. This further confirms that MWHS adds additional robustness to the observing system.

As MWHS has larger instrument noise than MHS, the results suggest that instrument noise is presently not a critical factor for the assimilation of MWHSs. This may be because of the fact that for humidity-sensitive radiance errors from sources other than instrument noise (e.g., radiative transfer or representativeness) play a larger role (e.g., Bormann and Bauer 2010). Another reason may be that the background error is large for humidity, so even an observation with poorer noise can produce a considerable improvement.

Based on the encouraging results, FY-3B MWHS data have been actively used in the ECMWF operational forecasting system since 24 September 2014. This is the first time ECMWF has used Chinese satellite data and also the first time that Chinese polar-orbiting satellite data have been actively used for operational weather forecasts outside of China.

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