Impact of FY-3D MWRI Radiance Assimilation in GRAPES 4DVar on Forecasts of Typhoon Shanshan

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ABSTRACT

In this study, Fengyun-3D (FY-3D) MicroWave Radiation Imager (MWRI) radiance data were directly assimilated into the Global/Regional Assimilation and PrEdiction System (GRAPES) four-dimensional variational (4DVar) system. Quality control procedures were developed for MWRI applications by using algorithms from similar microwave instruments. Compared with the FY-3C MWRI, the bias of FY-3D MWRI observations did not show a clear node-dependent difference from the numerical weather prediction background simulation. A conventional bias correction approach can therefore be used to remove systematic biases before the assimilation of data. After assimilating the MWRI radiance data into GRAPES, the geopotential height and humidity analysis fields were improved relative to the control experiment. There was a positive impact on the location of the subtropical high, which led to improvements in forecasts of the track of Typhoon Shanshan.

Key words: Fengyun-3D (FY-3D), Microwave Radiation Imager (MWRI), Global/Regional Assimilation and PrEdiction System (GRAPES), four-dimensional variational (4DVar), typhoon forecast

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1. Introduction

Microwave observations from space are capable of measuring both atmospheric and surface parameters (Moncet et al., 2011) and have helped to improve global weather forecasts through the assimilation of data (Kazumori et al., 2014; Yang et al., 2016). China successfully launched the Fengyun-3D (FY-3D) satellite with the MicroWave Radiation Imager (MWRI) onboard in 2017. The MWRI has similar capabilities to many of its predecessors, such as the Scanning Multichannel Microwave Radiometer (SMMR; Madrid, 1978), Special Sensor Microwave/Imager (SSM/I) onboard the Defense Meteorological Satellite Program (DMSP; Hollinger et al., 1990), Microwave Imager (TMI) onboard the Tropical Rainfall Measuring Mission (TRMM; Kummerow et al., 2000), Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) onboard NASA’s Aqua Spacecraft (Kawanishi et al., 2003), WindSat Polarimetric Radiometer onboard the Coriolis satellite (Gaiser et al., 2004), and AMSR 2 onboard the Japan Aerospace Exploration Agency (JAXA) Global Change Observation Mission Water Cycle (GCOM-W1; Oki et al., 2010; JAXA, 2013).

The MWRI observes environmental parameters, such as the ocean wind speed (Sun et al., 2012; Dou et al., 2014; Zhang et al., 2015), intensity of precipitation on the surface (liquid or solid; Peng et al., 2011; Li et al., 2012; Wu et al., 2012; Yin et al., 2016), integrated water vapor content (Yang et al., 2013), cloud liquid content (Yang et al., 2013), soil moisture content (Peng et al., 2011; Chen and Jin, 2012; Wu et al., 2012; Bao et al., 2014), sea ice cover, sea/land surface temperature (Peng et al., 2011; Chen and Jin, 2012; Wu et al., 2012; Bao et

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al., 2014), snow cover (Peng et al., 2011; Wu et al., 2012), and precipitation (Yang et al., 2013; Yin et al., 2016). The observational data are used in environmental monitoring and meteorological research. The assimilation of MWRI data can also improve the skills of numerical weather prediction.

The Numerical Weather Prediction Center (NWPC) of the China Meteorological Administration (CMA) has been developing a new generation of global/regional NWP models, i.e., the Global/Regional Assimilation and Prediction System (GRAPES), which includes a Global Forecast System (i.e., GRAPES_GFS), since 2007 (Chen et al., 2008; Xue and Chen, 2008; Ma et al., 2018). A three-dimensional variational (3DVar) assimilation system was constructed in 2008 to match the framework of the GRAPES global prediction model (Xue et al., 2008). Four-dimensional variational (4DVar) data assimilation (Bouttier and Courtier, 2002) was then developed for this forecast system, and the GRAPES global 4DVar system using a 3DVar analysis scheme became available in 2016 (Wang et al., 2017). The GRAPES global 4DVar system became operational on 1 July 2018 (Zhang et al., 2019a). Although various TMI data have been assimilated successively in operation by the ECMWF, Met Office, Météo-France, and Japan Meteorological Agency (JMA) (Geer et al., 2018), no passive TMI (let alone MWRI) data have yet been assimilated into the GRAPES_GFS.

This study assimilated FY-3D MWRI radiance data from different initialization times to 0900 UTC 5 August 2018 after the required pre-processing steps, including quality control and bias correction in three pairs of experiments. A 120-h forecast, starting at 0600 UTC 5 August 2018, was performed by the GRAPES_GFS system based on the analysis field derived from the assimilation procedure in each experiment. The forecasts of the track of Typhoon Shanshan were analyzed and compared with the forecasts without assimilation of the MWRI data. The depictions of the subtropical high in some of the experiments were used to explain the impact of the assimilation of the MWRI radiance data on the typhoon forecast.

2. MWRI channel characteristics

The MWRI is a conical-scanning TMI onboard the FY-3B/C/D satellites. The MWRI provides brightness temperature ($T_b$) measurements at 5 frequencies from 10.65 to 89.0 GHz (i.e., 10.65, 18.7, 23.8, 36.5, and 89.0 GHz). Each frequency has a dual polarization mode with vertical (V) and horizontal (H) polarizations, giving 10 channels in total. The MWRI scans the earth over a swath width of 1400 km with zenith angle of 53.1° and completes each single scan line within 1.8 s. Data for 266 scan positions are obtained during each scanning cycle. The instantaneous fields of view (IFOV) for the channels from high to low frequencies are $51 \times 85$, $30 \times 50$, $27 \times 45$, $18 \times 30$, and $9 \times 15$ km², respectively. Table 1 summarizes the MWRI channel characteristics.

3. Data and methods

3.1 Dataset

MWRI Level-1 (L1) $T_b$ data from the National Satellite Meteorological Center of the CMA (http://satellite.nsmc.org.cn/PortalSite/Data/Satellite.aspx) were used. The two polarized channels at the lowest frequency are the most sensitive to surface emissivity, whereas the two polarized channels at the highest frequency are sensitive to areas of convective rain. The 19-V/H channels are sensitive to surface wind and ocean rain, the 24-V/H channels are available for the measurement of atmospheric water vapor, and the 37-V/H channels are designed to detect the cloud liquid water content. Only the radiance from the vertical polarized channels at 18.7, 23.8, and 36.5 GHz were assimilated in this study.

| Channel characteristic | Frequency (GHz) |
|------------------------|-----------------|
|                        | 10.65 | 18.7 | 23.8 | 36.5 | 89.0 |
| Polarization           | V     | V     | V     | V     | V     |
| Bandwidth (MHz)        | 180   | 200   | 400   | 400   | 3000  |
| NEAT (K)               | 0.5   | 0.5   | 0.5   | 0.5   | 0.8   |
| IFOV (km²)             | 51 \times 85 | 30 \times 50 | 27 \times 45 | 18 \times 30 | 9 \times 15 |
| Pixel (km²)            | 40 \times 11.2 | 40 \times 11.2 | 20 \times 11.2 | 20 \times 11.2 | 10 \times 11.2 |
| Range (K)              | 3-340 |       |       |       |       |
| Number of scan positions | 266   |       |       |       |       |
| Swath width (km)       |       | 1400  |       |       |       |
| Zenith angle (°)       | 45 ± 0.1 |       |       |       |       |
| Incident angle (°)     | 53.1  |       |       |       |       |
| Scan rate (s)          | 1.8 ± 0.1 |       |       |       |       |

Note: NEAT: noise-equivalent brightness temperature ($T_b$).
Several different types of MWRI L2 data, including the total precipitable water (TPW), sea surface wind speed (SWS), sea surface temperature (SST), and microwave rain rate (MRR), were applied for quality control of the data. The data were re-sampled to a 0.5° (longitude) × 0.67° (latitude) mesh. The calculation in the following section was based on some of the available data segments obtained during 4–5 August 2018.

3.2 Quality control and cloud detection

The quality control procedures in GRAPES were used; these procedures include multiple checks to ensure that all the radiance observations assimilated are reasonable. The MWRI quality control procedures consist of the following 10 steps.

1) An abnormal value check, which deletes observations with \( T_b < 70 \) or \( > 320 \) K (Huang et al., 2013).

2) A surface type check, which deletes pixels with the surface types of land, sea ice, snow cover, or coastal boundaries (Liu et al., 2012; Huang et al., 2013; Yang et al., 2017; Yu et al., 2017, 2018). Two methods are used to detect the sea ice pixels: (a) SST < 0°C and (b) the ARTIST (Arctic Radiation and Turbulence Interaction Study) sea ice algorithm (Spreen et al., 2008; Su et al., 2013). A pixel is removed if it is judged to be a sea ice pixel by either of these two methods.

3) A land/sea contamination check, which removes water pixels with vertically polarized 10.65-GHz \( T_b > 175 \) K or horizontally polarized 10.65-GHz \( T_b > 95 \) K (Huang et al., 2013).

4) An absolute departure check (Liu et al., 2007; Yang et al., 2016, 2017; Yu et al., 2017, 2018), which excludes observations whenever the innovations are > 3 K after bias correction (the bias correction procedure is introduced in the next section).

5) A relative departure check, which refuses the observations once the innovations are > 3 \( \sigma_0 \) after bias correction, where \( \sigma_0 \) is the standard deviation of the observation error (Yang et al., 2016).

6) A TPW check, which removes observations with TPW < 0 (Yang et al., 2017).

7) A wind speed check, which removes observations with SWS > 30 or < 0 m s\(^{-1}\) (Nielsen-Englyst et al., 2018).

8) A rain rate check, which removes observations with a rain rate not equal to zero (Liu et al., 2012; Zhu et al., 2016). Rain is also assumed if the data meet any of the following conditions (Bettenhausen et al., 2006; Zhao, 2013; Zhao and He, 2013; Guo et al., 2017):

\[
T_V^{37} - 0.979T_H^{37} < 55, \quad (1)
\]

\[
1.175T_V^{19} - 30 > T_V^{37}, \quad (2)
\]

\[
T_V^{19} > 170, \quad (3)
\]

\[
T_V^{37} > 210, \quad (4)
\]

where \( T \) is the brightness temperature (\( T_b \)), the superscript represents the channel frequency, and the subscript represents the channel polarization.

9) Cloud detection. The radiative transfer model for the TIROS (Television Infrared Observation Satellite) Operational Vertical Sounder (RTTOV) version 93 is used in GRAPES_GFS_2-1-2-2, but RTTOV-SCATT, which is a separate interface for microwave/infrared sounders that provides an accurate and fast simulation of radiative transfer in the presence of clouds, has not previously been included. The radiative transfer model has indispensable role (Geer et al., 2018), but is currently unavailable for the assimilation of MWRI data affected by cloud and precipitation. This study therefore focused on the impact of the clear sky assimilation of MWRI data on the newly established GRAPES_GFS 4DVar system. The impact of clear sky assimilation depends on the exact detection of clouds. Three schemes are used here to distinguish clear and cloudy skies:

(a) The observation is retained only if \( T_V^{37} - T_H^{37} > 50 \) K (Krasnopolsky et al., 1995; Connor and Chang, 2000; Dou et al., 2014).

(b) The observation is considered to be a cloudy region and screened only if the atmosphere opacity index (AOI) is > 5 (Kuria and Koike, 2011), where AOI is defined by:

\[
AOI = \frac{T_V^{39} - T_V^{37}}{T_V^{39} + T_V^{37}} \frac{T_H^{33} - T_H^{10}}{T_H^{33} + T_H^{10}}. \quad (5)
\]

(c) Cloud-contaminated observations are recognized from the radiance data by using the cloud liquid water path (LWP) retrieval algorithm. The LWP can be retrieved by measurements from two channels (Grody et al., 1992; Hargens et al., 1992; Ferraro et al., 1996; Weng et al., 1997; Sun and Weng, 2008) as follows:

\[
LWP_{chan} = a_0 [\ln(290 - T_1) - a_1 - a_2 \ln(-T_2)]. \quad (6)
\]

The LWP retrieval algorithm for the MWRI on the FY-3C satellite, which is the same as the MWRI on the FY-3D satellite, was developed by Tang and Zou (2017) and can be written as:
where WVP represents the vertically integrated water vapor calculated by the algorithm reported by Alishouse et al. (1990) and modified by Ferraro et al. (1996):

\[
WVP = 232.89 - 0.1486(T_{19}^V) - 0.3695(T_{37}^V)
\]

\[
- [1.8291 - 0.006193(T_{24}^V)]T_{24}^V,
\]

(8)

\[TPW_{corrected} = -3.753 + 1.507(TPW) - 0.1933(TPW)^2 + 0.00219(TPW)^3.\]

(9)

During the retrieval process, the TPW is firstly computed by using Eq. (8). Simultaneously, we also acquire a scattering index (SI) from the equation

\[SI = ESTT_{89}^V - T_{89}^V;\]

(10)

where EST\_89\_V is defined as

\[
ESTT_{89}^V = \begin{cases} 
438.5 - 0.46(T_{19}^V) - 1.735(T_{24}^V) \\
-0.00589(T_{37}^V)^2, \text{ for land;}
\end{cases}
\]

\[-182.7 - 0.75(T_{19}^V) + 2.543(T_{24}^V) \\
-0.00543(T_{37}^V)^2, \text{ for ocean.}
\]

(11)

If the SI is > 10 K, then the additional cubic correction in Eq. (9) is made to the raw TPW data (Sun and Weng, 2008). Because only the clear sky region of the ocean was assimilated in this study, only the lower half of Eq. (11) was used.

The regression coefficients in Eq. (1) were also determined. The regression coefficients used in Tang and Zou (2018) were applied in this study (Table 2).

The clear sky data in each channel over the oceans were defined as the data with an LWP smaller than the corresponding threshold given in Table 3, as proposed by Kazumori et al. (2008).

(10) Radio frequency interference (RFI) check. Although the existence of RFI mainly contaminates the observations at 10.65 GHz, the channels at 18.7 GHz may also be affected (Lawrence et al., 2017). In general, the values of the MWRI \(T_b\) increase as the channel frequency increases (Li et al., 2012; Zou et al., 2012, 2013). For example, \(T_b\) of the 23.8-GHz channel should be higher than that at 18.7 GHz on most land surfaces (i.e., \(T_{19}^V - T_{24}^V < 0\), \(T_{19}^H - T_{24}^H < 0\), \(T_{10}^H - T_{19}^H < 0\) should be satisfied). However, \(T_b\) of the lower frequency channel will increase and the opposite case will appear if there are RFI in the 18.7-GHz channel (i.e., \(T_{19}^H - T_{24}^H > 0\), \(T_{10}^H - T_{19}^H > 0\), \(T_{10}^V - T_{19}^V > 0\)).

The observations in the two 18.7-GHz channels were screened whenever RFI were detected.

### 3.3 Bias correction

There is systematic error (i.e., bias) in all the radiance data, which must be appropriately eliminated prior to assimilation because it is an assumption of data assimilation that neither the observations nor the forecast background contain bias (Liu et al., 2012; Han and Bormann, 2016; Yang et al., 2016). In general, the coefficients of bias correction are considered to be dependent on the channel and can be evaluated offline (Harris and Kelly, 2001). Previous research showed a clear 2-K ascending–descending bias for all channels of the FY-3C MWRI (Lawrence et al., 2017). Zhang et al. (2019b) surveyed the node-dependent bias and attributed it to the abnormal increase in the hot load reflector emissivity. Xie et al. (2019) proposed a physically based correction algorithm for the FY-3C MWRI calibration taking into account the emissivity of the hot load reflector. This bias correction algorithm was very effective. In light of this, it is necessary to gain a clear understanding of this bias in the FY-3D MWRI before the data can be assimilated for numerical weather prediction. Statistics were calculated for the FY-3D MWRI data after applying the quality control procedures described in the previous section and Fig. 1 plots the mean observation-minus-background (OMB) of each channel for the ascending and descending data of the FY-3D MWRI. Figure 1 shows that the ascending–descending bias was not found in the MWRI loaded on the FY-3D satellite and only very small differences (~0.1 K) were seen for the 19-V/H, 23-V/H, and 37-V channels.

### Table 2. Coefficients \(a_0, a_1, \text{ and } a_2\) in Eq. (6) for the MWRI

| Channel   | \(a_0\) | \(a_1\) | \(a_2\) |
|-----------|--------|--------|--------|
| 10-V      | -3.87  | 4.47   | 0.09   |
| 19-V      | -1.94  | 3.03   | 0.37   |
| 37-V      | -0.97  | 2.74   | 0.39   |
| 89-H      | -0.37  | 3.08   | 1.68   |

### Table 3. Threshold of the LWP corresponding to the three channels assimilated in this study

| Channel   | LWP (mm) |
|-----------|----------|
| 10-V      | 0.3      |
| 19-V      | 0.25     |
| 37-V      | 0.1      |
In view of the lack of an ascending–descending bias in the FY-3D MWRI data, the conventional scheme of bias correction was followed in this study. Five predictors were used in the bias correction implementation of MWRI: the scan position, the 1000–300-hPa layer thickness, the 200–50-hPa layer thickness, the surface skin temperature, and the total column water vapor (Liu et al., 2007, 2012). The MWRI radiance data from 0300 UTC 25 July to 0300 UTC 1 August 2018 were used to calculate the bias correction coefficients in the following experiments.

3.4 Overview of the tropical cyclone case

Typhoon Shanshan (2018) was chosen to measure the impact of assimilating the MWRI radiance limited to clear sky areas. On 2 August, Typhoon Shanshan emerged to the east-northeast of Guam as a tropical depression. On 3 August, its intensity was reinforced to the level of a tropical storm. As the system gradually developed, the environmental conditions became favorable for intensification and Typhoon Shanshan became a severe tropical storm. The deep convection wrapped into its rising center and Typhoon Shanshan developed into a typhoon on the following day. The 10-min winds of Typhoon Shanshan subsequently reached 130 km h\(^{-1}\) (80 mph) and its minimum pressure reached 970 hPa. This intensity was maintained and strengthened for a few days until 6 August. On this date, Typhoon Shanshan’s eye was displaced and appeared slightly ragged, and the typhoon experienced a slightly weakened trend before beginning to re-intensify on 7 August. When it moved close to the southeastern coast of Japan, it attained a lifetime-maximum intensity of a severe typhoon with 1-min winds as high as 165 km h\(^{-1}\) (105 mph) before rapidly decaying. At the same time, it suddenly turned around to the northeast and became extratropical at 0600 UTC 10 August. There were reports that Typhoon Shanshan caused as much as US$13,200 of damage to the infrastructure and agriculture of Miyagi Prefecture in Japan.

3.5 Experimental setup

To evaluate the MWRI radiance assimilation in GRAPES_GFS, three pairs of cycling analysis–forecast experiments were performed with different durations of assimilation. All the experiments used version 2-1-2-2 of the GRAPES_GFS. The horizontal grid spacing was set to 25 km, the number of vertical levels to 60, and the height of the model top to 3 hPa. Every experiment shared the following parameterizations (Ma et al., 2018): the MRF planetary boundary layer scheme (Hong and Pan, 1996); the RRTMG LW/SW radiation scheme (Pincus et al., 2003; Morcrette et al., 2008); the New Simplified Arakawa–Schubert (NSAS) shallow and deep convection scheme (Arakawa and Schubert, 1974; Pan and Wu, 1995; Liu et al., 2015); and the Common Land Model (CoLM) scheme (Dai et al., 2003). The revised two-moment cloud microphysical scheme (Liu et al., 2003), the large-scale cloud condensation scheme (Chen et al., 2007), and the explicit prognostic cloud cover scheme (Tiedtke, 1993) were used for cloud processes after being embedded into GRAPES_GFS.

The analysis–forecast experiments were implemented in two steps. In the first step, the three pairs of experiments performed data assimilation for 6, 18, and 30 h, respectively, until 0900 UTC 5 August. The initialization times of assimilation were therefore 0300 UTC 5, 1500 UTC 4, and 0300 UTC 4 August, respectively. The analysis fields were gained every 6 h (0300, 0900, 1500, and 2100 UTC) during the cycling analysis–forecast experiments. The background fields, which should be used in the first analysis of each pair of experiments, were given by the 3-h forecast initiating, in turn, from the Final Operational Global Analysis dataset at 0000 UTC 5, 1200 UTC 4, and 0000 UTC 4 August. The background fields were the 6-h GRAPES forecast initialized from the analysis field of the prior cycle during the other cycles. The observational data within the ±3-h time window were assimilated at each analysis time. In the second step, a 120-h GRAPES forecast was initialized from 0600 UTC 5 August, 48 h after Typhoon Shanshan was announced as a tropical storm, to 0600 UTC 10 August, 24 h after Typhoon Shanshan reached its nearest location to the coastline of Japan. At this stage, the proper GRAPES forecasts were still taken as the lateral boundary condi-
tions. Figure 2 shows a flow chart of the three pairs of experiments to illustrate the experimental procedures, design, and setup.

Each pair of experiments contained two experiments carried out in parallel to inspect the impacts of the assimilation of MWRI radiance into GRAPES 4DVar on the prediction of Typhoon Shanshan. The control experiments (CTL1, CTL2, and CTL3 corresponding to the experiments within 6, 18, and 30 h of assimilation, respectively) assimilated the conventional operational observations, such as the satellite-derived winds, the GPS refractivity observations, and observations from aircraft, oceanic/land surface stations, and radiosondes. The sensitivity experiments (EXP1, EXP2, and EXP3 corresponding to CTL1, CTL2, and CTL3, respectively) were set to be identical to the analogous control experiments, except that the MWRI radiance data were added in the assimilation process after quality control and bias correction. The original radiance data were thinned and then re-weighted into a mesh within 0.5° (longitude) × 0.67° (latitude), so that the potential correlations among the observations were cleaned. The size of our thinning mesh was narrower than the operational value, making it easier to resolve the structure of the tropical cyclone near its center, where the gradient was the strongest (Liu and Rabier, 2002).

4. Results

4.1 Assessment of the FY-3D MWRI data

The FY-3D MWRI radiance data and the validity of the quality control schemes described in Section 3.2 were assessed and verified by a quality control experiment. The data within a ±3-h time window at 0600 UTC 5 August were assimilated into the GRAPES 4DVar systems and quality control schemes were performed to screen out the “bad” observations. The 6-h data roughly covered most regions of Typhoon Shanshan and contained 127,639 observations. To clarify the effect of the quality control procedures, the bias correction procedure was temporarily shut down.

Figure 3 shows the results of this experiment. To reveal the normal distribution of the observation $T_b$ and the OMB data after quality control, the absolute/relative departure checks are both switched off in Fig. 3. All three channels appear to have unacceptable deviations before the quality control procedures. Some of the OMB data exceeded the range of the horizontal axis and are not shown here. Their distributions also show large deviations from a normal distribution, with the profile of 19-V appearing as bimodal. There were many abnormal positive values of the OMB in each channel, leading to an anomalously high $T_b$ related to the land surface, sea ice, or cloud/precipitation. The situation substantially improved after activation of the quality control procedures. The excessively high/low values of the OMB were filtered and all the profiles were similar to a normal distribution, with negative mean values that were eliminated by the bias correction. Before quality control, the average OMB values of the 19-V, 24-V, and 37-V channels were 11.27, 7.51, and 5.15 K, respectively, whereas these values were decreased to −0.66, −1.78, and −1.76 K after quality control and the corresponding standard deviations decreased from 29.98, 26.17, and 20.69 K to 1.91, 2.60, and 2.45 K, respectively. These results indicate the
dependable effectiveness of the quality control procedures.

Figure 4 plots the results of the quality control experiment at latitude and longitude. The observations after quality control (Figs. 4b, d, f) are compared with the actual situation (Fig. 4a), and the observations before quality control (Fig. 4c) and background (Fig. 4e). The image from the FY-3D MERSI satellite on the same day (Fig. 4a) shows that Typhoon Shanshan had a clear spiraling cloud band and asymmetrical convection concentrated on its southeast flank. Figure 4c shows that the observed $T_b$ has an abnormally high value on the land surface as a result of the microwave emissivity of the land surface. The value near the polar regions (omitted here) is attributed to the present of sea ice and snow cover. In general, the observed $T_b$ of the ocean in the tropics is larger than that in higher latitudes (omitted here), which can be explained by the abundant water vapor near the equator. Some high-value regions of observed $T_b$ for the ocean are caused by the cloud liquid content and precipitation, and therefore, we can see the clear spiraling cloud bands of Typhoon Shanshan. The simulated background (Fig. 4e) is from the 6-h forecast initiating from the Final Operational Global Analysis dataset at 0000 UTC 5 August 2018, and it matches the observations reasonably well. The simulated $T_b$ values among the precipitating and cloudy regions, including Typhoon Shanshan, are much lower than the observed $T_b$ values, and therefore, only the contour profile of Typhoon Shanshan is plotted because the input does not include cloud variables.

Cloud contamination is characterized by the LWP, which is retrieved via the algorithm described at step (9) in Section 3.2, and Fig. 4b shows the cloud regions identified within the threshold set to 0.1 mm (the threshold of the 37-V channel). The color bar ranges between 0.1 and 0.35 mm (the threshold of the 10-V channel) and those pixels with LWP > 0.35 mm, which means that they are rejected for each channel, are marked by red dots. The cloud regions in Fig. 4a are generally recognized by the LWP retrieval algorithm and the corresponding threshold value. The center of Typhoon Shanshan and some other dense clouds have large LWP values. This proves that the adopted cloud detection algorithm is feasible.

Figures 4d and 4f show the OMB data. After quality control, the numbers of remaining pixels that are assimilated into the system for the 19-V, 24-V, and 37-V channels are 32,649, 32,636, and 28,723, respectively. The deleted pixels therefore represent about 74.4%, 74.4%, and 77.5% of the total number of observations in the 19-V, 24-V, and 37-V channels, respectively. All our experiments were carried out within the GFS, whereas Fig. 4 only shows the representative region near the location of Typhoon Shanshan, so many of the global observations are not shown here. These results indicate that the quality control procedures successfully removed pixels over the land surface, coast, sea ice, and other complex surfaces. Most of the influence of clouds and other contaminants were also excluded. The differences between the observations and the background of the pixels that pass the quality control tests were both small and valid (Fig. 4f). They still have a negative bias toward zero, which is consistent with the results shown in Fig. 1, and would be eliminated by the bias correction procedure in the subsequent experiments. This quality control procedure therefore performs well and is effective.

In terms of the range of radio frequencies, only the 10.65- and 18.7-GHz channels of the MWRI can be contaminated by RFI, whereas the 19-V channel was assimilated in this study. The detection of RFI was therefore only applied to this channel. Zhou et al. (2017) sugges-
ted that RFI in the 19-V channel is limited to the coast of North America as a result of US direct TV signals. Figure 5 plots the RFI, which is characterized by the difference in $T_b$ between neighboring vertical channels. RFI was detected around both the east and west coasts of the USA, especially around the Boston–Washington corridor, consistent with previous research (Zhou et al., 2017). A few pixels with RFI were missed by the spectral difference method, although most of these pixels were distributed along the coast and were removed by
surface type and departure checks. In some cases, the spectral difference method cannot distinguish abnormal increases in $T_b$ resulting from RFI or cloud/rain, but this will not affect our results because it overlaps with the detection of clouds. Therefore, the detection of RFI in this study is both effective and economic.

Figure 6 shows the effect of bias correction. Quality control was performed to better display the distribution of the valid data, with the absolute/relative departure check being shut down temporarily to display how far the profiles were from a normal distribution. The observations with an absolute value of the OMB > 3 K or three times the standard deviation were screened in the following cycling experiments. For each channel, the implementation of bias correction reduced the mean value of the OMB PDF to near zero. The observed $T_b$ values of the 19-V, 24-V, and 37-V channels had a negative bias before bias correction, with average values of about $-0.68$, $-1.81$, and $-1.78$ K, respectively. However, these values were adjusted to $-0.10$, $-0.149$, and $-0.104$ K, respectively, after bias correction. Bias correction also changes the PDFs of the OMB from a slightly skewed distribution to a roughly normal distribution. Therefore, our bias correction scheme is effective for the channels assimilated in this study and the deviation between the observations and the background are considerably improved.

4.2 Effect of FY-3D MWRI data assimilation

Given that the MWRI is sensitive to water vapor in the atmosphere, its assimilation is expected to show some improvement in the specific humidity of the analysis field. To indicate the effect of the assimilation of the FY-3D MWRI radiance data, the specific humidity analysis increment of the GRAPES 4DVar assimilation at 0300 UTC 5 August 2018 in the EXP3 experiment was compared with those in CTL3 experiment. Only the area corresponding to Fig. 4 is shown here. Because the weight function of the MWRI is mainly distributed between 700 and 900 hPa (Zou, 2012), the analysis increments of EXP3 (Fig. 7a) and CTL3 (Fig. 7b) at 850 hPa were compared first. These two performances were very different. The latter had a region with a significant negative increment near eastern China. However, when the MWRI data were assimilated, the “blue” area clearly moved eastward and became deeper. The increment in Japan, which is essentially positive in CTL3, changed its sign in EXP3. The increase in specific humidity along the coast of Southeast Asia was significantly strengthened when the MWRI was assimilated. In the area shown in the figure, only the examples near Hokkaido and the region (10°–20°N, 130°–140°E) were roughly unchanged in the
Given that the center of Typhoon Shanshan was close to 23°N, 147°E at 0300 UTC 5 August 2018, the increments in the specific humidity analysis were also plotted in the section of the corresponding latitude (Figs. 7c, d). The most increments were distributed below 500 hPa. If the MWRI was not assimilated, then there were negative increments between 120° and 130°E, with Typhoon Shanshan positioned to the east. However, once the MWRI had been assimilated, the large “blue” region shifted eastward and covered the range of the typhoon. Only a narrow and weak “blue” band remained within 120°–130°E. At the same time, some “red” regions appeared within 110°–125° and 130°–134°E. The results at 850 hPa in the lower panel are consistent with those in the upper panel. These findings suggest that the areas in which Typhoon Shanshan was located and would pass through became drier after the MWRI radiance data were assimilated.

### 4.3 Forecasts of Typhoon Shanshan

To clarify the mechanism by which the assimilation of radiance data affects the forecast of typhoons, Fig. 8 shows the 120-h forecast path and intensity of Typhoon Shanshan initialized about 4 days before it arrived at the location nearest to mainland Japan in the experiments. The observed values were also presented. In the first pair of experiments with the 6-h 4DVar assimilation (Fig. 8a), the locations of the center of the typhoon in both CTL1 and EXP1 were close to the observed locations. There was no clear difference between CTL1 and EXP1 on the first day. The results of EXP1 began to diverge from those of CTL1 from the second day, and from the second day onward, the track forecast given by EXP1 was consistently better than that given by CTL1. In the second pair of experiments with 18-h assimilation (Fig. 8b), the EXP2 forecast was slightly poorer than the CTL2 forecast in the first 40 hours. However, the deviations between the two forecasts were very small in this time period. The improvement gained by the assimilation of the MWRI into EXP2 appeared from 8 August when Typhoon Shanshan changed direction. The speed of the typhoon after it turned around was faster in EXP2 than in CTL2, which indicates that EXP2 was closer to the actual state. In the third pair of experiments with 30-h assimila-
tion (Fig. 8c), the results of both CTL3 and EXP3 agreed very well with the observed path during the first 24 hours. The EXP3 track coincided more closely with the best track on the following day, although both tracks were in good agreement with the observed path. EXP3 clearly gave a better prediction during the last three days, whereas CTL3 showed a clear westward bias. All three pairs of experiments showed that the assimilation of the MWRI radiance data improved the forecast of the track of Typhoon Shanshan within a series of assimilation times. The beneficial impact was clear at the location of the sudden turn of the typhoon near the coast of Japan, which was closely related to human activity (RFI contamination).

To explore the mechanism by which the MWRI data improve the forecast skills, it was necessary to compare and discuss the synoptic situation, especially the subtropical high, between the observations and the experimental results. EXP3 and CTL3 were used as examples to indicate how the assimilation of the MWRI data improved the forecast of the track of Typhoon Shanshan within a series of assimilation times. The beneficial impact was clear at the location of the sudden turn of the typhoon near the coast of Japan, which was closely related to human activity (RFI contamination).

Figure 9a shows the 500-hPa observations at 2000 UTC 8 August 2018 and the subtropical high, typhoon, and westerly troughs are clearly marked. The subtropical high, as a large-scale circulation, breaks into two parts, located on either side of Typhoon Shanshan, as its intensity decreases. Typhoon Shanshan later interacts with three systems, including the western continental high-pressure zone, the shortwave troughs in the westerly circulation, and the western Pacific subtropical high. The interaction between Typhoon Shanshan and these systems appears to control the impact of the changes in these systems on the typhoon, as well as the steering effect of a stronger airflow on the movement of the typhoon. First, the western Pacific subtropical high drives Typhoon Shanshan to move clockwise along its edge (Giorgi et al., 1999; Lee and Suh, 2000) (i.e., northeastward). Second, although the wind along the southeast edge of the continental subtropical high is toward the southwest, there is a stronger airflow toward the east along its north edge, and in general, the steering effect is dependent on the more intense airflow on the edge of the subtropical high. Third, the southerly airstream in front of the east Asian low-pressure trough (marked by the red arrowheads) simultaneously influences Typhoon Shanshan. As a result of these three steering effects, Typhoon Shanshan is induced to turn northeastward. Our analysis is consistent with previous studies by Zhang et al. (2005) and Zhou and Yu (2015).

Figure 9b shows the subtropical high of CTL3/EXP3 at 72 h after forecast initialization (i.e., 1800 UTC 8 Au-
Figure 9. The subtropical high represented by the contour line of 588 dagpm at 500 hPa given by (a) observational results in MICAPS (Meteorological Information Comprehensive Analysis and Process System) and (b) the forecast results in CTL3 and EXP3 at 72 h after forecast initialization. In (a), the Asian low-pressure trough is marked by the red arrowheads. In (b), the contour line of 587.1 dagpm at the same height and same time is also plotted because of some unavoidable deviation; the results of CTL3 and EXP3 are shown by dashed green line and solid blue line, respectively.

As of August 2018, 2 h before Fig. 9a). Because there are some deviations between the simulation and the observed values, the 587.1-dagpm contour lines at 500-hPa height are plotted in addition to the 588-dagpm contour lines. EXP3 simulates the break in the subtropical high fairly well, whereas in the CTL3 experiment, the two subtropical highs are mistakenly connected and form a single high. The air current along the southern edge of the narrow junction is dominated by an easterly wind, which leads Typhoon Shanshan in the opposite direction and causes the clear westerly bias of the forecast track in CTL3 (Fig. 8). This confirms that the assimilation of the MWRI radiance data has a positive impact on the analysis of the subtropical high and therefore improves the forecasting skills for this tropical cyclone.

5. Summary

This study is the first attempt to assimilate FY-3D MWRI radiance data into GRAPES_GFS through the 4DVar scheme and its impact was evaluated based on the forecasts and analyses of the high-latitude Typhoon Shanshan (2018), the track of which turned suddenly near the coast of Japan. The quality control schemes used for the passive microwave instruments were summarized and adopted to remove invalid observations caused by factors such as the equipment, weather conditions, underlying surface, and human activity (RFI contamination). The ascending–descending bias characteristic of the FY-3D MWRI was investigated and compared with the FY-3C MWRI before using a bias correction procedure to correct the observed $T_b$. The analysis–forecast experiments were performed on GRAPES_GFS_2-1-2-2 to assess the impact of assimilating the oceanic clear sky MWRI radiance, compared with a control experiment without the assimilation of the MWRI radiance. Taking the specific humidity as an example, the contribution of the MWRI radiance data to the analysis increment was discussed. Verification against the control experiment showed that the experiment with the assimilated MWRI data gave a significantly more accurate prediction of the track of the typhoon. The difference in the subtropical high between the experiments with and without the assimilation of the MWRI data was introduced to explain the improvement in the typhoon forecast. The assimilation of the all-sky MWRI radiance, including observations over the land surface and cloudy regions, will be explored in future studies.

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