Assimilation of *FY-3D* MWHS-2 Radiances with WRF Hybrid-3DVAR System for the Forecast of Heavy Rainfall Evolution Associated with Typhoon Ampil

WEI SUN^{a,b} AND YOUPIING XU^a

^a *Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China*

^b *National Space Science Center, Chinese Academy of Sciences, Beijing, China*

(Manuscript received 24 April 2020, in final form 21 January 2021)

ABSTRACT: A detailed investigation about the effects of the Microwave Humidity Sounder-2 (MWHS-2) radiances on board the *Fengyun-3D* (*FY-3D*) satellite is combined with developments within the Weather Research and Forecasting Data Assimilation (WRFDA) system and analyses on the evolution of the heavy rainfall associated with Typhoon Ampil during 23–24 July 2018. In the analysis field, the position of Typhoon Ampil is found out to be distinctly affected by the MWHS-2 assimilation. The experiment that assimilates MWHS-2 radiances through hybrid-3DVAR generates the best analysis with large increments around the typhoon, which contributes to the typhoon moving inland to the southwest. In the forecast fields, the MWHS-2 assimilation improves the rainfall in not only the accumulated amount, but also the evolution characteristics. The hybrid-3DVAR experiment reduces the RMSE of the rainfall amount, and enhances the spatial correlation and the fractions skill score of the rainfall evolution to the greatest extent, followed by the 3DVAR MWHS-2 experiment. As for the cause of the rainfall improvements, analyses suggest that it could be closely connected with the characteristics of the circulation structures related to the typhoon evolution. On one hand, the increases of the rainfall amount and intensities in the MWHS-2 assimilation experiments (previously underestimated) correspond to the strengthened typhoon structures with strong anomalies in both the upper-layer temperature and the lower-layer geopotential height. On the other hand, the better rainfall evolution in the hybrid-3DVAR experiment could be explained by its clearer evolution of the structure of typhoon under the effects of an approaching upper trough, and its smallest typhoon track errors around the middle time period.

KEYWORDS: Atmospheric circulation; Hurricanes/typhoons; Precipitation; Synoptic-scale processes; Numerical weather prediction/forecasting; Data assimilation

1. Introduction

Tropical cyclones (TCs) have always been a great threat to human lives and properties by causing disastrous precipitation. In China, about eight TCs or typhoons (typhoons hereafter, according to the convention in the study region) hit the mainland from the southern or eastern coasts per year, causing economic losses of 45.784 billion Yuan (RMB) and affecting 37.77 million people annually (Zhang et al. 2017). As most of the typhoon disasters are concentrated in the landfall period, the greatest losses are usually caused by the typhoons with long life cycles. However, it is still challenging to accurately forecast the heavy rainfall associated with the typhoons, especially the rainfall evolution processes after typhoon landfall, which are filled by complicated impacts from both atmospheric circulation and topography (Roy and Kovordányi 2012; Wu et al. 2015; Yen et al. 2011). Recently, as a tropical storm maintained over 60 h after landfall, Typhoon Ampil became the first typhoon to impact northern China at a tropical storm intensity over the past decades, and brought long-duration heavy rainfall to the local area. Under this circumstance, it is significant to investigate the heavy rainfall associated with Typhoon Ampil

with emphasis on its evolution process after typhoon landfall, and to find potential approaches to improve the related forecasts.

In the studies of typhoons, the assimilation of satellite observations has been widely proven to be skillful at improving the forecasts, especially the microwave satellite observations (Liu et al. 2012; Shen and Min 2015; Xu et al. 2013, 2015; Zhang et al. 2016). For example, the Advanced Technology Microwave Sounder (ATMS) data in the European Centre for Medium-Range Weather Forecasts (ECMWF) system (Bormann et al. 2013), the Advanced Microwave Sounding Unit-A (AMSUA) and the ATMS data in the National Centers for Environmental Prediction (NCEP) system (Collard et al. 2012; Zhu et al. 2016), and the *MetOp-A* Microwave Humidity Sounders (MHSs) data in the Weather Research and Forecasting Data Assimilation (WRFDA) system (Newman et al. 2015; Schwartz et al. 2012). For the microwave satellite observations focusing on China, the Microwave Humidity Sounder-2 (MWHS-2) observations on board *Fengyun-3C* (*FY-3C*) have drawn much attention. Using the Met Office and the ECMWF assimilation systems, the quality of the data from the 183-GHz channels of the MWHS-2 is found to be comparable to that of the ATMS, and the operational use of some of the MWHS-2 channels is considered in both the assimilation systems (Lu et al. 2015). In the Met Office global model, the MWHS-2 contributes to the 24-h forecast error reduction significantly by 0.6%. Meanwhile, a combination of MWHS-2 on board *FY-3C* and MWHS-1 on board *FY-3B* is shown to

Denotes content that is immediately available upon publication as open access.

Corresponding author: Wei Sun, sunwei@lasg.iap.ac.cn

DOI: 10.1175/MWR-D-20-0127.1

© 2021 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).

improve the fit to the model background by up to 1% (Carminati et al. 2018).

Since November 2017, the MWHS-2 began to fly on the second operational satellite of China's second generation polar-orbiting meteorological satellites, *Fengyun-3D* (*FY-3D*), constituting an all-day observation network as afternoon observations along with *FY-3C* as morning observations (Y. Guo et al. 2019). Although the MWHS-2 radiances on board *FY-3C* are available in some operational forecast systems (Carminati et al. 2018; Lu et al. 2015), the MWHS-2 assimilation capability has not been supported in the public released data assimilation (DA) system, such as the WRFDA system (Barker et al. 2012). Furthermore, very few studies directly explore the ability of MWHS-2 observations on board *FY-3D* in improving the typhoon forecasts, and assimilate the MWHS-2 radiances through a hybrid (ensemble-3DVAR) method that could provide a more descriptive background error covariance (Wang 2011; Wang et al. 2008). The recent study using hybrid method on the assimilation of microwave observations similar as the MWHS-2 was based on the microwave humidity and sounder (MWHS-1) on board *FY-3B* (Xu et al. 2016), which only has the humidity channels and serves as the predecessor of the MWHS-2 on board *FY-3C* and *FY-3D*. Therefore, the WRFDA system is developed to assimilate the radiances of MWHS-2 on board *FY-3C* and *FY-3D* in this study, and then used to investigate the impacts of *FY-3D* MWHS-2 radiances with both 3DVAR and hybrid-3DVAR assimilation method.

In addition, among the DA studies of heavy rainfall associated with typhoons, the impacts of DA are usually evaluated from the accumulated rainfall amount, instead of the detailed rainfall characteristics within the evolution process. For example, Xu et al. (2016) explored the assimilation impacts of MWHS-1 during a binary typhoon case from the 24-h accumulated precipitation, finding out that DA corrects the location and the amount of the precipitation. Schwartz et al. (2012) studied the assimilation of microwave radiances from multiple satellites for Typhoon Morakot. The disparity between the accumulated precipitation and the precipitation maximum among the DA experiments were investigated by partitioning the 72-h precipitation into three subperiods. However, it should be noted that the characteristics and properties of rainfall could be more hidden in the evolution process (Chen et al. 2016; Li et al. 2013, 2011; Yu et al. 2013). For example, for the heavy rainfall over northern China, the convective rainfall benefited from local instabilities is mainly concentrated in the afternoon with short duration, while the large-scale heavy rainfall occurs more during nighttime with long duration (Sun et al. 2015; Yuan et al. 2012, 2013). In result, it could be beneficial to dig into the evolutionary process of rainfall when evaluating the effects of DA. Combining the aspects above, this study investigates the assimilation effects of *FY-3D* MWHS-2 radiances on the evolution process of the heavy rainfall associated with Typhoon Ampil through both 3DVAR and hybrid-3DVAR method, and further explores the improvements in the rainfall processes by analyzing the circulation structures related to the typhoon evolution. To get a further understanding of the impacts of MWHS-2, a comparison of additional radiances assimilation from ATMS, which is a

widely used temperature and humidity microwave sounder similar as MWHS-2, is presented with the process of the investigations. Results could not only deepen the understanding of the DA effects on the typhoon related heavy rainfall, but also provide helpful information in evaluating the newly equipped MWHS-2 on board the *FY-3D* satellite.

In the rest of the paper, an overview of the observations, model configuration, and methodology is presented in section 2, followed by impacts of assimilating MWHS-2 radiances on the analyses in section 3, and impacts on the forecast of heavy rainfall process in section 4. Section 5 analyzes the forecast rainfall improvements from the circulation structures related to the typhoon evolution. Conclusions and discussions are given in section 6.

2. Observations, model configuration, and methodology

a. Observations

The MWHS-2 has flown on the *FY-3D* polar-orbiting satellite since November 2017. The list of information about MWHS-2 in different channels is given in Table 1. A detailed description for this instrument has been given by Jieying et al. (2015). In this study, the MWHS-2 radiances around 0600 UTC 22 July 2018 (red dots in Fig. 1) are assimilated through WRFDA to improve the forecast of the heavy rainfall process associated with Typhoon Ampil (track as in white dots in Fig. 1), and the MWHS-2 radiances around 0600 UTC on each day from 1 July 2018 to 15 July 2018 are used to compute the observation error and the bias correction parameter. The satellite observations are downloaded from the Chinese National Satellite Meteorological Center data archive at <http://satellite.nsmc.org.cn/portalsite/default.aspx?currentculture=en-US>.

To get a comprehensive understanding of the impacts of MWHS-2, the radiances from the Joint Polar Satellite System (JPSS) Advanced Technology Microwave Sounder (ATMS), which is a widely used sounder with both temperature and humidity channels as MWHS-2, are also assimilated through WRFDA. The data are downloaded from the National Center for Atmospheric Research (NCAR) research data archive at <http://rda.ucar.edu/datasets/ds735.0/>.

The conventional observations used in this study are from the Global Telecommunications System (GTS) from a wide variety of sources, which contains land surface, marine surface, radiosonde, pibal, aircraft reports, and dropsondes (downloaded from <http://rda.ucar.edu/datasets/ds337.0/>).

The precipitation observations used in the verification are the $0.1^\circ \times 0.1^\circ$ hourly precipitation analysis product from the China Meteorological Administration Multisource merged Precipitation Analysis System (CMPA-Hourly), which is provided by National Meteorological Information Center of CMA (<http://data.cma.cn/en/?r=data/index&cid=6d1b5efbdcfb9a58>). The dataset merges high-density, hourly data from automatic weather stations over China and the CMORPH precipitation product through an improved probability density function-optimal interpolation (PDF-OI) merging algorithm. A detailed description of the dataset has been given by Shen et al. (2014). The heavy rainfall over northern China associated with Typhoon

TABLE 1. Information about MWS-2 in different channels.

Channel	Center frequency (GHz)	Polarization	Bandwidth (MHz)	Calibration accuracy (K)
1	89.0	V	1500	1.3
2	118.75 ± 0.08	H	20	2.0
3	118.75 ± 0.2	H	100	2.0
4	118.75 ± 0.3	H	165	2.0
5	118.75 ± 0.8	H	200	2.0
6	118.75 ± 1.1	H	200	2.0
7	118.75 ± 2.5	H	200	2.0
8	118.75 ± 3.0	H	1000	2.0
9	118.75 ± 5.0	H	2000	2.0
10	150.0	V	1500	1.3
11	183.31 ± 1	H	500	1.3
12	183.31 ± 1.8	H	700	1.3
13	183.31 ± 3.0	H	1000	1.3
14	183.31 ± 4.5	H	2000	1.3
15	183.31 ± 7	H	2000	1.3

Ampil is concentrated between 0000 UTC 23 July 2018 and 0000 UTC 24 July 2018, the following 18–42 h after DA. Figure 2a displays the accumulated 24-h rainfall over northern China revealed by the CMPA-Hourly data. Northern China is covered by heavy rainfall with daily maximum exceeding 100 mm.

To get a further understanding of the DA impacts on the circulation structures, the ERA-5 data (Hersbach et al. 2020) during the heavy rainfall period between 0000 UTC 23 July and 0000 UTC 24 July 2018 are used in section 5.

b. Model configuration

Version 4.1 of the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008) is used in this study to

simulate atmospheric evolution process along with the rainfall, of which the New Thompson scheme (Thompson et al. 2008), the Yosei University PBL scheme (Hong et al. 2006), the Grell 3D cumulus scheme (Grell and Dévényi 2002), the Rapid Radiative Transfer Model (RRTM) longwave radiation scheme (Mlawer et al. 1997), and the Goddard Space Flight Center (GSFC) shortwave radiation scheme (Tao et al. 2003) are used. The WRF Model is run on a 9-km domain with 559×469 horizontal grids covering the northwestern Pacific and East Asia (Fig. 1). Vertically, there are 57 levels with a model top at 10 hPa.

To assimilate the observations, version 4.1 of the WRFDA system (Barker et al. 2012) with 3DVAR and Hybrid components are used. The hybrid-3DVAR method produces the analysis through minimizing a scalar objective function $J(\mathbf{x})$ given by

$$J(\mathbf{x}, \alpha) = \frac{1}{2} \beta_1 (\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}_b) + \frac{1}{2} \beta_2 (\alpha)^T \mathbf{A}^{-1} (\alpha) + \frac{1}{2} [H(\mathbf{x}) - \mathbf{y}]^T \mathbf{R}^{-1} [H(\mathbf{x}) - \mathbf{y}], \quad (1)$$

where $\mathbf{x}_b$ denotes the background vector, $\mathbf{y}$ is a vector of the observations, and $\mathbf{B}$ and $\mathbf{R}$ represent the background and observation error covariance matrices, respectively. The covariance matrix determines how close the analysis is weighted toward the background and observations. The observation operator H interpolates the model gridpoint values to observation space and converts the model-predicted variables to observed quantities. The block diagonal matrix $\mathbf{A}$ controls the spatial correlation of α . The weights of the static and flow-dependent covariance are determined by factors β_1 and β_2 .

In this study, the WRFDA is developed to assimilate the MWS-2 radiances in clear-sky conditions, and the radiative

FIG. 1. Computational domain and observation distribution for (a) MWS-2 radiances at 0600 UTC 22 Jul 2018 used in the DA (red dots, radiances from channel 11), and (b) ATMS radiances at 0600 UTC 22 Jul 2018 used in the DA (red dots, radiances from channel 22). The white dots denote the track of Typhoon Ampil revealed by the Japan Regional Specialized Meteorological Center (RSMC) best track data during the experiment (from 0600 UTC 22 Jul to 0600 UTC 24 Jul 2018). The shading denotes the topography height (units: m).

FIG. 2. Accumulated 24-h rainfall (units: mm day^{-1}) over northern China during 0000 UTC 23 Jul–0000 UTC 24 Jul 2018 (a) revealed by the CMPA-Hourly data, and in experiments (b) NODA, (c) CON, (d) VAR, and (e) ENVAR. The white line denotes the section for Fig. 7. The black and dark red lines denote the track of Typhoon Ampil revealed by the Japan Regional Specialized Meteorological Center (RSMC) best track data during the 24-h heavy rainfall and the track of Typhoon Ampil in each experiment, respectively.

TABLE 2. The setting of four experiments and the purposes.

Experiment	Assimilation data	Assimilation method	Purposes for experiments
NODA	No	No	No assimilation experiment
CON	Conventional data	3DVAR	Impacts for conventional observations DA with 3DVAR method
VAR	Conventional data + MWHS2-radiances	3DVAR	Impacts for MWHS-2 radiances DA with 3DVAR method
ENVAR	Conventional data + MWHS-2 radiances	Hybrid-3DVAR	Impacts for MWHS-2 radiances DA with hybrid-3DVAR method
ENVAR_AT	Conventional data + ATMS radiances	Hybrid-3DVAR	Comparison for impacts of MWHS-2 radiances and ATMS radiances
ENVAR_ATMW	Conventional data + ATMS+MWHS-2 radiances	Hybrid-3DVAR	

transfer model RTTOV (Saunders et al. 2018) is used to compute the clear-sky radiances in the forward observation operator. In this development, the MWHS-2 radiances could be directly assimilated from the public released L1C dataset in HDF format. Meanwhile, several quality control steps are designed in the WRFDA procedure: radiance data from a mixture of surface types (e.g., over coastal areas) or with large scan angles on the edge are rejected; the observations with failure QC flags, with QC scores lower than 90 (acquired from the dataset), or with large bias (bias-corrected observation minus simulated brightness temperature exceeds either 15 K or three times the specified observation error) are not used. The cloud/precipitation is checked by the scatter index (SI) through the difference of the observed radiances between the two window channels at 89 GHz and 150 GHz. As the first illustration of the developed MWHS-2 assimilation ability within the WRFDA system, a relative higher threshold of 5 K is chosen in this study, based on the consideration of a lower threshold would remove more scattering-affected data but also remove a lot of data not affected by cloud (Lawrence et al. 2015). More tunings about the threshold of the cloud/precipitation identification are needed for further applications.

The observation error and the bias correction parameter are given based on the standard deviation of the $\mathbf{O}-\mathbf{B}$ and the offline bias correction statistics through 1 July to 15 July 2018. The case-dependent $\mathbf{B}$ matrix is estimated with the National Meteorological Center (NMC) method (Parrish and Derber 1992) from a 1-month WRF forecast over July 2018. In the hybrid DA experiment, the regional ensemble members are derived from the 21 ensemble members of the NCEP global ensemble forecasting system (GEFS) through the WRF pre-processing system (WPS), and 50% weights are used for both the static and the ensemble-based covariance.

c. Experimental design

To investigate the DA impact on the forecast of heavy rainfall process associated with Typhoon Ampil, six experiments are conducted in this study, including one control experiment without DA and five DA experiments. The model first initialized a 6-h forecast from 0000 UTC 22 July 2018, of which the initial condition/boundary conditions are updated from the GFS data. Using the 6-h forecast output as background, the five DA experiments update the initial condition (IC) through the WRFDA system and initialize a 48-h forecast

from 0600 UTC 22 July 2018. The one control experiment (named as NODA) initializes a 48-h forecast correspondingly but without DA. The only difference between the five DA experiments, named as CON, VAR, ENVAR, ENVAR_AT, and ENVAR_ATMW, is that the CON only assimilates the conventional observations from the GTS dataset; the VAR and ENVAR assimilate the conventional data with the MWHS-2 radiances through 3DVAR and hybrid-3DVAR method, respectively; the ENVAR_AT assimilates the conventional data with the ATMS radiances through hybrid-3DVAR method; the ENVAR_ATMW assimilates the conventional data with the ATMS and MWHS-2 radiances through hybrid-3DVAR method. A detailed comparison of the experiments along with their purposes are listed in Table 2.

According to Lawrence et al. (2017), channels 5–9 and 11–15 of MWHS-2 are strongly sensitive to cloud and precipitation; channels 8–9 are surface sensitive and may be considered as additional window channels. In result, this study only assimilates the MWHS-2 radiances of channels 5–7 and 11–15, the channels that are precipitation sensitive and not surface sensitive. Based on the offline bias correction statistics through 1 July 2018 to 15 July 2018, the observation errors for channels 5–7 are given as 0.74, 0.92, and 1.83 K, respectively; the observation errors for channels 11–15 are given as 2.45, 2.34, 2.22, 2.10, and 2.07 K, respectively. The radiances are thinned onto a 54-km grid. The ATMS radiances are assimilated with the provided configuration in the WRFDA, in which the radiances from channels 6–10 and 18–22 are used. The radiances are thinned onto a 54-km grid as well.

3. Impacts of DA on the analyses

To investigate the DA effects on the heavy rainfall process associated with Typhoon Ampil, this section first illustrates the impacts of DA on the analyses. Figures 3a–c presents the background (contour) and the analysis increments (shading) of 500-hPa geopotential height in the DA experiments. The position of Typhoon Ampil is significantly impacted by DA. In the CON and VAR experiments (Figs. 3a,b), geopotential height decreases appear to the southwest of Typhoon Ampil, and geopotential height increases appear to the northeast of Typhoon Ampil in experiment VAR. Benefited from these analysis increments, Typhoon Ampil could move inland to the southwest in these 3DVAR experiments. As for the

FIG. 3. Background (contours, units: gpm) and analysis increments (shading, units: gpm) of 500-hPa geopotential height in experiments (a) CON, (b) VAR, and (c) ENVAR, and (d) background (contours, units: gpm) and ensemble spread (shading, units: gpm) of 500-hPa geopotential height in experiment ENVAR.

hybrid-3DVAR experiment (Fig. 3c), the geopotential height decline to the southwest of the typhoon, and the geopotential height enhancement to the northeast of the typhoon become even stronger than that in the 3DVAR experiments. Given the ensemble spread in the hybrid DA could generally reflect the weather conditions that constrain the model, Fig. 3d displays the ensemble spread in the ENVAR experiment. Large ensemble spreads are situated to the southwest and northeast of the typhoon, suggesting that the position of Typhoon Ampil has a relative high uncertainty in the background. It is noted that the large static background error covariances in the 3DVAR experiments are situated around 30°N and 110°–120°E (figure omitted), which corresponded to the large analysis increments as shown in Figs. 3a and 3b. Compared to the ensemble spreads in the ENVAR experiment, the large uncertainties in the backgrounds of the 3DVAR experiments are relatively far away from the typhoon center. In other words, there could be larger background uncertainties near the typhoon center in the ENVAR experiment. As a result, the larger analysis increments around the typhoon in the ENVAR experiment might not be difficult to understand.

Focusing on the impacts of MWHS-2 radiances, Fig. 4 presents the analysis statistics of MWHS-2 assimilation in experiments VAR and ENVAR. Viewing from the temperature channel, there is a warm bias of -2.136 K in the background

(Fig. 4a). After the assimilation, the warm bias is distinctly reduced to -0.025 K in the VAR experiment, and the standard deviation and RMSE also drop from 2.282 and 0.803 K to 0.756 and 0.756 K, respectively (Fig. 4b). In the ENVAR experiment (Fig. 4c), the statistics become even better with further decreases in all the mean bias (-0.014 K), standard deviation (0.750 K), and RMSE (0.750 K). Similarly, viewing from the humidity channel, the ENVAR experiment corrects the dry bias (Fig. 4d) along with the standard deviation and the RMSE to the greatest extent, followed by the VAR experiment. According to these results, the assimilation of MWHS-2 updates the analysis with distinct positive effects. Based on the ensemble-based background error covariance, which allows the model error to grow flow dependently with the weather condition, the ENVAR experiment generates an even better analysis than the VAR experiment.

To further understand the impacts of MWHS-2 radiances, two additional experiments are conducted to assimilate the ATMS radiances (experiment ENVAR_AT) and the ATMS radiances along with MWHS-2 radiances (experiment ENVAR_ATMW), respectively. To compare with the best performing MWHS-2 experiment with the hybrid-3DVAR algorithm, these two experiments are based on the same DA algorithm. The used ATMS radiances around 0600 UTC 22 July 2018 are shown by the red dots in Fig. 1b. Figure 5

FIG. 4. Scatterplot for MWHS-2 assimilation in (a) observation vs background and in (b),(c) observations vs analysis for experiments VAR and ENVAR, respectively, from channel 5; and (d),(e) similar results for MWHS-2 assimilation from channel 14.

presents the number and the RMSE of the used radiances in experiments ENVAR, ENVAR_AT, and ENVAR_ATMW. The number of the used ATMS radiances are less than the MWHS-2 radiances: in experiments ENVAR and ENVAR_ATMW, the numbers of the used MWHS-2 radiances range from 3900 to 4500 (Figs. 5a,c); in experiments ENVAR_AT and ENVAR_ATMW, the numbers of the used ATMS radiances are mostly below 3500 except for channel 10 (Figs. 5b,d). As for the RMSE, the performance of ATMS radiances are comparable to that in the MWHS-2 radiances. The average decrease percentage of the RMSE after assimilating MWHS-2 radiances is 55.3% in experiment ENVAR (Fig. 5a), and 56.8% in experiment ENVAR_ATMW (Fig. 5c); the average decrease percentage of the RMSE after assimilating ATMS radiances is 58.5% in experiment ENVAR_AT (Fig. 5b), and 55.8% in experiment ENVAR_ATMW (Fig. 5d).

4. Impacts on the forecast of heavy rainfall process

After illustrating the DA impacts on the analyses, this section focuses on the DA impacts on the forecast of the heavy rainfall process. To begin with, Figs. 2b–d present the 24-h accumulated forecast rainfall (from 0000 UTC 23 July to 0000 UTC 24 July 2018) in the four experiments, and Fig. 6 displays the anomalies of the 24-h accumulated forecast rainfall relative to the observations revealed by the CMA-Weather

data. In the experiments without MWHS-2 assimilation (NODA and CON, Figs. 2b,c and 6a,b), the rainfall is clearly overestimated in the southwest and underestimated in the northeast, although the averaged RMSE over the heavy rainfall area (black rectangle in Fig. 6) are decreased in the CON experiment from 16.23 to 13.67 mm day⁻¹ with the contribution of conventional observation. After assimilating the MWHS-2 radiances (VAR and ENVAR, Figs. 2d,e and 6c,d), both the overestimation and the underestimation of the rainfall exhibit a further decrease, especially for the original large-scale underestimated rainfall in the northeast. In result, the averaged RMSE are decreased by 9.95% (from 13.67 to 12.31 mm day⁻¹) and 17.92% (from 13.67 to 11.22 mm day⁻¹) for experiments VAR and ENVAR, respectively, compared to the CON experiment. Besides, it is noted that the pattern of the anomalies become different in the ENVAR experiment: the overestimations situate in the middle and the underestimations situate in the northwest and southeast (Fig. 6d). Since the rainfall has an evolution process, this different anomalous pattern in the accumulated rainfall could be caused by the changes in the movement and the evolution of the rainfall.

Figure 7 presents the rainfall evolution along its moving direction (white lines in Fig. 2) in the observations and the four experiments. In the observations (Fig. 7a), the rainfall moves from southeast to northwest with two peaks around 5–9 and 17–24 h, respectively. In comparison between the experiments

FIG. 5. The number and RMSE of the used MWHS-2 radiances in experiments (a) ENVAR and (c) ENVAR_ATMW, and the number and RMSE of the used ATMS radiances in experiments (b) ENVAR_AT and (d) ENVAR_ATMW. OMA and OMB in the legends denote the observation minus analysis and observation minus background, respectively.

with (Figs. 7d,e) and without (Figs. 7b,c) MWHS-2 assimilation, the MWHS-2 assimilation improves the rainfall evolution by enhancing the rainfall intensities around the two peaks significantly. Correspondingly, the ENVAR experiment achieves the highest spatial coefficient in the rainfall evolution between the observations (0.64), followed by VAR (0.56) and experiments without MWHS-2 assimilation (0.51 for NODA and 0.50 for CON). Considering the rainfall evolution could be related to the typhoon track, the dark red lines in Fig. 2 display the forecasted typhoon tracks in each experiment during the 24-h heavy rainfall period, and the black lines denote the corresponding typhoon tracks in the observations revealed by the Japan Regional Specialized Meteorological Center (RSMC) best track data. Compared to the NODA and CON experiments, the typhoon tracks in the MWHS-2 experiments (VAR and ENVAR) are closer to the observations: to the south of 37°N, the typhoon is moved eastward toward the observations; to the north of 38°N, the typhoon is moved northward toward the observations. Correspondingly, as shown by the shading in Fig. 2, the rainfall center to the south of 37°N moves toward the rainfall transection in the MWHS-2 experiments (white lines in Fig. 2, especially for the ENVAR experiment), and the rainfall to the north of 38°N becomes stronger in the MWHS-2 experiments. These results might provide some explanations for the enhanced rainfall intensities

in the two rainfall peaks in the MWHS-2 experiments (Fig. 7, along the transections).

To further evaluate the DA impacts on the rainfall evolution quantitatively, Fig. 8 presents the fractions skill score (FSS) of the forecasted rainfall over the heavy rainfall area (black rectangle in Fig. 6) along 1–24 h with different intensity thresholds. The performances of the DA experiments are generally similar in the rainfall with 1, 2.5, and 5 mm h⁻¹ thresholds: experiment ENVAR achieves the highest FSS with averaged value of 0.81, 0.77, and 0.74 (corresponded to the three rainfall thresholds), followed by experiment VAR with averaged values of 0.77, 0.75, and 0.72, and then experiment CON with averaged value of 0.72, 0.64, and 0.58 (Figs. 8a–c). In percentage, the FSS improvements compared to experiment CON are 12.50%, 20.31%, and 27.59% for rainfall thresholds of 1, 2.5, and 5 mm h⁻¹ in experiment ENVAR, and 6.94%, 17.18%, and 24.14%, respectively, in experiment VAR. It is also noted that the improvements brought by MWHS-2 assimilations (green and blue lines in Figs. 8a–c) are much bigger than that by the conventional observation assimilation (red lines in Figs. 8a–c), especially for time period around 12–21 h. As for the heavy rainfall with 10 mm h⁻¹ threshold (Fig. 8d), the difference between MWHS-2 assimilations and conventional observation assimilation are still evident (0.63 in ENVAR and VAR, and 0.49 in CON), while the performance

FIG. 6. 24-h accumulated rainfall anomalies during 0000 UTC 23 Jul–0000 UTC 24 Jul 2018 in experiments (a) NODA, (b) CON, (c) VAR, (d) ENVAR, (e) ENVAR_AT, and (f) ENVAR_ATMW (units: mm d⁻¹). The anomalies are relative to the observations revealed by the CMPA-Hourly data. The number above each panel denotes the averaged RMSE over the heavy rainfall area (black rectangle). The rainfall anomalies as a whole are significant at the 99% confidence level in each experiment.

FIG. 7. Rainfall evolution along its moving direction (white line in Fig. 2) in (a) the CMPA observations, and in experiments (b) NODA, (c) CON, (d) VAR, (e) ENVAR, (f) ENVAR_AT, and (g) ENVAR_ATMW (units: mm h⁻¹). The number above each panel denotes the spatial correlation of the rainfall evolution between the DA experiments and the observations.

of experiment ENVAR becomes comparable to that of the experiment VAR.

In contrast, the performance of ATMS radiance assimilation in the rainfall forecast does not surpass the MWSH-2 radiance

assimilation for the case examined herein. Compared to the ENVAR experiment, the RMSE of the 24-h accumulated rainfall in the ENVAR_AT experiment enlarges from 11.22 (Fig. 6d) to 12.42 mm day⁻¹ (Fig. 6e). Meanwhile, the spatial

FIG. 8. Fractions skill score (FSS) of the forecasted rainfall along 1–24 h verified against the CMPA-Hourly data with rainfall thresholds of (a) 1, (b) 2.5, (c) 5, and (d) 10 mm h^{-1} . The FSS is calculated over the heavy rainfall area as in the black rectangle in Fig. 6. The numbers next to the legend denote the averaged FSS for each experiment.

coefficient for the rainfall evolution decrease from 0.64 (Fig. 7e) to 0.61 (Fig. 7f). However, after assimilating MWS-2 radiances along with the ATMS radiances, the ENVAR_ATMW experiment achieves the best rainfall forecast performance among all the experiments: the RMSE of the accumulated rainfall is 10.76 mm day^{-1} (Fig. 6f); the spatial coefficient for the rainfall evolution reaches to 0.74 (Fig. 7g). Besides, the anomalous pattern of the accumulated rainfall becomes different after assimilating the MWS-2 radiances along with the ATMS radiances. The overestimations situate in the middle and the underestimations situate in the northwest and the southeast (Fig. 6f). A similar result is also found in the ENVAR experiment that only assimilates MWS-2 radiances (Fig. 6d).

Viewing the rainfall forecast from different perspectives as above, MWS-2 assimilations could improve the rainfall forecast in not only the accumulated amount but also the rainfall evolution with different thresholds ranging from 1 to 10 mm h^{-1} , especially when using the hybrid-3DVAR method. Moreover, the performance of ATMS radiance assimilation in the rainfall forecast does not surpass the MWS-2 radiance assimilation under the same hybrid-3DVAR method. Among all the experiments, the one that assimilates MWS-2 radiances along with ATMS radiances achieves the best rainfall forecast performance. With this understanding, the question naturally arises about the cause of these rainfall improvements. To explain this question, and to deepen the understanding of the effects of DA on the typhoon related heavy rainfall, the following section analyzes the forecast improvements in the rainfall process from the circulation structures related to the evolution of Typhoon Ampil.

5. Circulation structures related to typhoon evolution

Figure 9 displays the 1–24-h-averaged (the heavy rainfall period) anomalous circulation transects around northern

China. To get an idea of the forecast performance in the circulation structures, the anomalies in Fig. 9a are for the NODA experiment and are relative to the ERA-5 data; to better reflect the increments in the DA experiments, the anomalies in Figs. 9b–d are for the DA experiments and are relative to the NODA experiment. Compared to the conventional observation assimilation experiment (CON), the MWS-2 assimilation experiments (VAR and ENVAR) exhibit a stronger circulation structure corresponded to the typhoon: evident upper-layer warm anomalies that correspond to the warm core of the typhoon dominate around 115°–120°E above 500 hPa (shading in Figs. 9c and 9d); strong middle and lower layers negative height anomalies that correspond to the cyclonic circulation of the typhoon situate around 110°–125°E below 400 hPa (contours in Figs. 9c and 9d). Viewing from the experiment without DA (Fig. 9a), the anomalies above are in the opposite phase of the forecast deviations: the temperature is generally underestimated in the upper layers above 400 hPa; the geopotential height is overestimated throughout most of the transects. Therefore, the circulation structures could be ameliorated by the anomalies above, and Typhoon Ampil could be strengthened in the MWS-2 assimilation experiments, which further provides favorable conditions for the heavy rainfall. Correspondingly, the large-scale underestimations of rainfall in the CON experiment are greatly reduced in the MWS-2 assimilation experiments (Fig. 6).

To investigate the evolution of the circulation structures, Fig. 10 presents the evolution of the anomalous transects (relative to NODA) of 300-hPa temperature (given the strong temperature anomalies are located around 300 hPa on average as shown in Figs. 9b–d) and 700-hPa geopotential height averaged around northern China. Compared to the CON experiment, there are evident upper-layer warm anomalies and lower-layer negative height anomalies around 110°–120°E in the VAR and ENVAR experiments (Figs. 10a–c). These

FIG. 9. Anomalous transects of temperature (shading, units: K) and geopotential height (contours, units: gpm) averaged over the heavy rainfall period during 1–24 h around northern China (35° – 40° N) in experiments (a) NODA, (b) CON, (c) VAR, and (d) ENVAR. The anomalies are relative to ERA-5 data in (a) and relative to experiment NODA in (b)–(d).

results are consistent with the time averaged results as shown in Figs. 9b–d, which suggest that Typhoon Ampil could be strengthened in the whole evolution process after assimilating the MWS-2 radiances. In association with the evolution of the forecast rainfall, the significantly increased rainfall intensities during its process in the MWS-2 assimilation experiments (compared to CON, Figs. 7d,e) may not be difficult to understand. Furthermore, compared to the VAR experiment, the typhoon structure (upper warm anomalies and lower negative height anomalies) in the ENVAR experiment move eastward from 115° to 120° E with a strengthening tendency, suggesting that the evolution and the track of Typhoon Ampil could be greatly changed in the ENVAR experiment. These results might provide an explanation for the eastward movement of the forecasted rainfall amount center in experiment ENVAR compared to VAR (Figs. 6c,d).

As for the evolution of the typhoon, Fig. 11 presents the anomalous divergence and zonal wind transects (relative to

NODA) averaged around the typhoon center during its movement (white dots in Fig. 1). Compared to the CON experiment, the anomalies in the divergence field (shading in Fig. 11) are almost stronger in the whole evolutionary process in experiments VAR and ENVAR, which suggests that the evolution of typhoon could be more changed due to the assimilation of massive observations from MWS-2. However, the anomalous patterns in the divergences field are quite different between the VAR and the ENVAR experiment. In the ENVAR experiment, Typhoon Ampil could be strengthened by strong anomalous divergence (convergence) in the middle and upper (lower) layers at most of the hours, while such a favorable anomalous divergence pattern for typhoon are mainly concentrated around 16 h in the VAR experiment.

As shown in Fig. 11c, westerly anomalies and divergence anomalies appear in the middle and upper layers around the middle time period (8–16 h) in the ENVAR experiment, accompanied by a downward stretch from 300 to 400–500 hPa.

FIG. 10. Evolution of the anomalous transects of 300-hPa temperature (shading, units: K) and 700-hPa geopotential height (contours, units: gpm) averaged around northern China (35°–40°N) in experiments (a) CON, (b) VAR, and (c) ENVAR. The anomalies are relative to experiment NODA.

It should be mentioned that there is an upper westerly trough moving eastward during the lifetime of Typhoon Ampil, bringing upper westerlies and divergences to the typhoon after it lands in northern China (R. Guo et al. 2019). To better illustrate the interactions between the typhoon and the upper trough in the DA experiments, Fig. 12 presents the anomalous transects of geopotential height and wind fields at 16 h (the time with evident westerly and divergence anomalies as shown in Fig. 11c). To understand the forecast performance, the anomalies in Fig. 12a are for the NODA experiment and are relative to the ERA-5 data; to better reflect the increments in the DA experiments, the anomalies in Figs. 12b–d are for the DA experiments and are relative to the NODA experiment.

Although the VAR experiment has stronger anomalies in the geopotential height and wind fields compared to the CON

experiment (Figs. 12b,c), the ENVAR experiment shows a favorable anomalous circulation structure for the typhoon and the upstream trough: negative height anomalies dominate around 118°E, and a trough appears in its upstream above 500 hPa (Fig. 12d). Similar results also exist around 8 h, which is another time period with strong westerly and divergence anomalies as shown in Fig. 11c. In association with the NODA experiment (Fig. 12a), the strong centers of these anomalies are in the opposite phase of the forecast deviations: the geopotential height is overestimated to the east of 118°E; around 116°–120°E, easterly winds are overestimated throughout most of the transects. According to these results, the evolution of Typhoon Ampil under the effects of an approaching upper trough could be better represented in the ENVAR experiment by its favorable

FIG. 11. Vertical transects of anomalous divergence (shading, units: 10^{-6} s^{-1}) and zonal wind (contours, units: m s^{-1}) averaged around the typhoon center during its evolution (white dots in Fig. 1) in experiments (a) CON, (b) VAR, and (c) ENVAR. The anomalies are relative to experiment NODA.

anomalous circulation structure for the typhoon and the upstream trough. Correspondingly, the rainfall evolution in the VAR experiment is distinctly improved in the ENVAR experiment, especially the previously underestimated rainfall during the similar middle time period under the effects of the upper trough (around 9–17 h, Figs. 7d,e). Moreover, since the middle time period is the relative weak rainfall period during the whole process (Fig. 7a), this clearer evolution of the structure of typhoon around the middle time period in the ENVAR experiment might provide an explanation for its highest FSS in the relative weak rainfall (thresholds below 5 mm h^{-1}).

Figure 13 presents the forecast track error of Typhoon Ampil in different experiments verified against the Japan Regional Specialized Meteorological Center (RSMC) best track data. Although the conventional observation DA reduces the averaged RMSE of the track error during the heavy rainfall period from 61.59 km (NODA) to 56.75 km (CON), the

MWHS-2 assimilations perform much better in the typhoon track forecast. Compared to the CON experiment, the track error drops evidently after 10 h in the VAR experiment and 7 h in the ENVAR experiment. The averaged RMSE of the typhoon track during the heavy rainfall period are reduced distinctly to 39.48 km (VAR) and 33.26 km (ENVAR) from 56.75 km (CON). Furthermore, the forecast of rainfall during the middle time period could be contributed by the forecast track error as well. Corresponding to the smallest forecast track errors around 7–18 h (Fig. 13a), experiment ENVAR performs the best in the rainfall intensities during the similar time period with weaker rainfall (around 9–17 h, Figs. 7a,d,e), and in the FSS for the weaker rainfall with thresholds below 5 mm h^{-1} (Figs. 8a–c).

Following the above analyses, to further explore the reason for the rainfall changes in the two experiments with ATMS radiances, Figs. 14a and 14b present their anomalous circulation transects averaged over the 1–24-h heavy rainfall period as

FIG. 12. Vertical transects of anomalous geopotential height (shading, units: gpm) and wind fields (vectors, units: m s^{-1}) averaged around northern China (35° – 41°N) at 16 h in experiments (a) NODA, (b) CON, (c) VAR, and (d) ENVAR. The anomalies are relative to ERA-5 data in (a) and relative to experiment NODA in (b)–(d).

in Figs. 9 and 14c,d present their anomalous circulation transects at the 16 h as in Fig. 12. In the experiment that only assimilates ATMS radiances, the anomalous circulation structure corresponds to the typhoon become weaker than that in the experiment that only assimilates MWS-2 radiances. On one hand, the upper-layer warm anomalies around 115° – 120°E and the negative geopotential height anomalies around 110° – 120°E in the ENVAR_AT experiment (Fig. 14a) are generally smaller than that in the ENVAR experiment (Fig. 9d). On the other hand, for the anomalies at 16 h, the negative height anomalies around 117°E (Fig. 14c) become weaker than that in the ENVAR experiment (Fig. 12d). It should be mentioned that these results are just for the case examined herein, which

might also be related to the different amount of observations being assimilated in the two experiments (Fig. 1). More concrete conclusions about the two instruments should be drawn with a further analysis on more cases.

After assimilating the MWS-2 radiances along with the ATMS radiances, the average anomalous transects become much stronger with both upper-layer warm anomalies around 115° – 120°E and middle–lower-layer negative height anomalies around 110° – 130°E (Fig. 14b). It is noted that the characteristics of the circulation structures of the ENVAR_ATMW experiment are similar to and even stronger than that in the ENVAR experiment (Figs. 9d and 12d). According to the analyses in the MWS-2 assimilation experiments, these

FIG. 13. The forecast track error of Typhoon Ampil in experiments (a) NODA, CON, VAR, and ENVAR and (b) ENVAR_AT, ENVAR_ATMW, and ENVAR. The forecast track error is verified against the Japan Regional Specialized Meteorological Center (RSMC) best track data, and the numbers next to the legend denote the track error averaged over 0–24 h for each experiment. The forecast track errors as a whole are significant on the confidence level of 99% in each experiment.

characteristics could compensate the deviations in the NODA experiment, such as the generally underestimated upper-layer temperature (shading in Fig. 9a), the generally overestimated geopotential height (contour Fig. 9a), and the overestimated easterlies around 116°E (Fig. 12a). Viewing from the forecast track of the typhoon (Fig. 13b), the ENVAR_ATMW experiment has the smallest track error on average with a RMSE of 32.98 km, followed by experiments ENVAR (33.26 km) and ENVAR_AT (35.44 km). The best forecast performance of the heavy rainfall in the ENVAR_ATMW experiment might be explained from these results.

According to the above analyses, the MWS-2 assimilation has significant impacts on not only the analyses but also the evolutions of the circulation structures related to the typhoon. In result, the forecast of rainfall is improved in both the accumulated amount and the evolution characteristics. After assimilating the MWS-2 radiances through a hybrid-3DVAR method, the experiment shows a better representation of the circulation structures associated with the typhoon evolution, and further improves the forecast performances in the accumulated rainfall amount and the rainfall evolution. In the comparison of assimilating either ATMS radiances or MWS-2

radiances under the same a hybrid-3DVAR method, the latter outperforms the former in the forecasts of the circulation structure and the rainfall for the case investigated herein. Correspondingly, the experiment that assimilates the MWS-2 radiances and the ATMS radiances together achieves the best rainfall forecast.

6. Conclusions and discussion

Focusing on the evolution process of the heavy rainfall associated with Typhoon Ampil, this study investigates the assimilation effects of *FY-3D* MWS-2 radiances through both 3DVAR and hybrid-3DVAR methods, and further explores the improvements in the rainfall process by analyzing the circulation structures related to the typhoon evolution. The major conclusions are summarized as below.

- 1) The position of typhoon in the analysis field is distinctly affected by assimilating the MWS-2 radiances, especially through the hybrid-3DVAR method. After incorporating the ensemble-based background error covariance, the hybrid-3DVAR experiment generates the large analysis increments around Typhoon Ampil in accordance with its ensemble spread, contributing the typhoon to move inland to the southwest. Correspondingly, the hybrid-3DVAR experiment reduces the bias along with the standard deviation and RMSE in the analysis to the greatest extent, followed by the 3DVAR experiment.
- 2) The DA experiments indicate that the MWS-2 assimilation could improve the rainfall forecast in not only the accumulated amount, but also the evolution characteristics. Compared to the conventional observation assimilation experiment, the MWS-2 assimilation experiments with 3DVAR and hybrid-3DVAR reduce the RMSE in the accumulated rainfall amount by 9.95% and 17.92%, respectively, and enhance the spatial correlation of the rainfall evolution by 12.00% and 28.00%, respectively. Moreover, the averaged FSS during the rainfall process are improved by 6.94%–28.57% (12.50%–28.57%) in the 3DVAR (hybrid-3DVAR) experiment for rainfall with thresholds of 1–10 mm h⁻¹.
- 3) The forecast improvements of the rainfall are found to be closely connected with the characteristics of the circulation structures related to the typhoon evolution. On one hand, compared to the conventional observation assimilation experiment, the increases of the rainfall amount and rainfall intensities in the MWS-2 assimilation experiments (previously underestimated) correspond to the strengthened typhoon structures with stronger anomalies in both the upper-layer temperature and the lower-layer geopotential height. On the other hand, compared to 3DVAR experiment, the better performance of the hybrid-3DVAR experiment in the rainfall evolutions during the weak rainfall period, and in the FSS for the weaker rainfall with thresholds below 5 mm h⁻¹ could be explained by its clearer evolution of the structure of typhoon under the effects of an approaching upper trough, as well as its small typhoon track errors around the corresponding time period.

FIG. 14. (top) As in the anomalous transects of temperature (shading, units: K) and geopotential height (contours, units: gpm) in Fig. 9, but for experiments (a) ENVAR_AT and (b) ENVAR_ATMW. The anomalies are relative to the NODA experiment. (bottom) As in the anomalous vertical transects of geopotential height (shading, units: gpm) and wind fields (vectors, units: m s^{-1}) at 16 h in Fig. 12, but for experiments (c) ENVAR_AT and (d) ENVAR_ATMW. The anomalies are relative to the NODA experiment.

Recently, Xian et al. (2019) investigated the impacts of MWHS-2 from FY-3C satellite on a binary typhoon case through all-sky assimilation, pointing out that the vertical structures of temperature and humidity around the core areas of the typhoons are significantly improved after the assimilation, and so does the heavy rainfall amount. By contrast, this study pays more attentions to the heavy rainfall process related to the typhoon, finding out that the detailed rainfall characteristics during the evolution process could be greatly improved through assimilating the MWHS-2 radiances from FY-3D. Meanwhile, the hybrid-3DVAR method are used in this

study to further explore the potential contributions of MWHS-2 radiances. These results could not only deepen the understanding of the DA effects on the heavy rainfall process related to the typhoon, but also provide beneficial information in evaluating the capability of the newly equipped MWHS-2 on board FY-3D satellite. As for the comparison between the assimilations of ATMS radiances and MWHS-2 radiances, the results do not necessarily mean that the MWHS-2 radiances would contribute more to the daily forecasts than the ATMS radiances. Given the comparison is focused on Typhoon Ampil in this study, investigations of more cases are needed for a further conclusion.

Based on the developed MWS-2 assimilation capability within the WRFDA, the investigations for MWS-2 impacts on more heavy rainfall cases with different evolutionary characteristic are undergoing. In the next step, study will focus on expanding the MWS-2 assimilation capability to more advanced DA algorithms, such as 4DVAR and hybrid-4DVAR.

Acknowledgments. This work is sponsored by the National Key Research and Development Program of China (2017YFB1002702), and the National Natural Science Foundation of China (Grant 41875112). The authors also acknowledge the Chinese National Satellite Meteorological Center for providing the satellite observations and the National Meteorological Information Center of CMA for providing the precipitation observations.

REFERENCES

- Barker, D., and Coauthors, 2012: The Weather Research and Forecasting Model's Community Variational/Ensemble Data Assimilation System: WRFDA. *Bull. Amer. Meteor. Soc.*, **93**, 831–843, <https://doi.org/10.1175/BAMS-D-11-00167.1>.
- Bormann, N., A. Fouilloux, and W. Bell, 2013: Evaluation and assimilation of ATMS data in the ECMWF system. *J. Geophys. Res. Atmos.*, **118**, 12 970–12 980, <https://doi.org/10.1002/2013JD020325>.
- Carminati, F., B. Candy, W. Bell, and N. Atkinson, 2018: Assessment and assimilation of FY-3 humidity sounders and imager in the UK Met Office global model. *Adv. Atmos. Sci.*, **35**, 942–954, <https://doi.org/10.1007/s00376-018-7266-8>.
- Chen, H., R. Yu, and Y. Shen, 2016: A new method to compare hourly rainfall between station observations and satellite products over central-eastern China. *J. Meteor. Res.*, **30**, 737–757, <https://doi.org/10.1007/s13351-016-6002-5>.
- Collard, A., J. Derber, R. Treadon, N. Atkinson, J. Jung, and K. Garrett, 2012: Toward assimilation of CrIS and ATMS in the NCEP Global Model. *Proc. 18th Int. TOVS Study Conf.*, Toulouse, France, TOVS, 1.21.
- Grell, G. A., and D. Dévényi, 2002: A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. *Geophys. Res. Lett.*, **29**, 1693, <https://doi.org/10.1029/2002GL015311>.
- Guo, R., X. Jia, D. Wu, and M. Li, 2019: Analysis on long-time maintenance mechanism of Typhoon Ampil (1810) after its landing (in Chinese). *Adv. Geosci.*, **9**, 408–419, <https://doi.org/10.12677/AG.2019.95046>.
- Guo, Y., J. He, S. Gu, and N. Lu, 2019: Calibration and validation of Feng Yun-3-D microwave humidity sounder II. *IEEE Geosci. Remote Sens. Lett.*, **17**, 1846–1850, <https://doi.org/10.1109/LGRS.2019.2957403>.
- Hersbach, H., and Coauthors, 2020: The ERA5 global reanalysis. *Quart. J. Roy. Meteor. Soc.*, **146**, 1999–2049, <https://doi.org/10.1002/qj.3803>.
- Hong, S.-Y., Y. Noh, and J. Dudhia, 2006: A new vertical diffusion package with an explicit treatment of entrainment processes. *Mon. Wea. Rev.*, **134**, 2318–2341, <https://doi.org/10.1175/MWR3199.1>.
- Jieying, H., Z. Shengwei, and W. Zhenzhan, 2015: Advanced Microwave Atmospheric Sounder (AMAS) Channel Specifications and T/V Calibration Results on FY-3C Satellite. *IEEE Trans. Geosci. Remote Sens.*, **53**, 481–493, <https://doi.org/10.1109/TGRS.2014.2324173>.
- Lawrence, H., N. Bormann, Q. Lu, A. Geer, and S. English, 2015: An evaluation of FY-3C MWS-2 at ECMWF. EUMETSAT/ECMWF Fellowship Programme Research Rep. 37, 26 pp., <http://www.ecmwf.int/sites/default/files/elibrary/2015/10668-evaluation-fy-3c-mwbs-2-ecmwf.pdf>.
- , and Coauthors, 2017: An evaluation of FY-3C MWRI and assessment of the long-term quality of FY-3C MWS-2 at ECMWF and the Met Office. ECMWF Tech. Memo. 798, 28 pp., <http://www.ecmwf.int/sites/default/files/elibrary/2017/17206-evaluation-fy-3c-mwri-and-assessment-long-term-quality-fy-3c-mwbs-2-ecmwf-and-met-office.pdf>.
- Li, J., R. Yu, W. Yuan, and H. Chen, 2011: Changes in duration-related characteristics of late-summer precipitation over eastern China in the past 40 years. *J. Climate*, **24**, 5683–5690, <https://doi.org/10.1175/JCLI-D-11-00009.1>.
- , —, and W. Sun, 2013: Duration and seasonality of hourly extreme rainfall in the central eastern China. *Acta Meteor. Sin.*, **27**, 799–807, <https://doi.org/10.1007/s13351-013-0604-y>.
- Liu, Z., C. S. Schwartz, C. Snyder, and S.-Y. Ha, 2012: Impact of assimilating AMSU-A radiances on forecasts of 2008 Atlantic tropical cyclones initialized with a limited-area ensemble Kalman filter. *Mon. Wea. Rev.*, **140**, 4017–4034, <https://doi.org/10.1175/MWR-D-12-00083.1>.
- Lu, Q., H. Lawrence, N. Bormann, S. English, K. Lean, N. Atkinson, W. Bell, and F. Carminati, 2015: An evaluation of FY-3C satellite data quality at ECMWF and the Met Office. ECMWF Tech. Memo. 767, 37 pp., <https://www.ecmwf.int/sites/default/files/elibrary/2015/14692-evaluation-fy-3c-satellite-data-quality-ecmwf-and-met-office.pdf>.
- Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, 1997: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res.*, **102**, 16 663–16 682, <https://doi.org/10.1029/97JD00237>.
- Newman, K. M., C. S. Schwartz, Z. Liu, H. Shao, and X.-Y. Huang, 2015: Evaluating forecast impact of assimilating microwave humidity sounder (MHS) radiances with a regional ensemble Kalman filter data assimilation system. *Wea. Forecasting*, **30**, 964–983, <https://doi.org/10.1175/WAF-D-14-00091.1>.
- Parrish, D. F., and J. C. Derber, 1992: The National Meteorological Center's spectral statistical-interpolation analysis system. *Mon. Wea. Rev.*, **120**, 1747–1763, [https://doi.org/10.1175/1520-0493\(1992\)120<1747:TNCSS>2.0.CO;2](https://doi.org/10.1175/1520-0493(1992)120<1747:TNCSS>2.0.CO;2).
- Roy, C., and R. Kovordányi, 2012: Tropical cyclone track forecasting techniques—A review. *Atmos. Res.*, **104–105**, 40–69, <https://doi.org/10.1016/j.atmosres.2011.09.012>.
- Saunders, R., and Coauthors, 2018: An update on the RTTOV fast radiative transfer model (currently at version 12). *Geosci. Model Dev.*, **11**, 2717–2737, <https://doi.org/10.5194/gmd-11-2717-2018>.
- Schwartz, C. S., Z. Liu, Y. Chen, and X.-Y. Huang, 2012: Impact of assimilating microwave radiances with a limited-area ensemble data assimilation system on forecasts of Typhoon Morakot. *Wea. Forecasting*, **27**, 424–437, <https://doi.org/10.1175/WAF-D-11-00033.1>.
- Shen, F., and J. Min, 2015: Assimilating AMSU-A radiance data with the WRF Hybrid En3DVAR system for track predictions of Typhoon Megi (2010). *Adv. Atmos. Sci.*, **32**, 1231–1243, <https://doi.org/10.1007/s00376-014-4239-4>.
- Shen, Y., P. Zhao, Y. Pan, and J. Yu, 2014: A high spatiotemporal gauge-satellite merged precipitation analysis over China. *J. Geophys. Res. Atmos.*, **119**, 3063–3075, <https://doi.org/10.1002/2013JD020686>.

- Skamarock, W. C., and Coauthors, 2008: A description of the Advanced Research WRF version 3. NCAR Tech. Note NCAR/TN-475+STR, 113 pp., <https://doi.org/10.5065/D68S4MVH>.
- Sun, W., J. Li, R. Yu, and W. Yuan, 2015: Two major circulation structures leading to heavy summer rainfall over central North China. *J. Geophys. Res. Atmos.*, **120**, 4466–4482, <https://doi.org/10.1002/2014JD022853>.
- Tao, W.-K., and Coauthors, 2003: Microphysics, radiation and surface processes in the Goddard Cumulus Ensemble (GCE) model. *Meteor. Atmos. Phys.*, **82**, 97–137, <https://doi.org/10.1007/s00703-001-0594-7>.
- Thompson, G., P. R. Field, R. M. Rasmussen, and W. D. Hall, 2008: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization. *Mon. Wea. Rev.*, **136**, 5095–5115, <https://doi.org/10.1175/2008MWR2387.1>.
- Wang, X., 2011: Application of the WRF hybrid ETKF–3DVAR data assimilation system for hurricane track forecasts. *Wea. Forecasting*, **26**, 868–884, <https://doi.org/10.1175/WAF-D-10-05058.1>.
- , D. M. Barker, C. Snyder, and T. M. Hamill, 2008: A hybrid ETKF–3DVAR data assimilation scheme for the WRF model. Part I: Observing system simulation experiment. *Mon. Wea. Rev.*, **136**, 5116–5131, <https://doi.org/10.1175/2008MWR2444.1>.
- Wu, C.-C., T.-H. Li, and Y.-H. Huang, 2015: Influence of mesoscale topography on tropical cyclone tracks: Further examination of the channeling effect. *J. Atmos. Sci.*, **72**, 3032–3050, <https://doi.org/10.1175/JAS-D-14-0168.1>.
- Xian, Z., K. Chen, and J. Zhu, 2019: All-sky assimilation of the MWHS-2 observations and evaluation the impacts on the analyses and forecasts of binary typhoons. *J. Geophys. Res. Atmos.*, **124**, 6359–6378, <https://doi.org/10.1029/2018JD029658>.
- Xu, D., Z. Liu, X.-Y. Huang, J. Min, and H. Wang, 2013: Impact of assimilating IASI radiance observations on forecasts of two tropical cyclones. *Meteor. Atmos. Phys.*, **122**, 1–18, <https://doi.org/10.1007/s00703-013-0276-2>.
- , X.-Y. Huang, H. Wang, A. P. Mizzi, and J. Min, 2015: Impact of assimilating radiances with the WRFDA ETKF/3DVAR hybrid system on prediction of two typhoons in 2012. *J. Meteor. Res.*, **29**, 28–40, <https://doi.org/10.1007/s13351-014-4053-z>.
- , J. Min, F. Shen, J. Ban, and P. Chen, 2016: Assimilation of MWHS radiance data from the FY-3B satellite with the WRF Hybrid-3DVAR system for the forecasting of binary typhoons. *J. Adv. Model. Earth Syst.*, **8**, 1014–1028, <https://doi.org/10.1002/2016MS000674>.
- Yen, T.-H., C.-C. Wu, and G.-Y. Lien, 2011: Rainfall simulations of Typhoon Morakot with controlled translation speed based on EnKF data assimilation. *Terr. Atmos. Oceanic Sci.*, **22**, 647–660, [https://doi.org/10.3319/TAO.2011.07.05.01\(TM\)](https://doi.org/10.3319/TAO.2011.07.05.01(TM)).
- Yu, R., W. Yuan, and J. Li, 2013: The asymmetry of rainfall process. *Chin. Sci. Bull.*, **58**, 1850–1856, <https://doi.org/10.1007/s11434-012-5653-6>.
- Yuan, W., J. Li, H. Chen, and R. Yu, 2012: Intercomparison of summer rainfall diurnal features between station rain gauge data and TRMM 3B42 product over central eastern China. *Int. J. Climatol.*, **32**, 1690–1696, <https://doi.org/10.1002/joc.2384>.
- , R. Yu, M. Zhang, W. Lin, J. Li, and Y. Fu, 2013: Diurnal cycle of summer precipitation over subtropical East Asia in CAM5. *J. Climate*, **26**, 3159–3172, <https://doi.org/10.1175/JCLI-D-12-00119.1>.
- Zhang, F., M. Minamide, and E. E. Clothiaux, 2016: Potential impacts of assimilating all-sky infrared satellite radiances from GOES-R on convection-permitting analysis and prediction of tropical cyclones. *Geophys. Res. Lett.*, **43**, 2954–2963, <https://doi.org/10.1002/2016GL068468>.
- Zhang, Y., G. Fan, Y. He, and L. Cao, 2017: Risk assessment of typhoon disaster for the Yangtze River Delta of China. *Geomatics Nat. Hazards Risk*, **8**, 1580–1591, <https://doi.org/10.1080/19475705.2017.1362040>.
- Zhu, Y., and Coauthors, 2016: All-sky microwave radiance assimilation in NCEP’s GSI analysis system. *Mon. Wea. Rev.*, **144**, 4709–4735, <https://doi.org/10.1175/MWR-D-15-0445.1>.