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FY-3A SATELLITE MICROWAVE DATA ASSIMILATION EXPERIMENTS IN TROPICAL CYCLONE FORECAST

YANG Yin-ming (杨引明)[1], DU Ming-bin (杜明斌)[2, 3], ZHANG Jie (张 洁)[2]

(1. Shanghai Meteorological Center, Shanghai 200030 China; 2. Shanghai Center for Satellite Remote Sensing and Application, Shanghai 201100 China; 3. School of Atmospheric Science, Nanjing University, Nanjing, 210093 China)

Abstract: China's new generation of polar-orbiting meteorological satellite FY-3A was successfully launched on May 26, 2008, carrying microwave sounding devices which had similar performance to ATOVS of NOAA series. In order to study the application of microwave sounding data in numerical prediction of typhoons and to improve typhoon forecasting, we assimilated data directly for numerical forecasting of the track and intensity of the 2009 typhoon Morakot (0908) based on the WRF-3DVar system. Results showed that the initial fields of the numerical model due to direct assimilation of FY-3A microwave sounding data was improved much more than that due to assimilation of conventional observations alone, and the improvement was especially significant over the ocean, which is always without conventional observations. The model initial fields were more reasonable in reflecting the initial situation of typhoon circulation as well as temperature and humidity conditions, and typhoon central position at sea was also adjusted. Through direct 3DVar assimilation of FY-3A microwave data, the regional mesoscale model improves the forecasting of typhoon track. Therefore, the FY-3A microwave data could efficiently improve the numerical prediction of typhoons.

Key words: satellite data assimilation; FY-3A microwave sounding; typhoon Morakot; 3DVar

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1 INTRODUCTION

Because of the lack of conventional data with relatively high spatial and temporal resolution over extensive oceans, reasonable extraction of effective information from satellite data for numerical prediction models holds great significance for improving forecasting accuracy of the numerical prediction model of tropical cyclones (TCs). Due to the ability to penetrate clouds[1], the vertical microwave sounding data from the satellites of NOAA has been used widely to forecast the TC[2,3] since AMSU (Advanced Microwave Sounding Unit) was first carried by NOAA-15, which was launched by the United States in March 1998. Less affected by ice clouds, AMSU observation data is of great use for the TCs and holds positive significance for the analysis and forecast of TCs[2]. Currently, many operational and research centers of numerical predication in the world apply various satellite data assimilation schemes in numerical weather prediction (NWP). Satellite data has become the principle part of observational data used in numerical prediction that has improved the accuracy of numerical prediction greatly. For example, European Centre for Medium Range Weather Forecasts (ECMWF) and National Centers for Environmental Prediction (NCEP) have applied the direct assimilation of TOVS and ATOVS radiance data in 3-dimensional or 4-dimensional variational assimilation systems[4-6]. In China, many studies have also been carried out on direct variational assimilation of satellite data[7-12]. Pan et al.[9] used the incremental 3-dimensional variational method for assimilating AMSU-A brightness temperature data, and then significantly improved the MM5 model prediction of temperature and water vapor mixing ratio. Zhang et al.[10, 11] applied the same method in assimilation of AMSU-A/B data of NOAA. And the experiments demonstrated that the assimilation of microwave sounding information reflects more

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Biography: YANG Yin-ming, senior engineer of research, primarily undertaking research on the atmospheric observation and mesoscale meteorological research and operation.

Corresponding author: DU Ming-bin, e-mail: nyicer@hotmail.com

reasonably the 3-dimensional structure of TCs and improves the track forecast. Zhu et al.[12] used the variational method to achieve the direct assimilation of AMSU-A and AMSU-B radiation data of NOAA-17 with the GRAPES-3DVar assimilation system. After the assimilation of radiation data, the analysis fields of model variables represented reasonable constraining relationship between the wind and the pressure.

FY-3 series are the new generation polar-orbiting meteorological satellites in China. The first satellite, FY-3A, was successfully launched in May 2008, carrying microwave sounding equipments with similar performance to that of the ATOVS series of NOAA. FY-3A microwave sounding devices are similar to AMSU in various functions and can be divided into Microwave Temperature Sounder (MWTS) and Microwave Humidity Sounder (MWHS), which are primarily used to detect the vertical distribution of atmospheric temperature and humidity, respectively. In the regional and global data assimilation systems they are important data sources for the application of atmospheric vertical sounding records observed by satellites. In this work, typhoon Morakot (0908) was taken as a sample to investigate the effect of FY-3A MWTS and MWHS data, which are directly assimilated by 3DVar, on the TC numerical prediction.

2 METHODS AND MODEL INTRODUCTION

2.1 *Methods*

A complex observation operator can be applied to the variational method to simplify the assimilation of observations which are non-linearly correlated with the model variables. The inverse problem is solved with the forward method so that the complex uncertainties in satellite inverse calculations can be avoided. In this way, the complexity of inverse problems can be avoided by addressing the issue of methodology and satellite radiance can be applied to data assimilation[13]. Based on the WRF-3DVar numerical assimilation model, we have established a direct variational data assimilation system for FY-3A MWTS and MWHS.

The orbit information of FY-3A satellite can be described by the approach of RTTOV 8.7 radiative transfer model by ECMWF, which can be adopted to handle the channel information of MWTS and MWHS, respectively. And the coefficient files of radiative transfer model (RTM coefficient files) were provided by the National Satellite Meteorological Center. For further calculating the satellite radiation of FY-3A microwave data, first the microwave data of FY-3A should match the geographic location in the numerical model. Therefore, each of the model layers is interpolated into 43 isobaric layers of RTTOV, respectively, which ranges from 0.1 to 1013.0 hPa. Moreover, bi-linear and log-linear interpolation is adopted respectively in the horizontal and vertical for the spatial interpolation. The profile of ozone input is of the climate and the layer of highest vapor saturation in the model is regarded as the cloud top to determine the cloud-top pressure. A fast radiative transfer model reflects a quasi-linear feature, while the direct variational assimilation of microwave channels is achieved with a related tangent model and an adjoint model. With the development of this assimilation system, the RTTOV 8.7 radiative transfer model of ECMWF can be used as the assimilation operator of WRF-3DVar to assimilate FY-3A microwave data.

2.2 *Model introduction*

FY-3A satellite microwave data is generated from the HDF-format L1b data of the National Meteorological Center of China and the assimilation time window is 3 hours. Background data is global forecast data of the Global Forecast System (GFS) with 26 vertical layers and horizontal resolution of 1.0°×1.0°. The numerical model contains 35 vertical levels with a horizontal resolution of 265°×265°, and its integration step is 50 seconds. The KF cumulus parameterization and YSU boundary layer are adopted and some important parameters are shown in Table 1.

Table 1. Some important parameters for 3DVar.

Grid settings	25°N, 127°E, 15 km, 265×265×35
Microphysical processes	WRF Single-Moment 6-class
process of short-wave radiation	Dudhia
process of long-wave radiation	RRTM
Surface Processes	Monin-Obukhov
Land surface process	Noah land-surface model
Planetary boundary layer scheme	YSU scheme
Cumulus parameterization scheme	Kain-Fritsch

3 EXPERIMENT DESIGN

3.1 *Experiment design*

Morakot was formed over the western North Pacific in early August 2009 and then gradually approached the offshore area east of Taiwan and slowed down. After crossing the island, it lingered along the Taiwan Strait for 31 hours before slowly landing in Xiapu of Fujian province. Morakot moved slowly and its gale range was large. Meanwhile, its path shifted toward the north when approaching the island with a reduced speed, making it more difficult to forecast. In the numeral experiment, the 84-hour forecast field of the Global Forecast System was taken as the background field. The initial time was set at 0000 Coordinated Universal time (UTC), August 6, 2009 (the same hereafter) and the assimilation time was set at 0000 UTC, August 6. The time window was set as three hours earlier and later. As shown in Figure 1, two orbits of FY-3A came across the area over eastern China during this period. Thus the 84-hour numerical forecasts were carried out after the assimilation. The model experiment design is described in Table 2, and the experiment area and the assimilation window are shown in Figure 1, where the colored dots indicate the final MWTS and MWHS data in model assimilation after thinning, quality control and bias correction. The colors of dots represent the degree of bias between the observation data and simulated radiation values from the background model (OMB) after bias correction. With the land surface influences on microwave data taken into consideration, only Channel 2, 3, and 4 of MWTS and Channel 3, 4, and 5 of MWHS were assimilated. After the thinning process and quality control, the FY-3A microwave information ultimately supplemented a great amount of effective observation data for the assimilation model. For example, 503 pixels in Channel 2 of MWTS were assimilated and 1159 pixels in Channel 3 of MWHS were assimilated. The detail of model assimilated microwave data is given in Table 3.

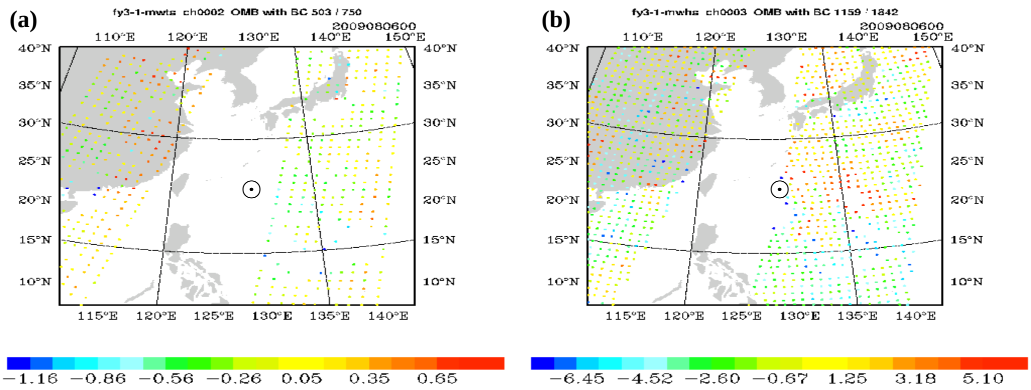

Figure 1. Assimilated data from FY-3A and OMB (⊙ represents typhoon center and the color represents its bias) (a): MWTS channel 2; (b): MWHS channel 3.

Table 2. Description of the numerical experiments.

Experiment Number	Experiment Name	Observation data	Assimilation window
Exp.1	CTRL	Null	Null
Exp.2	CONV	Conventional sounding and ground observation	2009-08-05_21:00-2009-08-06_03:00
Exp.2	CONV+FY3-MW	Conventional sounding and ground observation, FY-3A microwave data (including MWTS and MWHS)	2009-08-05_21:00-2009-08-06_03:00

Table 3. Statistics for FY-3A microwave data assimilated in the numerical experiments.

Instrument	Channel Number	Observational pixel number in model domain	Observational pixel number after thinning	Observational pixel number in assimilation model
MWTS	2	1112	750	503
MWTS	3	1112	750	530
MWTS	4	1112	750	490
MWHS	3	38764	1842	1159
MWHS	4	38764	1842	1083
MWHS	5	38764	1842	1030

3.2 *Data bias correction*

Direct assimilation of satellite data needs a scheme to simulate radiation value (or brightness temperature) by model background fields. During the assimilation, the combined effect of bias in each step will result in errors of radiation between the observation and the radiation simulated by the background model, which are often equivalent to radiation changes corresponding to typical errors of the atmospheric temperature field in short-term forecast of NWP. Unless the error of a radiative transfer model can be controlled and corrected to a lesser level, it would be difficult to use satellite radiation values directly in NWP with positive effect. Therefore, for applying direct assimilation of satellite radiation data in the NWP system, radiation bias between observed values and simulated ones should be corrected.

A bias correction scheme of FY-3A satellite microwave data was developed in this experiment based on both the WRF-3DVAR system and the TOVS radiation data bias correction scheme of Harris and Kelley[14, 15]. Considering the spatial variation and the air mass dependence of radiation data, scanning and air mass bias correction have been done according to satellite zenith angles and atmosphere climatic characteristics. The FY-3A microwave data applied in the data assimilation have already been calibrated and preprocessed. And δy was also with bias because of the difference between the observed radiances and simulated ones from the model first guess. It may probably include the observation bias itself (bias from the calibration error or bias from the data preprocessing). Primary and obvious relative bias of radiation data from the forecast model or other data (such as radio sounding) must be eliminated in numerical data assimilation. If possible, the absolute bias should also be eliminated, although its importance was secondary[15]. The experiment got its bias correction coefficient through the statistics for FY-3A microwave data of 14 successive days in August 2009. As seen in Figure 2, the fitting straight-lines of MWTS in Channel 2 and MWHS in Channel 3 are generally located on the main diagonal lines after bias correction. The distribution of major values of brightness temperature, which is simulated by the forward modes of observational operators and satellite observations with the use of background fields, presents a reasonable tendency, indicating the greatly reduced bias and the near-zero peak count value. The correction of Channel 3 and 4 (MWTS) and Channel 4 and 5 (MWHS) generates similar results, respectively (figures omitted).

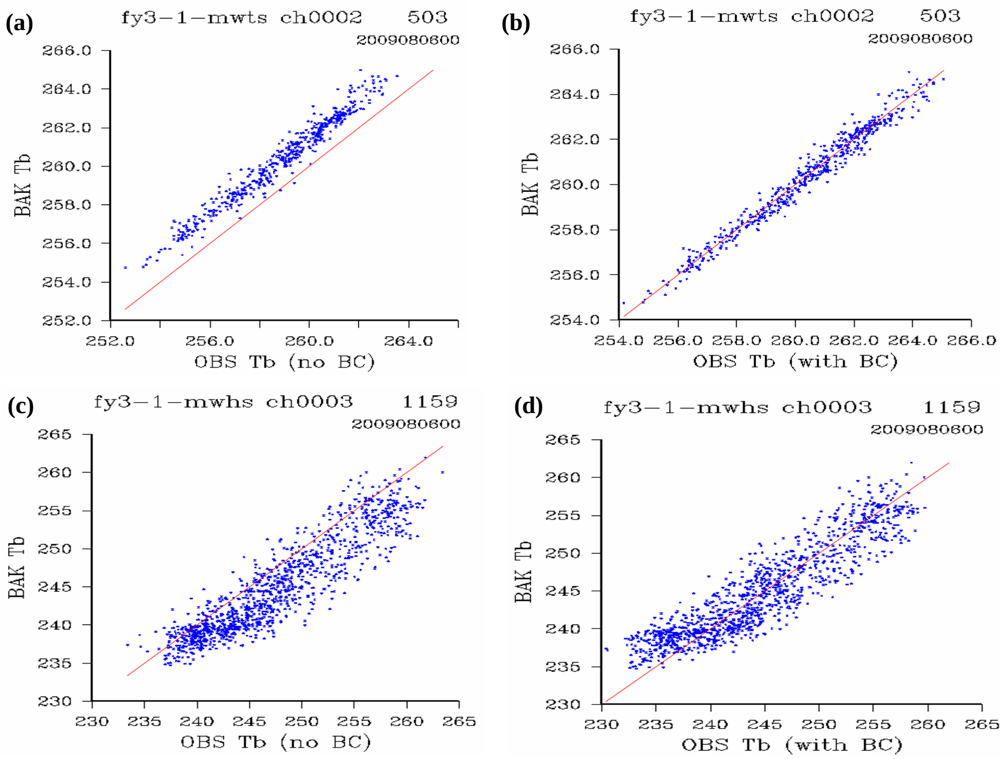

Figure 2. Bias Correction for FY-3A.

3.3 *Results*

It could be found in Figure 3 that the improvement is limited of typhoon track forecast from Exp. 2 with only the conventional observational data assimilated. However, Exp. 3 gets a better result after assimilating the data of FY-3A MWHS and MWTS. Specifically, the bias of initial typhoon position in the initial field has been significantly reduced in Exp. 3. The initial bias of the eye position is 76 km in the control experiment (Exp. 1). Being 62 km in Exp. 2 and 40 km in Exp. 3, the error has an 18% and 47% decrease, respectively.

With comprehensive analysis of the results of the three numerical assimilation experiments (Figure 4), it could be clearly found that Exp. 3 performs the best on the forecast typhoon track. In Exp. 3, the movement speed of typhoon after landing Taiwan has been clarified. And the second landing position is more southward than the other experiments (as shown in Figure 3) and closer to the observation. Compared with the control experiment (Exp. 1) output, the forecast result in Exp. 2—with only the conventional data assimilated, does not improve much since conventional observations are generally made on the land but scarcely over the ocean. The statistic results of the three experiments are collected and shown in Figure 5. Actually, Exp. 2 does not provide effective data for forecasting typhoon paths. But after assimilating the FY-3A microwave sounding information in Exp. 3, the error of track forecast greatly reduced by 26% in 24 hours and 54% in 48 hours compared to the control experiment of Exp. 1, respectively. However, the assimilation of FY-3A MWHS and MWTS data does not significantly improve the forecast of typhoon intensity (as shown in Figure 4b). The reasons need to be analyzed further.

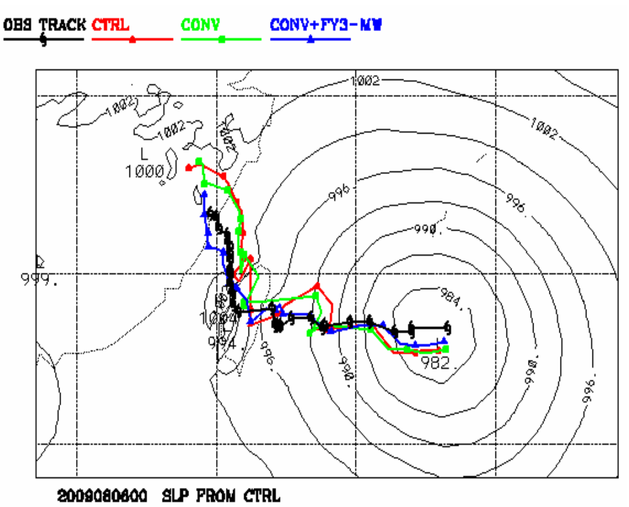

Figure 3. Tracks of "Morakot" from observation and various experiments (black line for observation, red for Exp. 1, green for Exp. 2, blue for Exp.3, respectively).

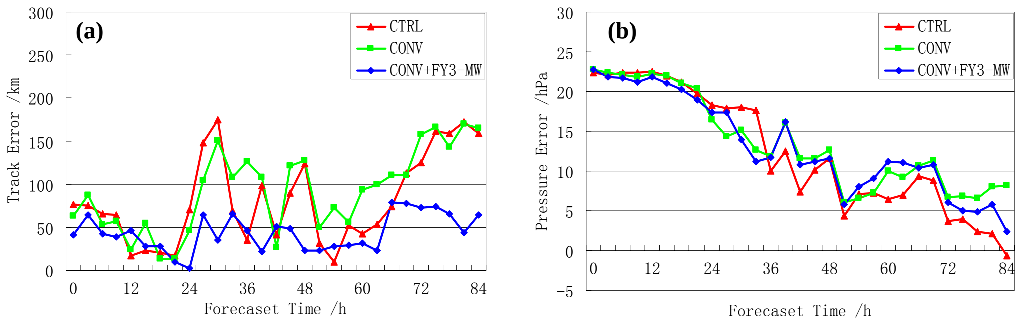

Figure 4. Errors for the experiments. (a): track error; (b): central pressure error.

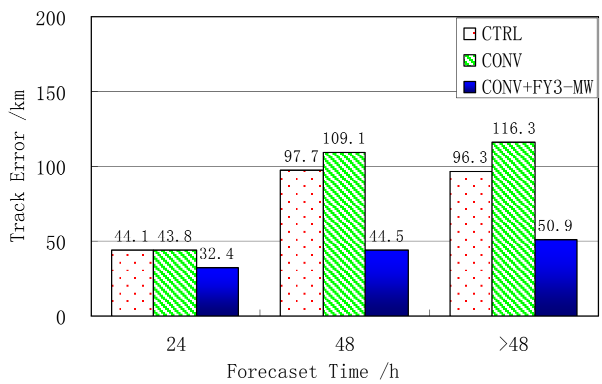

Figure 5. Statistics of track errors for the experiments.

3.4 *Analysis of experiments results*

The microwave temperature sounder (MWTS) has four channels, with the peak energy contribution distributed on the surface layer, 700 hPa, 300 hPa and 90 hPa, respectively, whereas the microwave humidity sounder (MWHS) has five channels and the peak energy contribution of the two channels is from the surface layer while that of the other channels are on 400 hPa, 600 hPa and 800 hPa, respectively.

Compared with Exp. 1, the data assimilation has brought about some significant results, indicating the advantage of microwave sounding data to the numerical prediction of typhoons. According to the typhoon position record of China National Meteorological Center, the center of Morakot at 0000 UTC on August 6, 2009 was (128.3ºE, 23.4ºN). Figures 6 and 7 present the horizontal distribution and the latitude-pressure cross sections of the difference between the assimilation experiments and control run along 23.4ºN (across the typhoon center).

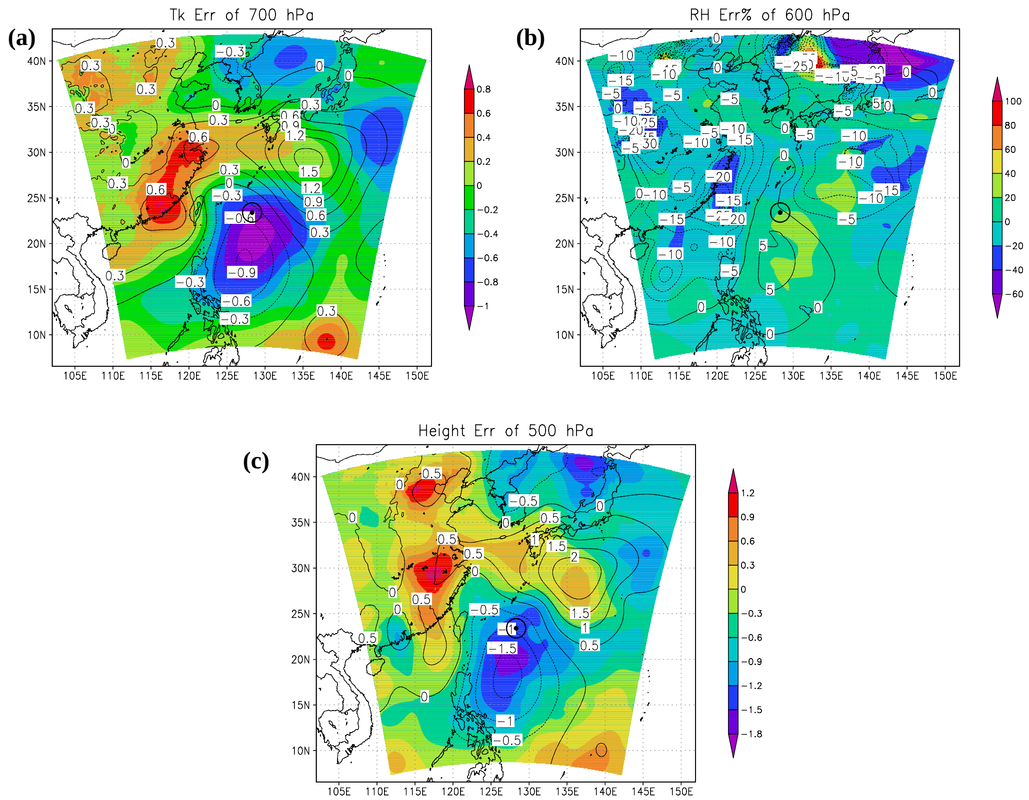

Figure 6. Difference field of the assimilation experiments compared with the control run (contours for Exp. 2, shades for Exp. 3, ⊙ presents the typhoon center). (a): temperature bias on 700 hPa; (b): relative humidity percentage bias on 600 hPa: (c): height bias on 500 hPa.

As shown in Figure 6a, the different temperature over land in Exp. 3 is similar to that in Exp. 2, but it is greatly distinct over the ocean as compared with that of Exp. 2. The difference field in Exp. 3 could reflect the position and structure of the typhoon more reasonably. Similar conclusions can be drawn from the profile map crossing the eye along the latitude. Over the land, the temperature difference of the entire model layer s is almost the same. But over the ocean, the temperature difference of Exp. 3 concentrates near the center of typhoon, accompanied by more significant values. For example, Figure 7a can better reflect the warm-core structure on the mid- and higher-level of the typhoon and the cool area, which are caused by the precipitation and ascending motion. The difference fields of relative humidity and temperature are featured similarly in the two assimilation experiments, as shown in Figures 6b and 7b. The difference value of Exp. 3 over the ocean is evidently greater than that of Exp. 2, and the difference value of Exp. 3 significantly reflects the humidity distribution around the typhoon position, while the Exp. 2 manifests little improvement over the ocean area. Therefore, it is very important to obtain the observational data over the ocean for improving the typhoon humidity field.

Assimilation of FY-3A microwave data has also improved the simulation of geopotential height field, and the result presents similar features as that of temperature and humidity, particularly on the lower levels. As the geopotential height can directly reflect the position and structure of typhoons, it adjusts their initial positions reasonably well over the ocean, although the difference of geopotential height in Exp. 3 improves the typhoon intensity a little. Moreover, Figure 6b shows that the subtropical anticyclone obtains smaller intensity increment in Exp. 3 than in Exp. 2, though Exp.3 obtains greater improvement of the geopotential height at 500 hPa over the area joining Hubei, Hunan and Guizhou provinces, which is just ahead of the second landing position of typhoon subsequently. And this difference of geopotential height is increasing with the altitude and also rising from north to south on the higher layers (as shown in Figure 7c). The analysis indicates that the high pressure difference impose significant impacts on the speed of Morakot at the later stage.

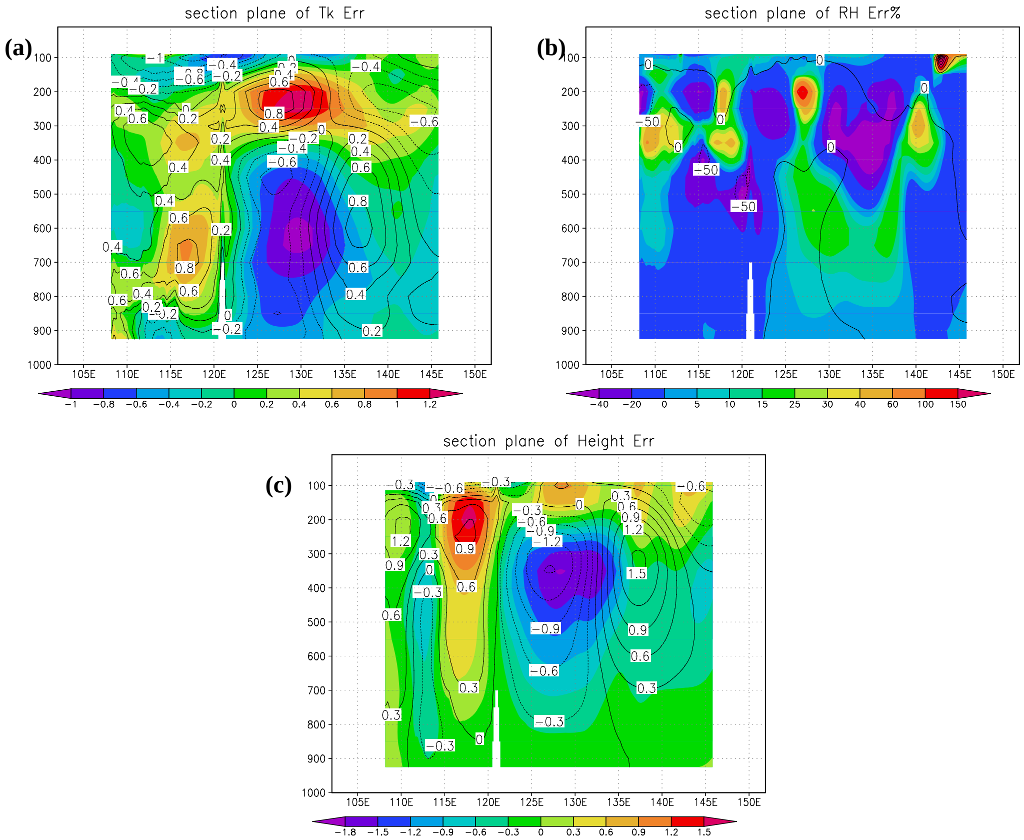

Figure 7. Difference field profiles of the assimilation experiments compared with the control (contours for Exp. 2, shades for Exp. 3). (a): temperature bias; (b): relative humidity percentage bias; (c): height bias.

4 CONCLUSIONS AND DISCUSSIONS

As China's new generation of polar-orbiting meteorological satellite, FY-3A has impressively improved its overall observing capacity for the Earth system and effectively supplemented for the typhoon observations over the ocean. The experiments of FY-3A microwave data assimilation indicate that the data assimilation enables a better reflection of the typhoon circulation on the ocean, manifests more reasonable temperature and humidity conditions of the initial model fields, and improves the typhoon track prediction. The specific conclusions are as follows.

(1) The distribution of brightness temperature bias presents a reasonable tendency, which has been greatly reduced after the correction.

(2) The experiments show that the assimilation added with FY-3A microwave data improves the effect of typhoon track prediction. However, the assimilation of conventional data alone cannot achieve the equivalent effect.

(3) Difference fields with the assimilation of microwave data reproduce more reasonably the structure of temperature and humidity fields and the position of typhoon and provide more effective improvement on the initial fields of numerical models than with the assimilation of conventional data alone, especially over the ocean.

(4) The assimilation of FY-3A microwave data also improves the geopotential height simulation, and the difference of temperature and humidity shows similar features. The improvement is especially significant on the lower levels. Although the assimilation of microwave data does not improve the simulation of typhoon intensity greatly, it can reasonably adjust the initial position of typhoon at sea.

(5) This work primarily focuses on the prediction of the environmental field and movement of the typhoon. Nevertheless, as the simulation errors of the radiative transfer model may be enlarged by the impact of heavy rain, it will be worthwhile to study the impacts of typhoon intensity and related wind and precipitation in the work that follows.

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