An Impact Study of GNSS RO Data on the Prediction of Typhoon Nepartak (2016) Using a Multiresolution Global Model with 3D-Hybrid Data Assimilation

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(Manuscript received 25 September 2020, in final form 17 March 2021)

ABSTRACT: Conventional soundings are rather limited over the western North Pacific and can be largely compensated by GNSS radio occultation (RO) data. We utilize the GSI hybrid assimilation system to assimilate RO data and the multi-resolution global model (MPAS) to investigate the RO data impact on prediction of Typhoon Nepartak that passed over southern Taiwan in 2016. In this study, the performances of assimilation with local RO refractivity and bending angle operators are compared for the assimilation analysis and typhoon forecast. Assimilations with both RO data have shown similar and comparable temperature and moisture increments after cycling assimilation and largely reduce the RMSEs of the forecast without RO data assimilation at later times. The forecast results at 60–15-km resolution show that RO data assimilation largely improves the typhoon track prediction compared to that without RO data assimilation, and assimilation with bending angle has better performances than assimilation with refractivity, in particular for wind forecast. The improvement in the forecasted track is mainly due to the improved simulation for the translation of the typhoon. Diagnostics of wavenumber-1 potential vorticity (PV) tendency budget indicates that the northwestward typhoon translation dominated by PV horizontal advection is slowed down by the southward tendency induced by the stronger differential diabatic heating south of the typhoon center for bending-angle assimilation. Simulations with the enhanced resolution of 3 km in the region of the storm track show further improvements in both typhoon track and intensity prediction with RO data assimilation. Positive RO impacts on track prediction are also illustrated for two other typhoons using the MPAS-GSI system.

KEYWORDS: Data assimilation; Numerical weather prediction/forecasting

1. Introduction

The western North Pacific (WNP) is the region with the most tropical cyclone activities in the world, where an average of 15.99 typhoons occurred per year during 1988–2019 (Met Office 2019). Taiwan island is in a key location, where many WNP tropical cyclones may landfall or pass around, and result in significant damages. According to the record of Central Weather Bureau (CWB) in Taiwan (C.-J. Chen et al. 2018), an annual average hit frequency of typhoon over Taiwan is 3–4 times per year. A typhoon could make severe impacts due to its intense wind and heavy rainfall. A better understanding of the synoptic environment, e.g., atmospheric temperature and moisture, in the numerical model could help improve the typhoon track prediction and thus further improve the rainfall forecast. In recent years, typhoon prediction has been much improved, for example, the error of 72-h track predicted by CWB is significantly reduced approximately from 400 to 200 km during 2008–15 (Leroux et al. 2018). However, the uncertainty of model prediction is significantly enlarged with longer time. As a result, the track error grows rapidly with

time, as also be found in many operational typhoon forecasts (Leroux et al. 2018).

Typhoons over the WNP have been extensively simulated using regional models, for example, the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008). Use of a regional model is particularly benefited by higher resolution than that for a global model. However, regional models usually use a nesting domain for a specific area with higher resolution, and require lateral boundary conditions provided by global analysis. Alternatively, multiresolution global models may also provide sufficient resolution comparable to regional model resolution. For example, a nonhydrostatic atmospheric model, the Model for Prediction Across Scales-Atmosphere (MPAS-A, hereafter MPAS), has been developed (led by the National Center for Atmospheric Research) with multiresolution unstructured grids (Skamarock et al. 2012). The MPAS model thus has a feature of variable-resolution grid mesh and the ability to ameliorate the abrupt evolution from nesting transitions (Skamarock et al. 2012). Park et al. (2014) examined the impact of the mesh refinement on MPAS and the nested grids on WRF, where the latter exhibits a significant reflection and distortion of waves near the lateral boundaries. The multiresolution MPAS model with 60–15-km or 60–15–3-km grid meshes has been utilized for simulations of typhoons over the WNP (Huang et al. 2017, 2019). Higher resolution better resolves the topographical effects of Taiwan and improves the track prediction in better agreement with the observed, especially for

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

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DOI: 10.1175/WAF-D-20-0175.1

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FIG. 1. The flowchart of the GSI hybrid data assimilation that includes two parts in the DA system. The EnKF part employs 36 members with a lower horizontal resolution of T179 to provide the background error covariances (BECs) for the GSI system (denoted by the upper blue-dashed box). The other part is the GSI DA with the hybrid BECs from the EnKF and climatology static with a higher resolution of T319 (denoted by the bottom blue-dashed box). The main analysis from GSI is then provided as an ensemble mean for recentering of the EnKF members for use in next cycling.

the captured track deflection of Typhoon Nesat (2017) when it approached Taiwan.

Initial conditions for a model play an essentially important role in numerical weather prediction (NWP), where data assimilation (DA) can be used to improve the initial analysis. The Gridpoint Statistical Interpolation (GSI) DA system is capable of assimilating multiple observations including conventional data and satellite radiance, etc., and can use both flow-dependent background errors and climatological static background errors in a hybrid data assimilation system (Hamill and Snyder 2000). For simulations of typhoons, it would be beneficial to assimilate more available observations over ocean. In addition to abundant satellite radiances, the Global Navigation Satellite System (GNSS) radio occultation (RO) data, which are globally distributed and unaffected by cloud and precipitation, and have high vertical resolution and accuracy (Kursinski et al. 1997), may help improve the analysis of the synoptic-scale atmosphere. The GNSS RO data have been assimilated by many operational models, e.g., the European Centre for Medium-Range Weather Forecasts (ECMWF) (Healy and Thépaut 2006), the National Centers for Environmental Prediction (NCEP) (Cucurull et al. 2007), Met Office (Rennie 2010), and Environment Canada (Aparicio and Deblonde 2008), etc., and all show positive impacts on global predictions, especially for the Southern Hemisphere where conventional observations are sparse. RO data have also

been shown to give promising positive impacts on typhoon predictions using a regional model (e.g., Huang et al. 2005, 2010; Kueh et al. 2009; Anisetty et al. 2014; Chen et al. 2009, 2015; S.-Y. Chen et al. 2018, 2020). Chen et al. (2015) found that assimilation with RO data may improve the 72-h track forecast by 5% for 11 typhoons over the WNP in 2008–10.

Typhoon Nepartak was the first typhoon over the WNP in 2016. On 2 July, a tropical depression, named by CWB and the Japan Meteorological Agency (JMA), formed near the ocean south of Guam and then moved northwestward toward Taiwan. On the next day, the vortex developed into a tropical storm. In the meantime, a subtropical high over the North Pacific was enhanced with a westward extension. The Nepartak storm was located at the southern flank of the subtropical high, and thus the environmental flow drives the storm west-northwestward with the moving speed of the cyclone increased to 25 km h^{-1} . On 4 July, a warm pool and weak wind shear appeared east of the Philippines, both being beneficial for development of the cyclone. Consequently, Nepartak is associated with rapid intensification (RI) during the period. During 6–7 July, the storm developed rapidly to reach a category 5 typhoon with a maximum wind speed of 58 m s^{-1} and central sea level pressure of 905 hPa. This supertyphoon then made landfall on southeast Taiwan at 2150 UTC 7 July.

Assimilation with RO bending angle has shown more positive impacts on global analysis and forecast than assimilation

FIG. 2. The procedure of the connection between the DA stage (the CWBGFS model and the GSI system) and the MPAS forecast stage.

with RO refractivity (e.g., Cucurull et al. 2013) and bending angle data have been the default data used in assimilation of operational global models. Assimilation with RO bending angle also further improves simulations of regional frontal rainfall episodes over Taiwan (Yang et al. 2014; Huang et al. 2016). In this study, we use the GSI DA system, which is the same as the CWB operational system, to assimilate RO data, and apply the multiresolution MPAS model to investigate the RO data impact on simulation of Typhoon Nepartak. This integration will allow for high-resolution forecasts using a global model with the merits of the operational GSI DA. We will also compare the performances of RO data assimilation with the local bending angle and refractivity operators in GSI. The numerical model and experiments are introduced in section 2. Section 3 gives the simulated results and discussion. Impacts of the RO data on simulations with the enhanced resolution of 3 km in the region of storm track are also discussed in this section. Conclusions are given in section 4.

2. Numerical models and experimental designs

a. The CWB global model and GSI data assimilation system

In this study, the Global Forecast System model at CWB (CWBGFS) (Liou et al. 1997; Su et al. 2019) and the GSI data assimilation system at NCEP (Wu et al. 2002; Kleist et al. 2009; Wang et al. 2013) are used for the cycling assimilation process. The CWBGFS is a nonhydrostatic global spectral model. The GSI is a community variational DA at NCEP, and it has been

implemented to interface with the CWBGFS for the CWB operational system. For the DA system, it is able to use either a variational-based or ensemble-based assimilation. A hybrid DA algorithm can be applied to improve the analysis by combining both methods (Hamill and Snyder 2000; Bannister 2017). Prasad et al. (2016) conducted data assimilations with a hybrid DA and a three-dimensional variation (3DVAR) DA to assess both DA influences on the prediction of Indian summer monsoon, and the results demonstrated that the hybrid assimilation improved the forecast. A triangular truncation of T319 (about 0.375° horizontal resolution) and 40 sigma-pressure hybrid levels in the vertical are employed in the assimilation and forecast processes of DA cycling in this study.

There are two parts in the DA system as shown in Fig. 1: the Ensemble Kalman Filter (EnKF), and the 3DVAR analysis. In this study, 36 members with a lower resolution of T179 (approximately 0.66°) are employed for the EnKF. Perturbations prepared for the 36 members are derived randomly within arbitrary 40 days according to the assimilation time from the CWB database. The database was established by a long-period (one year) model forecast, which can be used to derive the static background error covariance. Then, the EnKF analyses of 36 members are weighted with the additive inflation that adds the prepared perturbations (Wang et al. 2013). The ensemble-based flow-dependent background error covariances (BECs) can be estimated by the 36 ensemble 6-h forecasts. For a hybrid DA, blended BECs can be obtained by weighting the flow-dependent BECs from ensemble forecasts and the static (climatological) BECs. The static BECs are evaluated by

TABLE 1. Numerical experiments conducted for simulations of Typhoon Nepartak (2016).

Case	Observations for data assimilation	GPS variable
NODA	—	—
GTS	GTS (conventional data and satellite radiance)	—
REF	GTS + GPSRO	Refractivity
BND	GTS + GPSRO	Bending angle
GTS_H	As in GTS, but with the enhanced higher resolution of 3 km for forecast	
REF_H	As in REF, but with the enhanced higher resolution of 3 km for forecast	
BND_H	As in BND, but with the enhanced higher resolution of 3 km for forecast	

the long-term CWBGFS forecast errors, i.e., the NMC method (Parrish and Derber 1992). In this study, the weighting coefficients are 25% for the variational BECs and 75% for the flow-dependent BECs, following Hamill et al. (2011) and Kleist (2012). A higher horizontal resolution of T319 (approximately 0.375°) is then applied to the 3D variational framework with the blended BECs for minimization. Both EnKF and hybrid DA use the same observations to update the analyses,

FIG. 3. (a) The variable-resolution mesh of 60–15–3 km with a contour interval of 3 km for MPAS model. (b),(c) Taiwan topography (m) in the 60–15-km and 60–15–3-km MPAS meshes, respectively. The 60–15-km mesh is identical to the 60–15–3-km mesh, except that the latter uses increased resolution toward Taiwan and has a uniform 3-km resolution in the vicinity of Taiwan.

and the EnKF ensemble mean then is replaced by the hybrid analysis, i.e., recentering, which can centralize the ensemble analyses in EnKF by virtue of the hybrid analysis and help maintain the stability of cycling assimilation. The above processes are completed in one cycle of an assimilation time window and can be advanced with the control forecast of CWBGFS as the first guesses for next cycles. A detailed description of the hybrid DA formulations and procedures can be found in Kleist (2012) and Wang et al. (2013).

For GNSS RO data assimilation, there are two forward operators available in the GSI system, one is the refractivity N and the other is the bending angle α . The formulas of the refractivity are expressed as

$$N = k_1 \left(\frac{P_d}{T} \right) Z_d^{-1} + k_2 \left(\frac{P_w}{T} \right) Z_w^{-1} + k_3 \left(\frac{P_w}{T^2} \right) Z_w^{-1}, \quad (1)$$

where P_d and P_w are the pressure of the dry air and water vapor, respectively; T is the absolute temperature; k_1 , k_2 , and k_3 are the atmospheric refractivity constants of 77.689 K mb^{-1} , $71.2952 \text{ K mb}^{-1}$, and $3.75463 \times 10^5 \text{ K}^2 \text{ mb}^{-1}$, respectively (Rüeger 2002); and Z_d^{-1} and Z_w^{-1} are the compressibility factors that take into account small departures from the behavior of an ideal gas (Thayer 1974; Cucurull 2010). The RO bending angle is given by

$$\alpha(a) = -2a \int_a^\infty \frac{d \ln n / dx}{(x^2 - a^2)^{1/2}} dx, \quad x = nr, \quad (2)$$

where r is the distance between the center of a symmetrical Earth and a point on the raypath. The magnitude x is the refractive radius, and n is the index of refraction, and a the impact parameter (Born and Wolf 1980; Cucurull et al. 2013; Huang et al. 2016). The relationship between refractivity and index of refraction is $N = (n - 1) \times 10^6$. Both the refractivity and bending angle operators do not consider the measurement with an integrated effect of the GNSS signal along the raypath in which a spherical-symmetry assumption is adopted for the RO retrieval, but the bending angle operator uses a vertical integration that involves the vertical correlation. The observational errors for the two operators were estimated following the methodology of Desroziers et al. (2005), and several quality control criteria were executed before the minimization in DA (Cucurull 2010; Cucurull et al. 2013).

b. The MPAS model

The global model MPAS used for the forecast has unstructured centroidal Voronoi meshes and C-grid staggering of the state variables for the horizontal discretization in the fluid flow solver (Skamarock et al. 2012). The unstructured variable-resolution grid mesh allows for a smoothly varying resolution to reduce the abrupt change from transitions in the region of varying resolution. The MPAS model is fully compressible and nonhydrostatic for use in simulating multiscale weather phenomena. The MPAS version 5.2 is used for the final forecast in this study.

The flowchart of the connection between the DA stage (the GSI and CWBGFS) and the MPAS forecast stage is shown in Fig. 2. The cycling DA comprises the GSI and CWBGFS. After

FIG. 4. (a) The vertical variations of fractional differences (%) between the observation O and model first guess B as well as the observation O and DA analysis A for the refractivity. The blue line indicates the fractional innovation $(O - B)$ and the red line indicates the fractional difference between O and A . (b) As in (a), but for the bending angle.

several DA cycle runs, the analysis from the GSI will be provided as the first guess for the initial conditions of the MPAS model. Note that the analysis from the GSI cannot be directly used by MPAS and a convertor needs to be built. At the first step, the GSI output is converted to Gaussian grids on the original vertical levels, as an intermediate analysis which is interpolated on fixed horizontal grids and pressure levels in the Network Common Data Form (NetCDF). Then, the NetCDF

FIG. 5. Increments of temperature (shaded colors; K) at 500 hPa after the first DA cycle for the experiments (a) BND and (b) REF. (c),(d) As in (a) and (b), respectively, but at 700 hPa. (e),(f) As in (c) and (d), respectively, but for specific humidity (shaded colors; g kg^{-1}). The cross sign indicates the location of the RO sounding at 21.5°N , 138.7°E .

data are converted into a WRF Preprocessing System (WPS) intermediate file, which can be directly used by the MPAS model for final forecast.

c. Experimental settings

A spinup of the model state is first conducted by a 6-h forecast with CWBGFS at T319, which is initialized at

1800 UTC 1 July 2016. The 6-h forecast then is interpolated with the reduced resolution of T179 for EnKF to update the flow-dependent BEC for use in hybrid DA. After 2-day DA with 6-h cycles, the GSI analysis at 0000 UTC 4 July 2016 is converted to the MPAS initial condition for simulation of five days. GTS is the experiment with the assimilation of conventional data (e.g., radiosondes and surface stations) and satellite

FIG. 6. Locations of 1927 GPS RO soundings during 2 days of data assimilation for Typhoon Nepartak (2016). The black box indicates the region (10° – 30° N, 120° – 140° E) for the verification against NCEP analysis.

radiance including AMSU-A, AIRS, and IASI. To assess the GNSS RO data impact, two other experiments as in GTS are conducted but using different local RO operators to assimilate additional GNSS RO refractivity and bending angle, denoted by REF and BND, respectively. The RO operators and observation errors for both refractivity and bending angle were given by Cucurull (2010) and Cucurull et al. (2013). In this study, the GNSS RO data include *Formosa Satellite-3* and Constellation Observing System for the Meteorology, Ionosphere, and Climate (*FORMOSAT-3/COSMIC*), Meteorological Operational satellites (MetOp), Gravity Recovery and Climate Experiment (GRACE), X-Band TerraSAR satellite (*TerraSAR-X*), and *TerraSAR-X* add-on for Digital Elevation Measurement (*TanDEM-X*). An experiment with the initial condition from the NCEP analysis at 0000 UTC 4 July without data assimilation, denoted as NODA, was conducted for comparison (see Table 1 for details on the numerical experiments).

After the cycling data assimilation, the MPAS forecast with a variable resolution of 60–15 km is conducted. The model domain is centered in Taiwan with 15-km resolution covering the eastern Asia and WNP as shown in Fig. 3a. Impact of RO data on the forecast with enhanced resolution of 3 km centered at Taiwan is also investigated. With a high resolution of 3 km, the Taiwan topography is better depicted as seen in Figs. 3b and 3c. For the experiments, a suite of physics schemes for mesoscale resolution is used, including the New Tiedtke scheme for cumulus convection (Zhang and Wang 2017), WSM6 for cloud microphysics (Hong and Lim 2006), the Noah land surface model (Niu et al. 2011), YSU for the planetary boundary layer parameterization (Hong et al. 2006), and RRTMG for the radiance of longwaves and shortwaves (Iacono et al. 2008).

To understand the modifications produced by assimilation with RO refractivity and bending angle in the GSI system, a single RO sounding at (21.5° N, 138.7° E) is assimilated by both RO operators. Before DA, there are relatively large fractional differences between the model first guess B and observation O ,

i.e., $(O - B)/O$ (Fig. 4). After DA, the model analysis A is adjusted and is closer to observation, i.e., with smaller fractional differences, $(O - A)/O$. The reduction in the differences can be found in the whole vertical profile. Comparing the differences produced by the two RO operators, the use of the bending angle operator gives larger fractional differences up to 20% at the lower troposphere, and it can be reduced to half (about 10%), which is about the observational error for bending angle used in assimilation (Cucurull et al. 2013). Figure 4 shows that the fractional differences between the observation and analysis are reduced after the assimilation, regardless of use of RO refractivity operator or bending angle operator. For horizontal increments $(A - B)$, Figs. 5a–d show that both assimilations with bending angle and refractivity have similar variations, but the latter has larger magnitudes. The maximum temperature increment is about -0.3 K for bending angle, but is about -0.5 K for refractivity. For this RO sounding, both RO operators produce negative increments in temperature and specific humidity below the midtroposphere.

3. Simulated results and discussion

a. Initial analysis

During the 2-day period of cycling DA, there are more than nineteen hundred GNSS RO soundings available in the globe. The distribution of RO soundings is roughly even and is shown in Fig. 6. There are more than 200 RO soundings available at each assimilating time on average. To focus on the region affecting the tropical cyclone, a local area of 0° – 40° N and 110° – 170° E is chosen for investigation of the RO data analysis. Figure 7 shows the temperature differences between the analyses with RO data for REF or BND and without RO data for GTS at the initial time (i.e., 0000 UTC 2 July). The differences exhibit similar patterns for both REF and BND (Figs. 7a–d). Generally, RO assimilations produce lower temperature and

FIG. 7. (a) Difference of temperature (shaded colors; K) at 500 hPa between REF and GTS after the first DA cycle. (b) As in (a), but between BND and GTS. (c),(d) As in (a) and (b), respectively, but at 850 hPa. (e),(f) As in (c) and (d), respectively, but for specific humidity (shaded colors; g kg^{-1}). The dot points indicate the locations of RO observations.

higher moisture relative to that without RO assimilation for GTS over the WNP. The magnitudes of the differences are comparable for BND and REF, except that REF gives slightly larger negative temperature differences over the northeast corner of Fig. 7a, but less than 0.5 K. Specific humidity differences with and without RO data assimilation show a maximum range of about $\pm 1.2 \text{ g kg}^{-1}$. In general, REF and BND provide

similar impacts on temperature and moisture analyses at the initial time. The differences after a few cycling assimilations with RO data will also contain the contribution from the model forecasts during the DA time window.

After 2-day cycling assimilation, the differences averaged in the two days are shown in Fig. 8. The differences are produced without general resemblance of the data impacts to the RO

FIG. 8. As in Fig. 7, but for the averaged differences of all DA cycles. The black dashed circle is the moister region for BND that the cyclonic flow of Nepartak passes through.

observation positions as seen in Fig. 7, due to the accumulated contributions from the model forecasts that use the DA analysis at each cycle. Note that the center of Nepartak is located near 11.8°N , 142.0°E at 0000 UTC 4 July (the end of the cycling DA), which is consistent with positive time-averaged temperature differences for both REF and BND at mid- and lower troposphere (500 and 850 hPa) (Figs. 8a–d). BND provides a warmer environment near the storm than REF, relative to

GTS. At 850 hPa, both REF and BND exhibit a closer pattern of the differences in specific humidity, but the latter significantly more moistens the southwestern part of the subtropical high that the cyclonic flow of Nepartak passes through (Figs. 8e,f).

b. Typhoon track

All the experiments (GTS, REF, and BND) were conducted by MPAS for simulation of 5 days. Figure 9a shows that all the

FIG. 9. (a) The best track from CWB (black dot) and MPAS simulated tracks for NODA (gray circle), GTS (green inverted-triangle), REF (blue square), and BND (red triangle). The region of a dashed square is zoomed as shown at the upper-right corner. (b) As in (a), but the tracks during 5–7 Jul. All the tracks are marked by the symbols at an interval of 6 h.

simulated typhoons have consistent northwestward tracks in good agreement with the best track. Only the simulation without data assimilation (NODA) exhibits a southward deviation after the 18-h forecast, then followed by a northwestward deflection after 0000 UTC 7 July. In spite of similar typhoon movements, there are some small differences in the tracks. Figure 9b shows all the simulated tracks during 5–7 July for NODA, GTS, REF, and BND when Nepartak is approaching the most intense stage. Clearly, NODA has the slowest movement at the early stage, and the other experiments present comparable moving speeds. The simulated typhoon translation for GTS increases at a faster speed than BND and REF at later times, which is further away from the best track. In general, BND gives the best track prediction as seen in Fig. 9b. The improvement of the BND track before

landfall is mainly attributed to the simulated typhoon movement, which will be discussed later.

The above three experiments show reasonable track prediction consistent with the best track before landfall at Taiwan, (Fig. 10a), while BND performs the best, followed by REF and then GTS. The track for BND gives a maximum error less than 80 km in 72 h before landfall, while NODA has a larger departure from the best track in the first 60-h forecast (Fig. 10a) due to the southward track deviation (see Fig. 9a). The observed deepening of the typhoon has been captured before 30 h as seen in the central sea level pressure (CSLP) (Fig. 10b) for all the three experiments (GTS, REF and BND), but all the CSLPs becomes filled afterward unlike the observed rapid intensification down to about 905 hPa. Use of enhanced 3-km resolution in the region of the storm path can somewhat further

FIG. 10. (a) The track errors for NODA (gray dash), GTS (green), REF (blue), and BND (red). (b) As in (a), but for the simulated typhoon intensities and the best track data (in black).

deepen the CSLP at later stages as shown later. Additional RO data assimilation in REF or BND does not exhibit a significant impact on typhoon intensity. This can be attributed to the fact that the RO data assimilation only slightly modifies the thermodynamic variables and in turn has weak effects on the wind structure of the typhoon. Other factors, e.g., physical uncertainty, may also play an important role in the development of typhoon intensity.

c. Verification of typhoon prediction

The synoptic conditions after 2-day cycling assimilation for GTS, REF and BND show similar patterns (Figs. 11b–d). The westward and southward extent of the subtropical high, the location of the typhoon center, and typhoon intensity for the three experiments agree well with the NCEP global analysis at the initial time (Fig. 11a). The southern flank of the subtropical high that provides the steering flow is a major factor controlling the simulated typhoon tracks, as explained in Chen et al. (2015) for the RO data impact on the simulated tracks of 11 typhoons over the WNP in 2008–10. Although the root-mean-square errors (RMSEs) of temperature and moisture from the verification exhibit similar vertical variations for the three experiments (Figs. 11e,f), their magnitudes are further reduced when assimilation with additional RO data has been conducted in REF and BND. For example, smaller RMSEs are present for potential temperature above 600 hPa and specific humidity in the whole vertical layer (Figs. 11e,f). Clearly, the

RO data assimilation provides better initial conditions for REF and BND and thus improves their typhoon simulations.

The small differences in the initial analyses for the three experiments can be amplified with time in the later forecasts as shown in Fig. 12. At 0000 UTC 7 July, the NCEP global analysis shows an intense typhoon southeast of Taiwan, but with the enhanced flow at the northeast quadrant of the outer typhoon (Fig. 12a). The intense typhoon is well simulated as RO data are assimilated, while the outer enhanced flow is nearly missing for GTS and REF or somewhat weakened for BND (Figs. 12c–e). For NODA, the typhoon vortex core is larger but weaker than the other experiments and additional enhanced flow is present southeast of the outer typhoon (Fig. 12b). This enhanced flow is associated with larger northward pressure gradients that push the simulated typhoon more northward as compared to the other experiments. We note that the simulated flow for BND is relatively stronger but closest to the NCEP analysis in the region of 10° – 20° N and 120° – 130° E. Comparing the flow differences between BND and REF, we found that BND has stronger wind than REF around the typhoon center, and BND has more northward wind near the Luzon island which could push the vortex in BND to move northward (Fig. 12f). Consequently, BND exhibits a more northward track after 7 July closer to the best track (Fig. 9a).

Figure 13 shows the infrared satellite image from *Himawari-8* and the simulated outgoing longwave radiation fluxes for GTS, REF, and BND at 0300 UTC 6 July 2016 when Nepartak has developed to a category 5 typhoon. Since the longwave radiation is proportional to the temperature, lower longwave radiation will indicate lower temperature associated with overshooting of stronger convective updrafts. At this time, the observed typhoon has reached an intensity of about 910 hPa with a clear eye, intense eyewall and spiral cloud bands, all well depicted by the outgoing longwave radiation fluxes of the three simulations. All simulated eyes appear to be somewhat larger than the observed, due to use of 15-km resolution. BND gives lower outgoing longwave radiation fluxes at cloud top (in denser white) over the southern quadrant of the typhoon as a result of deeper convection as well as over the northwest quadrant of the outer typhoon (Fig. 13d), in consistence with the enhanced flow in Fig. 12. The stronger convection associated with BND is responsible for the generated more intense latent heating to influence the vortex motion in relation to the PV tendency budget, which will be discussed later.

For comparing the performances of the simulations with and without RO data assimilation, the simulation results are verified against the NCEP global analysis. A region of 10° – 30° N and 120° – 140° (indicated by the black box in Fig. 6) covering the typhoon circulation is chosen for the verification on all vertical layers. Figure 14 shows the RMSEs in potential temperature, specific humidity and horizontal wind in the verification region. After 60-h forecast (1200 UTC 6 July), the RMSEs largely increase as compared to the initial RMSEs (0000 UTC 4 July) (Fig. 14 versus Figs. 11e,f). Note that the differences of the RMSEs among the three experiments greatly increase with time. Consequently, BND gives the least RMSEs

FIG. 11. Geopotential height (contours; gpm), wind speed (shaded; m s^{-1}), and wind vectors at 850 hPa at 0000 UTC 4 Jul for (a) NCEP analysis, (b) GTS, (c) REF, and (d) BND. The RMS errors of the initial conditions after the DA stage verified against the NCEP analysis for (e) potential temperature (K) and (f) specific humidity (g kg^{-1}).

in temperature and horizontal wind, but with comparable RMSEs in specific humidity. In general, BND performs better than REF, and both are considerably better than GTS. The verification with better improved RMSEs in this region for BND than REF coincides with the larger similarity of the former with the NCEP analysis in Fig. 12.

Although NCEP global analysis has assimilated the RO soundings during the time of cycling DA, the RO data after the forecast time are not assimilated and thus can provide independent observation soundings used for verification. At the verification time of 1200 UTC 6 July, the GNSS RO data, consisting of FORMOSAT-3/COSMIC, MetOp-A and MetOp-B

FIG. 12. Geopotential height (contours), wind speed (shaded; m s^{-1}), and wind vectors at 850 hPa at 0000 UTC 7 Jul 2016 for (a) NCEP analysis, (b) NODA, (c) GTS, (d) REF, (e) BND, and (f) BND-REF. Contour intervals are 10 gpm, except for 20 gpm for (f).

FIG. 13. (a) Infrared satellite image from *Himawari-8*, and the simulated outgoing longwave radiation flux (W m^{-2}) at 0300 UTC 6 Jul 2016 for (b) GTS, (c) REF, and (d) BND.

above 8 km, *TerraSAR-X*, and *TanDEM-X*, are available over the WNP for the verification of the model forecasts. The GNSS RO soundings used for the verification on temperature and moisture forecasts are obtained from CDAAC postprocess, which are derived through the 1DVAR retrieval with the first guess from the ERA-Interim reanalysis. For having more RO data amounts for the verification, a larger area than that used for the previous verification with the NCEP analysis (Fig. 14) is adopted as shown in Fig. 15a. There are 33 RO soundings available in the verification region during the time window of ± 3 h at 1200 UTC 6 July. The forecasts are interpolated to the RO locations for the comparison. Figures 15b and 15c show the verification results for temperature and water vapor mixing ratio, respectively. Generally, BND presents smaller mean differences with the

RO observations for both temperature and moisture above 5–6 km than both REF and GTS. REF also gives improved temperature prediction than GTS (Figs. 15b,c), but with a large degradation near the surface.

The previous comparison with the observed satellite imagery has shown the best performance of BND for the cloud convection associated with the northwestward moving typhoon. It is particularly concerned about whether the rainfall forecast over Taiwan may be improved by RO data assimilation. Figure 16 shows the 24-h accumulated rainfall over Taiwan on 8 July during pre-landfall for the experiments of NODA, GTS, REF, and BND. Heavy rainfall with data assimilation is produced mainly over east Taiwan along the mountain, while NODA significantly overpredicts the northeastern rainfall and underpredicts the central rainfall

FIG. 14. The RMS errors of the model forecast for the experiments GTS (green), REF (blue), and BND (red) verified against the NCEP analysis for (a) potential temperature (K), (b) specific humidity (g kg^{-1}), (c) east-west wind component (u), and (d) north-south wind component (v), at 1200 UTC 6 Jul 2016.

along the east slope. Clearly, the along-slope rainfall in BND agrees best with the observed in terms of magnitude and position. The intense rainfall is produced more southward and is further overpredicted for both GTS and REF. The rainfall east of the central Taiwan for BND is more consistent and can be attributed to the improved typhoon track before landfall that is slightly more northward than REF.

d. Potential vorticity diagnostic for typhoon track

It is evident in Fig. 9b that the improvement of the simulated track with RO assimilation is mainly attributed to the typhoon movement. The different typhoon translational speeds can be explained by diagnostics of the potential vorticity (PV) tendency budget. The PV tendency budget has been demonstrated as a useful tool to quantify the typhoon movement (Wu and Wang 2000). Use of asymmetrical wavenumber-1 (WN-1) PV tendency is capable of explaining the TC translation (e.g., Chan et al. 2002; Li and Huang 2018; Huang et al. 2019). We use the same WN-1 PV tendency budget diagnostics (Huang et al. 2019) to quantify the contribution of each PV tendency

budget term for the impact of RO data assimilation. The PV tendency budget term is averaged in 1–8-km height and within the 200-km radius of the typhoon center for diagnostics of the regressed translation velocity. Figure 17 shows that the net WN-1 PV tendency budget contributes a northwestward translation in GTS, but a westward translation in BND, in consistency with their tracks shown in Fig. 9. Vertical PV advection is much weaker with induced smaller typhoon translation and is not shown in Fig. 17. The net PV tendency budget indicates a primary direction closely following the major WN-1 flow direction in the vicinity of the typhoon vortex. PV horizontal advection indeed dominates the PV tendency budget to significantly dictate the typhoon translation (Figs. 17b,e) for both GTS and BND, which is, however, somewhat modified by the effect of differential diabatic heating (Figs. 17c,f). The translation velocity induced by the diabatic heating term is southward for BND and is westward for GTS. The induced southward translation from the diabatic heating term for BND is coincident with the more dominant convection south of the typhoon center (see Fig. 13d). This may explain why the moving

FIG. 15. (a) The horizontal distribution of GNSS RO soundings (red dots) at 1200 UTC 6 Jul 2016. (b),(c) The mean differences between the GNSS RO soundings and model forecasts for the experiments GTS (green), REF (blue), and BND (red) for temperature (K) and water vapor mixing ratio (g kg^{-1}), respectively, at 1200 UTC 6 Jul 2016. The dot-dashed line indicates the accumulated RO data amount.

speed of the typhoon is slower and closer to the best track for BND (at 5.52 m s^{-1}) compared to GTS (at 9.19 m s^{-1}).

e. Simulations with 60–15–3-km resolution

The simulated typhoon intensities with 60–15-km resolution are weaker than the best track intensity (Fig. 10b). As the resolution of 15 km is increased to 3 km in the region of storm path, the track errors in the simulations with 60–15–3-km resolution are slightly reduced before landfall without the southward track deviation of the lower-resolution run as shown in Figs. 18a and 18b. Also, all GTS, REF, and BND with the higher resolution show improvements on track forecast compared to their lower resolution runs. The first 72-h average track errors with the higher resolution are given in Table 2. The track error for BND is only 43 km in 72 h with a reduction of 36 km compared to GTS, which signifies the great impacts of RO data assimilation. As indicated in Table 2, BND performs slightly better than REF for track forecast with the higher resolution. The typhoon intensity has also been somewhat improved with the 60–15–3-km resolution for the three experiments, GTS, REF, and BND (Fig. 18c). Although GTS has a comparable performance for typhoon intensity prediction, its track forecast (without the RO data assimilation) before landfall is much worse than both REF and BND.

f. Two other typhoon cases

Besides Typhoon Nepartak, two other typhoons, Soudelor (2015) and Megi (2016) with similar tracks approaching Taiwan, are also investigated. The MPAS configurations and physics schemes are the same as used for Nepartak. For track prediction, the multiresolution of 60–15 km is employed. The initial times of the MPAS forecast are 0000 UTC 5 August 2015 and 0000 UTC 24 September 2016 for Soudelor and Megi, respectively. Assimilations with and without RO bending angle are conducted for both typhoons. Compared to the best track, both GTS and BND predict a southward deflection but with comparable translation (Fig. 19a) for Soudelor. However, BND gives a slightly northward track than GTS in the first three days that is closer to the best track. Consequently, smaller track errors are obtained for BND than GTS (Fig. 19b), especially before 72 h. For Megi, both GTS and BND predict west-northwestward but slightly northward deflected tracks in the earlier days compared to the best track. The northward track deflection after the first day, however, is larger in GTS compared to BND. Megi passed through the central Taiwan on 27 September, but both GTS and BND predict a landfall at the southern tip of Taiwan. Despite the southward deviation at later times, BND gives a better performance in track prediction than GTS, with a large error reduction of about 50–100 km in 25–28 September (Figs. 19c,d).

4. Conclusions

GNSS RO data largely complement the observations over the ocean and may help on initial analysis for typhoon forecasts. In this study, we employ a GSI assimilation system at the

FIG. 16. The 24-h accumulated rainfall (mm) during 0000 UTC 7–8 Jul 2016 for (a) CWB observation, (b) NODA, (c) GTS, (d) REF, and (e) BND. Location and amount of the maximum rainfall (mm) in the panels are indicated at bottom right.

CWB to assimilate the GNSS RO data and the global MPAS model to simulate Typhoon Nepartak that passed over southern Taiwan in 2016. At relatively coarse resolution, the GSI is a hybrid scheme based on weighted background error

covariances of 3DVAR and EnKF, where a static (climatological) background error covariance is used for the former and a flow-dependent background error covariance is updated with 36 ensemble members for the latter in each DA cycle in

FIG. 17. Wavenumber-1 (WN-1) PV tendency budget (shaped colors) averaged in 1–8-km height at 2100 UTC 6 Jul 2016 for GTS for (a) net PV budget, (b) PV horizontal advection, and (c) differential diabatic heating with the overlaid WN-1 horizontal flow (vectors). (d)–(f) As in (a)–(c), but for BND. PV tendency is in units of 10^{-5} PVU. The regressed typhoon translation velocity (m s^{-1}) is indicated by the vector at the typhoon center with the magnitude given at the top of each panel. A reference wind vector (m s^{-1}) is given in the bottom right for the WN-1 flow.

FIG. 18. (a) The CWB best track (black dot) and the 60–15–3-km MPAS tracks for (gray circle), GTS_H (green inverted triangle), REF_H (blue square), and BND_H (red triangle) and the 60–15-km MPAS track for BND (dark dashed red). (b) As in (a), but for track errors. (c) As in (b), but for the central sea level pressure (hPa).

this study. Performances of RO refractivity operator and bending-angle operator are compared for the assimilation analysis and typhoon forecast. In this study, use of the multiresolution MPAS facilitates a high resolution of 15 km over the region of Asia and the WNP and the enhanced resolution of 3 km in the region of the storm path for the typhoon forecast.

Temperature and specific humidity increments are reasonably produced after the cycling DA at the initial time in the experiments REF and BND with RO refractivity and bending-angle assimilation, respectively. Although the increments are similar and comparable for both REF and BND,

TABLE 2. The 3-day mean track errors (km) during 0000 UTC 4–7 Jul 2016 for Typhoon Nepartak.

Case (60–15 km)	Track error (km)	Case (60– 15–3 km)	Track error (km)
GTS	90.2	GTS_H	79.1
REF	73.5	REF_H	53.8
BND	49.0	BND_H	43.1

their differences significantly increase with time and have led to different impacts on the typhoon track and intensity forecasts. The typhoon track prediction is greatly improved when the GNSS RO data are assimilated. BND gives the best performance with a 72-h average track error less than 50 km, followed by REF and then GTS. Verifications against NCEP analysis and GNSS RO soundings support the improved forecasts as RO data have been assimilated. Since the first guess used in the RO retrieval has applied the ERA-Interim reanalysis that already assimilates RO bending angle data, the forecast verification may lean a little bit on the forecast with bending angle assimilation rather than refractivity assimilation. It is also true for the forecast verification against NCEP analysis that operationally assimilates RO bending angle. The RMS errors of temperature and horizontal wind verified against the NCEP global analysis at the typhoon intensification stage for GTS are considerably reduced by RO data assimilation in both BND and REF. In general, BND outperforms REF, particularly for the wind forecast, due to the improved temperature forecast above 600 hPa.

It was found that the track errors are most reduced in the typhoon translation speed for BND, which can be explained by the WN-1 PV tendency budget. With more intense convection south of the typhoon center for BND, the typhoon translation induced by the differential diabatic heating is mainly southward to slow down the dominant translation induced by PV horizontal advection that essentially drives the typhoon northwestward. Use of the enhanced 3-km resolution in the region of the storm path somewhat improves the typhoon intensity prediction and further reduces the track errors of GTS for both RO assimilation experiments (REF and BND). Positive RO data impacts on typhoon track prediction with the multiresolution MPAS are also shown for Soudelor (2015) and Megi (2016) with similar tracks toward Taiwan.

The beneficial impacts of GNSS RO data on the typhoon forecast are explored with the GSI hybrid assimilation and a global multiresolution model in this study. This study, not pursued for a new RO impact, has illustrated a new test bed that allows for integrating the advantage of fully operational GSI with the multiple-resolution global model for general typhoon forecasts. Since FORMOSAT-7/COSMIC-2 RO data (up to 5000 daily soundings) have formally been released in early 2020, we plan to assimilate these plentiful RO data to explore their impacts on forecasts of the typhoons over the WNP. Use of the multiresolution MPAS for control forecast in the cycling DA is

FIG. 19. (a) The CWB best track (black dot) and the MPAS forecast tracks with multiresolution of 60–15 km for GTS (blue inverted-triangle), and BND (red circle) for Typhoon Soudelor (2015). (b) As in (a), but for track errors. (c),(d) As in (a) and (b), respectively, but for Typhoon Megi (2016).

also under testing, and the results will be presented in another paper.

Acknowledgments. This research was supported jointly by the Ministry of Science and Technology (MOST) and National Space Organization (NSPO) in Taiwan. The authors thank Dr. J.-H. Chen at CWB for support of computational resources.

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