The Effects of Typhoon Initialization and Dropwindsonde Data Assimilation on Direct and Indirect Heavy Rainfall Simulation in WRF model

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Abstract: A number of heavy rainfall events on the Korean Peninsula are indirectly influenced by tropical cyclones (TCs) when they are located in southeastern China. In this study, a heavy rainfall case in the middle Korean region is selected to examine the influence of typhoon simulation performance on predictability of remote rainfall over Korea as well as direct rainfall over Taiwan. Four different numerical experiments are conducted using Weather Research and Forecasting (WRF) model, toggling on and off two different improvements on typhoon in the model initial condition (IC), which are TC bogussing initialization and dropwindsonde observation data assimilation (DA). The Geophysical Fluid Dynamics Laboratory TC initialization algorithm is implemented to generate the bogused vortex instead of the initial typhoon, while the airborne observation obtained from dropwindsonde is applied by WRF Three-dimensional variational data assimilation. Results show that use of both TC initialization and DA improves predictability of TC track as well as rainfall over Korea and Taiwan. Without any of IC improvement usage, the intensity of TC is underestimated during the simulation. Using TC initialization alone improves simulation of direct rainfall but not of indirect rainfall, while using DA alone has a negative impact on the TC track forecast. This study confirms that the well-suited TC simulation over southeastern China improves remote rainfall predictability over Korea as well as TC direct rainfall over Taiwan.

Keywords: heavy rainfall, typhoon bogussing initialization, dropwindsonde observation, numerical simulation, data assimilation

Introduction

Tropical cyclones (TCs) often lead remote heavy rainfall in distant area, forming indirect effect (Wang et al., 2009; Galarneau et al., 2010; Hirata and Kawamura, 2014). In the Korean region, the indirect TC effect occurs when a TC is landed at southern China (e.g., Hwang et al., 2010; Byun and Lee, 2012). It provides warm and humid air into the Korean region, supporting favorable condition for the heavy rainfall by increasing instability of low-level atmosphere. Lee (1993) argued that the low-level jet (LLJ) transports heat and moisture to the Korean region from TCs landed in southern China, increasing convective instability and expediting precipitation process over Korea. Kim (2004) found that about 70 percent of extreme heavy rainfall cases in the 1980s and the 1990s excluding those directly influenced by TCs were formed when a TC located in southern China region. Studies of Kim (2004) and Jung (2013) argued that intensity of dissipating TC in southern China influences spatial and temporal distribution of heavy rainfall over Korea. Byun and Lee (2012) remarked importance of upper level jet strike and its secondary circulation to propagate indirect effects of TCs toward remote rainfall region such as Korea.

Appropriate TC simulation is important to improve predictability of those remote rain events in numerical prediction, which definitely needs an accurate initial condition. However, TCs described in global analysis have large uncertainties due to deficient observation over the ocean where TCs stay at their beginning
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Stage. Furthermore, coarse resolution of analysis limits presenting realistic intensity of TCs by smoothing meteorological variables such as central pressure and wind speed. Operational centers therefore have employed special treatments for model initial condition for TCs, namely TC initialization, which is also known as bogussing vortex process (e.g., Kurihara et al., 1993; Leslie and Holland, 1995; Ueno, 1995). This approach artificially modifies the smoothed TC to more realistic one based on empirical formulas. Numerous studies have reported that the TC bogussing improves performance of TC track and intensity forecasts in their numerical models (e.g., Kwon et al., 2002; Zhao et al., 2007; Lee and Choi, 2010; Nguyen and Chen, 2011).

When the Korean region is suffering from indirectly induced heavy rainfall by a TC, the Taiwan region usually suffers from direct effect of the TC (e.g., Chen and Chen, 2003; Su et al., 2012). To overcome deficit of accurate observation over the ocean where TCs stay in their beginning stage, international communities launched a target observation project for TCs, namely Drowindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR) program (Wu et al., 2005). This project has sent aircrafts to observe vertical structure of TCs using dropwindsondes when TCs are approaching. Numerous studies have conducted to see impact of data assimilation of this data (Kim et al., 2010; Chou et al., 2011; Weissmann et al., 2011; Jung et al., 2013); however, their main focuses were on improvement of track and intensity prediction of TC, whereas indirect effects of data assimilation (DA) on remote regions are rarely investigated.

The objective of this study is to examine indirect influence of typhoon simulation on remote rainfall predictability over Korea. Using a mesoscale numerical

Fig. 1. Surface weather charts at (a) 00 UTC 11, (b) 00 UTC 12, and (c) 00 UTC 13 July 2006.
model with toggling two different improvements for the typhoon, which are TC bogussing initialization and dropwindsonde DA. This article is organized as follow: Following section describes selected heavy rainfall case in this study by analyzing observation datasets. Second following section describes a setup for experiments and their results are described in third following section. Conclusion appears in the final section.

Case Description

Selected case for this study is a heavy rainfall event occurred at 12 July 2006 over Korea, with record-breaking daily precipitation of 399.0 mm. Mesoscale convective systems (MCSs) were developed along the “Changma” front located across the Korean peninsula. Typhoon “Bilis” was located at over western Pacific Ocean moving toward Taiwan.

Figure 1 shows surface weather charts analyzed by Korea Meteorological Administration (KMA). At 00 UTC 11 July (Fig. 1a), there was a southwesterly flow toward the Korean peninsula between the Northwestern Pacific high and the continental low in northeastern part of China. A migratory low pressure system was located over East Sea with a stationary front at the southwestern part of the system. The stationary front stayed along the south coast of the Korean peninsula, which was considered as a “Changma” front. Typhoon “Bilis” was located at the southeast of Taiwan recording 990 hPa for central pressure. At 00 UTC 12 July (Fig. 1b), the southwesterly flow toward Korea was remaining and the “Changma” front moved to the middle of the Korean peninsula. The low pressure system moved to the northeastern part of East Sea. Typhoon “Bilis” moved to northwest, approaching Taiwan with intensified central pressure as 975 hPa. At 00 UTC 13 July (Fig. 1c), the southwesterly flow near Korea and “Changma” front were remaining at their previous location while the low pressure system moved to the west. Typhoon “Bilis” approached nearby Taiwan dropping its central pressure to 970 hPa.

Aforementioned synoptic condition provides favorable condition to perform a significant heavy precipitation in Korea (Hong and Lee, 2009). The satellite observation captures rainfall band over Korea as well as rainfall directly induced by the typhoon over the Western Pacific (Fig. 2a). Here, the observed precipitation field is obtained from Tropical Rainfall Measuring Mission (TRMM) 3B42 dataset (Huffman et al., 2007). Considering fundamental limitations of satellite observation, it is obvious that rain gauges observes more reasonable quantities if they exist over
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In the middle of Korea, rain gauge measurement included in Automatic Weather Station system of KMA records local maximum rainfall amount of 399.0 mm, which caused flash floods in that region (Fig. 2b). For about a detailed structure and an evolution of the heavy rainfall, study of Hong and Lee (2009) provides referential further analyses and descriptions.

In the meantime, Taiwan region experienced massive rainfall amount by the direct influence of the typhoon. At July 11, southern inland orograph regions received rainfall more than 90 mm at local maximum points (Fig. 3a). The rainfall is concentrated on northern Taiwan at July 12 with incoming easterly flow induced by the approaching typhoon (see Figs. 1b and 3b). At July 13, Taiwan area experienced heavy rainfall exceeding 300 mm when the area is located within the sphere of TC influence (see Figs. 1c and 3c). Taiwan precipitation is tending to be strengthened by the steep topography in that region (Fig. 4).

**Experimental Setup**

Numerical experiments are conducted using Weather Research and Forecasting (WRF) model (Skamarock et al., 2005), which has a fully compressible non-hydrostatic dynamics on Arakawa-C grid system. The physics packages include WRF Single-Moment 6-Class (WSM6) microphysics (Hong and Lim, 2006), new Kain-Fritsch cumulus parameterization (Kain, 2004), Yonsei University planetary boundary layer (YSU-PBL; Hong et al., 2006), a simple cloud-interactive radiation scheme (Dudhia, 1989), and Rapid Radiative Transfer Model longwave radiation scheme (Mlawer et al., 1997).

The model configuration includes nested domains on Lambert conformal map projection (Fig. 4). Domain 1 covers East Asian and Western Pacific...
region with 48-km resolution 90 (east-west)×90 (north-south) grids. There are two second tier domains using 12-km resolution at different regions; around Korea region is covered by two-way interactive Domain 2a with 97×97 grids while one-way interactive Domain 2b covers around Taiwan using 61×61 grids. In Domain 2a, a two-way interactive high resolution domain, Domain 3, covers the Korean peninsula with 3-km distance 205×205 grids. All domains have 28 vertical layers using a terrain following sigma coordinate and model top is at 50 hPa. Cumulus parameterization is turned off at Domain 3 simulation, assuming it is explicitly calculated with this fine resolution. Initial and boundary conditions are derived from the National Centers for Environmental Prediction (NCEP) Final Analysis (FNL), which has 1×1 horizontal resolution. Model simulations are carried out for 36 hours starting from 12 UTC 11 July 2006.

To examine impact of TC bogussing and drop-windsonde DA, four different simulations are designed as listed in Table 1. Control (CTL) experiment uses NCEP FNL data for a model initial condition without employing any improvement on typhoon description.

**Table 1.** List of numerical experiments. Second and third column indicate whether TC initialization algorithm (i.e. bogussing) and drop-windsonde data assimilation (DA) is employed or not in each experiment

<table>
<thead>
<tr>
<th>Experiment Name</th>
<th>TC bogussing</th>
<th>Dropwindsonde DA</th>
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<tbody>
<tr>
<td>CTL</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>BOG</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>DOT</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>BOG+DOT</td>
<td>Yes</td>
<td>Yes</td>
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BOG experiment replaces typhoon in the FNL-given initial field to bogused vortex generated by the TC initialization algorithm. DOT experiment assimilates dropwindsonde data observed at 12 UTC 11 July 2006 as a part of DOTSTAR project, using WRF Three-dimensional variational data assimilation (3D-VAR) program package (Barker et al. 2004). BOG+DOT experiment employs both TC bogussing and dropwindsonde DA, but replacing to bogused vortex is limited within 200 km radius from TC center to avoid interfering impact of the dropwindsonde DA. Detailed descriptions for TC initialization and DOTSTAR are given in following subsections.

**a. TC initialization algorithm:** The Geophysical Fluid Dynamics Laboratory (GFDL) TC initialization algorithm (Kurihara et al. 1995) is implemented in the WRF Model to generate the bogused vortex. The GFDL hurricane prediction model has a sophisticated TC initialization procedure (Kurihara et al. 1995). The analysis fields are decomposed into basic and disturbance fields by scale consideration. A bogus region is carefully determined using a disturbance wind field at 850-hPa. The wind field is re-initialized using empirical formulas within a filter region surrounded by 24 boundary points. A replacing wind field is constructed by including the non-hurricane component and observations as well as the beta gyre. The generated target wind forces generating axisymmetric components at other levels (Kurihara et al., 1997). One of major difficulties in TC initialization lies in generation of secondary information depending refined wind field, such as humidity, temperature, geo-potential height, etc. Those variables should be dynamically and physically consistent to the replacing wind field. The
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original GFDL algorithm uses empirical axisymmetric formulas to generate the other variables. To reduce unbalancing between wind and other fields, Kwon et al. (2002) employed Four Dimensional Data Assimilation (FDDA) approach and minimized shock caused from unbalanced initial condition. Their methodology is keeping nudging the replacing wind field during the model simulation, thus adjust other fields to the given wind field. In this study, the GFDL algorithm is employed to generate the wind of the bogus vortex.
(Fig. 5) and 24-hr FDDA simulation is conducted to have balanced initial condition. As a last step, original typhoon in the initial field is replaced to the bogus vortex given from FDDA simulation. This approach was implemented to WRF model by Lee (2008), and has been used for researches (e.g., Shin and Hong, 2009; Jung, 2013) and the operational real-time numerical typhoon prediction system of Republic of Korea Air Force (Lee et al., 2010).

b. Dropwindsonde Observation-DOTSTAR: An observation campaign, Drowindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR) project, was started from 2003 for TCs surveillance and targeted observations in the western North Pacific using Global Positioning System (GPS) dropwindsondes (Wu et al., 2005). DOTSTAR is a collaboration project between researchers from National Taiwan University (NTU) and Central Weather Bureau (CWB), in partnership with scientists at Hurricane Research Division (HRD) and NCEP, both part of the National Oceanographic and Atmospheric Administration (NOAA), built upon work pioneered by HRD to improve tropical cyclone track forecasts. To maximize the use of the DOTSTAR data, the dropwindsonde soundings are transmitted and assimilated in real time into the numerical models of CWB, NCEP, the U.S. Navy’s Fleet Numerical Meteorology and Oceanography Center (FNMOC), and the Japanese Meteorological Agency (JMA). The dropwindsondes are thrown from the airplane which basically flights the most sensitive region around the TC, the area with the largest deep-layer-mean wind bred vectors from the NCEP Global Forecasting System ensemble (Aberson, 2003). Typhoon “Bilis” was observed at 12 UTC 11 July 2006 by dropwindsondes as a part of DOTSTAR program (Fig. 6).

Results

Figure 7 shows sea-level pressure (SLP) fields at 12 UTC 11 July 2006, model initial time. The CTL experiment captures location of the typhoon “Bilis” at the southeast of Taiwan, but its center is smoothed and weakened compared to the observation (cf. Figs. 1c and 7a). In all other experiments, SLP fields show intensified TC near its center region (Figs. 7b to 7d), while DOT experiment shows decreased wind speed at outer TC center region (Fig. 7c).

Figure 8 shows tracks of the typhoon obtained from observation and simulations. The best track was given from the Regional Specialized Meteorological Center (RSMC) Tokyo-Typhoon Center while simulated tracks are extracted by simply finding minimal sea-level pressure location at each time interval. There are
several different elaborate ways to pick the TC center, such as using maximum potential vorticity and/or tangential wind (e.g., Nguyen et al., 2014), but they are not discovered in this paper. Compared to the best track, every simulations show northward shifted TC position at first 6 hour (Fig. 8a). TC tracks obtained from BOG and BOG+DOT results follow the best track after then, whereas CTL and DOT results keep describing shifted track. DOT experiment shows expedited TC moving speed causing largest position error as 163.6 km than any other results (Fig. 8b).

Decreased initial wind speed at TC outer region may contribute to this outrunning and excess turning of the TC track (cf. Figs. 7c and 8a). BOG+DOT experiment shows smallest position error among simulations as 42.6 km (Fig. 8b).

Figure 8c shows observed and simulated time series of typhoon central pressure. The bogussing algorithm reduces the central pressure at the initial time and all experiments excluding CTL simulate over-intensified TC center pressure. Intensifying trends are similar in all experiments, which are larger than that observed.
This result is consistent with previous studies those argue that impact of ocean surface cooling, caused by ocean mixing due to typhoon’s strong low level wind, should be considered in simulations to avoid typhoon gaining excessive energy from prescribed and/or warm biased sea-surface temperature (e.g., Bender and Ginis, 2000; Jeong et al., 2013).

Figure 9 shows zonal vertical sections which crossing simulated TC center locations at first 6 hour obtained from each experiment (see Fig. 8a). All experiments show vertically developed TC structures with typhoon eyes. CTL result shows lower top and weaker low level wind than those from the other experiments (Fig. 9a) while DOT experiment shows larger top and stronger low level wind than those from the other experiments (Fig. 9c). This strongest structure corresponds to shifted track and over speeded movement of TC in the DOT result (cf., Fig. 8a). This negative impact is corresponding to previous studies those pointed out that insufficient description of TC’s vertical structure at the very center of the TC—because observations are conducted around the TC region—could obstruct taking advantage of dropwindsonde DA (Aberson, 2008; Weissmann et al., 2011; Jung et al., 2013). BOG and BOG+DOT experiments show similar heights of TC, but low level wind is slightly stronger and relative humidity field show cleared TC eye in BOG+DOT experiment than those from the BOG experiment (Figs. 9b and 9d).

Figure 10 shows accumulated rainfall during simulations at Domain 1. All experiments simulate comparable spatial distribution of precipitation bands over Taiwan and Korea, which are directly and indirectly influenced by typhoon “Bilis”, respectively, except for DOT.
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experiment (cf. Figs. 2a and 10). Precipitation in DOT experiment is closer to Taiwan region than those from the other experiments. BOG and BOG+DOT experiments show stronger rainfall intensity at inner TC region than CTL result. When magnifying each rainfall region, detailed distribution shows clear differences among experiments.

Figures 11 and 12 show detailed characteristics of simulated rainfalls at fine resolution domain. In Domain 2b, all experiments capture direct rainfall over Taiwan although CTL simulation underestimates rainfall amount (cf. Figs 3 and 11a). This underestimation is alleviated in BOG and BOG+DOT simulations (Figs. 11b and 11d) while DOT simulation overestimates rainfall due to false early approach of the typhoon (cf. Fig. 8a).

In the Korean region, included in Domain 3, CTL experiment captures the rain band in the middle part of the Korean peninsula although the rainfall amount is underestimated about 100 mm compared to the observation (Figs. 2b and 12a). CTL, BOG and DOT experiments show similar rainfall distribution that divided to two major parts over West Sea and the middle of Korea (Figs. 12a to 12c) while BOG+DOT experiment performs concentrated rainfall over the middle of Korea (Fig. 12d). Focusing on rainfall amount, BOG+DOT experiment shows most comparable result to the observation than any other simulations (Figs. 2b and 12).

The cause of difference in simulated rainfall amount over Korea and Taiwan can be found in Fig. 13. While the bogussing intensifies the wind speed in radius of short distance, small reduction of wind speed is shown in the northeast side of the typhoon in BOG experiment (Fig. 13a). This reduces the southerly flow into the Korean peninsula, but its impact is not
enough to make change the location of major rainfall band. However, the intensified wind field near the typhoon center increases rainfall amount in the Taiwan region by growing moist air supply. In DOT experiment, rainfall in Taiwan appears differently from the other experiments because of the over-speeded TC movement (Figs. 11a and 11c); however, there is less remarkable change in Korean region as well as in BOG experiment (Figs. 12a to 12c). In BOG+DOT experiment, differences to CTL experiment appear throughout the overall domain area (Fig. 13c). The wind speed at inner TC region is stronger than that in BOG experiment, which is contributing to increase of Taiwan rainfall amount. Furthermore, the southerly flow into the Korean peninsula is also intensified contributing to increase rainfall in the Korean region.

Fig. 10. The 36 hour accumulated rainfall amount (mm) until 00UTC 13 July 2006 obtained from Domain 1 of (a) CTL, (b) BOG, (c) DOT, and (d) BOG+DOT experiments.

Conclusion

This study investigates the impact of typhoon initialization and dropwindsonde data assimilation (DA) on typhoon simulation and its indirect and direct impact on heavy rainfall over Korea and Taiwan, respectively. The WRF model adequately captured synoptic environment and distribution of rainfall over the Korean and Taiwan region even though systematic underestimation was noted for rainfall amount. To improve typhoon description in the initial field of WRF model, either or both of the GFDL TC initialization algorithm (i.e., bogusing) and dropwindsonde DA were employed.

The control simulation, without any improvements in the initial field, showed shifted typhoon track and
Weakened intensity due to the exaggerated typhoon-eye. Both TC bogussing and DA contributed describing enhanced wind and sea level pressure fields at the inner core region of the TC in the initial condition. The reproducibility of the Taiwan rainfall was improved when only TC bogussing was employed. When only DA is applied, however, TC track forecast was deteriorated. This negative impact is mainly due to deficient representation of inner-core TC structure in the model field and the DA procedure, which corresponds to results of Aberson (2008), Weissmann et al. (2011), and Jung et al. (2013). When either TC bogussing or DA was applied, there was no significant improvement for Korean heavy rainfall. Otherwise, when both of TC bogussing and DA applied, typhoon track was most improved than any other experiments; furthermore, remote rainfall simulation over Korea was enhanced by the strengthened southerly flow near the Korean region, which was connected to the TC outer flow.

The TC bogussing methodology applied in this study is based on cold start, thus hydrometeors are omitted at the initial time step and the FDDA run for balancing between different model variables requires extra calculation in addition to model simulation. To overcome these weaknesses, Cha and Wang (2013)
Ji-Woo Lee proposed new TC bogussing methodology based on model operation cycling and warm start. Furthermore, overestimated TC intensification trend expects to be moderated when ocean model is coupled with; which can consider sea surface cooling effect caused by TC wind induced ocean mixing (Bender and Ginis, 2000; Jeong et al., 2013). Although there are aforementioned limitations in this study, however, this study still remarks that proper TC description at the initial condition and its simulation can be improved by using both TC bogussing and dropwindsonde DA and it is important to predict indirect rainfall in Korea as well as direct rainfall in Taiwan.

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Fig. 13. Same as Fig. 7b to 7d, but fields are time averaged for whole simulation period.

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