Binary interaction of typhoons Soulik and Cimaron in 2018 — Part I: Observational characteristics and forecast error

Eun-Jeong Cha\textsuperscript{a}, Sug-gyeong Yun\textsuperscript{a}, Il-Ju Moon\textsuperscript{b,*}, Dong-Hoon Kim\textsuperscript{c}

\textsuperscript{a} Meso-scale Research Team, Convergence Meteorological Research Department, National Institute of Meteorological Sciences, Korea Meteorological Administration, Seogwipo, Republic of Korea

\textsuperscript{b} Typhoon Research Center, Jeju National University, Jeju, Republic of Korea

\textsuperscript{c} Artificial Intelligence Convergence Research Center, Inha University, Incheon, Republic of Korea

Available online 18 March 2021

Abstract

To understand structural changes and forecast error, a case study of binary typhoons in the western North Pacific (WNP) of 2018 was investigated using best track and reanalysis data. Soulik was generated on August 16 and Cimaron was generated on August 18, respectively. The 19th typhoon Soulik and 20th typhoon Cimaron co-existed from August 18 to 24 and approached each other. Soulik was located on the western side and Cimaron was located on the eastern side of the WNP. They were located approximately 1300 km from each other at 00 UTC August 22. The Soulik structure began changing around August 22 and became weak and slow, while Cimaron maintained its intensity, size, and moving speed. This observational evidence is likely caused by the binary interaction between two typhoons within a certain distance and environmental steering flow, such as the location of the North Pacific high and strong jet stream of the northern flank of the North Pacific high.

Soulik was initially forecasted to make landfall and reach Seoul; however, its track changed from northward to northeastward from August 21 to 23 according to both official guidance and unified model (UM). Four global numerical weather prediction models forecasted different tracks of Soulik. UM and JGSM forecasted a northward track whereas ECMWF and GFS showed a northeastward track for 12 UTC August 21 through 12 UTC August 24. The latter models were similar to the best track. The track forecast error and spread of Soulik were larger than those of Cimaron. The mean absolute error of the maximum wind speed of Soulik was similar to the average of total typhoons in 2018.

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Keywords: Typhoon; Soulik; Cimaron; Binary typhoon interaction; Structure change; Forecast track; Intensity error

1. Introduction

Tropical cyclones (TCs) have substantially influenced both human lives and socio-economic communities as an important global meteorological phenomenon.

In 2018, there were 29 named TCs in the western North Pacific (WNP) basin, which is above the 30-year climatological mean of 25.6. Five of the 29 TCs influenced the area of responsibility of the Republic of Korea (ROK). These included the 7th Prapiroon (1807), 18th Rumbia (1818), 19th Soulik (1819), 24th Trami (1824), and 25th Kong-rey (1825) typhoons from July to October. Specifically, Soulik and Kong-rey made landfall in South Korea in August and October, respectively.

At the time of initial forecast issuance, Soulik was predicted to move inland through South Korea and cause substantial damage to heavy rainfall and strong winds nationwide. Soulik was forecasted to strike Seoul, the capital and most densely populated city of ROK, and its surrounding areas in...
the early morning of Friday, August 23. The Korea Meteorological Administration (KMA) issued typhoon warnings, and central and regional authorities took precautionary actions to minimize possible damage. Schools, airports, and important facilities closed temporarily for the typhoon on August 23. However, Soulik moved slowly and along a more southward track than the forecasted direction when it passed Jeju Island. In addition, the intensity and wind radii became much lower and smaller than forecasted from August 22 to 24. Therefore, Seoul was less damaged than officially warned by authorities. Furthermore, the Cimaron (1820) was expected to pass over mainland Japan and interact with Soulik from August 21 to 23. This raised the possibility of a “Binary interaction” called the “Fujiwhara effect,” in which two or more typhoons can affect each other’s track and intensity. The unexpected motion of Soulik was likely associated with Cimaron (National Typhoon Center, 2019).

There have been many cases of two or more TCs’ coexistence within a certain time and distance in the western North Pacific (WNP) from 1951 to 2019. A total of 98 binary TCs occurred with an annual average of 1.58 (Jang and Chun, 2015a,b). The highest number of TC coexistence instances was five in both 1960 and 1985 (Cha et al., 2019).

Many observational (Brand 1970; Dong and Neumann 1983; Wu et al., 2011, Jang and Chun 2015a) and numerical (DeMaria and Chan 1984, Ritchie and Holland 1993, Shin et al., 2006, Wei-Jen Chang 1983, Falkovich et al., 1995; Khain et al., 2000; Yang et al., 2008; Wu et al., 2012, Jang and Chun 2015b) studies of multi-TC interactions have been conducted since Fujiswara’s (1921, 1923, 1931) research. The interaction of two or multiple TCs plays a critical role in changing the TCs’ structures, such as their position, intensity, and moving speed. This unusual change can cause a large forecast error for both track and intensity (Brand 1970, Jarrell et al., 1978; Neumann 1981; Prieto et al., 2003).

The purpose of this study is to investigate the observational characteristics of the Soulik and Cimaron TCs and the effects of large-scale circulations on binary TCs by using several datasets from 2018. The data and methodology used in this study are described in section 2. The structural changes of binary TCs, the influence of environmental conditions, and the validation of the forecast track and intensity for two TCs are examined in section 3. In the final section, we summarize the study and provide conclusions and avenues for further study.

2. Data and methodology

2.1. Data

The best track data from the Japan Meteorological Agency (JMA) for the WNP from 1951 to 2019 are used in this study. These data include the 6-hourly information of an individual TC, such as the date, time, location, central pressure, and maximum wind speed. To investigate the effects of the North Pacific high, the environmental steering flow, geopotential height, and zonal and meridional winds from the 6-hourly European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA5) data with a 0.25° × 0.25° resolution were used.

The daily mean sea surface temperature (SST) data from the Navy Coupled Ocean Data Assimilation (NCODA) Hybrid Coordinate Ocean Model (HYCOM) with a 1/12° horizontal resolution were used to examine the effects of SST. Because SST showed a substantial change after the passage of Soulik, high resolution data are used to provide a detailed distribution of this information. The SST is defined by averaging 0–10 m surface temperatures. Ocean heat content (OHC) data with a 0.25° × 0.25° resolution were obtained from the National Centers for Environmental Information (NCEI) and National Oceanic and Atmospheric Administration (NOAA).

2.2. Methodology

To investigate the large-scale circulations of the two studied TCs, the potential vorticity at 850 hPa, geopotential height at 500 hPa, and wind vector at 200 hPa of ECMWF in the WNP (0–60 °N, 100–180 °E) were adopted.

KMA forecasts TCs, including their position, intensity, and wind radii for the area of responsibility (AOR) four (00, 06, 12, and 18 UTC) times a day. The forecasting position and intensity against the JMA final best track as a reference in 2018. TC position error is defined as the great-circle difference between a TC’s forecast center position and the best track position. Regarding forecast intensity error, maximum wind speed, for example, is used to define the mean absolute error (MAE) of the difference between forecast and best track intensity. MAE indicates the average magnitude of the intensity error. This analysis is widely adopted in analyzing typical tracks of TCs among official weather organizations, such as the KMA, JMA, China Meteorological Administration (CMA), and Joint Typhoon Warning Center (JTWC). The difference between the maximum wind speed of the best track and the forecast maximum wind speed is calculated to analyze the features of the forecasted intensity change.

3. Result

3.1. Genesis and termination

3.1.1. Soulik

Soulik was generated at 00 UTC on August 16 over the ocean approximately 260 km northwest of Guam. It reached a maximum intensity at 950 hPa (44 m/s) at 18 UTC on August 20 and continued at 03 UTC on August 22. It then transitioned into an extratropical cyclone at 18 UTC August 24 and terminated at 06 UTC August 30. Soulik then landed near Mokpo City, on the southwestern coastline of ROK, at 14 UTC on August 23 and had a 32 m/s maximum sustained wind speed and central pressure of 975 hPa (Fig. 1, Fig. 3a). The typhoon then moved toward AOR 1 (warning area, poleward to 25°N and westward to 135°E) and AOR 2 (emergency area, poleward to 28°N and westward to 132°E) of the ROK.
KMA forecasters issued a typhoon warning into the ROK’s southernmost island of Jeju at 17 UTC on August 21 and gradually enlarged to nationwide at 18 UTC on August 23.

Soulik passed slowly through the southwestern coast of Jeju Island from August 22 to 23; at this time, the island experienced high winds and extremely heavy rainfall. During this period, 1113 mm was recorded at the Sajebi area atop Mt. Halla on Jeju Island (Fig. 2a). The maximum wind speed of 30.2 m/s was observed at Gageodo in South Jeolla Province, and the peak gust was 62 m/s at Mt. Halla (Fig. 2b).

3.1.2. Cimaron

Cimaron occurred at 12 UTC on August 18 over the ocean approximately 1020 km east of Guam. Cimaron had a 44 m/s maximum sustained wind and central pressure of 950 hPa at 06 UTC on August 22. This time represented the mature stage. The typhoon then dissipated as an extratropical transition at 12 UTC on August 24 (Figs. 1 and 3a).

3.2. Structure change of two typhoons

3.2.1. Intensity

Based on best track data, the maximum sustained wind of Soulik at the beginning stage (00 UTC August 16) was 18 m/s. Furthermore, a maximum sustained wind of 44 m/s was recorded from 18 UTC on August 20 to 00 UTC on August 22. Soulik rapidly weakened late in its lifecycle, starting at 00 UTC on August 22 (44 m/s) and continuing through 18 UTC on August 23 (24 m/s) (Fig. 3a).

The intensity-maximum sustained wind of Cimaron was assessed at 12 UTC on August 18 (beginning stage), reaching 18 m/s. The maximum sustained wind of Cimaron at the mature stage was recorded as 42–44 m/s from 06 UTC on August 22 to 06 UTC on August 23. Cimaron quickly weakened starting at 18 UTC on August 23 (30 m/s) (Fig. 3a).

The intensity of Soulik was stronger than that of Cimaron from the beginning stage to 00 UTC on August 22. However, Soulik was weaker than Cimaron after this time (Fig. 3a).

3.2.2. Size (15 m/s wind radii)

JMA estimated a 15 m/s wind radii (R30) as the typhoon size. Fig. 3b shows the time series of two typhoons, R30, from generation to termination.

The R30 of Soulik from 00 UTC on August 16 to 12 UTC on August 19 was estimated between 280 km and 340 km and gradually increased to 380 km until 12 UTC on August 21. However, the R30 of Soulik decreased from 380 km to 280 km over 18 h and continued 280 km until 12 UTC on August 23. R30 increased again during the extratropical transition.

The R30 of Cimaron was estimated as 280 km at the beginning stage. However, it suddenly increased to 560 km at 06 UTC on August 20 and maintained its size during the lifetime. The size of Cimaron was double that of Soulik from August 22 to 24.

3.2.3. Speed and distance of the two typhoons

The movement speed of Soulik changed twice during its life span. First, the typhoon recurved from north to...
northwestward at 4–5 km/h on August 18 near 25°N, 140°E (Fig. 1 and denoted by * in Fig. 3c). Second, Soulik slowed as it changed directions by approximately 10 km/h at 00 UTC on August 23. This represented the typhoon’s closest proximity to Jeju Island and extended presence in the area (Figs. 1 and 3c, denoted by ⋄ in Fig. 3c). Typhoon Soulik passed quickly through (35 km/h) the Korean Peninsula’s central regions after landfall in the south western port city of Mokpo (Figs. 1 and 3c, denoted by ⬤ in Fig. 3c).

Cimaron increased its speed until it passed through at a speed of 52 km/h on the mainland of Japan (Figs. 1 and 3c).

Fig. 3d shows the distance and wind radii between the two typhoon center positions from August 22 to 24. The two typhoons co-existed from 12 UTC on August 18 to 06 UTC on August 24. Soulik and Cimaron were located within 1333 km at 06 UTC on August 22. Next, they approached each other with mutual distances of 969 km at 00 UTC on August 23, 785 km at 12 on UTC August 23, and 706 km at 18 UTC on August 23.

The structure of Soulik changed around 00 UTC on August 22, as the intensity weakened and became small (Fig. 3a and b). However, Cimaron maintained its intensity and wind radii (Fig. 3a and b), and moved quickly from August 22 to 24 (Fig. 3c).

One hypothesis for this dynamic is that two typhoons’ binary interaction likely activated during that period. As a result, Soulik changed its structure and position. This idea will be tested by a numerical modeling experiment in further studies.

Many observational studies have examined a representative binary typhoon track pattern using the long-term best track. Wu et al. (2011) categorized binary typhoons in the WNP into seven types. Jang and Chun (2013) used six types because they represented all the observed tracks with different characteristics suggested by Wu et al. (2011).

The tracks of Soulik and Cimaron are similar to type C, as shown in Fig. 5 (Jang and Chun, 2013a). Soulik corresponds to a western typhoon and Cimaron corresponds to an eastern typhoon. The western and eastern typhoons recurve to the east sea of the Philippines and near ocean at 20°N and 140°E, respectively. The recurving area of Soulik and Cimaron occurred more north than type C (Jang and Chun, 2013a).

Jang and Chun (2013) summarized the criteria for binary interactions, including those from Brand (1970), Dong and Neumann (1983), and Wu et al. (2011) in Table 1 of their paper. Brand (1970) adopted the strictest criterion. For example, a binary typhoon is defined as when two typhoons coexist within 1300 km of each other with a maximum wind speed of greater than 33.4 m/s over the open ocean. However, the coexistence time of two typhoons is defined as longer than consecutive 48 h by Dong and Neumann (1983) and Wu et al. (2011). The conditions of Soulik and Cimaron from August 22 to 24 were sufficient for the criteria of binary interaction suggested by the aforementioned studies.

3.2.4. Sea surface temperature and ocean heat content distribution

Fig. 4 presents the SST and OHC distribution on 00 UTC from August 22 to 25, respectively. The SST changed substantially between August 22 and 23 near Jeju Island. The SST on August 23 that was close to Soulik’s center position was 2–3°C cooler than that of the same area on August 22. Soulik on August 22 was entering an area of low OHC. This cold and low subsurface water mass may have played a role in the weakening Soulik. Park et al. (2019) explained that the rapid decay of Soulik was caused by the interaction between the strong wind of Soulik and the cold subsurface. The slowly moving typhoon substantial induced the cold SST. The local cool SST near Jeju Island continued after the passage of Soulik. The presence of the cold water mass and interaction between Soulik is an interesting subject. Further study related to this interaction and its contribution to the weakening of Soulik will be conducted.

3.3. Effect of large-scale circulation pattern

To examine the effects of environmental flow on binary typhoons during the evolution of binary typhoons, environmental circulation analysis is performed using global analysis.
data. Analysis maps of the geopotential height at 500 hPa and wind at 200 hPa from August 21 to 24 are shown in Fig. 5.

The North Pacific high presented in the region of the WNP and the western boundary of the 5880-gpm line reaches the Japan mainland (Fig. 5). This North Pacific high moved steadily into Japan from August 21 to 24.

The binary typhoons defined by the closed vortexes were present along the 20–30 °N latitude region, and this feature

Fig. 3. Time series for the Soulik (black, solid line) and Cimaron (black, dashed line) typhoons for (a) maximum wind speed, (b) 15 m/s wind radius (R30), (c) movement speed and distance between the two typhoons (gray line) and (d) best track from August 22 to 24. *denotes the first recurvature time. (●) means close to Jeju Island, (●) is landfall. The gray circles in (d) denote a 15 m/s wind radius (R30) for Soulik (solid) and Cimaron (dashed) at August 21-24 on 00 UTC.
was retained from August 21 to 23 (Fig. 5). A strong jet stream at 200 hPa was formed to the north of the North Pacific high (40°N, 130°–140°E) and rapidly moved eastward. As Soulik and Cimaron passed southern Japan and approached Korea, environmental circulations showed a strong 500 hPa high along 36°N just to the east of Japan, which appeared to be the dominant steering current for both typhoons. Aside from the northward shift observed in the present study, these large-scale conditions are likely to induce a continuous north-eastward recurve of Soulik and are similar to the middle and final stages demonstrated by Chang and Chun (2015a) in Fig. 6c of their paper.

3.4. Verification of forecast error

This section summarizes the verification of track and intensity for the two typhoons, wherein the typhoon track and intensity forecast results from the KMA official guidance and global model—unified model (UM)—are evaluated. To assess forecast accuracy, the two typhoons’ forecast errors are compared to the annual mean track (Table 1) and intensity (Table 2) errors in 2018 annual mean (Chen et al., 2019). The official forecast error of Soulik for every lead time was larger than the 2018 annual mean. While the UM forecast error in 24 h (63 km) was similar to the annual mean (65.7 km) in 2018, the 72 h error (255 km) was larger than the annual mean (185.3 km). These unstable model forecast results were likely to cause large error of official guidance. Both the official guidance and the UM of Cimaron forecast error were stable and accurate for all lead times.

3.4.1. Track

Notably, a large track error for the official guidance occurred twice for Soulik (Fig. 6a). The first largest track error of approximately 500 km at the 72 h lead time was at 18 UTC on August 23, issued at 18 UTC on August 20. This track error distribution corresponds to the change in moving speed (Figs. 1 and 3c, denoted by φ in Fig. 3c). Soulik was expected to approach Seoul on August 23. The second largest track error of 300 km at a 72 h lead time was on August 20, which was issued on August 17 with an initially forecasted recurve. The track error of Cimaron was not larger than that of Soulik (Fig. 6b). The largest track error was from August 22 to 23 with a 72 h lead time. At this time, the two typhoons moved close to each other.

Generally, the UM track error of Soulik (Fig. 6c) was similar to its official guidance (Fig. 6a). The largest peaks of the error corresponded to each other. However, the 24 h error of UM was smaller than the official guidance, except for the beginning stage from August 17 to 18. Specifically, the UM errors were smaller than KMA error except the largest peak from August 22 to 23 when the two typhoons approached together within 1300 km and were expected to make landfall on the southwestern coastline of the ROK. The 72 h error of UM was larger than its official guidance from August 22 to 23. This was an important time for forecasting as a result of this large error.

The 24 h UM track error of Cimaron (Fig. 6b) differed from its official guidance (Fig. 6d). For example, the largest peaks of the 72 h error from August 22 to 23 were opposite of each other. However, the 48 h error of UM was larger than the official guidance from August 22 to 23. The model track error of Cimaron is smaller than that of Soulik (Fig. 6c and 6d).

Fig. 7 shows the forecasted track of the official guidance and UM at different forecast issue times from August 20 to 23, with 24, 48, and 72 h lead times. The official guidance of Soulik (Fig. 7a) stayed consistent, whereas the UM of Soulik (Fig. 7b) changed every forecast issue time and showed a large spread. For example, the forecasted track at 12 UTC on August 20 did not make landfall in South Korea and instead moved northward. The forecasted track of 00 UTC on August 21 changed direction to the northeast and showed a landfall near Seoul. However, the forecasted track of 12 UTC on August 21 changed direction again, as it moved to the north and did not project landfall. Furthermore, the forecasted track of 00 UTC 22 changed dramatically again, projecting landfall with the typhoon traversing ROK. The forecasted tracks from 12 UTC 22 to 12 UTC August 23 became similar to the best track (black). As a result of the forecast track, the most sensitive time for model simulation was between 12 UTC on August 21 and 00 UTC on August 22. The distances of the two typhoons were approximately 1500 km at 12 UTC on August 21 and approximately 1300 km at 06 UTC on August 22 (Fig. 3c and 3d). The forecasted tracks were compared by global forecast models at 12 UTC on August 21 and 00 UTC on August 22 (Fig. 8). The forecasted track at 12 UTC on August 21 of the UM and JMA Global Spectral Model (JGSM) moved northward, whereas those of ECMWF and Global Forecast System (GFS) moved northeast, made landfall, and crossed the nation. The official guidance of the KMA was similar to ECMWF and GFS (Fig. 8a). However, the forecasted tracks produced by the four models and the KMA official guidance at 00 UTC on August 22 showed a similar trend (Fig. 8b).

3.4.2. Intensity

Fig. 9 shows the time series of the difference between the forecasted maximum wind speed and best track at each lead time for both Soulik and Cimaron.

A dominant large difference and weak trend can be observed at the initial stage for Soulik (both official and UM). The large differences in the time series corresponded to the track error (Fig. 8a). The first largest difference at a 24 h lead time was from August 17 to 20, with an initially forecasted

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Table 1
Summary of mean track error both Soulik and Cimaron. The unit is km.

| Lead Time | 2018 Annual mean | Soulik | UM | Cimaron | Official guidance | UM |
|-----------|------------------|-------|----|---------|------------------|----|
| 24 h      | 65.7             | 95    | 63 | 79      | 24               | 72 |
| 48 h      | 112.5            | 132   | 137| 77      | 48               | 79 |
| 72 h      | 185.3            | 194   | 255| 108     | 72               | 68 |

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Fig. 4. Sea surface temperature (upper) and ocean heat content (lower) from August 22 to 25. The dots denote the TC position of Soulik. The solid (Soulik) and dashed (Cimaron) ellipse denote 15 m/s wind radii of Soulik and Cimaron.
recurve. The second largest intensity difference at the 24 h lead time was at 18 UTC on August 23, which was issued at 18 UTC on August 20. Soulik was expected to approach Seoul on August 23. Cimaron was forecasted to be weak in the life span every lead time. The maximum wind speed difference of Soulik was smaller than that of Cimaron (Table 2). However, the intensity error was not as a dominant characteristic like the track forecast error.

4. Summary and avenues for further study

This study explains the observational characteristics and forecast errors of binary typhoons in 2018. The 19th typhoon of Soulik and 20th typhoon of Cimaron co-existed from August 18 to 24. Moreover, they were located within 1300 km at 06 UTC on August 22 and approached each other over time. Furthermore, Soulik moved slowly and weakened around August 22, whereas Cimaron did not change its structure. The characteristics of these binary typhoons show that the relatively small and weak typhoon Soulik was more affected by large and strong typhoon Cimaron.

Soulik passed slowly through the southwestern coast of Jeju Island from August 22 to 23. During this period, heavy rainfall and wind gust were recorded on Jeju Island. The typhoon landed near the southwestern coastline of ROK on the night of August 23 (local time) and quickly passed through onto land. However, Soulik weakened after landfall, with no substantial rainfall and wind occurring within the country.

KMA forecasted that the Soulik would impact the Korean mainland around August 23. However, the official and model on the KMA track forecast changed the direction and landfall area at every forecast issue time. By contrast, the forecasted track of Cimaron did not change as much as the forecasted track of Soulik. This was likely caused by the binary...
interaction. As a result of the unstable model forecast of Soulik, its track error was larger than that of Cimaron.

The models forecasted different results at 12 UTC on August 21. For example, the UM and JGSM moved northward whereas the ECMWF and GFS moved northeastward and projected landfall along the southwest coastline. However, the results forecasted by four models at 00 UTC on

Table 2
Summary of MAE for both Soulik and Cimaron. The unit is m/s.

| Lead Time | 2018 average | Soulik | Cimaron |
|-----------|--------------|--------|---------|
|           | Official guidance | UM | Official guidance | UM |
| 24 h      | 3.9  | 3.2   | 5.6  | 4.7   | 5 |
| 48 h      | 5    | 3.9   | 7.9  | 5.4   | 7.3 |
| 72 h      | 5.7  | 3.5   | 4.8  | 7.3   | 8.4 |

Fig. 6. Forecasted track error for (a) the official guidance of Soulik, (b) the official guidance of Cimaron, (c) the UM of Soulik, and (d) the UM of Cimaron at 24, 48, and 72 h. The unit is km. X-axis denotes forecasted time.

Fig. 7. Best track and forecasted track for (a) official guidance and (b) UM at 24, 48, and 72 h forecast lead times. The black track is the JMA best track. The different colors denote forecast issuance times.
August 22 were similar, as they all moved northeastward. The disagreement between the models at different forecast issuance times is likely depended on how models reproduced the binary typhoons. Additionally, erroneous model tracking of Soulik was responsible for a large track error in the official guidance and accumulated rainfall forecast. This will remain a topic for future studies. To better understand the role of Cimaron and environmental flows that can cause observed and forecasted changes in two coexisting typhoons, various modeling experiments will be conducted in a forthcoming study.

The lessons from this case study can summarize these subjects. First, the forecasters are the final decision makers; therefore, they must require long-term operational experience and ensure capacity building. For example, forecasters can carry out real-time analysis of various observational datasets.

The diagrams illustrate the forecasted tracks and intensity errors for Soulik and Cimaron, highlighting the discrepancies between the models and the official guidance.
such as satellite, radar, and in situ, as well as account for expected degradations to numerical model track forecasts. Furthermore, forecasters can understand the unique traits of different models.

Second, the feedback system between research and operation should be strengthened. For example, forecasters analyze the difference between the observational data and the model result, such as the 500 hPa geopotential height difference between the observation and model. Developers address this difference by modifying the scheme of model that affects the 500 hPa geopotential height.

Third, a case study of large forecast errors will be needed in order to understand the occurrence of large errors in specific forecast issue time, for example, recurvature and landfall. The case studies that follow will show that the mechanism of binary typhoon interaction is comparatively easy to understand if the forecaster is familiar with the corresponding clues and has access to the appropriate model fields and field display tools.

Acknowledgments

This research was supported by the “Research and Development for Numerical Weather Prediction” and “Support to Enhancement of Convergence Technology of Analysis and Forecast on Severe Weather” under Grant (KMA2018-00122) by the Korea Meteorological Administration Research and Development Program.

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