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This article is a companion to Xu et al. (2022), https://doi.org/10.1029/2021JD036265.

Key Points:

- The control simulation reasonably reproduced the movement of typhoons In-fa and Cempaka and the distribution and amount of extreme rainfall
- The southerly flow was crucial to the simulated extreme rainfall event and sensitive to the movement of In-fa and the presence of Cempaka
- In the absence of Cempaka, although the motion of In-fa still affected rainfall, the effect was much smaller than in the presence of Cempaka

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Indirect Effects of Binary Typhoons on an Extreme Rainfall Event in Henan Province, China From 19 to 21 July 2021: 2. Numerical Study

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Abstract An extreme precipitation event over Henan province, China from 19 to 21 July 2021 led to flood disasters in this region and widespread concern about the subsequent loss of life and livelihoods. We conducted numerical simulations to examine the impacts of typhoons In-fa (2021) and Cempaka (2021) on this extreme rainfall event. The control simulation reasonably reproduced the motion of typhoons In-fa and Cempaka and the associated distribution and amount of extreme rainfall. Sensitivity experiments were conducted in which typhoon In-fa was artificially moved in both northerly and westerly directions in the initial conditions. The results indicated that the southerly flow between typhoon Cempaka and Henan, which determined the structure and distribution of the extreme rainfall event, was sensitive to the motion of typhoon In-fa. Numerical experiments that removed typhoon Cempaka confirmed that both the movement of In-fa and its interaction with Cempaka were closely associated with southerly flows and had a significant effect on the extreme precipitation event. In the absence of typhoon Cempaka, although typhoon In-fa still had a remote effect on precipitation, the effect was much smaller than in the presence of Cempaka. Our simulation of this extreme rainfall event in Henan and the associated sensitivity experiments are consistent with the results of previous studies of multiple tropical cyclones, which showed that interactions among multiple tropical cyclones can lead to changes in their outer circulation that affect extreme precipitation events.

Plain Language Summary This is a case study of an extreme rainfall event related to a binary typhoon. The aim of the study was to simulate the effects of multiple typhoons and their interactions, which lead to remote extreme rainfall events that can cause flood disasters. This study follows on from an earlier study (Part 1, Xu et al., 2022; https://doi.org/10.1029/2021JD036265) that focused the indirect effects of binary typhoons on an extreme rainfall event in Henan province, central China. We reasonably reproduced the distribution and amount of rainfall in a numerical model and conducted sensitivity experiments to identify the effects of Cempaka and In-fa on the extreme rainfall event in Henan. Our results showed that, in the absence of Cempaka, although typhoon In-fa still affected the precipitation event, this effect was much smaller than the effect in the presence of Cempaka. This study confirms that the interaction of binary typhoons and their outer circulation has a significant remote effect on extreme precipitation events.

1. Introduction

Part 1 of this study (Xu et al., 2022) examined the influence of typhoons In-fa and Cempaka on an extreme rainfall event in Henan province, central China from 19 to 21 July 2021 using an ensemble-based analysis. The extreme rainfall event was directly influenced by both southerly and southeasterly flows and the Huang-Huai cyclone. The ensemble-based analysis in Part 1 (Xu et al., 2022) suggested that, although they had little impact on the southeasterly flow, the northwesterly motion of typhoon In-fa (2021) and the existence of typhoon Cempaka (2021) in the global ensemble model may have led to a change in the southerly flow and evolution of the Huang-Huai cyclone. This may have influenced the forecasting skills of this extreme precipitation event. The southerly flow to the south of Henan province was weakened via the northwesterly movement of typhoon In-fa. This reduced the transport of moisture to the Henan region, leading to a significant decrease in precipitation. In addition, the circulation around typhoons In-fa and Cempaka indicated an interaction between the two typhoons and a clear influence on the southerly flow.

Because multiple typhoons occur almost every year in the northwest Pacific Ocean (L. Chen, 2010; Jang & Chun, 2015a; Wu et al., 2003, 2009), it is important to investigate the quantitative influence of binary typhoons on the development of indirect extreme rainfall events. As in Part 1 (Xu et al., 2022), indirect rainfall refers to the indirect effect of a tropical cyclone on the rainfall that occurs outside its circulation, but which is physically associated with the tropical cyclone (L. Chen, 2010; Cote, 2007). Although the European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble-based analyses provided a reliable basis for analyzing the influence of the northwesterly movement of typhoon In-fa on the remote extreme rainfall event, the contributions of typhoons In-fa and Cempaka to the simulated extreme rainfall event cannot be further separated in operational ensemble forecasting (Du & Chen, 2018; Lynch & Schumacher, 2013; Schumacher, 2011). We therefore conducted numerical simulations to further analyze the remote effects of typhoons In-fa and Cempaka on the extreme rainfall event in Henan by removing one of the typhoons and/or artificially relocating the location of typhoon In-fa in the initial conditions. Because the northwesterly motion of typhoon In-fa, its interaction with typhoon Cempaka and their contribution to the southerly flow are all important, well-designed convection-resolving numerical sensitivity experiments were conducted to investigate related processes and to help understand the mechanisms.

Numerical sensitivity experiments are efficient tools with which to gain quantitative insights into the processes associated with tropical cyclones. Many studies have used similar techniques to explore the remote effects of tropical cyclones (L. Chen, 2010; Schumacher & Galarneau, 2012; Xu et al., 2014) and the interactions among multiple tropical cyclones (Jang & Chun, 2013; Wu et al., 2010; Xu & Du, 2015; Xu et al., 2011, 2013). The remote effects of tropical cyclones suggest that the transport of moisture ahead of the cyclones can greatly increase the amount of rainfall at mid-latitudes and intensify the effects of the resulting floods (L. Chen, 2010; Schumacher & Galarneau, 2012; Xu et al., 2014). Examining the transport of water vapor related to tropical cyclones and their remote effects on extreme precipitation is crucial for both short- and medium-term forecasting of extreme precipitation events and the resultant flooding (Schumacher & Galarneau, 2012).

High-resolution numerical sensitivity experiments are important in understanding the close relation of tropical cyclones with extreme rainfall events because they not only reasonably reproduce the intensity of precipitation and its associated physical processes, but can also separate the influence of individual tropical cyclones. For example, the extreme rainfall event related to tropical cyclone Erin was simulated by Schumacher and Galarneau (2012) using the Weather Research and Forecasting (WRF) model. Their results suggested that the evolution of the rainfall event was consistent with the convergence of the moisture flux. By comparing the control simulation with the decrease in relative humidity in the model, it was shown that the remote effects of tropical cyclone Erin played an important part in the extreme rainfall event, leading to an increase in precipitation in Hokah and Minnesota of 25%. Similarly, through sensitivity experiments removing typhoon Songda, Wang et al. (2009) showed that the transport of moisture associated with the outer circulation of typhoon Songda accounted for >90% of the precipitation in Japan. Both removing or decreasing the relative humidity related to a tropical cyclone could bring the initial precipitable water to climatological levels, but this method does not necessarily represent a change in the vertical structure of water vapor caused by changes in the track of tropical cyclones. Although previous studies have used ensemble approaches to investigate the remote effects of recurving tropical cyclone (T.-C. Chen & Wu, 2016; Schumacher et al., 2011), numerical simulations are needed to quantitatively investigate the contribution of the movement of tropical cyclones to the transport of moisture and extreme rainfall.

Interactions among multiple tropical cyclones, also known as the Fujiwhara effect (Fujiwhara, 1921, 1923), are a major cause of errors in predicting tropical cyclones (E.-J. Cha et al., 2021). As one tropical cyclone approaches a second, its track, intensity wave and the distribution of precipitation are all affected by their interactions (Brand, 1970; Carr & Elsberry, 1998; Carr et al., 1997; Chang et al., 2021; Dong & Neumann, 1983; Jang & Chun, 2015a; Yang et al., 2008). The interactions between multiple tropical cyclones and the environmental flow are highly complex and the accurate prediction of extreme rainfall events influenced by binary typhoons remains challenging (Jang & Chun, 2015b; Shin et al., 2006; Wu et al., 2003; Yang et al., 2008).

The interactions of multiple typhoons have been shown to have a large impact on the transport of water vapor (Jang & Chun, 2013; Wu et al., 2010; Xu & Du, 2015; Xu et al., 2011, 2013), which could significantly modify both the structure and distribution of rainfall related to a tropical cyclone. For example, Wu et al. (2010) studied the influence of tropical storm Paul (1999) on the simulated rainfall of typhoon Rachel (1999) near Taiwan using a mesoscale numerical model combined with a sensitivity experiment that removed the circulation of tropical storm Paul. They found that tropical storm Paul played a significant part in the movement of typhoon Rachel,

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which was one of the key factors in increasing precipitation in southern Taiwan. Typhoon Morakot (2009) was analyzed in detail by Xu et al. (2011). A numerical sensitivity experiment that removed typhoon Goni (2009) showed that the moisture attributable to typhoon Goni was responsible for enhancing the heavy rainfall associated with typhoon Morakot in Taiwan by about 70%. This increase contributed to exceptionally severe disasters in Taiwan (3,000 mm of rainfall in the Alishan region) and resulted in deadly flash floods and mud–rock flows. These studies show that numerical sensitivity experiments are also very effective in studies of the interactions of multiple typhoons. However, few studies have examined the remote effects of multiple typhoons on the structure and distribution of extreme rainfall events.

Our ensemble-based analysis in Part 1 (Xu et al., 2022) showed that the extreme rainfall event in Henan province was influenced by uncertainties in typhoons In-fa and Cempaka. To further quantify the influence of typhoons In-fa and Cempaka, we used a high-resolution numerical model to examine the remote influence of the typhoons on the simulated extreme rainfall event. Sensitivity experiments were also performed by removing the circulation of typhoon Cempaka and artificially relocating typhoon In-fa in the initial conditions. We investigated the transport of moisture related to the tropical cyclones by comparing the control (CTRL) experiment that correctly reproduced the track and transport of moisture related to these two typhoons with the sensitivity experiments that removed either In-fa or Cempaka or followed tracks of In-fa that were different from the observations. Section 2 describes the model configuration and set-up and the results are presented in Section 3. Section 4 gives our discussion and conclusions.

2. Model Configuration and Set-Up

We used the WRF Advanced Research Weather (WRF-ARW) model, version 4 (Skamarock et al., 2019) to examine the remote effects of typhoons In-fa and Cempaka on water vapor transport and extreme rainfall in Henan. All the simulations were initialized at 00:00 UTC on 18 July 2021, with the initial and lateral boundary conditions from the ECMWF Reanalysis v5 (ERA5) data set (Hersbach et al., 2020). This simulation allows a spin-up time of 24 hr prior to the extreme rainfall event, which is long enough for the initiation of convection. We also carried out the simulation with earlier initial times, such as 00:00 UTC on 17 July (not shown), but the simulated precipitation was significantly smaller than that in observations and the CTRL experiment. The simulations include 2 two-way nested domains with horizontal grid spacings of 12 and 3 km and grid sizes of (652×463) and (345×385), respectively (Figure 1a). There are 50 stretched vertical levels from the surface to 50 hPa. All the numerical simulations cover a 72-hr period from 00:00 UTC on 18 July to 00:00 UTC on 21 July 2021.

The Kain–Fritsch cumulus parametrization (Kain, 1993, 2004) was applied in the 12 km domain (D01; Figure 1a), but not in the 3 km domain (D02; Figure 1b). The other relevant model physics used include the Mellor–Yamada–Nakanishi–Niino (MYNN) planetary boundary layer, which is one of the popular PBL schemes in WRF model (Xu & Duan, 2022; Xu & Wang, 2021), and surface layer parameterization (Nakanishi & Niino, 2006; Olson et al., 2019; Siebesma et al., 2007), the aerosol-aware Thompson microphysics scheme (Thompson & Eidhammer, 2014), the Rapid Radiative Transfer Model for Global Climate radiation scheme (Iacono et al., 2008) and the revised the Rapid Update Cycle Land Surface Model scheme (Smirnova et al., 2016).

The ensemble-based analysis in Part 1 (Xu et al., 2022) suggested that, although they had little impact on the southeasterly flow, the northwesterly motion of typhoon In-fa and the existence of typhoon Cempaka in the global ensemble model may have led to a change in the southerly flow. We therefore conducted sensitivity experiments that included the movement of typhoon In-fa and the existence of typhoon Cempaka to study their influence on precipitation in Henan province. Based on the uncertainties in forecasting typhoons In-fa and Cempaka in the global operational ensemble system (ECWMF) in Part 1 of this study (Xu et al., 2022), a set of sensitivity experiments was conducted by artificially removing typhoons In-fa or Cempaka or by varying the location of typhoon In-fa in the initial conditions to examine the effects of this typhoon on rainfall over Henan. We followed the method of D.-H. Cha and Wang (2013) and the filtering approach of Van Nguyen and Chen (2011) was applied to separate the tropical cyclone from the initial conditions. A cylindrical filter proposed by Kurihara et al. (1993) was used to isolate the axisymmetric vortex from the disturbance component. The axisymmetric vortex is considered as the vortex of the tropical cyclone in the model initial field and was used in the following sensitivity experiments.

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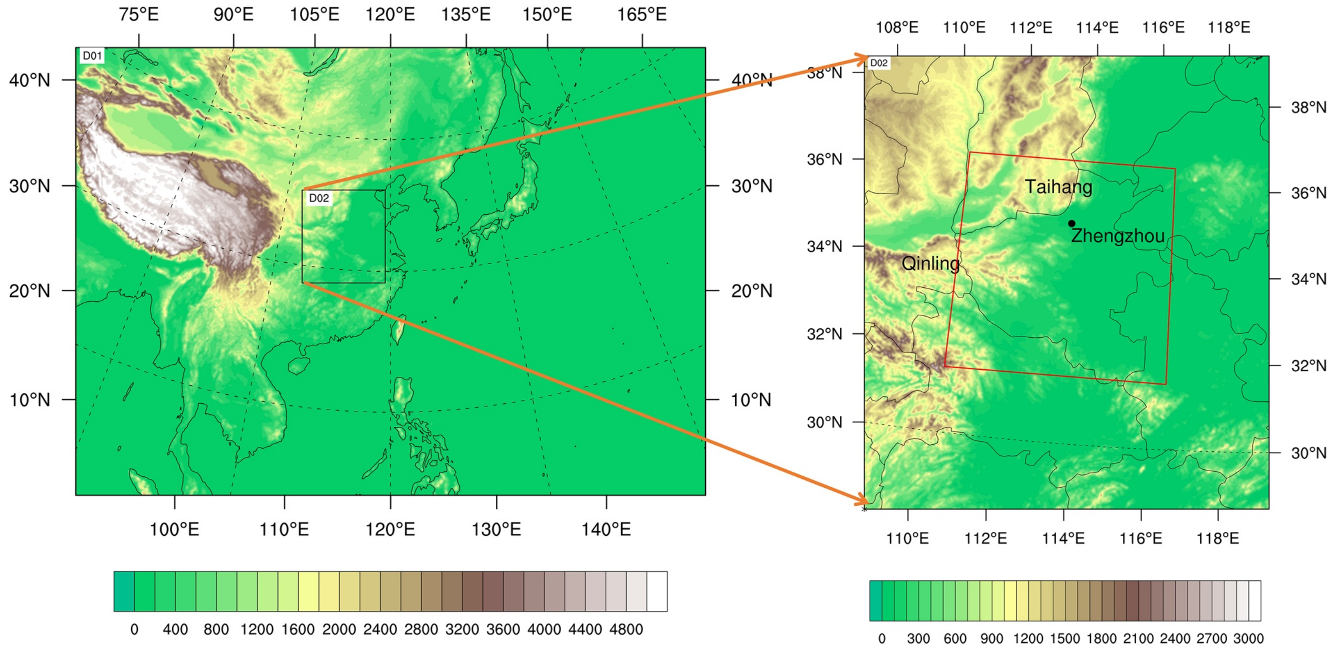

Figure 1. (a) Configuration of the Weather Research and Forecasting (WRF) model domains (D01 and D02); shading represents the terrain height (m). (b) Configuration of the WRF model domain for D02. The location of Zhengzhou city is marked as a black dot and the mountains mentioned in the text are shown. The red box is the location of the area used for averaging the precipitation.

We conducted 11 numerical experiments (Table 1). Specifically, the vortices of typhoons Cempaka and In-fa were initiated with the ERA5 data in the control experiment (CTRL). For the No_In-fa experiment, the model set-up was configurated to be the same as the CTRL experiment, but typhoon In-fa was removed from the initial fields. Four additional sensitivity experiments were conducted to determine the extent to which the northwesterly motion of typhoon In-fa affected the extreme rainfall event. The vortex of typhoon In-fa in the NW_60km, NW_120km, NW_180km, and NW_240km experiments (see Table 1) were moved 60, 120, 180, and 240 km in both westerly and northerly directions relative to the CTRL experiment. Given that an error in the tropical cyclone track can reach <400 km within 120 hr, 240 km in both the westerly and northerly directions was taken

Table 1
List of Designed Experiments

Experiment	Name	Remarks
1	CTRL	Locations of Typhoons Cempaka and In-fa initiated by ERA5 data
2	NO_In-fa	Same as CTRL, but with the removal of Typhoon In-fa
3	NW_60km	Same as CTRL, but with the center of Typhoon In-fa moved 60 km in both westerly and northerly directions
4	NW_120km	Same as CTRL, but with the center of Typhoon In-fa moved 120 km in both westerly and northerly directions
5	NW_180km	Same as CTRL, but with the center of Typhoon In-fa moved 180 km in both westerly and northerly directions
6	NW_240km	Same as CTRL, but with the center of Typhoon In-fa moved 240 km in both westerly and northerly directions
7	NOC	Same as CTRL, but with Typhoon Cempaka removed
8	NW_60km_NOC	Same as NW_60km, but with Typhoon Cempaka removed
9	NW_120km_NOC	Same as NW_120km, but with Typhoon Cempaka removed
10	NW_180km_NOC	Same as NW_180km, but with Typhoon Cempaka removed
11	NW_240km_NOC	Same as NW_240km, but with Typhoon Cempaka removed

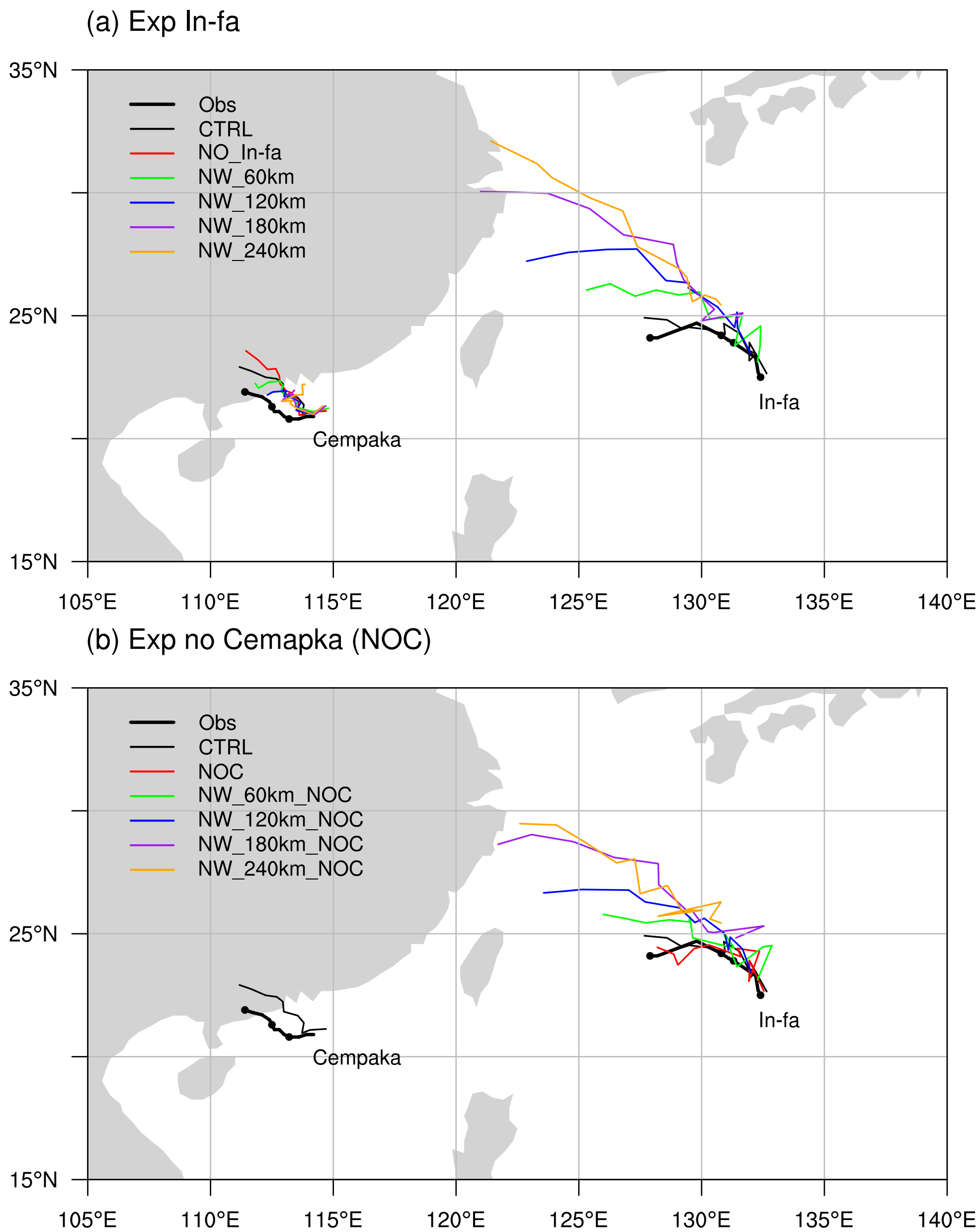

Figure 2. (a) Best-track data from the China Meteorological Administration (CMA) (bold) and the simulated tracks from the NW experiments from 00:00 UTC on 19 July and 06:00 UTC on 19 July to 00:00 UTC on 21 July for In-fa and Cempaka, respectively. (b) Best-track data from the CMA (bold) and the simulated tracks from the NW_NOC experiments from 00:00 UTC on 19 July and 06:00 UTC on 19 July to 00:00 UTC on 21 July for In-fa and Cempaka, respectively. Note that the two typhoons started at different times because the best-track data of Cempaka began at 06:00 UTC on 19 July.

as the maximum value in this group of experiments. The simulated tracks from the In-fa experiment complied with the modulation of the initial location of In-fa (Figure 2a), suggesting that the track of In-fa was varied effectively in these experiments. There were nonlinear differences among these experiments because changes in the position of In-fa affected its steering flow, which was largely influenced by the position of the typhoon relative to the subtropical high and the southwesterly monsoon flow. It is worth noting that the change in the movement of typhoon In-fa has a significant impact on the track of Cempaka, indicating that there is an interaction between the binary typhoons.

A second set of sensitivity experiments was conducted with the removal of typhoon Cempaka to determine its effect on the extreme rainfall event. For the NOC run, the model set-up was configured to be the same

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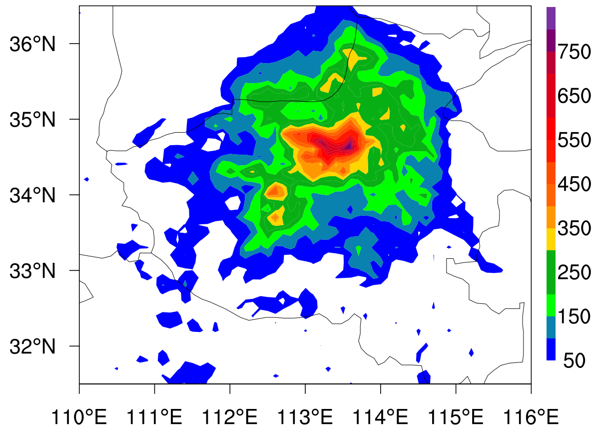

Figure 3. 48-hr accumulated precipitation (mm) between 00:00 UTC on 19 July and 00:00 UTC on 21 July 2021 from the China Meteorological Administration observations.

as in the CTRL experiment, but typhoon Cempaka was removed from the initial fields. Four extra experiments without typhoon Cempaka were also performed. The NW_60km_NOC, NW_120km_NOC, NW_180km_NOC, and NW_240km_NOC experiments were the same as the NW_60km, NW_120km, NW_180km, and NW_240km experiments, but with the removal of typhoon Cempaka. These sensitivity experiments are referred to as the NW_NOC experiments because Typhoon In-fa was artificially moved further to the northwest and Typhoon Cempaka was removed in the initial conditions. The track of typhoon In-fa was more southerly in the NW_NOC runs (Figure 2b) than in the NW runs. These differences in the simulated tracks suggest that the existence of Typhoon Cempaka may have affected the motion of Typhoon In-fa.

Note that the sensitivity experiments were only modified in the initial condition at 00:00 UTC on 18 July, about 24 hr before the onset of the extreme precipitation event in Henan. After this time, the simulations were configured to be the same as the CTRL experiment and proceeded without further modification. As a result, these sensitivity simulations allow a direct comparison with the CTRL experiment, which reasonably reproduces the distribution and amount of extreme rainfall, and show what might have happened if Typhoons In-fa and Cempaka influenced the transport of deep tropical moisture into Henan.

3. Results

3.1. Verification

We first evaluated the simulated tracks because these are important in the variability of the distribution of simulated precipitation. Figure 2a shows the simulated tracks of the CTRL experiment and the best-track data from the China Meteorological Administration (CMA) for 19–21 July 2021. The simulated motion of Typhoon In-fa agreed well with the best-track data in terms of its slower motion during 19–20 July and the subsequent acceleration after 20 July, but with a general northerly bias in the final 24 hr of the simulation. Despite the even northerly bias of the track of Cempaka in the numerical simulation for 19–21 July the CTRL experiment reproduced the northwesterly movement in the observed track of Cempaka prior to landfall over the South China Sea.

Figures 3 and 4a show the 48 hr cumulative precipitation from the CMA observations and the CTRL experiment, respectively, between 00:00 UTC on 19 July and 00:00 UTC on 21 July 2021. Comparison of the CTRL experiment with the observations shows that, although there was some deviation in the location, the distribution of the simulated rainfall in the CTRL experiment was consistent with the observations; in particular, the area of heavy rainfall was simulated accurately. The simulation results also gave the intensity of precipitation, with the maximum precipitation of >800 mm near Zhengzhou city, close to observed maximum of 818 mm. Note that there is an area of heavy rainfall located southwest of Henan (34°N, 112.3°E) in both the observations and the simulations. Although the precipitation in the CTRL experiment is much larger than that in the observations, it is not implied here that the regions of heavy precipitation are necessarily unrealistic. In general, the extreme precipitation event was reasonably reproduced in the CTRL experiment. The distant effects of Typhoons In-fa and Cempaka on the southerly and southeasterly flows and the extreme rainfall event in Henan on 21 July 2021 will therefore be discussed using the simulation results of the CTRL experiment combined with the sensitivity experiments with the modulation of the typhoons.

3.2. Effects of Typhoon In-Fa and Its Northwesterly Motion

Figures 4b–4f shows the 48-hr cumulative precipitation from the NO_In-fa and NW experiments. When Typhoon In-fa was removed from the NO_In-fa experiment, there was a difference in the distribution of precipitation in Henan compared with the CTRL run (Figure 4a), but the regions with large amounts of precipitation were similar, indicating that the removal of Typhoon In-fa did not have a large effect on the heavy precipitation event. However, there were significant effects on precipitation over the Henan region in the NW sensitivity experiments. A comparison of the CTRL and NW sensitivity experiments with Typhoon In-fa moving further northwest

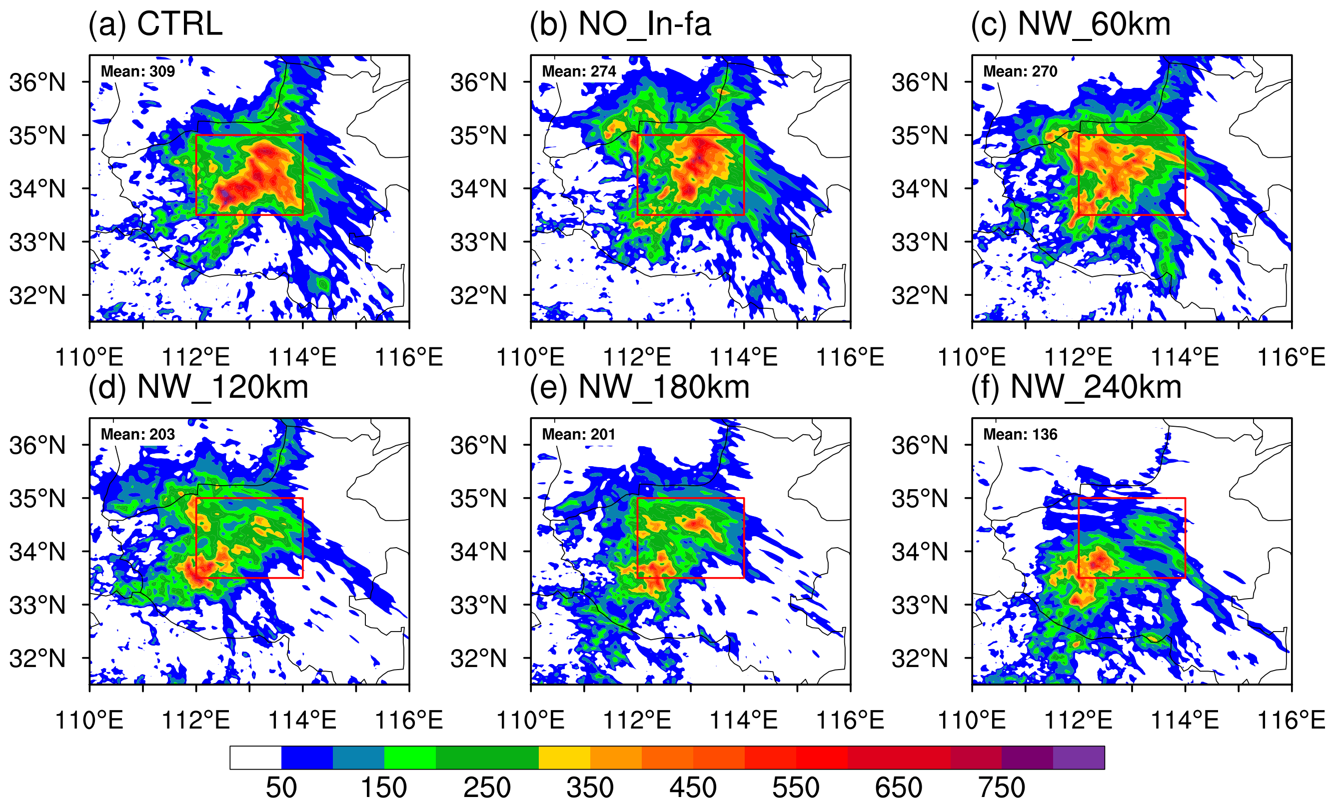

Figure 4. 48-hr accumulated precipitation between 00:00 UTC on 19 July and 00:00 UTC on 21 July 2021 for the (a) CTRL, (b) NO_In-fa, (c) NW_60km, (d) NW_120km, (e) NW_180km, and (f) NW_240km experiments. The red box is the location of the area of heavy rainfall.

(Figures 4c–4f) showed that precipitation was substantially reduced over the Henan region, indicating that the movement of In-fa had a negative effect on precipitation in Henan. Importantly, the total precipitation generally decreased as In-fa moved further northwest. For example, the area-averaged precipitation over the Henan region decreased in the NW_120km, NW_180km, and NW_240km experiments (Figures 4d–4f) and was much lower than in the CTRL run (Figure 4a). By contrast, there were smaller discrepancies between the NW_60km (Figure 4c) and CTRL experiments (Figure 4a). The heavy rainfall in the NW experiments was displaced further to the southwest and there was a smaller area of stratiform precipitation than in the CTRL run with the more northwesterly motion of Typhoon In-fa. This remote effect may be attributed to the influence of the large-scale flow pattern caused by the northwesterly motion of Typhoon In-fa. The following analysis investigates the mechanism for the effects of Typhoon In-fa on precipitation over the Henan region.

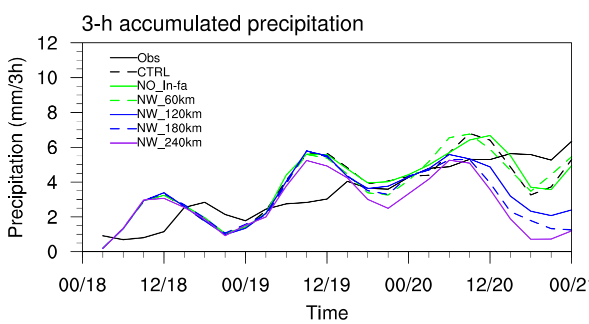

Figure 5. Time series of the 3-hourly precipitation (mm) from 00:00 UTC on 18 July to 00:00 UTC on 21 July averaged over the red boxes in Figure 1b from the CTRL and NW sensitivity experiments and the China Meteorological Administration observations.

Figure 5 shows the time series of the 3-hourly precipitation (mm) in a box covering (31.5–36.5°N, 110.5–116.5°E; Figure 1b, red box) from the CTRL, NO_In-fa and NW simulations and the CMA satellite-station merged observations. Although the CTRL run overestimated the 3-hourly precipitation in the given region, the overestimation mainly occurred during the time period 00:00–20:00 UTC on 19 July 2021—namely, before the period of heaviest rainfall. Nevertheless, a decrease in precipitation in the Henan region due to the removal of Typhoon In-fa (the NO_In-fa experiment) was not evident, which is consistent with the analysis of accumulated precipitation and indicates that the contribution of the presence of Typhoon In-fa to precipitation over Henan was non-significant. This may due to the large-scale circulation fields; in particular, the extreme rainfall in the CTRL and NO_In-fa experiments were similar, suggesting that the pre-conditioned circulation system was not obviously altered by Typhoon In-fa. However, Figure 5 also shows that the precipitation changed substantially and systematically in the Henan

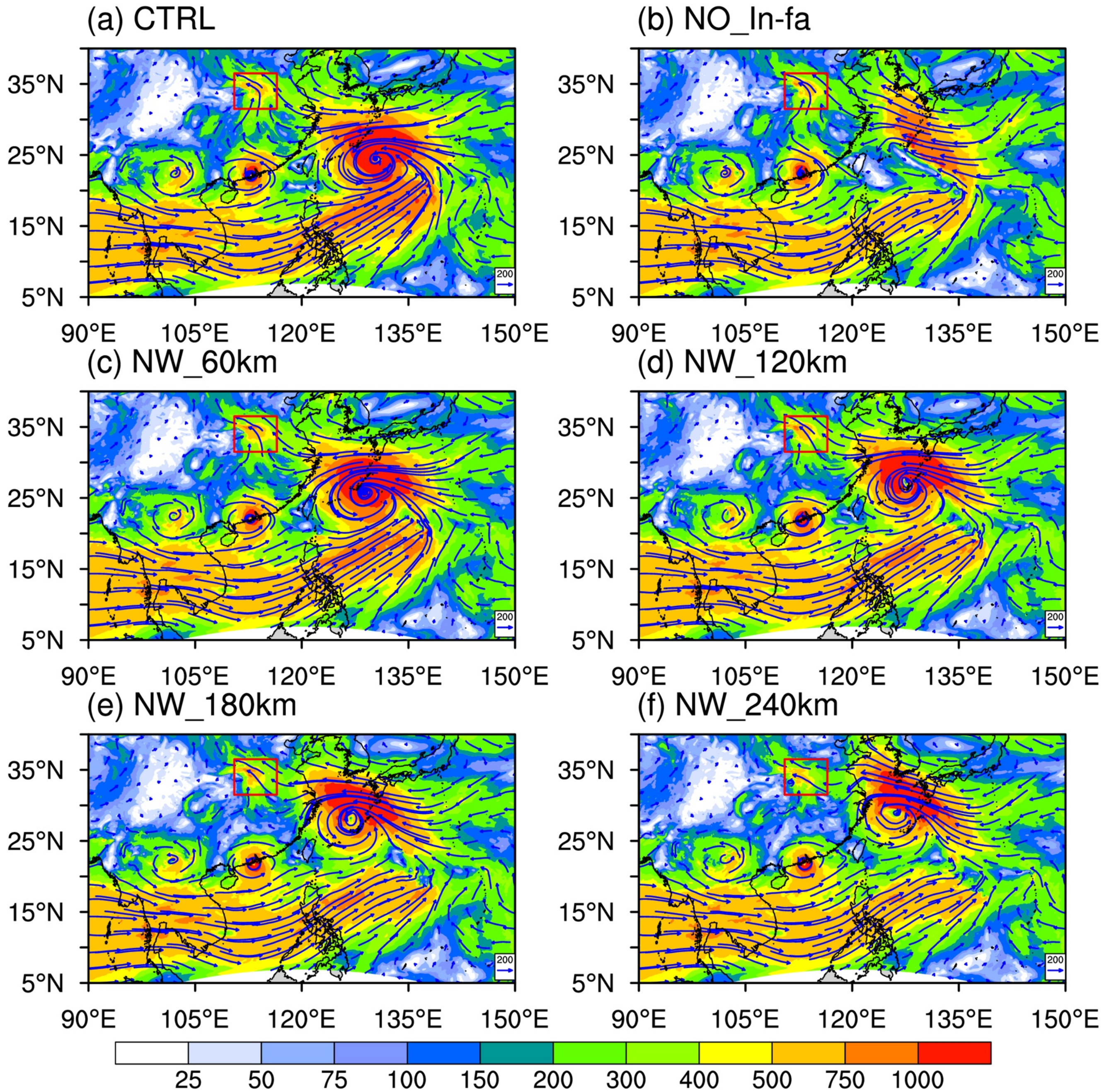

Figure 6. Column-integrated moisture flux (vectors) and its magnitude (shading; kg m^{-1} s^{-1}) at 00:00 UTC on 20 July 2021 for the (a) CTRL, (b) NO_In-fa, (c) NW_60km, (d) NW_120km, (e) NW_180km, and (f) NW_240km experiments. The red rectangles indicate the location of the Henan region.

region due to the movement of Typhoon In-fa in the NW sensitivity experiments. The precipitation showed a general decrease with the modulation of Typhoon In-fa from 60 to 240 km. The average difference in precipitation between the strongest and weakest rainfall was about 50% between the CTRL and NW_240km experiments from 00:00 UTC on 20 July to 00:00 UTC on 21 July. To further examine how Typhoon In-fa influenced remote precipitation in Henan, we conducted a diagnostic analysis of the transport of water vapor.

Figure 6 shows the horizontal distribution of the column-integrated water vapor flux and its magnitude at 00:00 UTC on 20 July for the CTRL, No_Infa and NW sensitivity experiments. As shown in Part 1 of this study (Xu et al., 2022), the rainfall in the CTRL experiment was closely associated with moisture from the southerly and southeasterly flows. These important features were reproduced well in the CTRL experiment, where there were two distinct channels of water vapor moving toward Henan province, mainly distributed in the southeasterly flow from eastern China and the southerly flow from southern China. When Typhoon In-fa was removed in the NO_In-fa experiment, the southerly and southeasterly moisture fluxes to the south of Henan region were similar to the fluxes in the CTRL experiment, indicating a non-significant influence of Typhoon In-fa on the moisture fluxes toward Henan region when it was located at the same position as in the CTRL experiment. By contrast, the differences in the southerly flow gradually weakened with the modulation of northwestward movement of Typhoon In-fa. In the NW_60km, NW_120km, NW_180km, and NW_240km runs (Figures 6c–6f), the southerly wind gradually reduced from southern China and the South China Sea to the vicinity of Henan province. Taking the NW_240km run as an example (Figure 6f), the southerly wind was significantly reduced and confined near Henan, which was related to the Huang-Huai cyclone. This has the consequence of reducing the transport of moisture to the Henan region, making the heavy rainfall region drier and increasing the movement of the Huang-Huai cyclone. However, note that the southeasterly flow from eastern China to Henan was similar in the CTRL and NW experiments, suggesting that the southeasterly flow was not substantially changed by Typhoon In-fa.

Figure 7 shows the difference in the column-integrated moisture flux (vectors) and its magnitude (shading; kg m^{-1} s^{-1}) between the CTRL run and the NO_In-fa and NW runs. In the NO_In-fa run (Figure 7a), the areas with a large difference in moisture flux were collocated with Typhoon In-fa as a result of its removal. In additional, an east–southeast-elongated difference in moisture flux in eastern China and its coastal areas was associated with the southeasterly flow, but this difference had relatively little influence on Henan.

By contrast, in the NW sensitivity experiments (Figures 7b–7e), there were large differences in the column-integrated moisture flux in the core region of Typhoon In-fa as a result of its distinct motion. It is interesting that the modulation of northwestward movement of Typhoon In-fa had a large influence on the southerly moisture fluxes. With Typhoon In-fa moved more to the northwest in the NW experiments, although the difference in moisture flux associated with the southeasterly flow marginally changed (Figures 6b–6e), the moisture flux difference belt from southern China to the region of heavy rainfall was evidently enhanced (Figures 7b–7e). The southerly flow showed a general decrease with the more northwesterly motion of Typhoon In-fa from the NW_60km to NW_240km experiments. This indicates that the southerly flow weakened in the NW experiments as Typhoon In-fa moved northwest, which could lead to a large decrease in precipitation (Figure 4).

A Huang-Huai cyclone is a cyclonic circulation that occurs in the mid- and lower reaches of the Huang-Huai River in China. Schumacher and Johnson (2008) showed that the presence and location of a mesoscale vortex close to the regions with heavy rainfall increases the possibility that the related convergence could help to maintain convection during extreme precipitation events. Part 1 of this study (Xu et al., 2022) showed that this mechanism was also important in the extreme rainfall event in Henan province. The stronger Huang-Huai cyclone in the wet composite may be caused by the transport of more water vapor to Henan via the southerly flow, making it wetter with stronger convergence over the Henan region. In the NW sensitivity simulations, as In-fa's motion was modified from the CTRL to the NW_240km experiments, the intensity of the Huang-Huai cyclone (near 110°E, 34°N, green dot) decreased with the weaker southerly flow caused by the interactions of the binary typhoons (Figures 7b–7e). This is consistent with the results from the ensemble-based analysis. For example, the cyclonic difference in the magnitude of the column-integrated moisture flux near Henan (110°E, 35°N) is about 25–75 kg m^{-1} s^{-1} in the NW_60km and NW_120km experiments (Figures 7b and 7c) and 75–150 kg m^{-1} s^{-1} in the NW_180km and NW_240km experiments (Figures 7d and 7e). Although changes in the intensity of the Huang-Huai cyclone are crucial in extreme precipitation events, an investigation of the physical processes that influence the Huang-Huai cyclone is beyond the scope of this study.

The divergence of the column-integrated water vapor flux is a good method of detecting the contribution of water transport to precipitation (Banacos & Schultz, 2005) and is also an effective tool for the remote transport of water vapor by typhoons (Wang et al., 2009). To investigate the influence of the binary typhoons on the extreme precipitation event, we examined the divergence of the column-integrated water vapor flux in the NW sensitivity experiments at 00:00 UTC and 12:00 UTC on 20 July 2021 (Figure 8). The location of the convergence zone (red contour) at 00:00 UTC on 20 July 2021 in Henan did not change significantly throughout the modulation of the motion of Typhoon In-fa from NW_60km to NW_240km. However, for the modulation of In-fa's motion from NW_60km to NW_240km experiments (Figures 8c–8f), the location of the convergence zone (shaded), which is closely related to the Huang-Huai cyclone, at 12:00 UTC on 20 July 2021 reached 34°N in the NW_60km,

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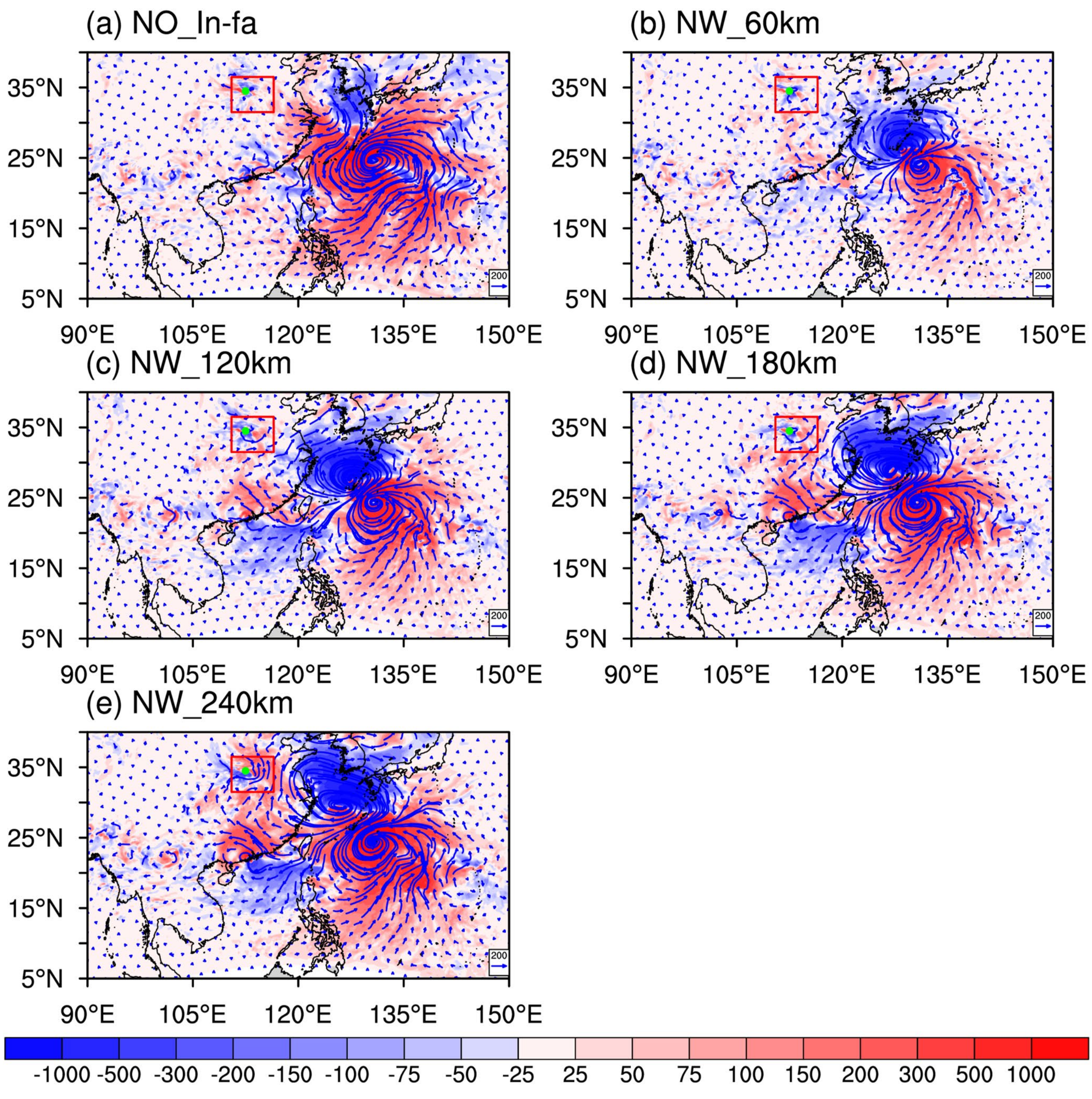

Figure 7. Difference in the column-integrated moisture flux (vectors) and its magnitude (shading; kg m^{-1} s^{-1}) between the CTRL and (a) NO_In-fa, (b) NW_60km, (c) NW_120km, (d) NW_180km, and (e) NW_240km experiments at 00:00 UTC on 20 July 2021. The green dots indicate the approximate location of the Huang-Huai cyclone in CTRL.

32–33°N in the NW_120km and NW_180km and 32°N in the NW_240km run, compared with about 34°N in the CTRL run. Quasi-stationary convergence zone in CTRL run is crucial for convection continuously passing over the same region, and are more possible to produce extreme rainfall (Houze et al., 1990; Xu & Yao, 2015). Removing Typhoon In-fa and the NW_60km run had much more impact on the horizontal distribution of the convergence zone, but less impact on the its motion, which were closer to the CTRL run. By contrast, accelerated movement of the convergence zone from NW_120km to NW_240km runs may have the consequence of significantly decreasing precipitation in the Henan region.

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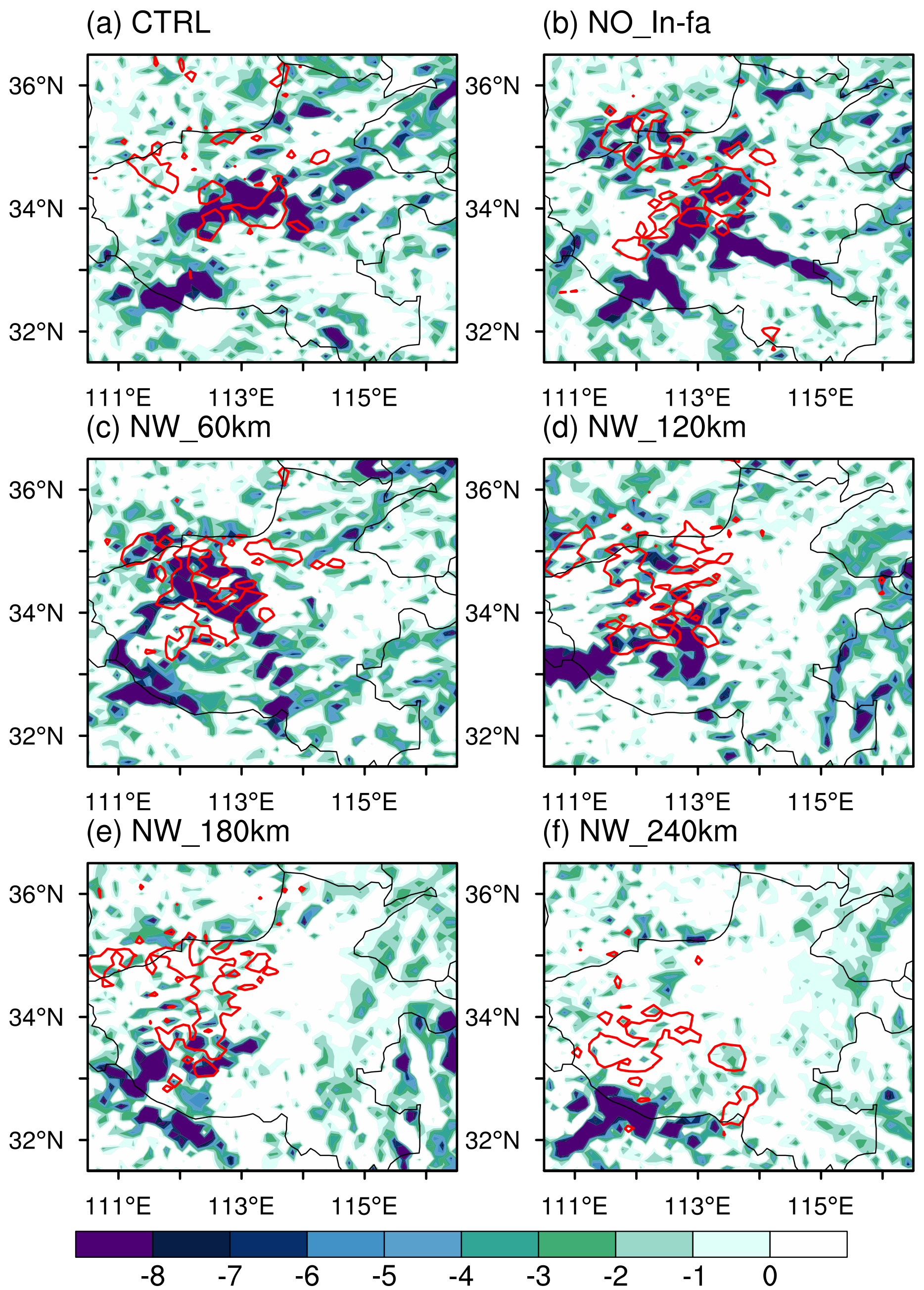

Figure 8. Column-integrated moisture flux divergence at 12:00 UTC (shading; kg m^{-2} s^{-1}) on 20 July 2021, and 00:00 UTC on 20 July 2021 (red contour; <-7 kg m^{-2} s^{-1}) for the (a) CTRL, (b) NO_In-fa, (c) NW_60km, (d) NW_120km, (e) NW_180km, and (f) NW_240km experiments.

A comparison of the CTRL and NW sensitivity experiments showed that the modulation of the movement of Typhoon In-fa may be crucial to the movement of the convergence zone related to the extreme rainfall event. Notably, the convergence zone in the vicinity of Henan (Figure 8) was collocated with the area of heavy rainfall (Figure 4). When Typhoon In-fa was further to the northwest, the inhibited southerly flow led to faster southwestward movement of the convergence zone and less precipitation (Figures 8d–8f) in the Henan area. By contrast, when Typhoon In-fa was not as far northwest and had less influence on the southerly flow (Figures 8a and 8c), it transported more moisture to the south of Henan, leading to a near-stationary convergence zone (about 113°E, 34°N) in Henan with more precipitation (Figures 4a and 4c) compared with the NW_120km, NW_180km, and NW_240km runs (Figures 8d–8f). In addition, the intensity of the Huang-Huai cyclone was slightly decreased near the Henan region in the NW_120km, NW_180km, and NW_240km runs (Figures 8d–8f), implying that the northwesterly motion might play a part in suppressing the Huang-Huai cyclone near Henan. This effect could be attributed to the modification of the southerly flow by the transport of more moisture to Henan and the northwesterly outer circulation of Typhoons In-fa and Cempaka.

The conclusions reported here seem to be different from those of previous studies of the indirect (Schumacher et al., 2011; Schumacher & Galarneau, 2012; Xu et al., 2014) or binary effects of tropical cyclones (Wu et al., 2010; Xu & Du, 2015) on extreme rainfall events, which supports a strong influence of the presence of a tropical cyclone. This could be because tropical cyclones had an important role in enhancing the transport of moisture to the rainfall region in these earlier studies, whereas in this study Typhoon In-fa had only a weak influence in changing the northeasterly and southerly flows to the Henan region. Although the presence of Typhoon In-fa had little influence on the southeasterly flow, its northwesterly motion and the existence of Typhoon Cempaka led to a clear change in the southerly flow. The southerly flow to the south of Henan province was weakened via the northwesterly movement of Typhoon In-fa and the circulation induced by its interaction with Typhoon Cempaka. This reduced the transport of moisture and convergence near the Henan region, leading to a significant decrease in precipitation. However, to place these results in context, the >400 mm accumulated rainfall in the NW_240km run is rare in central China. This emphasizes the fact that large-scale features, such as the subtropical high and monsoons, and the mesoscale environment were both favorable for heavy rainfall.

Changes in the track of In-fa and its influence on the southerly flow simulated by the NW set of experiments were consistent with the results of the ensemble-based analysis. The difference between the CTRL and NW sensitivity experiments (Figure 7) was very close to the difference between the wet and dry members of the operational ensemble forecast analyzed in Part 1 (Xu et al., 2022). This strongly indicates that the connection between the southerly flow and the movement of Typhoon In-fa is very robust. The weaker southerly flow when Typhoon In-fa was more to the northwest would therefore transport less moisture to the region of heavy rainfall and consequently reduce precipitation in this region. This further confirms that the simulated extreme rainfall event was largely influenced by the modulation of the motion of Typhoon In-fa from the NW_60km to the NW_240km experiments. We therefore assessed the connection between Typhoon Cempaka and the extreme rainfall event based on the NOC and NW_NOC sensitivity experiments.

3.3. Effects of Typhoon Cempaka

Our analysis showed that the NW sensitivity experiments indicated a large influence of the modulation of the northwestward movement of Typhoon In-fa on the 21 July 2021 extreme rainfall event. The weather systems affected by Typhoon In-fa include the transport of moisture by the southerly flow, the intensity of the Huang-Huai cyclone and the amount of precipitation. When we varied the location of Typhoon In-fa in the simulation, the track of Typhoon Cempaka was significantly affected (Figure 2a), which may indicate the binary interaction between Cempaka and In-fa. It might therefore be anticipated that the interaction of Typhoons In-fa and Cempaka would clearly influence the amount of precipitation in this event. To test this hypothesis, five extra sensitivity simulations with the removal of Typhoon Cempaka (NOC and NW_NOC experiments; Table 1) were conducted using the method described in Section 2.

The effects of Typhoon Cempaka and its interactions with Typhoon In-fa on the extreme rainfall event were examined by comparing the NOC and NW_NOC experiments with the CTRL experiment. Figure 9 shows the 48-hr accumulated precipitation (mm) between 00:00 UTC on 19 July and 00:00 UTC on 21 July 2021 for the CTRL, NOC, and NW_NOC experiments. These results suggest a significant influence of Typhoon Cempaka on the distribution and location of extreme rainfall. For the NOC experiments (Figure 9b), the most striking change was in the location and structure of the heavy precipitation. Most significantly, although the peak precipitation was comparable with that in the CTRL run, the area of heavy precipitation was further north and was narrower and precipitation mainly occurred south of Taihang Mountain.

The column-integrated moisture flux (Figure 10b) shows that the southerly flow over southern China strengthened as we removed Typhoon Cempaka, allowing for the enhanced and more northerly transport of moisture. The differences in the column-integrated moisture flux (Figure 11a) show a stronger southerly outer circulation of Typhoon Cempaka over southern China between NOC and CTRL. For CTRL experiment, this indicate stronger northerly winds induced by outer circulation of Typhoon Cempaka, and the associated weakening of the southerly

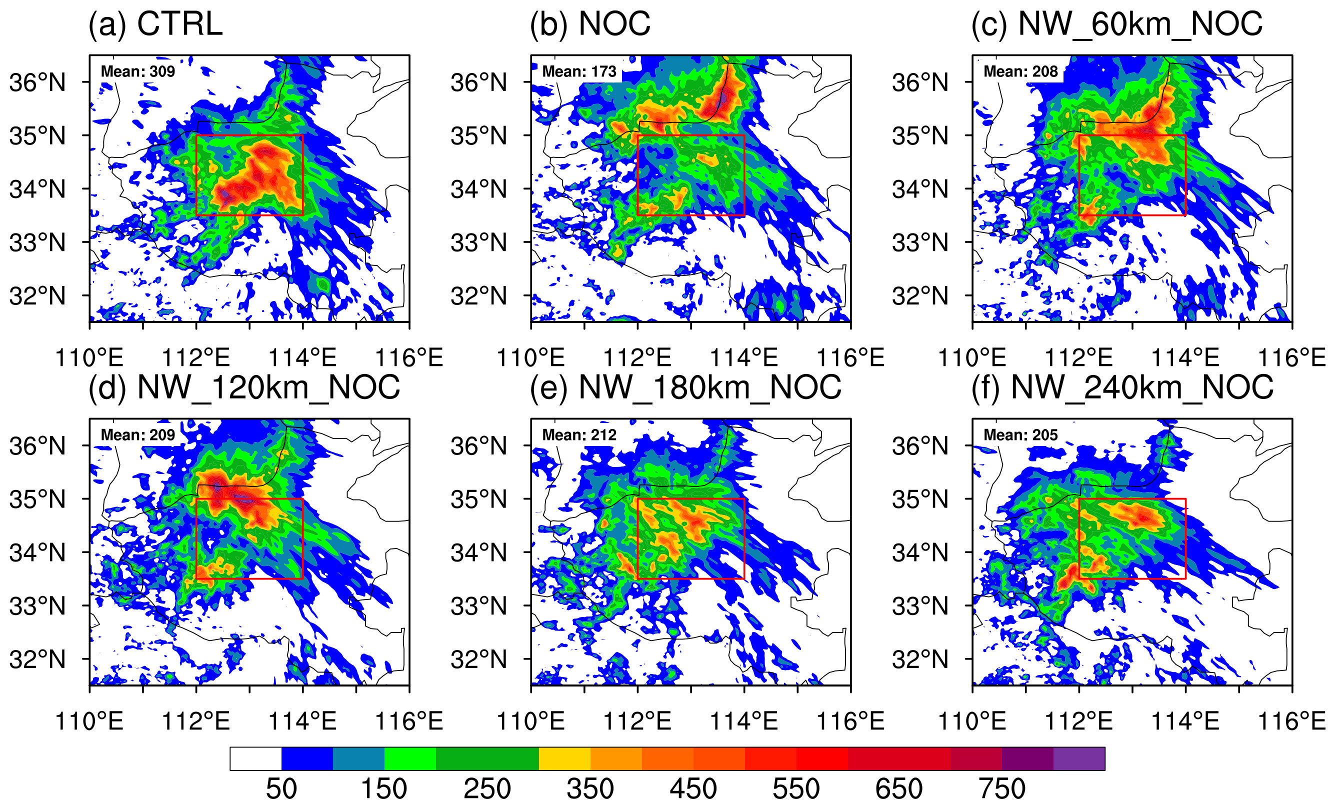

Figure 9. 48-hr accumulated precipitation (mm) between 00:00 UTC on 19 July and 00:00 UTC on 21 July 2021 for the (a) CTRL, (b) NOC, (c) NW_60km_NOC, (d) NW_120km_NOC, (e) NW_180km_NOC, and (f) NW_240km_NOC experiments.

winds along the southerly flow. For the NOC run, this change is significant in determining the location and distribution of extreme rainfall (Figures 9a and 9b). The enhancement of the southerly flow by removing Typhoon Cempaka has a significant impact on the area-averaged intensity of precipitation (Figure 12), but also changed the distribution of the precipitation intensity.

Far more dramatic changes were seen in the NW_NOC sensitivity experiments. A comparison of Figures 9c–9f (NW_NOC group) with Figures 4c–4f (NW group) and Figure 9 (CTRL) shows that Typhoon Cempaka changed the simulated distribution of rainfall in the storm system. The maximum rainfall in the NW_NOC run was located more to the north and more closely enhanced by the topography compared with the NW run, but there was rainfall reduced as compared with the CTRL run. The column-integrated moisture flux (Figures 10c–10f) shows that the evolution of the moisture channel, including the southerly flow, was also in agreement with the NOC experiment, indicating that the movement of Typhoon In-fa had much less influence on moisture transport than that in NW runs.

Figures 11c–11f shows that the positive bias of the moisture flux in NW run (Figures 7b–7e), while still present, was significantly reduced in the NW_NOC run. Although it has some influence on the southerly flow, it was much smaller than in the NW run. This difference may be due to the northeasterly flow induced by the interaction of the binary Typhoons. Previous experience with the high-resolution simulation of multiple typhoons has shown that the circulation can be sensitive to the intensity and track of the vortex, particularly for typhoons related to the environmental transport of moisture (Xu & Du, 2015; Xu et al., 2013). In this example, the numerical simulations suggest some sensitivity to the interaction of the binary tropical cyclones. Specifically, the existence of Typhoon Cempaka and the northwesterly motion of Typhoon In-fa could together influence the distribution and location of extreme rainfall.

We conclude that the removal of Typhoon Cempaka resulted in intensification of the southerly flow, which, in turn, allowed the water vapor to be transported further and to accumulate in the area south of Taihang Mountain, resulting in a large increase in topographic precipitation in this region. The interaction between Typhoons

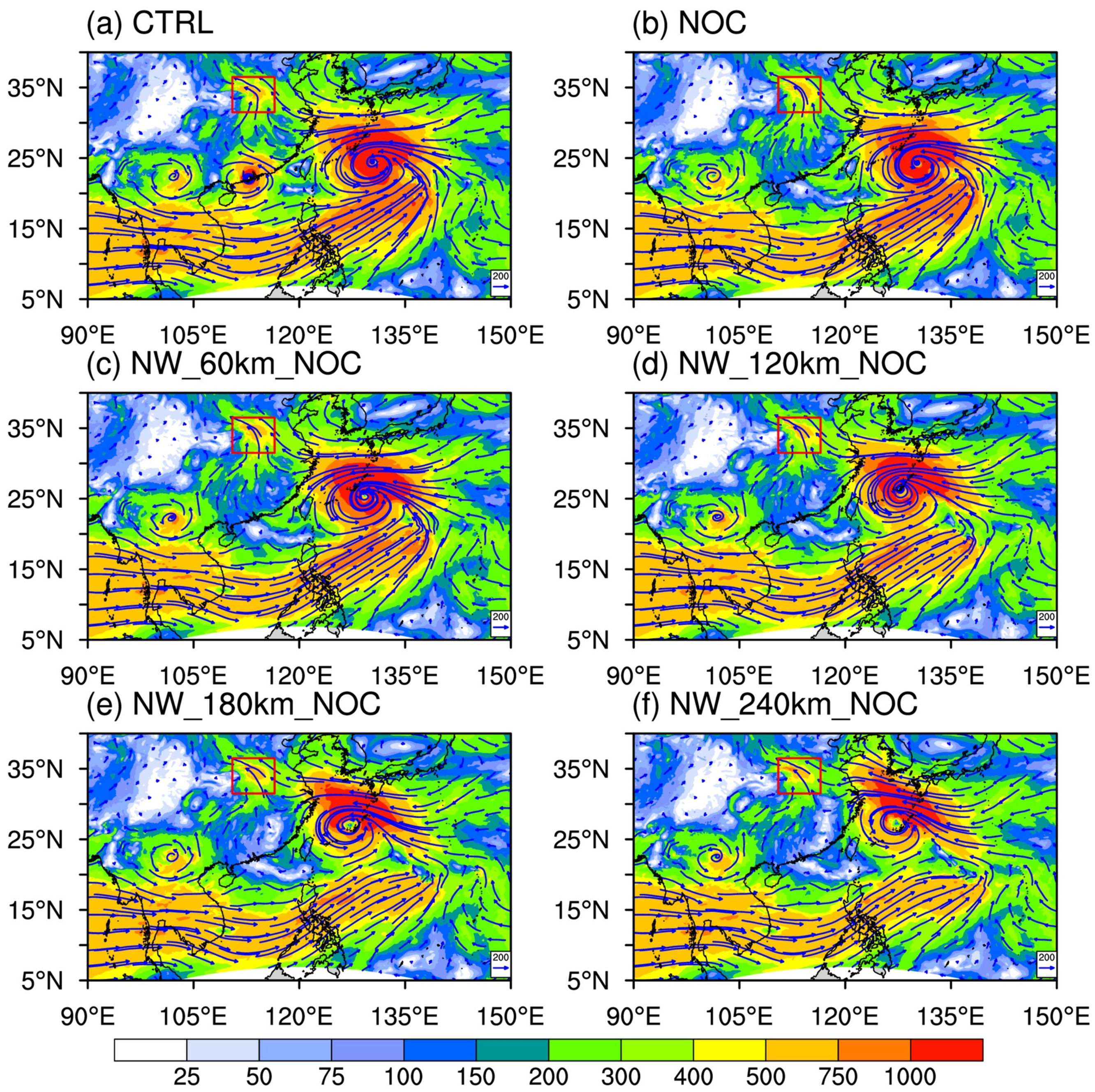

Figure 10. Column-integrated moisture flux (vectors) and its magnitude (shading; kg m^{-1} s^{-1}) at 00:00 UTC on 20 July 2021 for the (a) CTRL, (b) NOC, (c) NW_60km_NOC, (d) NW_120km_NOC, (e) NW_180km_NOC, and (f) NW_240km_NOC experiments.

Cempaka and In-fa is also important. In the absence of Typhoon Cempaka, although Typhoon In-fa still affected precipitation, this effect was much smaller than in the presence of Cempaka. For example, precipitation decreased by 50% in the NW_240km experiment (Figure 5), but only by 25% in the NW_240km_NOC experiment (Figure 12). This suggests that both the movement of Typhoon In-fa and its interaction with Typhoon Cempaka had a significant effect on the extreme precipitation event.

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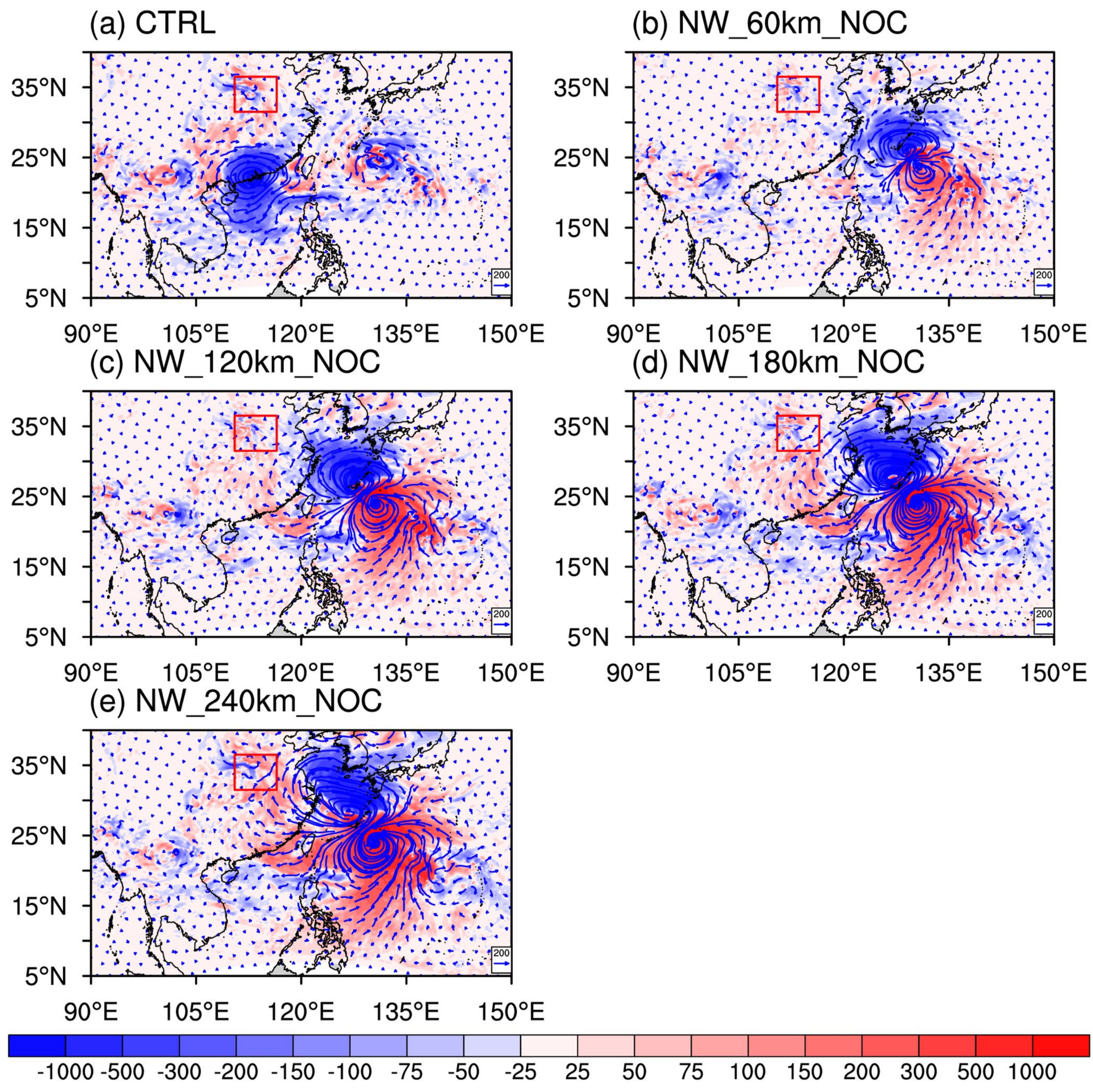

Figure 11. Difference in the column-integrated moisture flux (vectors) and its magnitude (shading; kg m^{-1} s^{-1}) at 00:00 UTC on 20 July 2021 between the NOC and the (a) CTRL, (b) NW_60km_NOC, (c) NW_120km_NOC, (d) NW_180km_NOC, and (e) NW_240km_NOC experiments.

4. Effects of the Interactions of Binary Typhoons

The interaction of binary tropical cyclones involves the interaction of two storms. This is not only crucial to the track and intensity of the tropical cyclones, but also significantly affects the related precipitation and waves (Carr & Elsberry, 1998; Carr et al., 1997). As discussed in Part 1 (Xu et al., 2022), distance is a useful criterion in observational statistics to determine whether tropical cyclones are interacting. However, the critical distance is very different in different studies, ranging from 500 to 1600 km (Chang et al., 2021), as a result of the large differences in typhoon size and intensity. For example, the critical distance in E.-J. Cha et al. (2021) was 1300 km, whereas it was 1600 km in Jang and Chun (2015a). Previous studies (Xu et al., 2011, 2013) have also shown that the intensity and distribution of rainfall is greatly affected by the cyclonic circulation formed by binary tropical

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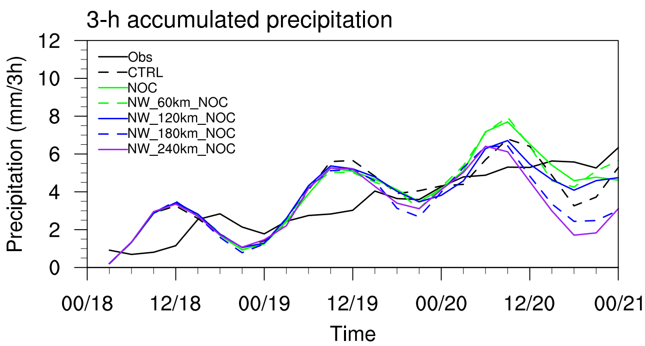

Figure 12. Time series of the 3-hourly precipitation (mm) from 00:00 UTC on 18 July to 00:00 UTC on 21 July 2021 averaged over the red boxes in Figure 1b from the CTRL and NW_NOC sensitivity experiments and the China Meteorological Administration observations.

cyclones. It is therefore reasonable to identify the interaction of binary tropical cyclones through the cyclonic circulation formed by their interaction when considering heavy precipitation events.

Many observational studies of binary tropical cyclones have estimated their interaction in terms of the critical distance. We show here how the distance varies between different simulations. Figure 13 compares the mean sea-level pressure simulated by the NW sensitivity experiments at 12:00 UTC on 20 July with the column-integrated moisture flux superimposed in each experiment. An examination of the distance between the two typhoons in the sensitivity experiment for Typhoon In-fa shows that the distance between two typhoons has a clear influence on the heavy rainfall event. The distance between the two typhoons decreased from about 1893–1218 km with the modulation of In-fa's motion from the CTRL run to the NW_240km run. Specifically, the distance between the two storms was 1893 km in the CTRL experiment (Figure 13a), 1669 km in the NW_60km (Figure 13b) experiment, which is close to the critical distance in Jang and Chun (2015a), 1336 km in the NW_120km experiment (Figure 13c), 1235 km in the NW_180km experiment (Figure 13d) and 1218 km in the NW_240km experiment (Figure 13e).

Following Xu et al. (2013), we examined the circulation induced by the interaction between Typhoons In-fa and Cempaka. The low pressure surrounding In-fa and Cempaka was pronounced. When In-fa's motion was modified from the CTRL to the NW_240km experiments (Figure 13), two key results emerged: (a) the pressure between and around In-fa and Cempaka decreased, resulting in a lower simulated pressure over southern China and the coastal areas, lending support to the suggestion that a decrease in the distance between two storms favors their interaction; and (b) the angle between the line of the centers of the two typhoons and the east–west direction changed. The relative positions of the two typhoons changed from east–west in the CTRL (Figure 13a) experiment to northeast-southwest in the NW_180km (Figure 13d) and NW_240km (Figure 13e) experiments. This caused the northeasterly winds north of the two typhoons to become stronger, leading to more pronounced weakening of the southerly wind and a significant decrease in precipitation. These results indicate that many of the differences in the NW sensitivity experiments can be attributed to the circulation induced by the interaction between Typhoons In-fa and Cempaka.

The binary interactions between Typhoons In-fa and Cempaka can also be seen from the differences of the tracks in the NW sensitivity experiments. These changes in track also show that Typhoons Cempaka and In-fa interact. The track of Typhoon Cempaka over the South China Sea coast showed significant variations throughout the modulation of the motion of Typhoon In-fa from the NW_60km to the NW_240km experiments (Figure 2a). The track of Typhoon Cempaka changed from northwestward in the CTRL experiment to westward in the NW_60km and NW_120km experiments and then turned into a looped track in the NW_180km and NW_240km experiments. Both the motion and circulation induced by Typhoons In-fa and Cempaka indicate that there is a clear interaction between the two typhoons, with the track of typhoon In-fa further to the northwest. The closer the two typhoons were to each other, the stronger their interaction and the weaker the southerly flow. As a result, the precipitation in Henan region was significantly reduced.

5. Discussion and Conclusions

The quantitative prediction of extreme precipitation has always been challenging, especially for events influenced by multiple typhoons. The impacts of typhoons In-fa and Cempaka on the extreme rainfall event in Henan from 19 to 21 July 2021 were investigated using numerical simulations with the ARW-WRF model. We focused on how the binary typhoons affected the transport of moisture to the Henan extreme rainfall event. Consistent with the observations, the abnormal track of the typhoons was reasonably reproduced, with the maximum accumulated rainfall falling in Henan. In particular, the model captured the northwesterly movement of Typhoon In-fa and the slow movement of Typhoon Cempaka during the extreme rainfall event. The CTRL experiment also reproduced the structure and distribution of precipitation over the Henan region.

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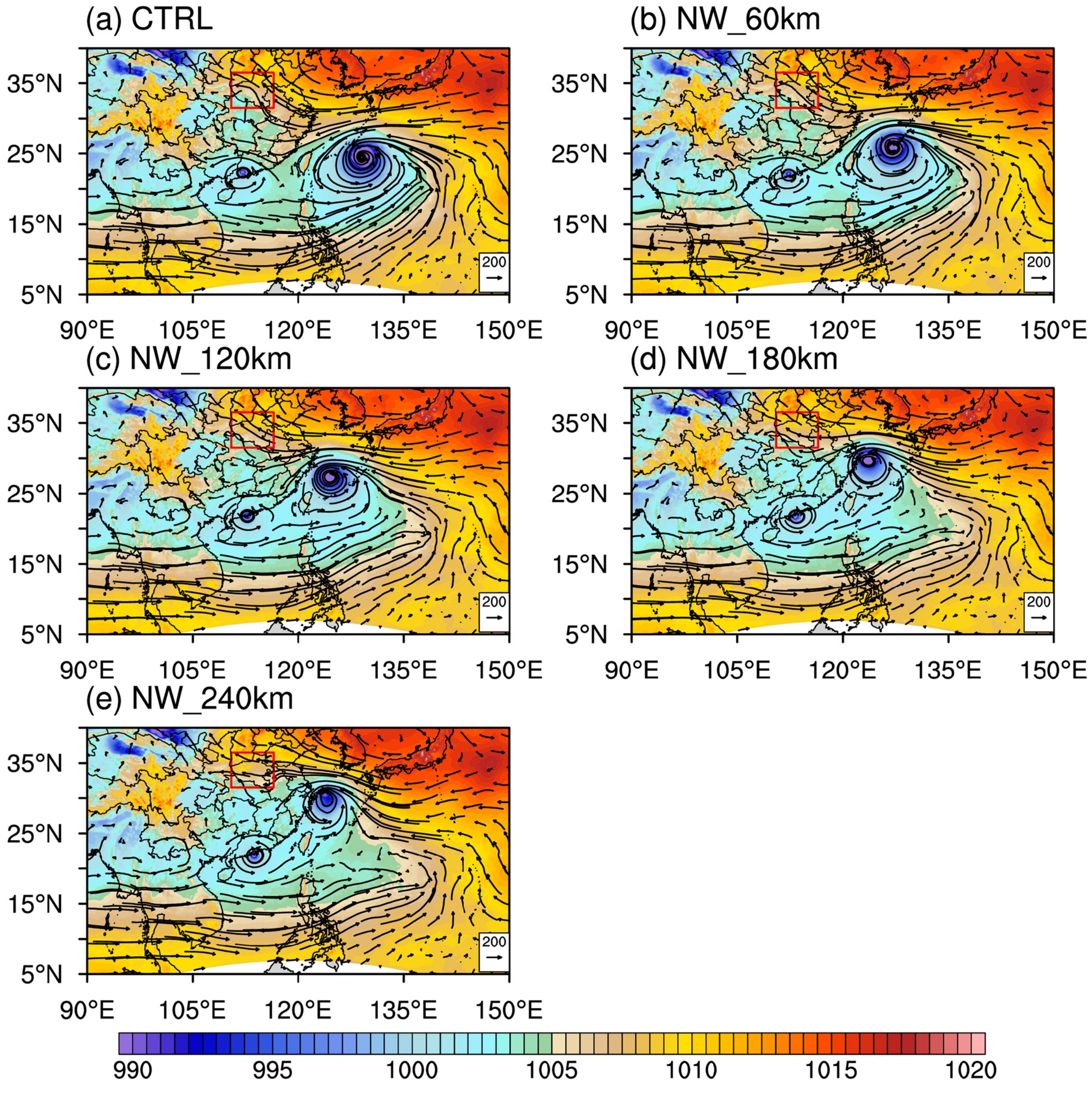

Figure 13. Column-integrated moisture flux (vectors; kg m^{-1} s^{-1}) and its sea-level pressure (shading; hPa) at 12:00 UTC on 20 July 2021 for the (a) CTRL, (b) NW_60km, (c) NW_120km, (d) NW_180km, and (e) NW_240km experiments.

To demonstrate the impact of the movement of Typhoon In-fa on remote precipitation in Henan, sensitivity experiments (NW experiments) were conducted in which the typhoon vortex was moved 60, 120, 180, and 240 km in both northerly and westerly directions using the initial and lateral boundary conditions from the ECWMF ERA5 data set. The artificial modulation of Typhoon In-fa largely suppressed the southerly flow and associated rainfall over Henan province, indicating the impact of the movement of Typhoon In-fa on the remote rainfall event. In addition, the variation of the track of Typhoon In-fa and the associated southerly flow simulated by the NW runs were consistent with the results of the ensemble-based analysis reported in Part 1 (Xu et al., 2022). The difference between the CTRL and NW runs was very close to the difference between the dry and wet members. This strongly suggests that the connection between the southerly flow and the modulation of northwesterly motion of Typhoon In-fa was very robust.

In addition, in the experiment with Typhoon Cempaka removed over southern China (NOC), although the area-averaged amount of rainfall was similar to that in the CTRL experiment, the distribution and location of precipitation changed significantly, indicating that Typhoon Cempaka played a crucial part in the location and distribution of extreme precipitation. Another set of similar numerical experiments was conducted with the removal of Typhoon Cempaka. The results indicated that in the absence of Typhoon Cempaka, although Typhoon In-fa still affected precipitation, the effect was much smaller than in the presence of Cempaka. For example, the precipitation decreased by 50% in the NW_240km experiment, but by only 25% in the NW_240km_NOC experiment during the periods of maximum precipitation. This indicates that both the movement of Typhoon In-fa and its interaction with Typhoon Cempaka had a significant remote effect on the extreme precipitation.

This study is the second part of a series on extreme precipitation over Henan, central China associated with binary typhoons. In Part 1 (Xu et al., 2022), we applied an ensemble-based analysis to identify Typhoons In-fa and Cempaka as key factors in the extreme rainfall event. In this study (Part 2, this paper), we conducted high-resolution numerical experiments and confirmed that the northwesterly motion of Typhoon In-fa and its interaction with Typhoon Cempaka had a significant role in the extreme rainfall event through the southerly flow. The major process involved in the remote influence of Typhoon In-fa was through the southerly flow into Henan region caused by its northwesterly motion and its interaction with Typhoon Cempaka. The movement of Typhoon In-fa was crucial to the simulated extreme rainfall event in Henan, even though Typhoon In-fa was >1500 km to the southeast over the western North Pacific. However, Typhoon In-fa affected the extreme precipitation event by reducing the transport of water vapor to the region of extreme rainfall. This seems to contrast with previous numerical studies of the remote effects of tropical cyclones on rainfall by enhancing the transport of water vapor (Schumacher et al., 2011; Wang et al., 2009; Wen et al., 2015). One possible reason for these different results is that the circulation of binary typhoons not only enhances the transport of water vapor, but also weakens the transport of water vapor under specific conditions. These processes are determined by the direction of transport of water vapor in the environment (Xu et al., 2013).

The results of this study, as well as those from research on the remote effects of tropical cyclones, strongly suggest that more effort should be made to investigate how multiple tropical cyclones control environmental processes. We plan to study more extreme precipitation events affected by multiple tropical cyclones to clarify their remote effects on extreme rainfall events, which may change under different atmospheric conditions.

Data Availability Statement

The model outputs presented in this manuscript are available from Xu (2022). ECMWF Reanalysis v5 data are available on the website https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form (CDS, 2022).

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