Article ID: 1006-8775(2021) 01-0034-14

The Key Supply Source of Long-Distance Moisture Transport for the Extreme Rainfall Event on July 21, 2012 in Beijing

LI Juan (李 娟)[1,2,3], XU Xiang-de (徐祥德)[4], LI Yue-qing (李跃清)[2,3], ZHAO Tian-liang (赵天良)[1], WU Chong (吴 翀)[4]

(1. Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, PREMIC, Nanjing University of Information Science and Technology, Nanjing 210044 China;
2. Institute of Plateau Meteorology, China Meteorological Administration, Chengdu 610072 China;
3. Heavy Rain and Drought-Flood Disasters in Plateau and Basin Key Laboratory of Sichuan Province, Chengdu 610072 China; 4. State Key Laboratory of Severe Weather (LASW), Chinese Academy of Meteorological Sciences, Beijing 100081 China)

Abstract: In this study, the Weather Research and Forecasting (WRF) model and meteorological observation data were used to research the long-distance moisture transport supply source of the extreme rainfall event that occurred on July 21, 2012 in Beijing. Recording a maximum rainfall amount of 460 mm in 24 h, this rainstorm event had two dominant moisture transport channels. In the early stage of the rainstorm, the first channel comprised southwesterly monsoonal moisture from the Bay of Bengal (BOB) that was directly transported to north China along the eastern edge of Tibetan Plateau (TP) by orographic uplift. During the rainstorm, the southwesterly moisture transport was weakened by the transfer of Typhoon Vicente. Moreover, the southeasterly moisture transport between the typhoon and western Pacific subtropical high (WPSH) became another dominant moisture transport channel. The moisture in the lower troposphere was mainly associated with the southeasterly moisture transport from the South China Sea and the East China Sea, and the moisture in the middle troposphere was mainly transported from the BOB and Indian Ocean. The control experiment well reproduced the distribution and intensity of rainfall and moisture transport. By comparing the control and three sensitivity experiments, we found that the moisture transported from Typhoon Vicente and a tropical cyclone in the BOB both significantly affected this extreme rainfall event. After Typhoon Vicente was removed in a sensitivity experiment, the maximum 24-h accumulated rainfall in north China was reduced by approximately 50% compared with that of the control experiment, while the rainfall after removing the tropical cyclone was reduced by 30%. When both the typhoon and tropical cyclone were removed, the southwesterly moisture transport was enhanced. Moreover, the sensitivity experiment of removing Typhoon Vicente also weakened the tropical cyclone in the BOB. Thus, the moisture pump driven by Typhoon Vicente played an important role in maintaining and strengthening the tropical cyclone in the BOB through its westerly airflow. Typhoon Vicente was not only the moisture transfer source for the southwesterly monsoonal moisture but also affected the tropical cyclone in the BOB, which was a key supply source of long-distance moisture transport for the extreme rainfall event on July 21, 2012 in Beijing.

Key words: rainfall; moisture transport; typhoon; tropical cyclone; Beijing
CLC number: P407.7 **Document code:** A
https://doi.org/10.46267/j.1006-8775.2021.004

1 INTRODUCTION

North China is located in the middle latitude of East Asia and has a complex terrain. Extreme rainfall events frequently occur in Beijing and adjacent regions, making it one of the three major rainfall areas in east China during summer (Xie et al. [1]; Tao et al. [2]; Sun [3]; Zhu et al. [4]). Rainstorms in north China typically have regional characteristics and are intense and concentrated in time and location, often causing serious flooding. Summer rainfall accounts for more than 50% of the annual rainfall in north China. This concentrated rainfall is often caused by several rainstorms, with the daily rainfall of a single rainstorm sometimes reaching more than 50% of the monthly rainfall (Tao et al. [5]; Writing Group of heavy rain in North China [6]). However, each rainstorm has unique synoptic scale systems and mesoscale forcing sources, making it difficult for us to forecast catastrophic rainstorm events (Wu et al. [7]; Li

Submitted 2020-10-10; **Revised** 2020-11-15; **Accepted** 2021-02-15

Funding: National Natural Science Foundation of China (91937301, 42030611); Second Tibetan Plateau Scientific Expedition and Research Program (2019QZKK0103, 2019QZKK0105); Scientific and Technological Research Program of China Railway Eryuan Engineering Group CO. LTD (KYY2020066 (20-22))

Biography: LI Juan, Ph. D. candidate, primarily undertaking research on diagnostic analysis and model evaluation of weather and climate.

Corresponding author: XU Xiang-de, e-mail: xuxd@cma.gov.cn

et al. [8]).

The interaction of mesoscale systems in favorable large-scale circulation usually induces heavy rainfall. Some studies have investigated the large-scale circulation of heavy rainfall in north China (Cong et al. [9]; Duan et al. [10]; Liang et al. [11]; Shan et al. [12]). Tao [5] summarized the "63 · 8" rainstorm in north China and reported that under specific longwave conditions, a stagnant synoptic scale system, sufficient supply of water vapor, and favorable terrain all contribute to sustained heavy rainfall in north China. Lei [13] conducted a synthetic analysis of ten persistent meridional torrential rainfall events in north China and suggested that the upper subtropical jet and low-level southerly jet are direct dynamic conditions that contribute to rainstorms. Zhou's [14] analysis of the circulation of approximately 50 regional torrential rainfall events in north China indicated that western Pacific subtropical high (WPSH) is the dominant system affecting the interaction of various weather systems on the mid- and high-latitude westerly belt and low-latitude easterly belt. Sun et al. [15] conducted a statistical study on the summer heavy rainfall in north China during the 1990s. Based on different weather systems, they identified five types of heavy rainfall events. The first type features long-distance interaction between typhoon and low trough (low vortex), the second involves interaction between low vortex (landfalling typhoon) and westerly trough, the third entails landfalling typhoon with northward movement stagnated by high pressure, the fourth and fifth is low vortex type and warm shear type, respectively. For them, typhoon and low vortex are the most prominent events. Zhang et al. [16] studied heavy rainfall events that occurred over the past 50 years in north China and suggested that a new observation method and numerical simulation should be combined to conduct a more detailed study to look into mesoscale weather systems of heavy rainfall in north China. Such an approach would reveal the three-dimensional structural characteristics of heavy rainfall events and associated physical mechanisms.

An extreme rainfall event hit Beijing on July 21, 2012, with 24-h accumulated rainfall reaching 460 mm in Hebei Town of Fangshan District. This event recorded the heaviest rainfall in Beijing since 1951 (Chen et al. [17]). It caused severe disasters around the region and induced major urban flooding in Beijing, leading to 79 deaths and economic losses of about 2 billion U. S. dollars. Many studies have been conducted on this extreme rainfall event in terms of precipitation characteristics, large-scale circulation fields, water vapor transportation, and mesoscale convective system development (Liu et al. [18]; Liu et al. [19]). Chen et al. [17] indicated that the "7 · 21" extreme rainfall event in Beijing exhibited a typical north China rainstorm circulation pattern. The large-scale circulation was basically consistent with the "long-distance interaction between typhoon and low trough (low vortex)" circulation type identified by Sun [15]. The low vortex shear, low-level jet, ground convergence line, and topography corporately triggered and maintained heavy rainfall in extremely high moisture regions in the boundary layer, and warm and moist air transported from the tropics and subtropics provided abundant water vapor for rainstorm. Sun et al. [20] reported that tropical cyclone activities are favorable for moisture transport to the East Asian continent. The source of moisture during heavy rainfall includes the Bay of Bengal (BOB), the Bohai Sea, and the Yellow Sea. Low-level moisture mainly comes from the Bohai Sea and the Yellow Sea, and mid-level moisture mainly comes from the BOB.

An abundant supply of water vapor is a key factor to rainstorm development. The moisture in north China rainstorms usually comes from the BOB, the South China Sea, and the western Pacific (the East China Sea and the Bohai Sea); however, the relative importance of these sources varies with weather systems. The "7 · 21" extreme rainfall event had two obvious water vapor channels: one was the southeasterly water vapor transported from the western Pacific by Typhoon Vicente and a subtropical high, and the other was the warm and moist air of the Indian Ocean carried by southwest monsoon (Fig. 8). However, which of the two water vapor channels was the main one and what role did they play in water vapor transport and convergence is unclear and deserves further research. Xu et al. [21] conducted a numerical simulation and sensitivity experiment using the Weather Research and Forecasting (WRF) model that excluded Typhoon Vicente. The comparative analysis verified the effect of moisture transfer among the three systems of the southwest monsoon airflow, typhoon vortex, and circulation of the rainstorm region during the extreme rainfall event in Beijing. Additionally, tropical cyclone in the BOB contributes to the large-scale water vapor transport of the southwest monsoon. However, few studies have focused on the impact of the tropical cyclone in the BOB on the moisture transport for the rainstorm region in Beijing; therefore, the interaction of moisture transport between the BOB tropical cyclone and Typhoon Vicente is worth further investigation.

In this paper, we analyzed the long-distance impact of Typhoon Vicente and tropical cyclone in the BOB on this extreme rainfall event and focused on the moisture transport interaction of the typhoon vortex and tropical cyclone, which contributed to the heavy rainfall event in Beijing on July 21, 2012. The remainder of this article is organized as follows. Section 2 introduces the data and method used in this study. Section 3 describes the favorable larger-scale conditions for extreme rainfall. Section 4 examines the numerical experiments and the sensitivity of precipitation to the model. Section 5 discusses the interrelation of Typhoon Vicente and the tropical cyclone in the BOB with respect to moisture transport for extreme rainfall. Section 6 provides a summary and discussion.

2 DATA AND METHODOLOGY

This study uses hourly rain gauge data collected from more than 2000 automatic meteorological stations. The data have been quality controlled and are archived at the National Meteorological Information Centre of China. To describe atmospheric conditions, this study also uses the ERA-Interim reanalysis data (Dee et al. [22]) with a horizontal resolution of 0.75° × 0.75° and a time interval of 6 h.

This study focuses on the long-distance moisture transport for extreme rainfall in Beijing. We calculate the column-integrated moisture (Q) and its fluxes in the zonal (Q_u) and meridional (Q_v) directions. The equations for these calculations are as follows:

$$Q = \frac{1}{g}\int_{P_s}^{p} q\,\mathrm{d}p, \tag{1}$$

$$Q_u = \frac{1}{g}\int_{ps}^{p} qu\,\mathrm{d}p, \tag{2}$$

$$Q_v = \frac{1}{g}\int_{ps}^{p} qv\,\mathrm{d}p. \tag{3}$$

In these equations, g represents gravity, q denotes specific humidity, u and v are the zonal and meridional wind components, respectively, P_s denotes the surface pressure, and P is the pressure at 300 hPa.

To explain the relationship between extreme rainfall in Beijing and column-integrated moisture transport, particularly the long-distance moisture transport from Typhoon Vicente and tropical cyclone in the BOB, we compute a correlation vector to track moisture sources and transport pathways. It is expressed as

$$\vec{R}(x,y) = R_x(x,y)\,\vec{i} + R_y(x,y)\,\vec{j}, \tag{4}$$

where R_x (x, y) and R_y (x, y) represent the correlation coefficients between the column-integrated moisture and column-integrated zonal / meridional moisture fluxes, respectively.

3 OVERVIEW OF THE EXTREME RAINFALL EVENT

The extreme rainfall event, which occurred on July 21-22, 2012 in Beijing, recorded the heaviest rainfall in Beijing since 1961. Fig. 1 shows the 24-h accumulated rainfall (from 00: 00 UTC on July 21, 2012 to 00: 00 UTC on July 22, 2012) at rain gauge stations. The heavy rainfall areas were mainly located in Beijing and its surrounding regions (enclosed in the blue box in Fig. 1) parallel to the southwest-northeast-oriented mountain ranges (Yu [23]). The average rainfall amount received in Beijing area during this rainfall event was estimated to be more than 190 mm, with the maximum rainfall amount of 460 mm observed at Hebei town station. The distribution of rainfall amounts every 6 h (shaded in Fig. 2) shows that the rainfall started in the southwest part of Beijing near the mountain ranges and moved northeastward, and the rainfall in Beijing area reached its maximum between 06:00 and 12:00 UTC.

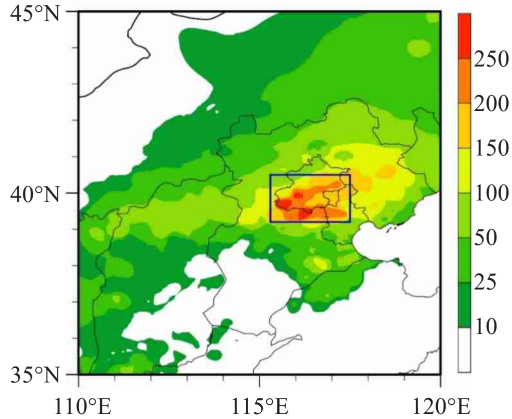

Figure 1. Observed 24-h accumulated rainfall from 00: 00 UTC on July 21, 2012 to 00:00 UTC on July 22, 2012 (units: mm, the blue box is the main rainstorm region).

This extreme rainfall event was closely related to circulation conditions. Fig. 2 shows the large-scale circulation of every 6 h on July 21, 2012 at 850 and 500 hPa, together with the observed 6-h accumulated rainfall event. Before the rainstorm reached its peak, Typhoon Vicente gradually approached the coastal province of Guangdong from the South China Sea and the WPSH extended northward to near the East China Sea. There was a strong southeasterly airflow on the west side of the subtropical high and on the north side of the typhoon vortex. The southwesterly monsoonal flow from the BOB converged with the southeasterly airflow along the eastern edge of the Tibetan Plateau (TP), transporting abundant moisture to the rainstorm region through a south-southwest pathway. Meanwhile, there was a tropical cyclone in the BOB. Beijing is located ahead of a major 500-hPa trough, which was blocked by the subtropical high and moved eastward toward Beijing during the rainfall event.

The large-scale synoptic systems described above provided favorable conditions for rainfall and caused strong convection instability in Beijing and its surrounding areas. Combined with factors such as local topography and mesoscale convective systems, these conditions jointly triggered the extreme rainfall event in Beijing. The study of this rainstorm event has indicative significance for the exploration of the influence of long-distance moisture transport of typhoons and southwest monsoon on the rainstorm region.

4 NUMERICAL SIMULATION AND SENSITIVITY STUDIES

To further investigate the impacts of Typhoon Vicente and tropical cyclone in the BOB on the extreme rainfall event that occurred in Beijing on July 21, 2012, the present study uses the WRF model (version 3.4.1) (Skamarock et al. [24]) to simulate this extreme rainfall event. The period from 00:00 UTC on 20 July 2012 to 00:00 UTC on 22 July 2012 is simulated, covering the

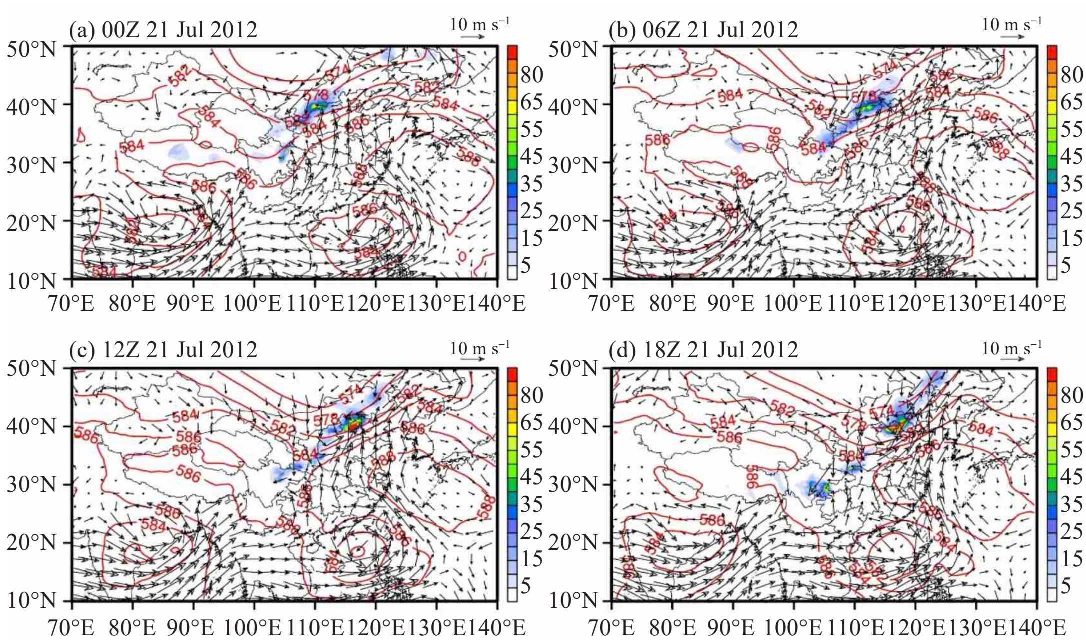

Figure 2. Large-scale horizontal 850-hPa wind (vectors, units: m s^{-1}) and 500-hPa geopotential height (contours, units: dagpm) at (a) 00:00, (b) 06:00, (c) 12:00, and (d) 18:00 UTC on July 21, 2012. The shaded region represents 6-h accumulated rainfall (units: mm).

entire precipitation event. The nested domains of the simulation are centered at 30°N, 116.5°E. Moreover, the model horizontal spacing is 30, 10, and 3.3 km for each domain, and the numbers of model horizontal grid points are 375 × 246, 238 × 160, and 394 × 286, respectively. All domains have 28 vertical levels, with the top level at 50 hPa. The time step for the simulation is 60 s, and the output data time step is every hour. The initial and lateral boundary conditions of all experiments are based on the National Centers for Environmental Prediction (NCEP) Final Operational Global Analysis (FNL) with a horizontal resolution of 1° × 1° and a time interval of 6 h. Table 1 shows the physical parameter options of the model.

Table 1. Model configuration and parameters.

Model physical options	Parameters	References
Cumulus convective parameterization scheme	Kain-Fritsch (The third domain is not used)	Kain et al. [25], [26]
Shortwave radiation scheme	Dudhia	Dudhia [27]
Longwave radiation scheme	RRTM	Mlawer et al. [28]
Surface layer scheme	Monin-Obukhov	Janjić [29]; Beljaars [30]
Microphysics scheme	WSM5	Hong et al. [31]
Land-surface model	Noah	Chen et al. [32]
Planetary boundary layer	YSU	Hong et al. [31]

Furthermore, the vortex bogus scheme of the WRF-TC model (Fredrick et al. [33]) is conducted to remove Typhoon Vicente and tropical cyclone in the BOB from the initial fields as sensitivity experiments based on the control experiment to quantitatively explain their respective contributions to water vapor transport to the heavy rainfall area. In the TC bogus scheme, the maximum relative vorticity is first searched in the pressure field closest to the surface (usually 1000 hPa) within a 400 km radial distance from the best track location of the tropical cyclone, which is defined as the center of the vortex to be removed. Thereafter, the nondivergent and divergent winds are calculated based on the stream function (ψ) and velocity potential (χ) in the circular domain centered on this maximum relative vorticity within a radius of 300 km by solving the Laplace equations for both relative vorticity ($\nabla^2\psi = \zeta$) and divergence ($\nabla^2\chi = \delta$). Next, the nondivergent and divergent winds are calculated using equations $v_\psi = k \times \nabla\psi$ and $v_\chi = \nabla\chi$, respectively. Then, the calculated nondivergent and divergent winds are subtracted from the first-guess U and V wind fields. The geopotential height anomaly associated with the vortex is solved using equation $\nabla^2\varphi = \zeta_g f_0$, and the geostrophic wind is calculated using $v_g = k \times \nabla\varphi$. Then, v_g is subtracted from the first-guess field. The perturbation temperature and moisture fields can also be calculated using the above method. After the perturbation dynamic and thermodynamic fields are removed from the corresponding analysis fields, only the background flow where the first-guess vortex was originally located remains. Lastly, the vortex is removed from the metgrid file, and the new initial fields are reintegrated using the same simulation parameters as those used in the control experiment.

Figure 3 shows the initial wind fields at 850 hPa for the control and sensitivity experiments. Both Typhoon Vicente and tropical cyclone in the BOB are present in the initial wind field of the control experiment (Fig. 3a, defined as CTRL). However, in the sensitivity experiment where Typhoon Vicente (Fig. 3b, defined as NOTC) is excluded, the typhoon vortex completely disappears and the tropical cyclone in the BOB is removed in the sensitivity experiment of Fig. 3c (defined as NOTCL). Both Typhoon Vicente and tropical cyclone in the BOB are removed in the sensitivity experiment of Fig. 3d (defined as NOTC&L). Fig. 4 shows the corresponding simulated 24-h accumulated rainfall distributions from 00:00 UTC on July 21, 2012 to 00:00 UTC on July 22, 2012. The control experiment well simulates this extreme rainfall event (Fig. 4a), and the simulated rainbelt trend, range of rainfall, rainfall center location, and magnitude are basically consistent with the observed, particularly in the case of the linear precipitation distribution caused by linear mesoscale convective systems (Zhang et al. [34]). Compared with those in the control experiment, the rainbelt moves northward and the rainfall is greatly weakened in the sensitivity experiment wherein the typhoon is removed (Fig. 4b). The maximum 24-h accumulated rainfall in north China is approximately 150 mm, which is 50% lower than that of the control experiment. This finding indicates that Typhoon Vicente had a significant effect on the occurrence of extreme rainfall on July 21, 2012 in Beijing. The sensitivity experiment removing the tropical cyclone (Fig. 4c) shows that two distinct rainbelts are formed in north China, with the rainbelt along the terrain being similar to that of the control experiment. However, the rainfall intensity decreases, and the heavy rainfall center is located in the southwest of the control experiment. The maximum 24-h accumulated rainfall in this experiment is approximately 230 mm, a reduction of approximately 30% compared with that in the control experiment. The other rainbelt that crosses the terrain is parallel to the rainbelt along the terrain and receives less rainfall. The 24-h accumulated rainfall for the sensitivity experiment where both Typhoon Vicente and tropical cyclone in the BOB are removed (Fig. 4d) has the same distribution as the sensitivity experiment where the tropical cyclone is removed separately; however, the rainbelt that crosses the terrain is stronger, and the precipitation is more concentrated. These simulation results show that both the typhoon vortex and southwest monsoon of tropical cyclone in the BOB contributed to the extreme rainfall event in Beijing, which directly affected moisture transport to the heavy rainfall area.

To evaluate the reasons for rainfall formation, Fig. 5 shows the mean large-scale circulation at 700 hPa and column-integrated moisture distribution on July 21, 2012 in the control experiment and the three sensitivity experiments. All three sensitivity experiments (Fig. 5b,

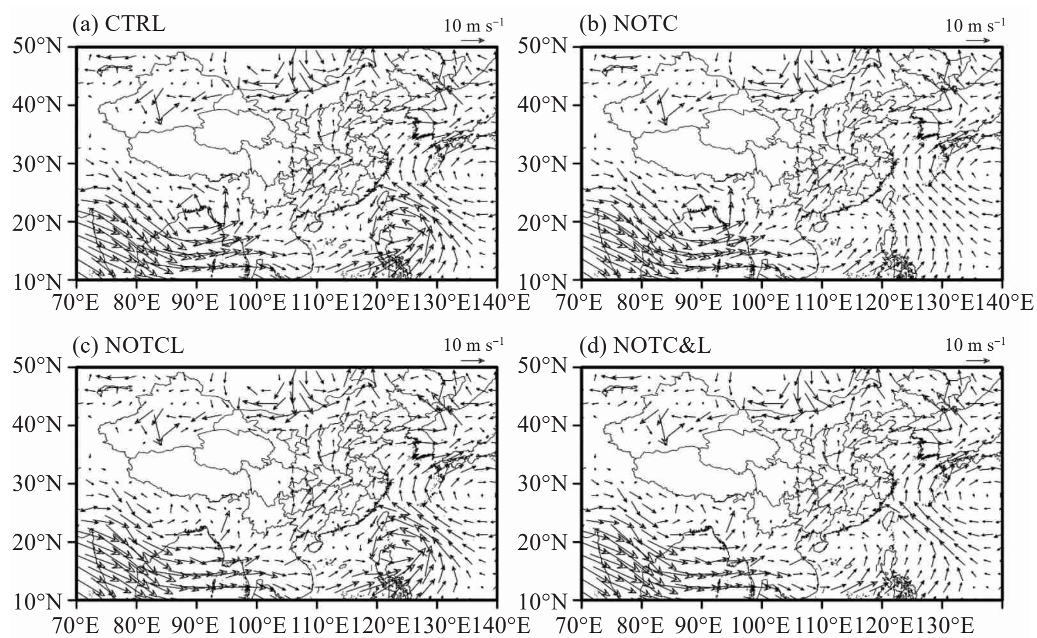

Figure 3. Initial wind fields at 00:00 UTC on July 20, 2012 at 850 hPa (vectors, units: m s^{-1}) for the control experiment (a), the sensitivity experiment with Typhoon Vicente removed (b), the sensitivity experiment with the tropical cyclone in the Bay of Bengal removed (c), and the sensitivity experiment with both Typhoon Vicente and the tropical cyclone removed (d).

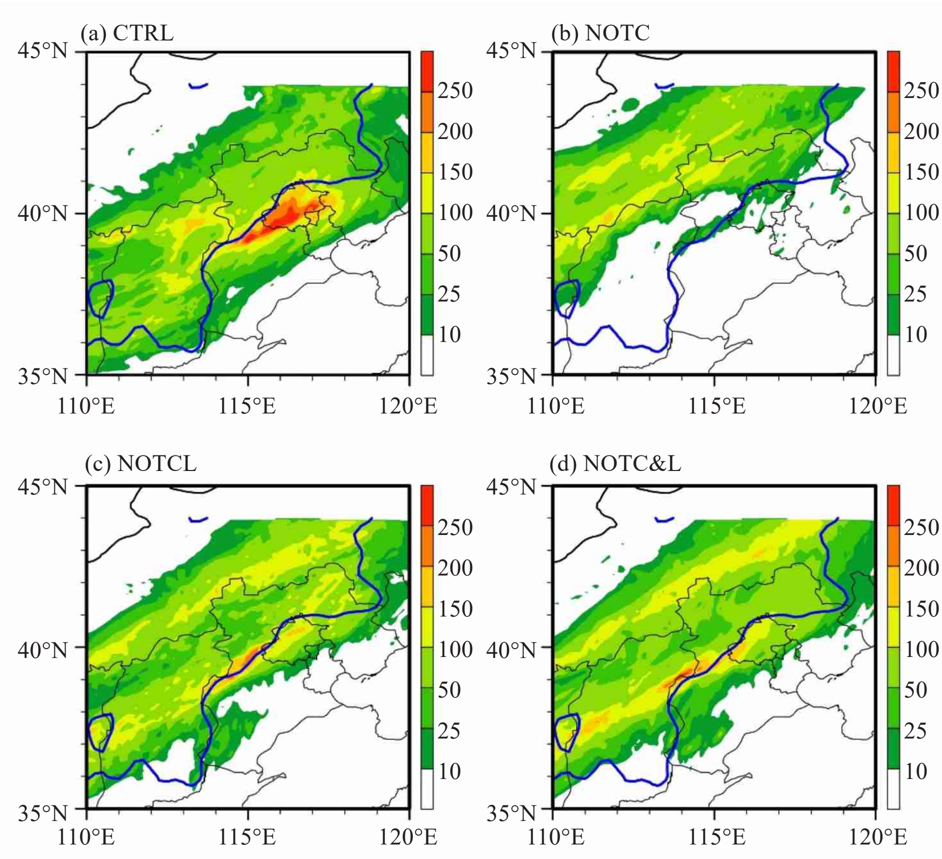

Figure 4. WRF model simulated 24-h accumulated rainfall from 00:00 UTC on July 21, 2012 to 00:00 UTC on July 22, 2012 for the control experiment (a), the sensitivity experiment with Typhoon Vicente removed (b), the sensitivity experiment with the tropical cyclone in the Bay of Bengal removed (c), and the sensitivity experiment with both Typhoon Vicente and the tropical cyclone removed (d) (units: mm, the blue solid line shows the terrain height of 1000 m).

5c, and 5d) ideally remove the vortex in the simulation. Compared with that in the control experiment (Fig. 5a), the southwesterly airflow is strengthened in the sensitivity experiments and warm and moist air from the BOB is transported farther north by the southwesterly airflow. Meanwhile, the cold air in the north weakens southward owing to the blocking of the southwesterly airflow. Therefore, the rainfall shifts northward in all three sensitivity experiments. Furthermore, the removal of Typhoon Vicente weakens the tropical cyclone in the BOB and decreases its moisture transferred by the typhoon, and the column moisture in Beijing is reduced, with less rainfall in the rainstorm area. Additionally, in the sensitivity experiment where the tropical cyclone in the BOB is removed (Fig. 5c), the column moisture in north China is stronger than that in the experiment where Typhoon Vicente is removed (Fig. 5b) and rainfall in the Beijing area also increases slightly. This is because that after the removal of the tropical cyclone in the BOB, the southwesterly airflow becomes stronger than that in the control experiment. Hence, warm and moist air transported from the BOB can cross the complex terrain of southwestern China to reach north China and converge with cold air to contribute to rainfall in the northern part of north China. Moreover, warm and moist air from the South China Sea, carried by Typhoon Vicente, merges with the southwesterly airflow along the eastern edge of the TP due to orographic lift, which favors precipitation along the topography. The results in the sensitivity experiment where both Typhoon Vicente and tropical cyclone in the BOB are removed (Fig. 5d) are similar to those in Fig. 5c, with a stronger southwesterly airflow without the typhoon transfer effect and tropical cyclone branch effect. Therefore, the rainfall in the northern rainbelt is slightly stronger. Comparison of the three sensitivity experiments indicates that both the transfer effect of westerly airflow from Typhoon Vicente and the tropical cyclone branch effect of the easterly airflow in the BOB significantly affect the occurrence of extreme rainfall on July 21, 2012 in Beijing.

We further study the differences in moisture transport between the control experiment and the three sensitivity experiments. Fig. 6 shows the differences in the mean column-integrated moisture flux and their magnitudes between the control experiment and the three sensitivity experiments on July 21, 2012 (each sensitivity experiment subtracts the control experiment). Compared with the control experiment, the sensitivity experiment with Typhoon Vicente removed shows

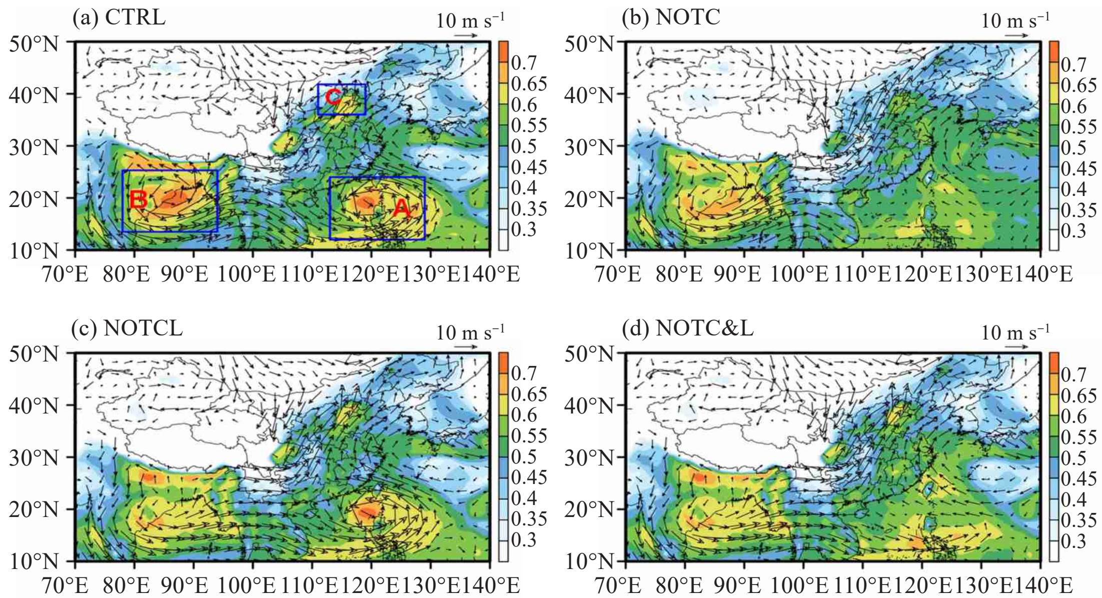

Figure 5. The mean wind at 700 hPa (vectors, m s^{-1}) and column moisture (integrated from surface to 300 hPa, shaded, kg m^{-2}) every 6 h on July 21, 2012 for the control experiment (a), the sensitivity experiment with Typhoon Vicente removed (b), the sensitivity experiment with the tropical cyclone in the Bay of Bengal removed (c), and the sensitivity experiment with both Typhoon Vicente and the tropical cyclone removed (d). A, B, and C illustrate the Typhoon Vicente region, tropical cyclone region, and extreme rainfall region, respectively.

obvious changes in column moisture transport channels (Fig. 6a). The region where the typhoon is originally located becomes an anticyclonic circulation, and the moisture convergence zone is located at the north of the rainbelt in the control experiment. Moisture from the BOB is a main moisture source for this heavy rainfall event. The intensity and direction of the southwesterly airflow from the BOB are changed by Typhoon Vicente. Thus, removing Typhoon Vicente implies that moisture from the BOB can be directly transported northward to north China, steered by the large-scale mid-tropospheric southwesterly airflow without the moisture transfer effect of the typhoon. This leads to an obvious northward movement of the rainbelt relative to the control experiment. However, owing to a lack of moisture from the South China Sea transported by Typhoon Vicente and moisture transfer by the typhoon from the BOB, rainfall in the Beijing area is significantly weakened. Additionally, when Typhoon Vicente is removed, the column moisture flux of the tropical cyclone in the BOB also weakens and the difference in the moisture transport becomes an anticyclonic circulation. This reveals the chain reaction of the moisture transport between the typhoon vortex and the tropical cyclone in the BOB. Typhoon Vicente can influence the intensity of tropical cyclone in the BOB; it plays a vital role in maintaining and strengthening the tropical cyclone through its westerly airflow.

For the sensitivity experiment where the tropical cyclone in the BOB is removed (Fig. 6b), an anticyclonic difference in the column moisture transport in the BOB is observed; however, removing the tropical cyclone has no effect on Typhoon Vicente. The removal of the tropical cyclone in the BOB leads to the weakening of the easterly airflow on the north side of the cyclone. Thus, less moisture is carried by the easterly airflow and the moisture from the BOB is directly transported to north China by the southwesterly monsoonal airflow. Compared with that in the control experiment, the southwesterly moisture transport from the BOB to the rainstorm region is notably strengthened. This result is consistent with that of Jiang et al. [35], who found that suppressing rainfall in the northern BOB may cause abnormal anticyclonic circulation that transports more moisture to the TP. Moreover, the southerly airflow is strengthened. As the southwesterly jet stream carrying warm and moist air from the BOB drives northward, the southwest-northeast-oriented rainbelt is formed across the terrain in the northern part of north China (Fig. 4c). Compared with that in the sensitivity experiment where Typhoon Vicente is removed, the added southeasterly moisture transport carried by Typhoon Vicente from the South China Sea and transferred by the typhoon from the BOB contributes to greater rainfall in the Beijing area. The sensitivity experiment where both Typhoon Vicente and tropical cyclone in the BOB are removed significantly differs from the control experiment (Fig. 6c). Without the transfer effect of Typhoon Vicente and the tropical cyclone branch effect of the easterly airflow in the BOB, the southwesterly moisture transport along the eastern edge of the TP is significantly enhanced compared with those in the other two sensitivity experiments. Moreover, the rainfall of its northern rainbelt increases slightly (Fig. 4d). Thus, the strengthening of Typhoon Vicente intensifies the tropical cyclone in the BOB, resulting in the weakening of southwesterly moisture transport along the eastern edge of the TP to the Beijing area. These findings indicate that Typhoon Vicente is an important moisture transfer source, which transfers southwest monsoonal moisture and affects the strength of the tropical cyclone in the BOB. These occurrences significantly affected the long-distance moisture transport for the extreme rainfall event on July 21, 2012 in Beijing.

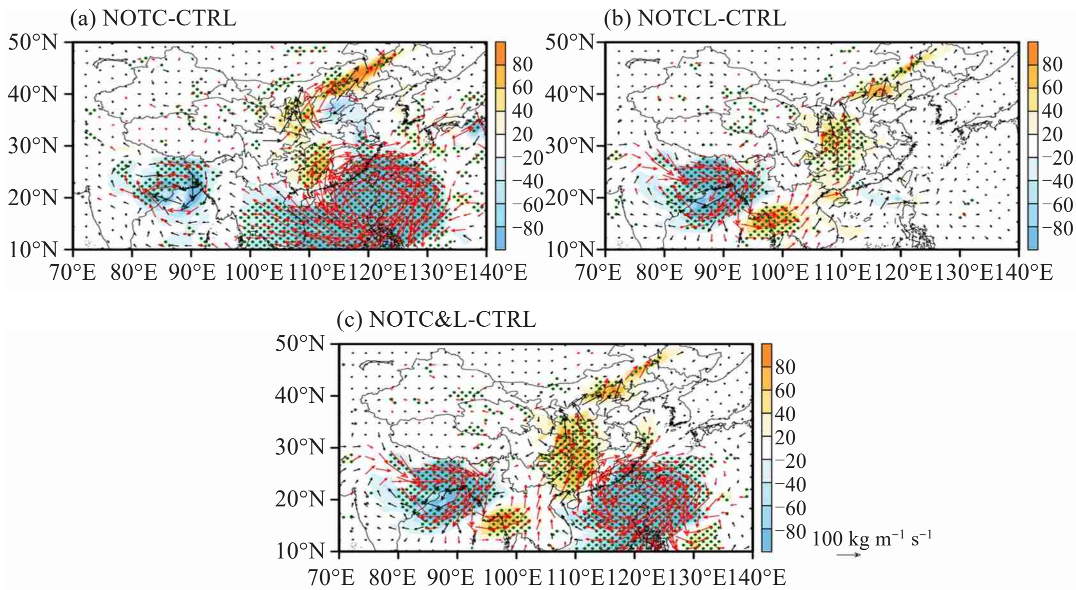

Figure 6. Differences in the mean column moisture flux (integrated from surface to 300 hPa, vectors, units: kg m^{-1} s^{-1}) and their magnitudes (shaded, kg m^{-1} s^{-1}) every 6 h on July 21, 2012 for the sensitivity experiment with Typhoon Vicente removed minus the control experiment (a), the sensitivity experiment with the tropical cyclone in the Bay of Bengal removed minus the control experiment (b), and the sensitivity experiment with both Typhoon Vicente and the tropical cyclone removed minus the control experiment (c). The red vectors and green dots indicate a significance of >90%.

Figure 7 shows the variations in the mean column-integrated moisture flux in the regions of Typhoon Vicente, tropical cyclone in the BOB, and heavy rainfall in north China. When Typhoon Vicente is removed, the column moisture flux in the typhoon region decreases sharply and the column moisture flux in the tropical cyclone and heavy rainfall regions weakens. When the tropical cyclone in the BOB is removed, the column moisture flux in the typhoon region is similar to that in the control experiment and the moisture flux in the tropical cyclone region is reduced by 30%. However, the column moisture flux in the heavy rainfall region increases by around 22 kg m^{-1} s^{-1} compared with that in the control experiment. Furthermore, the column moisture flux in the heavy rainfall region increases further when both Typhoon Vicente and tropical cyclone are removed. This finding indicates that both Typhoon Vicente and the tropical cyclone in the BOB affected the southwesterly moisture transport of this rainstorm event.

5 CHARACTERISTICS OF LONG-DISTANCE MOISTURE TRANSPORT

The numerical simulation studies described in section 4 indicate that both Typhoon Vicente and the tropical cyclone in the BOB played a vital role in the moisture transport of the extreme rainfall event on July 21, 2012 in Beijing. Based on the ERA-Interim reanalysis dataset (Fig. 8), the column-integrated moisture transport shows two prominent channels of moisture transport from low latitudes into the Beijing area. In the early stages of the rainstorm (Fig. 8a and 8b), warm and moist air was continuously transported from the BOB and the Indian Ocean to the Beijing area by southwesterly monsoonal airflow along the eastern edge of the TP; moreover, the southeasterly moisture transport of the WPSH and Typhoon Vicente was weaker at this time. During the heavy rainstorm period (Fig. 8c and 8d), as Typhoon Vicente approached the coastal areas of Guangdong Province, its associated southeasterly airflow and subtropical high became another strong moisture transport channel that transported moisture from the South China Sea and the East China Sea to the rainstorm region. Meanwhile, the southwesterly moisture transport from the BOB to the rainstorm region was weakened because of the transfer effect of the typhoon (Xu et al. [36]), and the moisture transport channel from the BOB to Typhoon Vincente strengthened. The typhoon circulation not only facilitated the transport of moisture from the low-latitude western Pacific to the inland areas of north

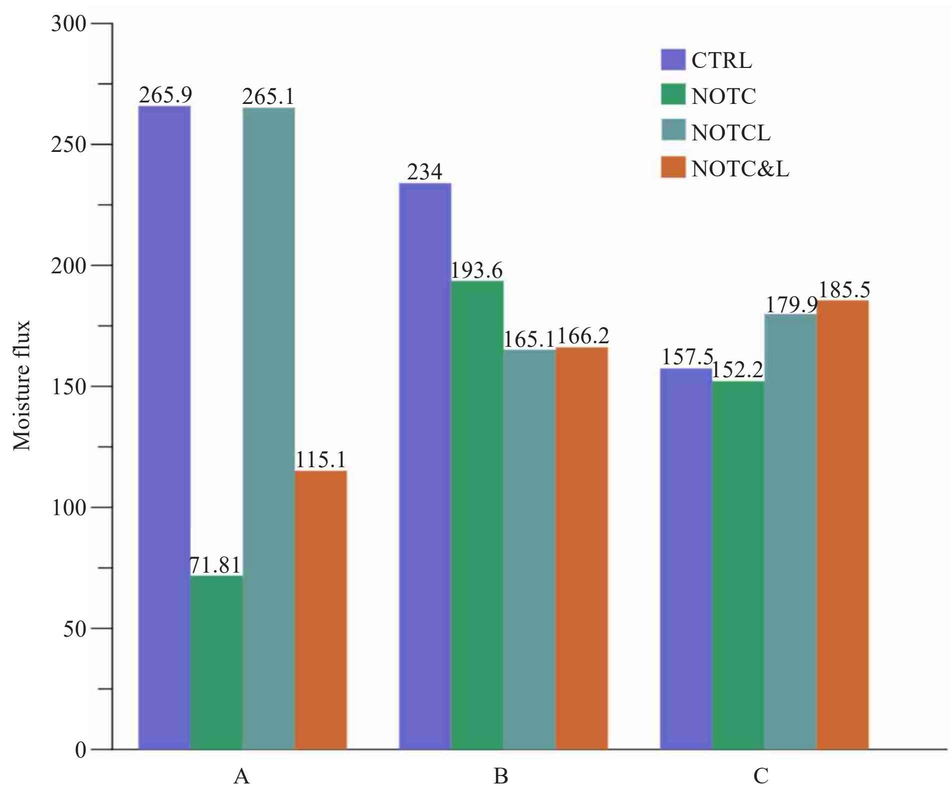

Figure 7. Mean column-integrated moisture flux values (units: kg m^{-1} s^{-1}) of the Typhoon Vicente region (A), the tropical cyclone in the Bay of Bengal region (B), and the heavy rainfall region (C) (shown in Fig. 5) for the control experiment and three sensitivity experiments on July 21, 2012. CTRL, control experiment; NOTC, sensitivity experiment with Typhoon Vicente removed; NOTCL, sensitivity experiment with tropical cyclone in the BOB removed; NOTC&L, sensitivity experiment with both Typhoon Vicente and tropical cyclone in the BOB removed.

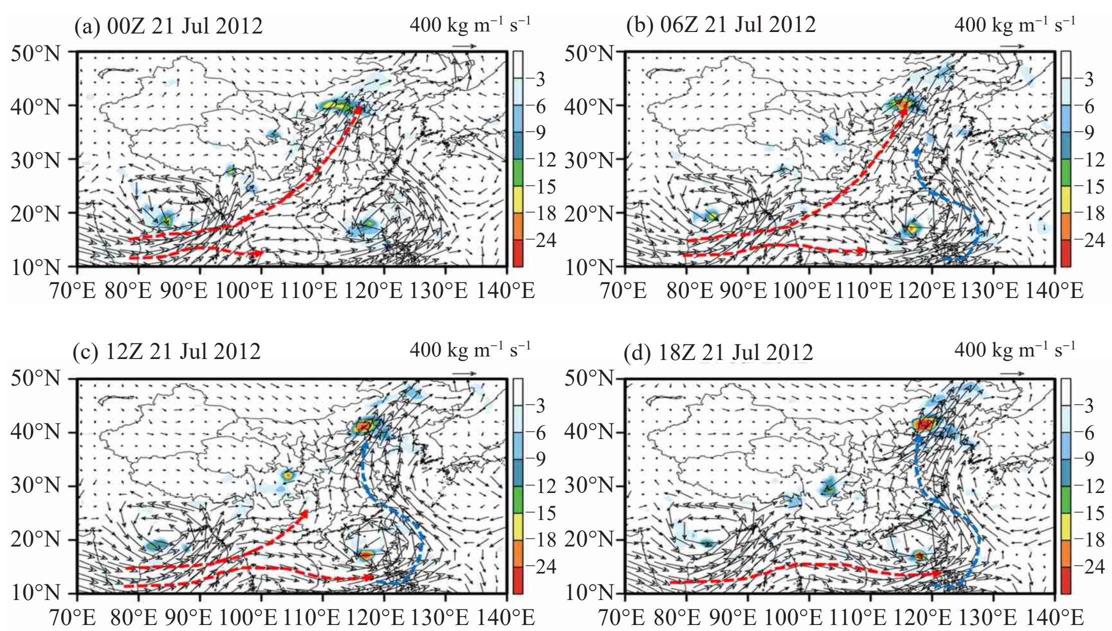

Figure 8. Column-integrated moisture flux (integrated from surface to 300 hPa, vectors, units: kg m^{-1} s^{-1}) and its divergence (shaded, units: 10^{-4} kg m^{-2} s^{-1}) at (a) 00:00, (b) 06:00, (c) 12:00, and (d) 18:00 UTC on July 21, 2012.

China but also induced changes in the intensity and direction of the southwesterly monsoonal airflow from the BOB. This phenomenon significantly affected the rainfall intensity and duration in Beijing, thus justifying the results of simulations. Moreover, some part of the moisture from the BOB flowed around the TP under the blocking of high topography and then merged with the southerly and southwesterly moisture transport channel in the eastern TP. Two significant moisture transport channels associated with the southwesterly and southeasterly airflow converged in central north China, with Beijing located at the center of this strong moisture convergence. The continuous transport of warm and moist air from the tropics and subtropics provided abundant water vapor and energy for the rainstorm region.

To track the water vapor source of the extreme rainfall event in Beijing on July 21, 2012, Fig. 9 shows the correlation vectors for the column-integrated moisture of the rainstorm region (the blue box in Fig. 1) and the column-integrated moisture transport flux before the rainfall event (July 10-22, 2012). The correlation vector fields also exhibit two distinct moisture transport channels, i.e., one from the BOB and the other from the western Pacific and the South China Sea. Warm and moist air from the BOB at low latitudes was steered by the southwesterly monsoon airflow and transported along the eastern edge of the TP to Beijing. The southeasterly airflow associated with Typhoon Vicente transported warm and moist air from the South China Sea and the western Pacific to the heavy rainfall area in Beijing. To further verify the relationship of moisture transport between Typhoon Vicente and tropical cyclone in the BOB, Fig. 10 shows the correlation vectors for the column-integrated moisture of the typhoon area (the blue box in Fig. 10) and column-integrated moisture transport flux, and the correlation fields for the column-integrated moisture of the typhoon area and the East Asian region. The column moisture of Typhoon Vicente had a significant positive correlation with the column moisture of the tropical cyclone in the BOB and the rainstorm area in Beijing. Additionally, the column moisture of the typhoon area showed an obvious cyclonic correlation with the column-integrated moisture transport flux of the tropical cyclone in the BOB, which indicated that one of the moisture supply sources of Typhoon Vicente also came from the tropical cyclone in the BOB. The southeasterly moisture transport of Typhoon Vicente and the southwesterly moisture transport of the tropical cyclone in the BOB cooperatively contributed to the occurrence of extreme rainfall in Beijing. This reveals that the low-latitude warm and moist air carried by the tropical cyclone in the BOB was not only a direct source of moisture for the rainfall area in Beijing but also one of the moisture supply sources for Typhoon Vicente. This finding confirms that the moisture transfer effect of Typhoon Vicente played an important role in the long-distance moisture transport supply source of the extreme rainfall event on July 21, 2012 in Beijing.

We further examine the long-distance moisture transport at different levels. Fig. 11 shows the column-integrated moisture transport in the lower troposphere (from surface to 850 hPa), middle troposphere (from 850 hPa to 500 hPa) and upper troposphere (from 500 hPa to 200 hPa), respectively. The moisture in the lower

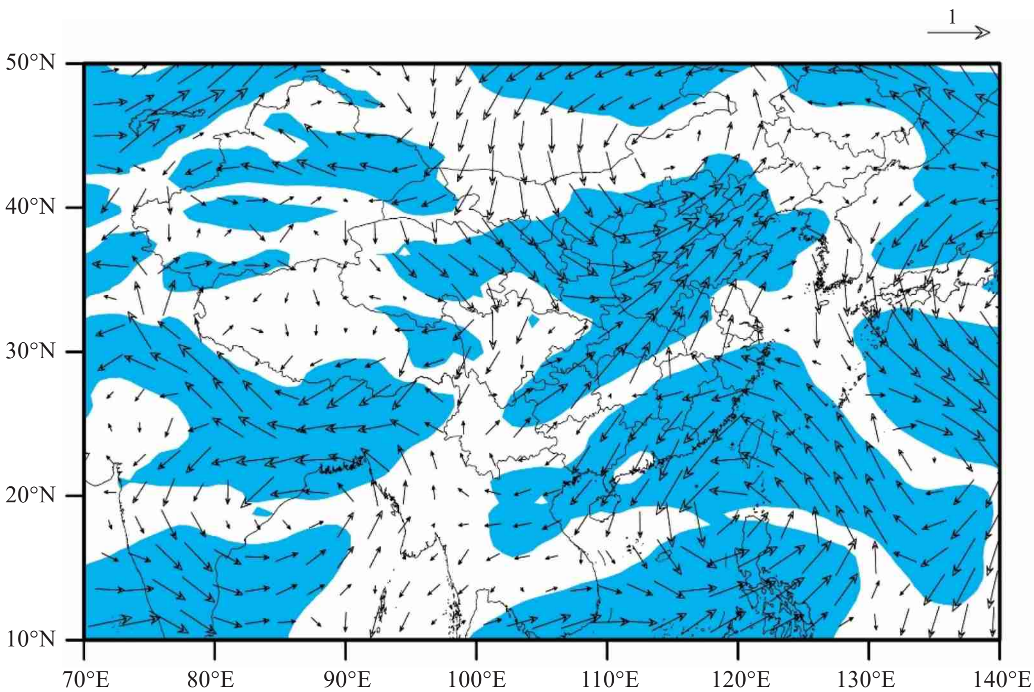

Figure 9. Correlation vectors for the column moisture of the Beijing rainstorm region (blue box in Fig. 1) and column moisture flux before the rainstorm event in Beijing (July 10-22, 2012). The shading indicates a significance of >90%.

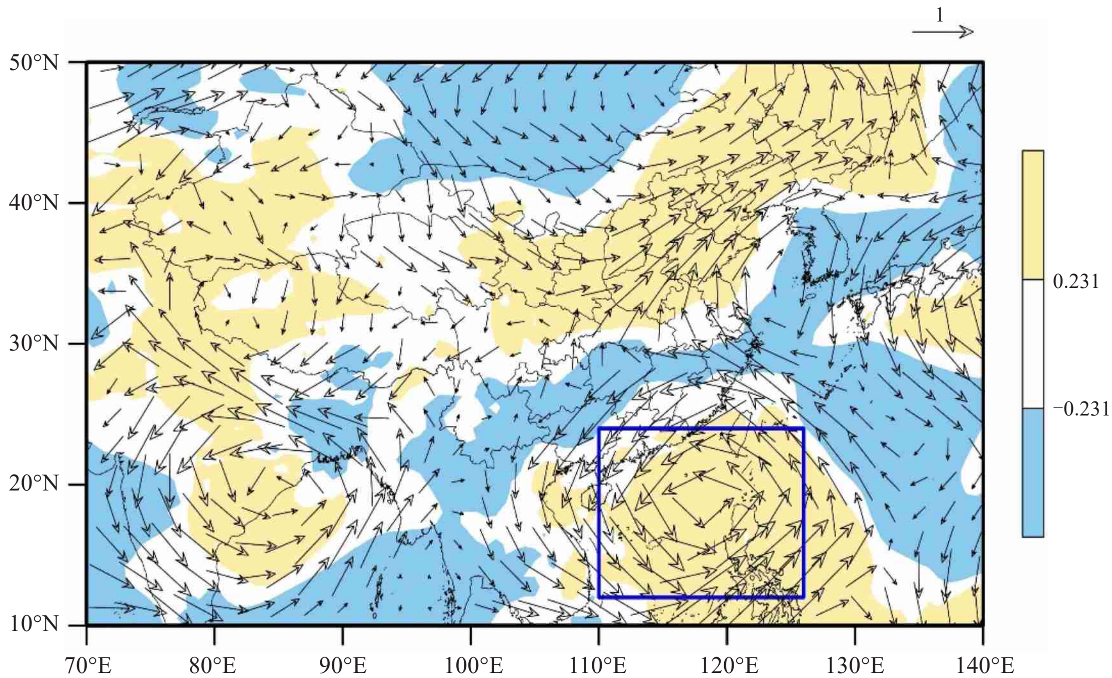

Figure 10. Correlation vectors for the column moisture of the typhoon region (blue box) and column moisture flux (vectors), and the correlation fields for the column moisture of the typhoon region and the East Asian region (shaded) before the rainstorm event in Beijing (July 10-22, 2012).

troposphere (Fig. 11a) was mainly transported from the South China Sea and the East China Sea associated with the southeasterly airflow of Typhoon Vicente and the WPSH. The southwesterly moisture transport from the BOB was weaker in the lower troposphere. In the middle-lower troposphere (Fig. 11b), the moisture transport in the rainstorm region was stronger, and the southwesterly moisture transport from the BOB and Indian Ocean became the main moisture transport channel. Meanwhile, the moisture transport channel from the BOB to Typhoon Vincente was enhanced, and Typhoon Vincente forced the changes of the southwesterly moisture transport. The southeasterly moisture transport of Typhoon Vincente disappeared in the middle-upper troposphere (Fig. 11c), and the easterly airflow in the north of the tropical cyclone in the BOB carried some moisture flowing around the TP to Beijing. Thus, moisture in the lower troposphere was mainly transported from the South China Sea and the East China Sea, and moisture in the middle troposphere was mainly transported from the BOB and Indian Ocean.

6 CONCLUSION AND DISCUSSION

In this study, the WRF model and ERA-Interim reanalysis data were used to examine the key long-distance moisture transport sources for the extreme rainfall event on July 21, 2012 in Beijing. This event was closely related to the distant phenomenon of Typhoon Vicente and tropical cyclone in the BOB, which provided abundant moisture for the rainstorm area in Beijing.

The control and sensitivity experiments were conducted by artificially removing vortexes in the initial conditions of sensitivity experiments to investigate their effects on the extreme rainfall event. The experimental results showed that the WRF model well reproduced the spatial distribution and intensity of the extreme rainfall event in the control experiment. In the sensitivity experiment where Typhoon Vicente was removed, the rainfall decreased by approximately 50%. Alternatively, in the sensitivity experiment where the tropical cyclone in the BOB was removed, the rainfall decreased by 30% with the rainbelts moving northward compared with that in the control experiment. The double rainbelts appear in the two sensitivity experiments where the tropical cyclone in the BOB was removed.

The extreme rainfall event in Beijing had two significant moisture transport channels. In the early stage of the rainfall event, moisture in the Beijing area mainly came from the BOB and the Indian Ocean and was transported by southwesterly monsoonal airflow along the eastern edge of the TP by orographic uplift. During the heavy rainstorm, as Typhoon Vicente approached the coastal province of Guangdong, the southeasterly airflow between Typhoon Vicente and the WPSH became another dominant moisture transport channel, transporting moisture from the South China Sea and the East China Sea to the rainstorm area. Meanwhile, the southwesterly moisture transport was weakened owing to the moisture transferred by Typhoon Vicente. The southwesterly and southeasterly moisture transport merged at the eastern edge of the TP and then

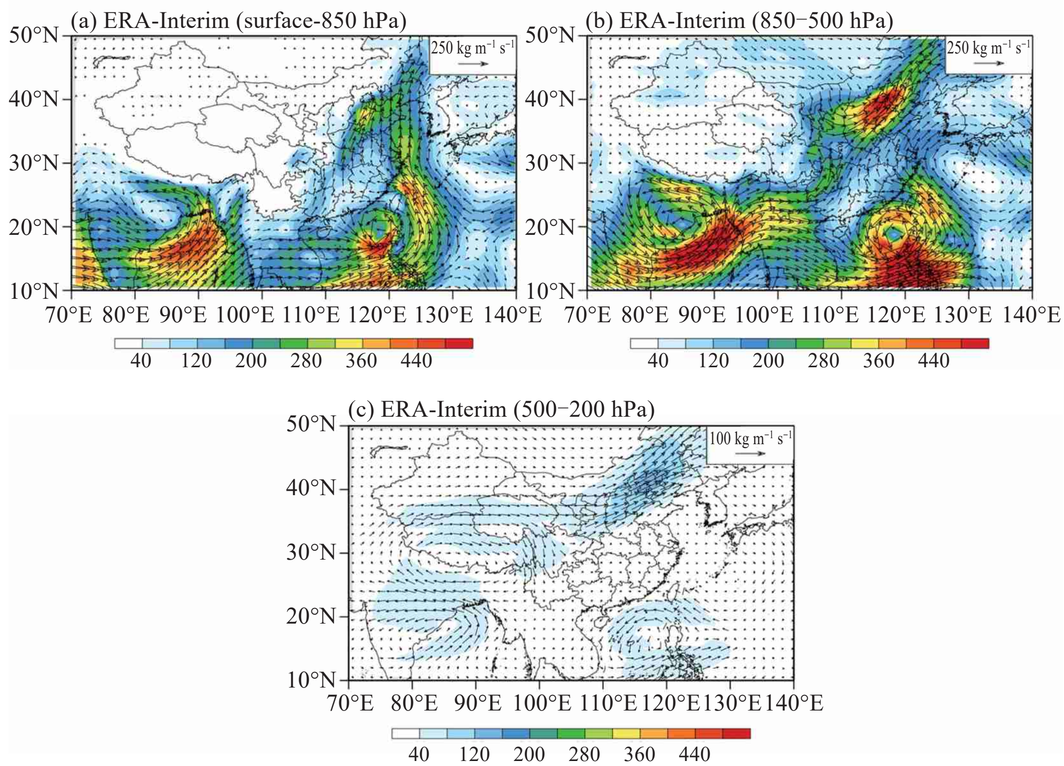

Figure 11. Column-integrated moisture flux (vectors, units: kg m^{-1} s^{-1}) and their magnitudes (shaded, units: kg m^{-1} s^{-1}) on July 21, 2012, integrated (a) from surface to 850 hPa, (b) from 850 hPa to 500 hPa, and (c) from 500 hPa to 200 hPa.

moved to north China, triggering the extreme rainfall event in Beijing. The lower troposphere moisture in the Beijing area was mainly transported from the South China Sea and the East China Sea, and the moisture in the middle troposphere mainly came from the BOB and Indian Ocean.

The WRF simulations showed that the long-distance moisture transport of Typhoon Vicente and tropical cyclone in the BOB both affected the extreme rainfall in Beijing. The moisture connected pump of Typhoon Vicente attracted the southwesterly monsoonal moisture through its westerly airflow and then transported moisture to the Beijing area via its southeasterly airflow, which weakened the direct southwesterly moisture transport. The tropical cyclone in the BOB carried some southwesterly moisture through its easterly airflow, weakening the southwesterly moisture transport. Therefore, when Typhoon Vicente and tropical cyclone in the BOB were removed, southwesterly moisture transport was enhanced in all three sensitivity experiments. Moreover, removing the typhoon vortex decreased the column-integrated moisture flux of the tropical cyclone in the BOB by approximately 40 kg m^{-1} s^{-1}, thus revealing the interlocking effect of Typhoon Vicente on the tropical cyclone. The correlation analysis of column-integrated moisture and moisture transport flux among Typhoon Vicente, tropical cyclone in the BOB, and heavy rainfall region further confirms that Typhoon Vicente played an important role in maintaining and strengthening the tropical cyclone. The low-latitude warm and moist air carried by Typhoon Vicente was not only the direct moisture source supplying the rainstorm area in Beijing but also a moisture transfer source for the southwesterly monsoonal airflow, which had a dominant influence as a key supply source of long-distance moisture transport for the extreme rainfall event on July 21, 2012 in Beijing.

It should be noted that this extreme rainfall event in Beijing occurred under a favorable large-scale background, combined with the complex conditions like mesoscale convective system and topography (Sun et al. [20]). This study only preliminarily discussed the influence of long-distance weather systems on the rainstorm region from the perspective of large-scale moisture transport using the WRF model. When the vortex system is removed, local weather changes should be studied further.

REFERENCES

[1] XIE Y B, WANG Y S, SU F Q, et al. A preliminary survey of certain rain-bearing systems over China in spring and summer [J]. Acta Meteorologica Sinica, 1956, 27(1): 1-23 (in Chinese).

[2] TAO S Y, NI Y Q, ZHAO S X, et al. Study on Formation Mechanism and Forecast of Heavy Rainfall in China in Summer of 1998 [M]. Beijing: Meteorological Press, 2001: 2-8(in Chinese).

[3] SUN W. Analysis of the climatic characteristics and the

variations of the rainstorm in Beijing area [J]. Climatic and Environmental Research, 2010, 15(5): 672-676(in Chinese), https://doi. org / 10.3878 / j. issn. 1006-9585.2010.05.17.

[4] ZHU Hao-ran, LI Xiao-fan. Diurnal cycles of convective and stratiform precipitation over north China during summer [J]. J Trop Meteor, 2019, 25(3): 324-335, https://doi.org/10.16555/j.1006-8775.2019.03.004.

[5] TAO S Y. Heavy Rain in China [M]. Beijing: Science Press, 1980: 181-186(in Chinese).

[6] Writing Group of Heavy Rain in North China. Heavy Rain in North China [M]. Beijing, China: Meteorological Press, 1992: 5-15(in Chinese).

[7] WU Jie, GAO Xue-jie. Simulation of tropical cyclones over the western north Pacific and landfalling in China by RegCM4 [J]. J Trop Meteor, 2019, 25(4): 437-447, httsp://doi.org/10.16555/j.1006-8775.2019.04.002.

[8] LI Qing-lan, LIU Bing-rong, WAN Qi-lin et al. Operational forecast of rainfall induced by landfalling tropical cyclones along Guangdong coast [J]. J Trop Meteor, 2020, 26(1): 1-13, httsp://doi.org/10.16555/j.1006-8775.2020.001.

[9] CONG C H, CHEN L S, LEI X T, et al. An overview on the study of tropical cyclone remote rainfall [J]. J Trop Meteor, 2011, 27(1): 264-270(in Chinese), https://doi.org/10.3969/j.issn.1004-4965.2011.02.016.

[10] DUAN L, ZHANG J, WANG J J, et al. Effect of Typhoon Krosa (0716) on an autumn heavy rainfall in Beijing [J]. J Trop Meteor, 2012, 28(5): 664-674(in Chinese), httsp://doi.org/10.3969/j.issn.1004-4965.2012.05.006.

[11] LIANG J, LI Y, ZHANG S J, et al. The comparative analyses of circulation characteristics and their effect on precipitation over Liaodong Peninsula associated with typhoons turning westward over Yellow Sea [J]. J Trop Meteor, 2012, 28(6): 861-872(in Chinese), httsp://doi.org/10.3969/j.issn.1004-4965.2012.06.008.

[12] SHAN L, TAN G R, YAO Y Q, et al. On the water vapor condition and moisture transport for a rain caused by a remote tropical cyclone [J]. J Trop Meteor, 2014, 30(2): 353-360(in Chinese), httsp://doi.org/10.3969/j.issn.1004-4965.2014.02.016.

[13] LEI Y S. The compositive analysis of the meridional type persistent severe rainstorms [J]. Acta Meteorologica Sinica, 1981, 39(2): 166-180(in Chinese).

[14] ZHOU M S. The circulation analysis of regional heavy rainstorms in the north of China [J]. Meteorol Mon, 1993, 19(7): 14-18(in Chinese).

[15] SUN J H, ZHANG X L, WEI J, et al. A study on severe heavy rainfall in north China during the 1990s [J]. Climatic and Environmental Research, 2005, 10(3): 492-506(in Chinese), https://doi. org / 10.3878 / j. issn. 1006-9585.2005.03.20.

[16] ZHANG W L, CUI X P. Main progress of torrential rain researches in North China during the past 50 years [J]. Torrential Rain and Disasters, 2012, 31(4): 384-391(in Chinese), https://doi. org / 10.3969 / j. issn. 1004-9045.2012.04.014.

[17] CHEN Y, SUN J, XU J, et al. Analysis and thinking on the extreme of the 21 July 2012 torrential rain in Beijing, Part I: Observation and thinking [J]. Meteorol Mon, 2012, 38 (10): 1255-1266(in Chinese).

[18] LIU H W, QUAN M L, ZHU Y X, et al. The role of frontogenesis and secondary circulation in maximum precipitation enhancement and maximum precipitation in a 21 July 2012 rain in Beijing [J]. J Trop Meteor, 2014, 30 (5): 911-920(in Chinese), https://doi. org / 10.3969 / j. issn.1004-4965.2014.05.011.

[19] LIU Y J, DING Y H, ZHANG Y X, et al. Role of a warm and wet transport belt of Asian summer monsoon and cold air from north in the Beijing July 21 heavy rainstorm [J]. J Trop Meteor, 2015, 31(6): 721-732(in Chinese), https://doi.org/10.16032/j.issn.1004-4965.2015.06.001.

[20] SUN J H, ZHAO S X, FU S M, et al. Multi-scale characteristics of record heavy rainfall over Beijing area on July 21, 2012 [J]. Chin J Atmos Sci, 2013, 37(3): 705-718(in Chinese), https://doi. org / 10.3878 / j. issn. 1006-9895.2013.12202.

[21] XU H X, XU X D, ZHANG S J, et al. Long-range moisture alteration of a typhoon and its impact on Beijing extreme rainfall [J]. Chin J Atmos Sci, 2014, 38(3): 537-550(in Chinese), https://doi. org / 10.3878 / j. issn. 1006-9895.2013.13173.

[22] DEE D P, UPPALA S M, SIMMONS A J, et al. The ERA-Interim reanalysis: configuration and performance of the data assimilation system [J]. Quart J Roy Meteorol Soc, 2011, 137: 553-597, https://doi.org/10.1002/qj.828.

[23] YU X D. Investigation of Beijing extreme flooding event on 21 July 2012 [J]. Meteorol Mon, 2012, 38(11): 1313-1329, https://doi. org / 10.7519 / j. issn. 1000-0526.2012.11.001.

[24] SKAMAROCK W C, KLEMP J B, DUDHIA J, et al. A description of the advanced research WRF version 3 [M]. NCAR Technical Note NCAR/TN-475+STR, 2008.

[25] KAIN J S, FRITSCH J M. A one-dimensional entraining/detraining plume model and its application in convective parameterization [J]. J Atmos Sci, 1990, 47(23): 2784-2802.

[26] KAIN J S, FRITSCH J M. Convective parameterization for mesoscale models: The Kain-Fritsch scheme [M]// EMANUEL K A, RAYMOND D J (eds). Representation of Cumulus Convection in Numerical Models, Boston: American Meteorological Society, 1993, 165-170.

[27] DUDHIA J. Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model [J]. J Atmos Sci, 1989, 46(20): 3077-3107, https://doi.org/10.1175/1520-0469(1989)046<3077:NSOCOD>2.0.CO;2.

[28] MLAWER E J, TAUBMAN S J, BROWN P D, et al. Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave [J]. J Geophys Res: Atmos, 1997, 102(D14): 16663-16682, https://doi.org/10.1029/97JD00237.

[29] JANJIĆ Z I. Nonsingular implementation of the Mellor-Yamada level 2.5 scheme in the NCEP meso model [M]. NCEP Office Note #437, 2001: 61.

[30] BELJAARS A C M. The parametrization of surface fluxes in large-scale models under free convection [J]. Quart J Roy Meteorol Soc, 1995, 121(522): 255-270, https://doi.org/10.1002/qj.49712152203.

[31] HONG S Y, NOH Y, DUDHIA J. A new vertical diffusion package with an explicit treatment of entrainment processes [J]. Mon Wea Rev, 2006, 134(9): 2318-2341, https://doi.org/10.1175/MWR3199.1.

[32] CHEN F, DUDHIA J. Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5

modeling system, Part I: Model implementation and sensitivity [J]. Mon Wea Rev, 2001, 129(4): 569-585, https://doi. org / 10.1175 / 1520-0493(2001)129<0569: CAALSH>2.0.CO;2.
[33] FREDRICK S, DAVIS C, GILL D, et al. Bogussing of tropical cyclones in WRF Version 3.1 [Z]. Colorado: Nam National Center for Atmospheric Research Boulder, 2010.
[34] ZHANG D L, LIN Y H, ZHAO P, et al. The Beijing extreme rainfall of 21 July 2012: “Right Results” but for wrong reasons [J]. Geophys Res Lett, 2013, 40(7): 1426-1431, https://doi.org/10.1002/grl.50304.
[35] JIANG X W, TING M F. A dipole pattern of summertime rainfall across the Indian Subcontinent and the Tibetan Plateau [J]. J Climate, 2017, 30(23): 9607-9620, https://doi.org/10.1175/JCLI-D-16-0914.1.
[36] XU X D, LU C, XU H X, et al. A possible mechanism responsible for exceptional rainfall over Taiwan from typhoon Morakot [J]. Atmos Sci Lett, 2011, 12(3): 294-299, https://doi.org/10.1002/asl.338.

Citation: LI Juan, XU Xiang-de, LI Yue-qing, et al. The key supply source of long-distance moisture transport for the extreme rainfall event on July 21, 2012 in Beijing [J]. J Trop Meteor, 2021, 27(1): 34-47, https://doi.org/10.46267/j.1006-8775.2021.004.