Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2023, 11, 184-200
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Analysis of Rainstorm Process over Henan Province of China in July 2021

Zhiyuan Chen, Wei Wang*

Plateau Atmosphere and Environment Key Laboratory of Sichuan Province, College of Atmospheric Sciences, Chengdu University of Information Technology, Chengdu, China
Email: 947274106@qq.com, *wei2009@cuit.edu.cn

How to cite this paper: Chen, Z. Y., & Wang, W. (2023). Analysis of Rainstorm Process over Henan Province of China in July 2021. *Journal of Geoscience and Environment Protection, 11,* 184-200.
https://doi.org/10.4236/gep.2023.1110013

Received: September 20, 2023
Accepted: October 22, 2023
Published: October 25, 2023

Abstract

Based on the data from the China National Meteorological Station and the fifth-generation reanalysis data of the European Center for Medium-Range Weather Forecasts, we investigated and examined the precipitation, circulation, and dynamic conditions of the rainstorm in Henan in July 2021. The results show that: 1) This precipitation is of very heavy rainfall level, beginning on the 19th and lasting until the 21st, with a 3-hour cumulative precipitation of more than 200 mm at Zhengzhou station at 19:00 on the 20th. The major focus of this precipitation is in Zhengzhou, Henan Province, and it also radiates to Jiaozuo, Xinxiang, Kaifeng, Xuchang, Pingdingshan, Luoyang, Luohe, and other places. 2) The Western Pacific Subtropical High (WPSH), typhoons "In-Fa" and "Cempaka", as well as the less dynamic strengthening of the Eurasian trough ridge structure, all contributed to the short-term maintenance of the favorable large-scale circulation background and water vapor conditions for this rainstorm in Henan. 3) The vertical structure of low-level convergence and high-level dispersion near Zhengzhou, together with the topographic blocking and lifting impact, produced favorable dynamic lifting conditions for this rainstorm.

Keywords

Henan Rainstorm, Circulation Pattern, Vertical Profile, Dynamic Factors

1. Introduction

With the aggravation of global warming, extreme precipitation occurs frequently, which leads to various natural disasters and has a great impact on human life, production, property safety, and the ecological environment (Gao et al., 2020). China is a country with frequent rainstorms, in which large-scale severe floods caused by continuous rainstorms have brought great losses to people's lives and properties (Ding, 2019). For example, the heavy rain in Beijing on July 16, 2018, had a certain impact on urban transportation, power, and other systems (Lei et al., 2020). Another example: the rare extraordinarily heavy rainfall in northern Henan on July 18-20, 2016, caused flash floods in many parts of the province, river flooding, urban flooding, basic paralysis of traffic, electricity, and communication systems in some areas, and serious waterlogging in a large number of agricultural and crop areas, resulting in about 1.67 million people affected, of whom 17 died and 9 were missing due to the disaster (Li et al., 2018).

Through the efforts of several generations, Chinese scholars have established the theory of rainstorms in China, which has made a great contribution to the study of rainstorm theory and mechanism in the world, from the process and the physical mechanism of multi-scale interaction and feedback between large-scale circulation and mesoscale systems. In recent years, great achievements have been made in the study of extreme precipitation (Ding, 2019; Zhao & Sun, 2019).

Torrential rainfall in North China has strong regional characteristics, and many meteorologists have paid attention to and carried out related research on precipitation in North China (Zhang & Cui, 2012). Gao et al. (2020) summarized the research on torrential rain in North China in their research progress on the formation mechanism and forecasting methods of heavy rain in China. In response to the heavy rain in North China, Chinese scholars have also carried out research on water vapor conditions, terrain, the underlying surface, and the urban heat island effect (Lei et al., 2020; Ji & Li, 2021; Zhou et al., 2020; Li et al., 2016). They pointed out that the rainstorms in North China generally occurred under favorable large-scale background conditions, and the rainstorm vapors in North China were mainly contributed by the western Pacific and the South China Sea; the formation of rainstorms was also closely related to the high- and low-level jets. Zhang et al. (2021) conducted a high-resolution simulation and characteristic analysis of a heavy rainstorm in southern Jiangsu, and Xi et al. (2021) used satellite radar and other data to study the "7.19" rainstorm in Henan and pointed out a favorable large-scale circulation background The low vortex cyclone and the terrain of the Taihang Mountains provided sufficient water vapor and convergence, and uplifting conditions for this heavy rain.

Foreign scholars have also carried out many studies on heavy rain. Du et al. (2022) conducted a related study using global daily precipitation data from 1961 to 2010 and pointed out that the frequency of continuous daily extreme precipitation events (EPCDs) in Europe has increased significantly in recent decades. The findings of Khouakhi et al. (2017) suggest that typhoons play an important role in producing extreme rainfall in different regions of the world. The spatial distribution of annual mean typhoon-induced rainfall further indicated that the Philippines, the southern coastal areas of China, southeastern Japan, and the islands in the Philippine Sea had the highest total rainfall. Lin et al. (2001) and Weisse & Bois (2001) analyzed the heavy precipitation weather and topographical and mesoscale environmental characteristics in the European Alps, Taiwan (China), and Japan, respectively, and found that the conditional or potentially unstable airflow encountered the steep terrain in the mountains. Helps release its conditioned or convective instability.

Henan has frequent summer rainstorms and a high population density. The losses caused by rainstorms and floods are huge every year. The impact of the heavy rainstorm in Zhengzhou, Henan, in July 2021 is particularly prominent. Using the station data of the National Meteorological Station of China and the fifth-generation reanalysis data (EAR5) of the European Centre for Medium-Range Weather Forecasts (ECMWF), this paper will diagnose the extreme precipitation process and its possible causes that occurred in Zhengzhou, Henan Province of China, on July 20, 2021.

2. Research Region and Data

2.1. Research Region

Henan Province is located in the central part of China, bounded by 31˚23'N-36˚22'N, 110˚21'E-116˚39'E, Anhui and Shandong to the east, Hebei and Shanxi to the north, Shaanxi to the west, and Hubei to the south. Hubei has a complete area of 167,000 square kilometers. Figure 1 indicates the geographical location and altitude distribution of Henan Province. The overall terrain of Henan is high in the west, and low in the east. It is surrounded by mountains in the north, west and south. There are Qinling Mountains, Zhongtiao Mountains, Wangwu Mountains, Taihang Mountains, and other mountains in the west and north.

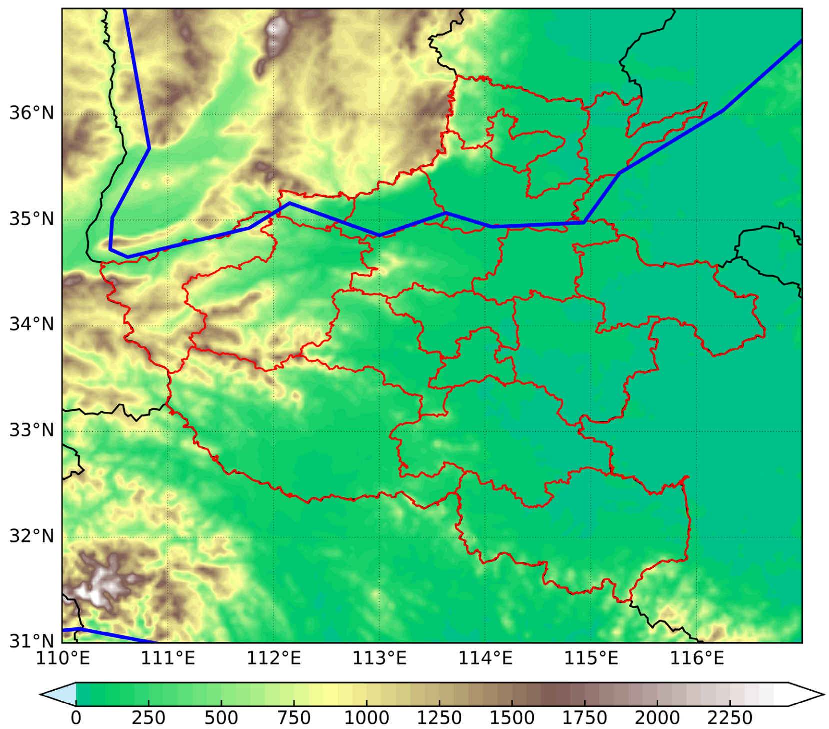

Figure 1. The terrain elevation of Henan Province (unit: m).

Mang Mountain, Funiu Mountain, and so on; the Yellow River passes through the central and northern parts of the country. The central and eastern parts of Henan Province are the Huanghuaihai alluvial plain, and the southwestern part is the Nanyang Basin. Plains and basins occupy 55.7% and 26.6% of the overall location, respectively, and are the primary landforms of Henan Province.

The rainstorm studies since there are records in Henan Province have pointed out that the topography of Henan has an obvious effect on precipitation (Zhang & Su, 2014; Li et al., 2018; Su et al., 2019, 2021).

2.2. Data

The data used in this paper include:

1) The 24-hour, 12-hour, and 3-hour cumulative precipitation data are meteorological station data provided by the China Meteorological Administration. The cumulative period is July 18 to 24, 2021.

2) The ERA5 reanalysis data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) are used for the fundamental physical data, with a temporal resolution of 1 hour, a spatial resolution of 0.25˚ × 0.25˚, and a total of 27 layers from 1000 to 100 hPa in the vertical direction.

3) The whole text is unified in Beijing time and the corresponding time of the reanalysis data is increased by 8 hours.

3. Results

3.1. Precipitation Process over Henan Province

3.1.1. 48-Hour Cumulative Precipitation

Figure 2 shows the temporal evolution of 3-hourly precipitation at the Zhengzhou station from 07:00 on July 18 to 10:00 on July 22, 2021. 3-hourly precipitation at the Zhengzhou station was within 50 mm from 18 to noon on

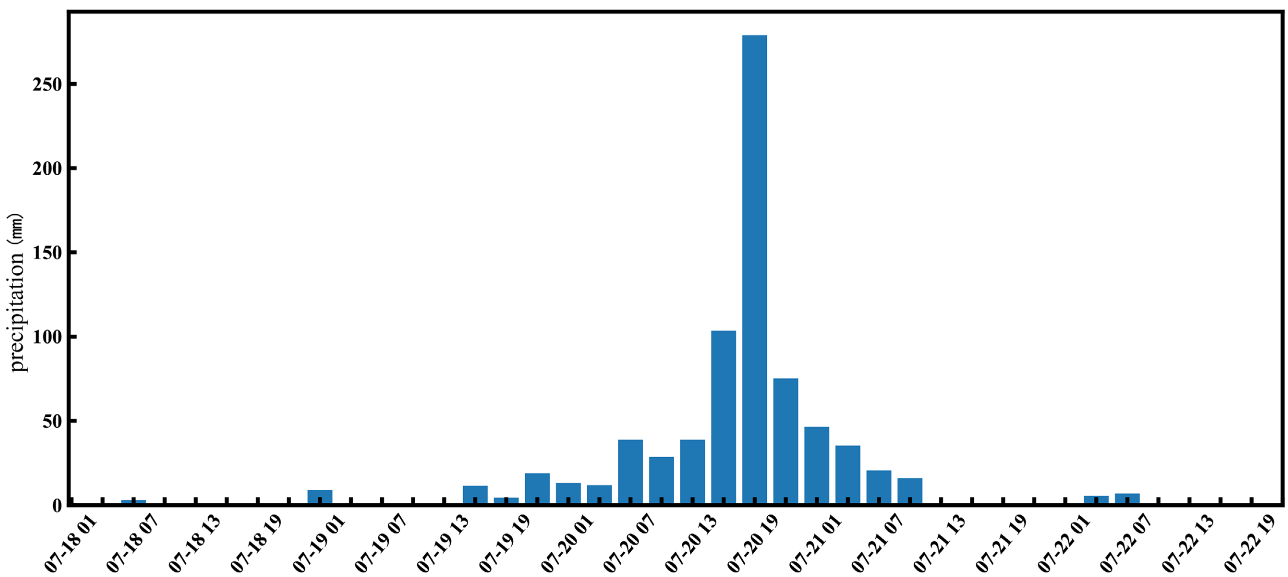

Figure 2. The series of 3-hour precipitation at Zhengzhou station during July 18 07:00-22 10:00 (unit: mm).

July 20; 3-hourly cumulative precipitation reached 278 mm from 16:00 to 19:00 on July 20; 3-hourly precipitation fell back to within 50 mm on July 21, and the precipitation process basically ended in the morning of July 22.

Figure 3 displays the spatial distribution of the 48-hour cumulative precipitation from 08:00 on July 19 to 08:00 on July 21, 2021. 48-hour cumulative precipitation in Zhengzhou exceeded 500 mm between 08:00 on July 19 and 08:00 on July 21, and the cumulative precipitation in the surrounding urban area of about 5000 square kilometers also reached more than 150 mm. The rainstorm process was large in scope, with Zhengzhou in Henan Province as the main center of precipitation, radiating to Jiaozuo, Xinxiang, Kaifeng, Xuchang, Pingdingshan, Luoyang, Luohe, and other places.

3.1.2. 12-Hour Cumulative Precipitation

To further understand the evolution characteristics of the rain belt during this torrential rain, Figure 4 depicts the evolution of the spatial distribution of accumulated precipitation in Henan over the 12 hours from July 19 to 22, 2021. From 08:00 to 20:00 on the 19th (Figure 4(a)), precipitation began to appear in the western part of Zhengzhou, and the cumulative precipitation at the precipitation center reached 100 mm; by 20:00 on the 19th to 08:00 on the 20th (Figure 4(b)), the precipitation center was located at the junction of Luoyang and Zhengzhou. The central precipitation intensity increased from 100 mm to 150 mm, and the precipitation range expanded to Zhengzhou, Luoyang, Pingdingshan, and Xuchang. The precipitation area showed a radial distribution from the center to the surrounding area; by 08-20 on the 20th (Figure 4(c)), the precipitation center changed from The junction of Luoyang and Zhengzhou moved to the central area of Zhengzhou and the precipitation intensity continued to intensify and reached 200 mm. The precipitation range began to expand from Zhengzhou

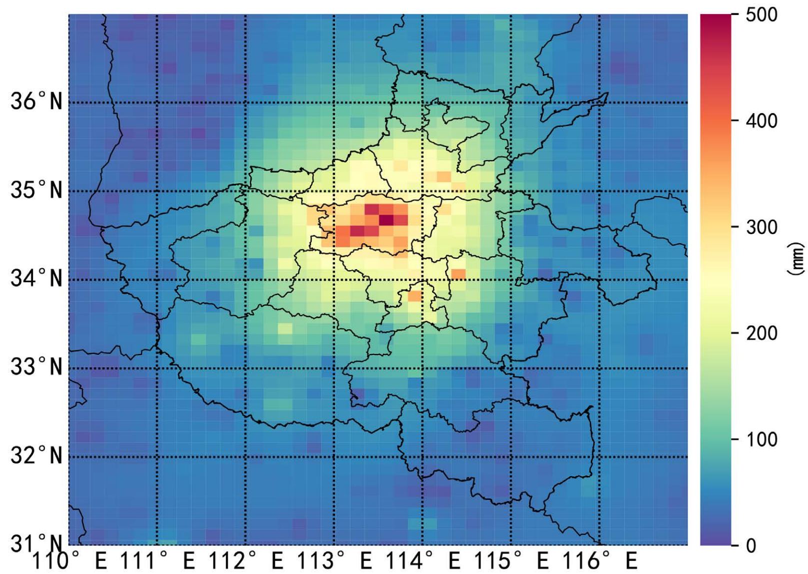

Figure 3. Spatial distribution of 48-hour accumulated precipitation in the Henan region from 08:00 on July 19 to 08:00 on July 21, 2021 (unit: mm).

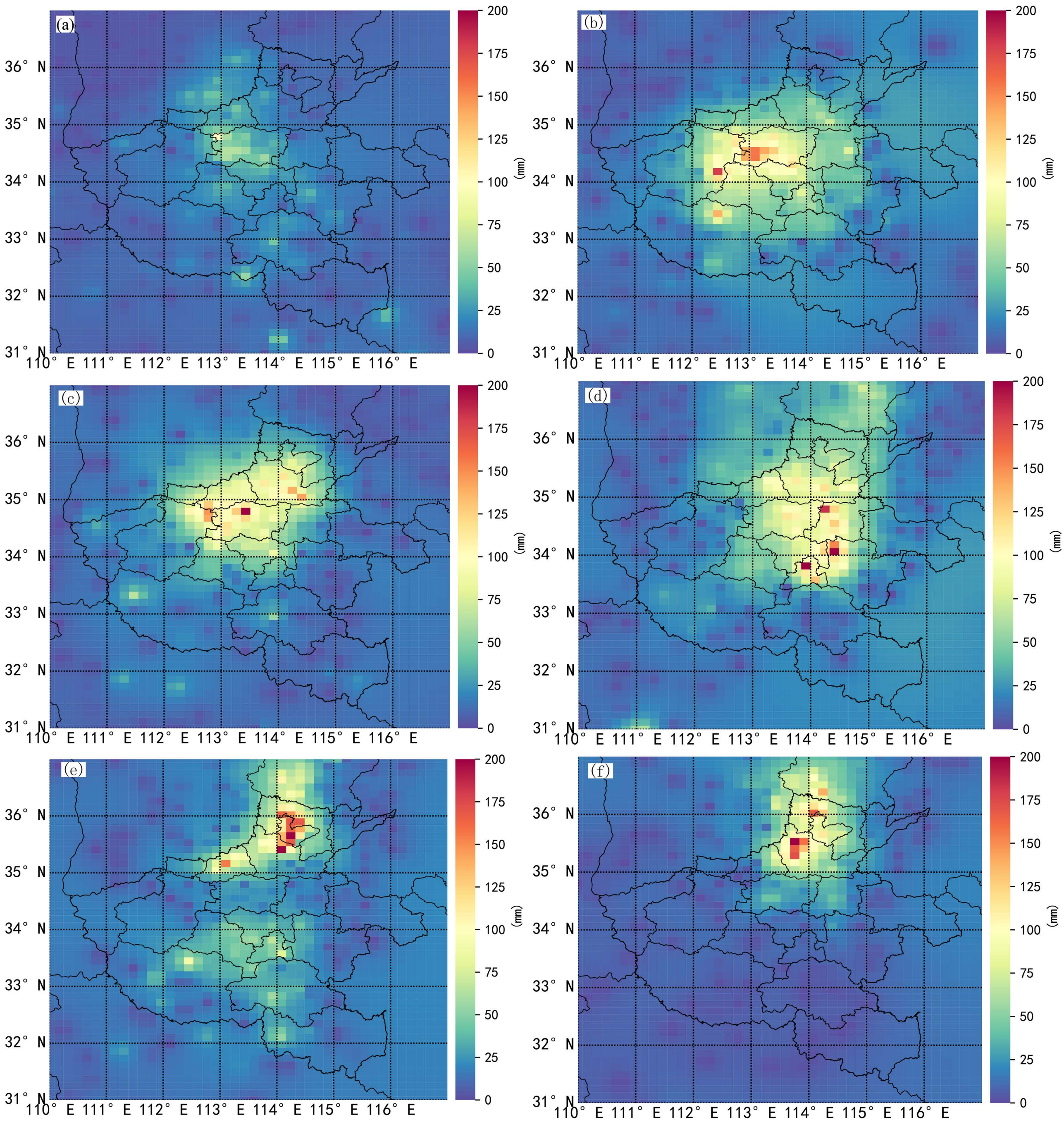

Figure 4. Spatial distribution of 12-hour accumulated precipitation in Henan from July 19-22, 2021 (unit: mm): (a) From 08:00 of 19th; (b) From 20:00 of 19th; (c) From 08:00 of 20th; (d) From 20:00 of 20th; (e) From 08:00 of 21st; (f) From 20:00 of 21st.

to the north. The accumulated precipitation in Xinxiang and Jiaozuo was over 100 mm, and the rain belts trended from southwest to northeast; At 20:00 on the 21st (Figure 4(d)), the precipitation center continued to move to the southeast, and the precipitation rain belt was in a north-south direction. There were two precipitation centers, one of which was located at the junction of Kaifeng and Zhengzhou, and the other was located in Zhoukou, Xuchang, and Luohe. The precipitation intensity can always be maintained at 200 mm; from 08:00 on the

21st to 08:00 on the 22nd (**Figure 4(e)** & **Figure 4(f)**), the precipitation range shrinks significantly, and the precipitation center moves northward to the Xinxiang, Anyang, and Hebi areas, and is basically concentrated in the Taihang Mountains along the mountain, but the precipitation intensity at the precipitation center remained at 200 mm.

3.2. Circulation Situations of Henan Rainstorm

Numerous studies have found that favorable large-scale circulation is one of the factors that contribute to the formation of torrential rain (Wang et al., 2022; Zhang et al., 2022; Xi et al., 2021). The circulation situation of this rainstorm will be analyzed below.

3.2.1. 500 hPa Circulation Situations

Figure 5 shows the distribution of the geopotential height field and wind field at

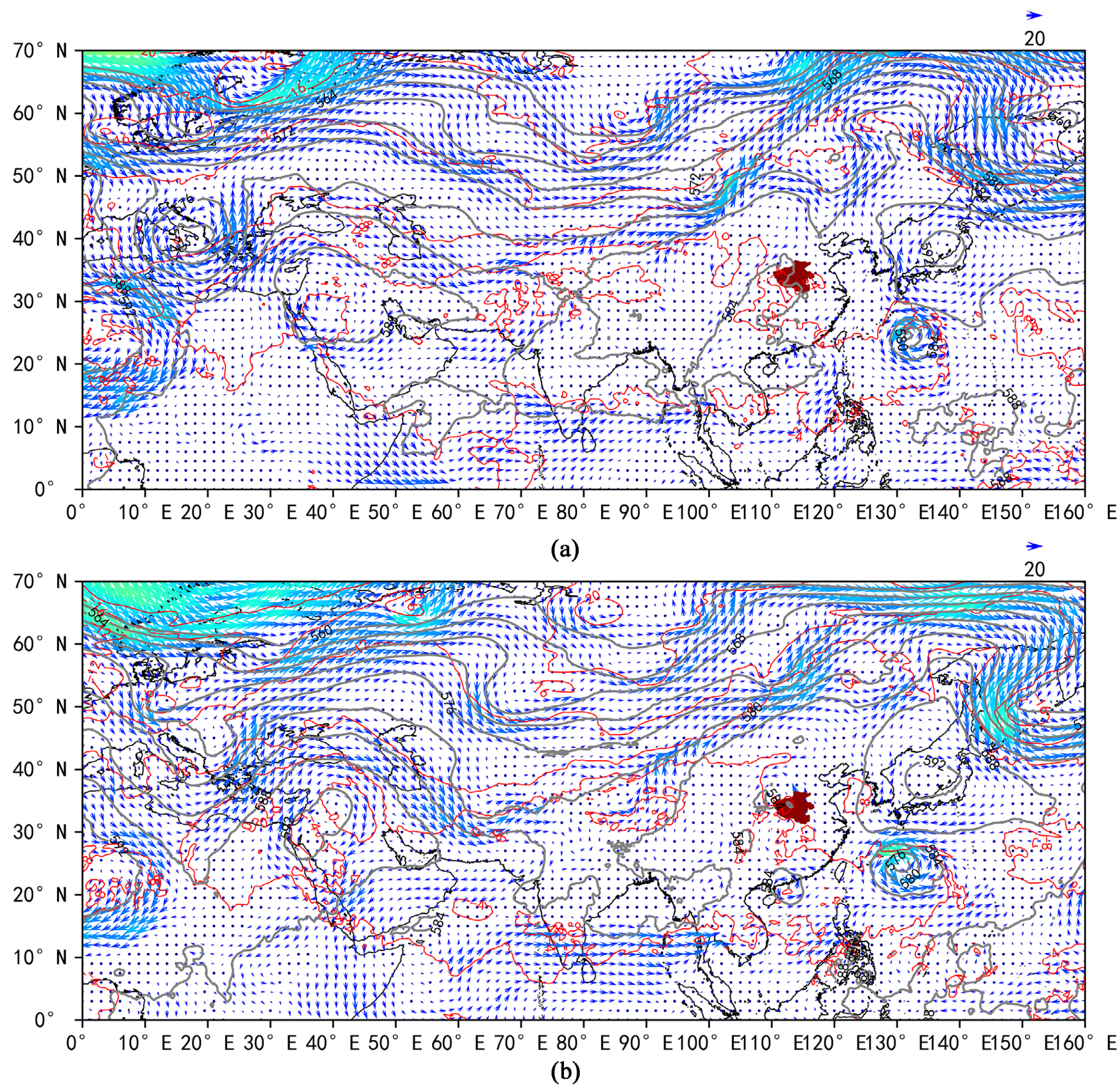

Figure 5. Distribution situations of 500 hPa geopotential height (contour, unit: dagpm) and wind fields (vector, unit: m·s−1) at 08:00 on July 19-20, 2021: (a) 08:00 on July 19; (b) 08:00 on July 20, Henan Province is the red filled area.

08:00 on July 19-20, 2021. At 08:00 on August 19 (**Figure 5(a)**), the main body of the WPSH is located north of 30˚N, and its center can reach 592 dagpm. The ridge corresponding to the contour line of 588 dagpm rises westward and extends into Jilin Province, China. There is a closed low pressure system in the south of the WPSH, corresponding to the active position of typhoon "In-Fa". There is a ridge of high pressure from the north of Northeast China to East Siberia and a trough of low pressure in West Siberia. At 08:00 BST (**Figure 5(b)**) on May 20, the WPSH moved westward and strengthened, and the ridge of the 588 dagpm contour line reached the Bohai Sea in China. Its center was located in the Sea of Japan, and the center potential reached 592 dagpm, and the range increased significantly. Typhoon "In-Fa" is located in the southeast of the WPSH, moving very slowly, and the intensity and center range are enhanced. The southeasterly wind between the typhoon and the WPSH is conducive to the long-term import of water vapor from the Pacific Ocean and the Bay of Bengal into Central China. At 08:00 on August 20, a small cyclone appeared in the South China Sea and formed a 588 closed line. The development of WPSH and typhoon "In-Fa" and the coordination of the trough and ridge situation in the upper high latitudes provided a favorable large-scale circulation background for this torrential rain.

3.2.2. 700 hPa Circulation Situations

Figure 6 shows the spatial distribution of the geopotential height field and wind field at 700 hPa at 08:00 and 20:00 on July 20, 2021. At 08:00 (**Figure 6(a)**) on July 20, the distribution of the geopotential height field is basically the same as

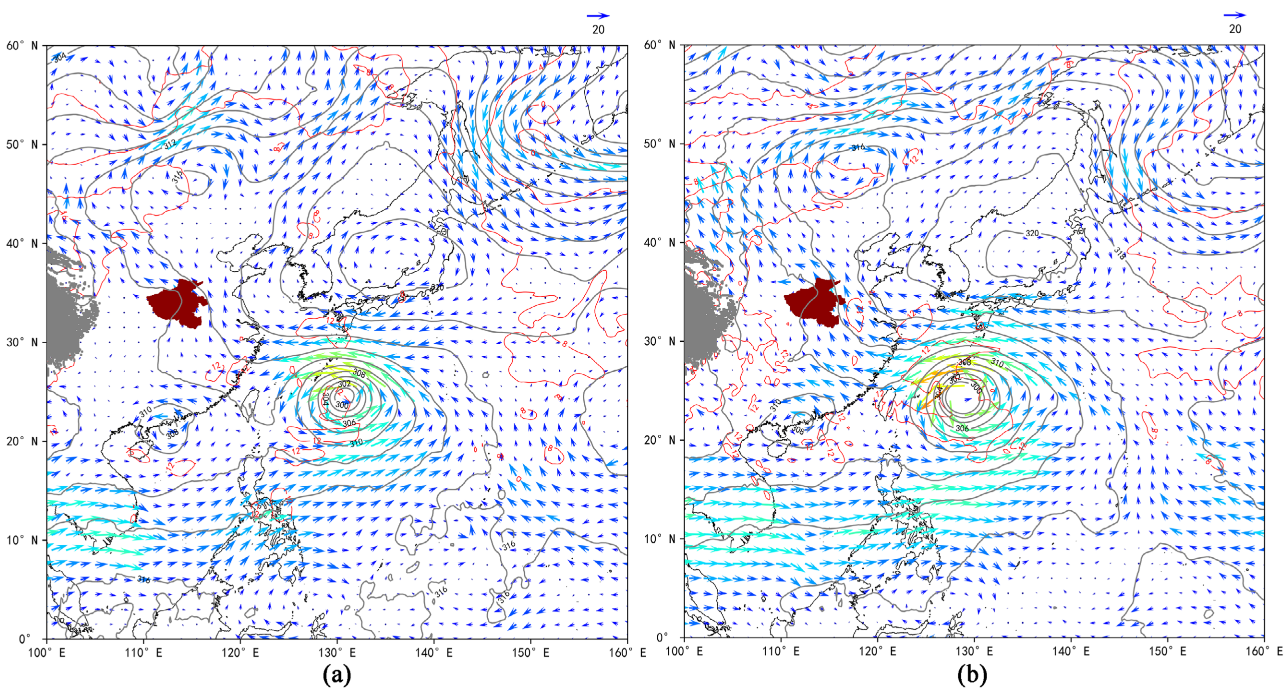

Figure 6. Spatial distribution of the 700 hPa geopotential height field (contours, unit: dagpm) and wind fields (vector, unit: m·s⁻¹) at 08(a) and 20(b) on July 20, 2021.

that at 500 hPa. Along 30˚N, the north-south anti-phase structure is high in the north and low in the south. The high-pressure center in the north is located in Japan and the Sea of Japan, extending westward to the Bohai Sea in China. The low-pressure center in the south corresponds to typhoon "In-Fa". The anti-phase structure of the north and south continuously transports abundant water vapor to Henan Province in China. There is a closed small high-pressure center in the north of Henan, and the high-pressure center reaches 316 dagpm. With the cooperation of the above situation, southeast winds prevail in the northeast of Henan Province, which is conducive to the occurrence and development of the rainstorm. At 20:00 BT on July 20 (**Figure 6(b)**), the high pressure to the north of Henan strengthened, the WPSH moved westward, and the 318 dagpm contour line reached the Shandong Peninsula in China. The typhoon's intensity increased and moved westward. The anomalous northerly WPSH and the westward movement of typhoon "In-Fa" increased the low-level potential gradient over the Northwest Pacific Ocean, thus accelerating the transport of water vapor on the ocean surface by the southeasterly wind and continuing to enhance the rainstorm process.

3.2.3. 850 hPa Circulation Situations

Figure 7 gives the spatial distribution of the 850 hPa geopotential height field and wind field at 08 and 20 July 2021, respectively. At 08:00 on the 20th (**Figure 7(a)**) the influence of the typhoon and the WPSH on the 850 hPa water vapor transport was still obvious, mainly to the northeastern part of Henan Province, and a warm shear near east-west direction appeared in the northeastern part of

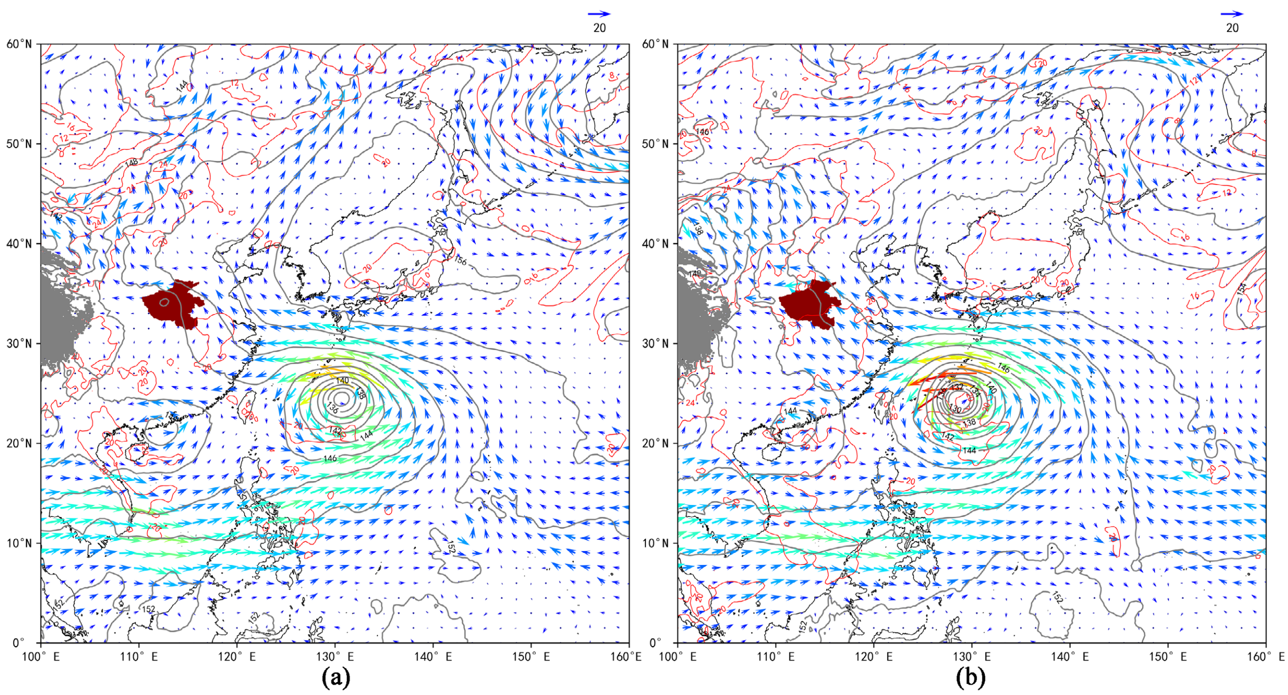

Figure 7. Spatial distribution of 850 hPa geopotential height (contours, unit: dagpm) and wind fields (vector, unit: m·s⁻¹) at 08 (a) and 20 (b) on July 20, 2021.

Henan Province, providing conditions for the upcoming convergent upward motion. At 08:00 on the 20th (**Figure 7(b)**) the typhoon and the subalpine continued to move westward, strengthen, and continue, thus providing good conditions for the convergent upward motion over Henan. At 20:00 on the day (**Figure 7(b)**) the typhoon and the WPSH continued to move westward, intensify, and continue, forming a steady southeasterly rush, thus providing good water vapor and energy conditions over Henan.

3.2.4. Vertical Velocity

Figure 8(a) & **Figure 8(b)** shows that at 08:00 on the 20th, from 850 to 500 hPa overall showed a strong upward movement, and which was enhanced with the increase in height. At 500 hPa height over Zhengzhou City reached 6.0 Pa/s; the low level has water vapor from "In-Fa" and is brought by the WPSH. By 08:00 on the 21st (**Figure 8(c)** & **Figure 8(d)**), the maximum zone of 500 hPa vertical velocity began to move from the area of Zhengzhou to the north of Henan, and

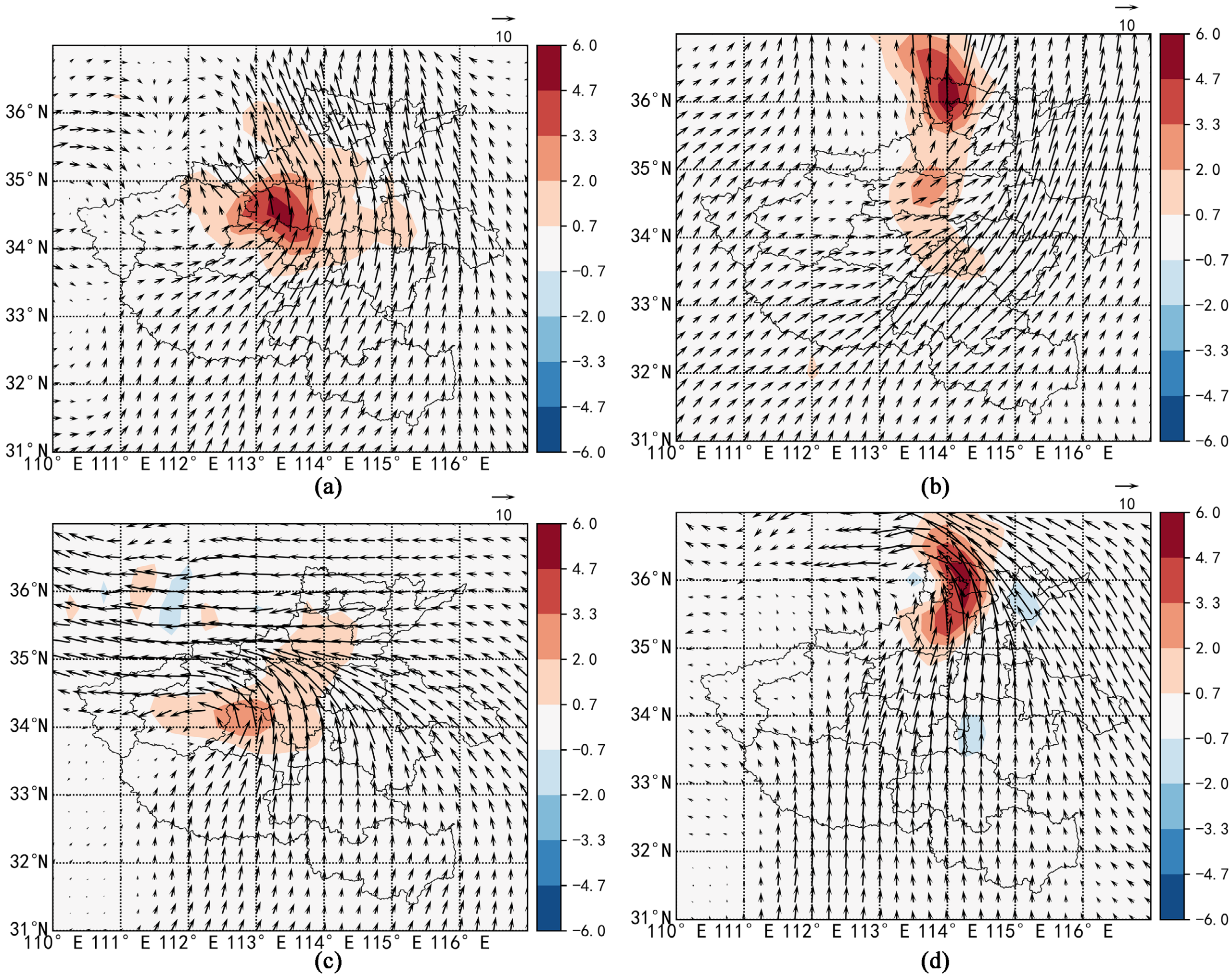

Figure 8. Distribution situation of wind field (vector, unit: m·s^{-1}) and vertical velocity (filled color map, unit: Pa·s^{-1}) in the Henan area on different height layers on July 20-21, 2021: (a) 08:00 on 20th, 500 hPa; (b) 08:00 on 20th, 850 hPa; (c) 08:00 on 21st, 500 hPa; (d) 08:00 on 21st, 850 hPa.

the maximum value still remained 6.0 Pa/s. The strong convective motion provided good conditions for the development of heavy rainfall, and the area of strong convective activity corresponded to the central range of precipitation fallout (**Figure 3**).

3.3. Dynamic Conditions

Si et al. (2021) in their study of the July 9, 2016 rainstorm pointed out that the flared structure of the windward side slopes at the eastern foot of the middle Taihang Mountains in Henan Province provided favorable topographic uplift for the formation of the rainstorm. The aforementioned analysis shows that this heavy rainfall process mainly occurred on July 20-21. Combining with the main precipitation fall areas in **Figure 3**, the following analysis will be carried out in conjunction with the dynamic conditions formed by the topographic uplift, and the main analysis range and time period are: 112˚-115˚E, 33˚N-36˚N, July 20-21.

3.3.1. Vertical Profile of Vorticity and Vertical Circulation

For this heavy rainfall process, the vorticity and wind fields on the longitudinal profile (**Figure 9**) and on the latitudinal profile (**Figure 10**) were plotted along the heavy precipitation center Zhengzhou (113.5˚E) as well as along (34.5˚N) from 08:00 on July 20 to 20:00 on July 21, 2021.

At 08:00 on the 20th (**Figure 9(a)**), the areas below 500 hPa over 34˚N were all positive vorticity, and the maximum value appeared in the middle layer of 700-500 hPa. The positive vorticity center could reach $27 \times 10^{-5}\ s^{-1}$ and was accompanied by extremely strong vertical upward motion. There was a large negative vorticity area near 300 hPa, and the anti-phase oblique pressure configuration of high and low altitudes was favorable to the heavy rain development. Meanwhile, **Figure 10(a)** shows that the positive vorticity zone is located over 114˚E and up to 350 hPa, and the center is roughly between 700 - 500 hPa, with vorticity values up to $50 \times 10^{-5}\ s^{-1}$, corresponding to the strong convective motion, and there is a weak negative vorticity zone above 500 hPa on the north side.

At 20:00 on the 20th (**Figure 9(b)**), there was a weakened positive vorticity zone in the lower layer over 34˚N and in the middle layer over 36˚N - 38˚N, and the convective activity was relatively weakened. A similar weakened positive vorticity and weakened convective motion was observed around 113.5˚E (**Figure 10(b)**).

At 08:00 on the 21st (**Figure 9(c)**), the positive vorticity area was over 34˚N-37˚N, and the center moved over 36˚N, with a maximum value of $50 \times 10^{-5}\ s^{-1}$, accompanied by enhanced upward motion and enhanced convective activity, but no corresponding enhancement of the latitudinal structure (**Figure 10(c)**), indicating that the meridional wind transport and structure played a major role. This also matches the movement of the rain band in **Figure 4**.

At 20:00 on the 21st (**Figure 9(d)**) the positive vorticity zone remained over the vicinity of 36˚N with strong convective motion. However, there is no more obvious change in the profile at 34.5˚N (**Figure 10(d)**).

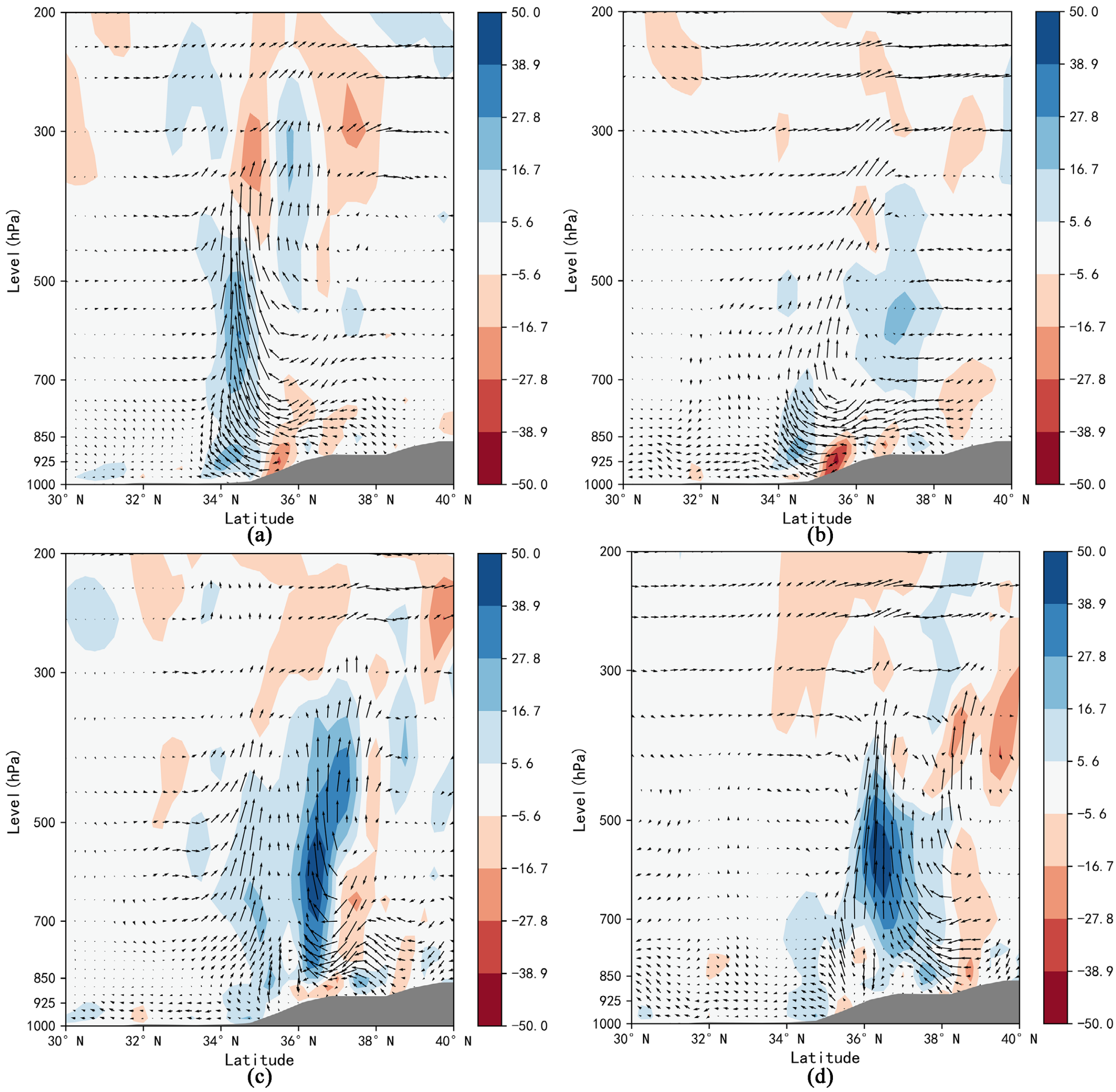

Figure 9. Vertical profiles of the vorticity (filled color map in 10^{-5} s^{-1}) and meridional winds (in $m \cdot s^{-1}$) with vertical velocity (in 10^{-1} $Pa \cdot s^{-1}$) along the center of heavy rainfall (113.5˚E) on July 20-21, 2021 (arrows): (a) 08 on 20; (b) 20 on 20; (c) 08 on 21; (d) 20 on 21.

3.3.2. Vertical Profile of Despersion

For this heavy rainfall process, the scatter and wind fields on the longitudinal profile (Figure 11) and on the latitudinal profile (omitted) were plotted along the center of heavy precipitation, Zhengzhou City (113.5˚E), as well as along (34.5˚N) from 08:00 on July 20 to 20:00 on July 21, 2021.

At 08:00 on the 20th (Figure 11(a)), the positive scatter area was above 500 hPa over 34˚N-35˚N, with the central scatter exceeding 38.9×10^{-5} s^{-1}, and the negative scatter area was below 500 hPa, with the negative scatter center less than -16.7×10^{-5} s^{-1}, forming a strong upward motion situation of lower level

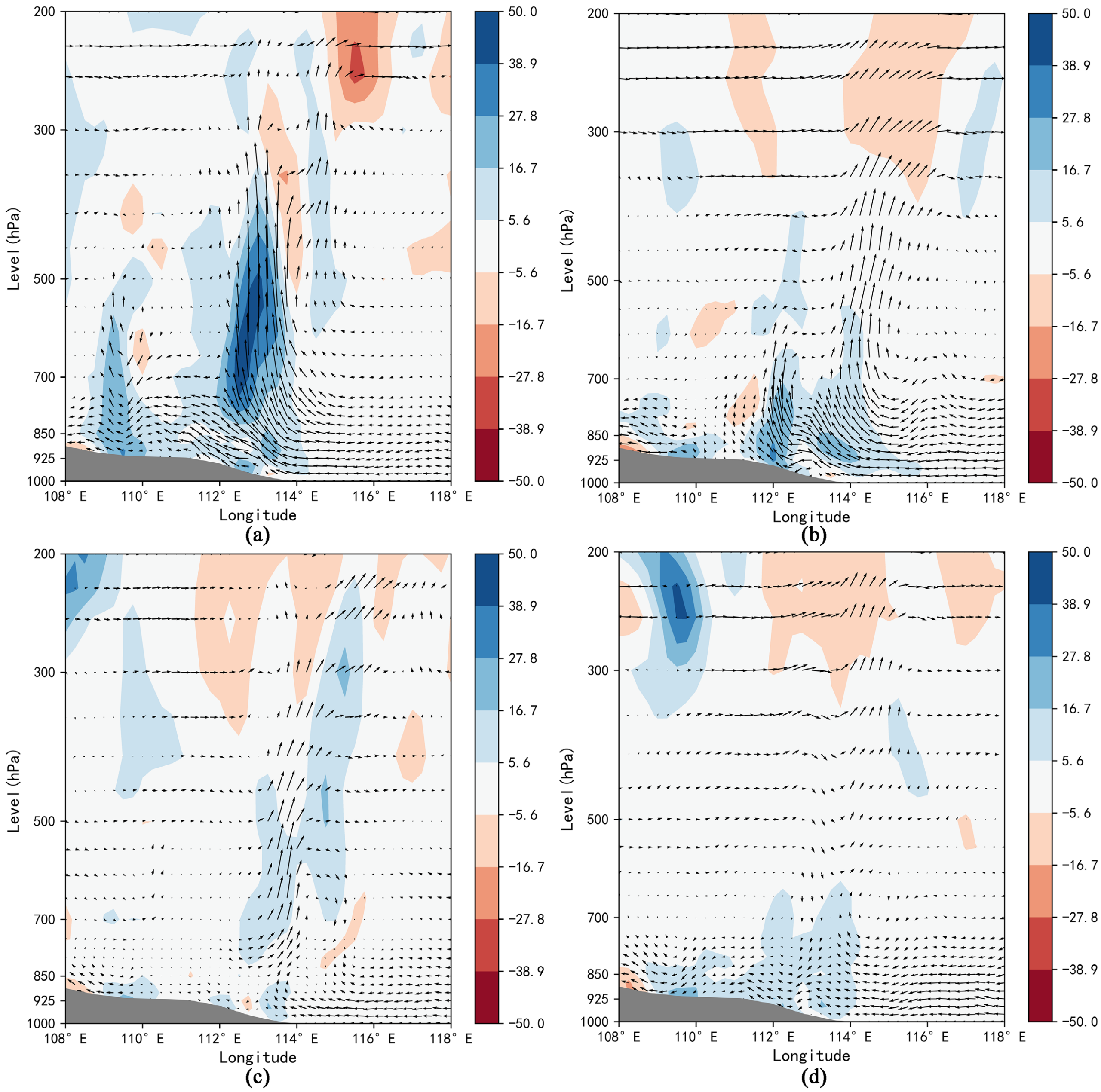

Figure 10. Vertical profiles of the vorticity (filled color map in 10^{-5} s^{-1}) and latitudinal winds (in $m \cdot s^{-1}$) with vertical velocity (in 10^{-1} $Pa \cdot s^{-1}$) along the center of heavy rainfall (34.5˚N) on July 20-21, 2021 (a) at 08:00 on the 20th; (b) at 20:00 on the 20th; (c) at 08:00 on the 21st; (d) at 20:00 on the 21st

convergence and upper level divergence. At 08:00 on the 21st (Figure 11(c)), in the range of 37˚-38˚N, a clear positive dispersion zone appeared at 500-300 hPa, while at 850-500 hPa, a clear negative dispersion distribution was observed, and the vertical velocity increased, forming two major upward zones and strengthening convective motion. 20:00 on the 21st (Figure 11(d)), compared with On the 20th, the high-low configuration shifted northward, mainly located at 36˚N-38˚N, and the two main upward movements were further strengthened compared to 08:00 on the 21st. The configuration of low-altitude convergence

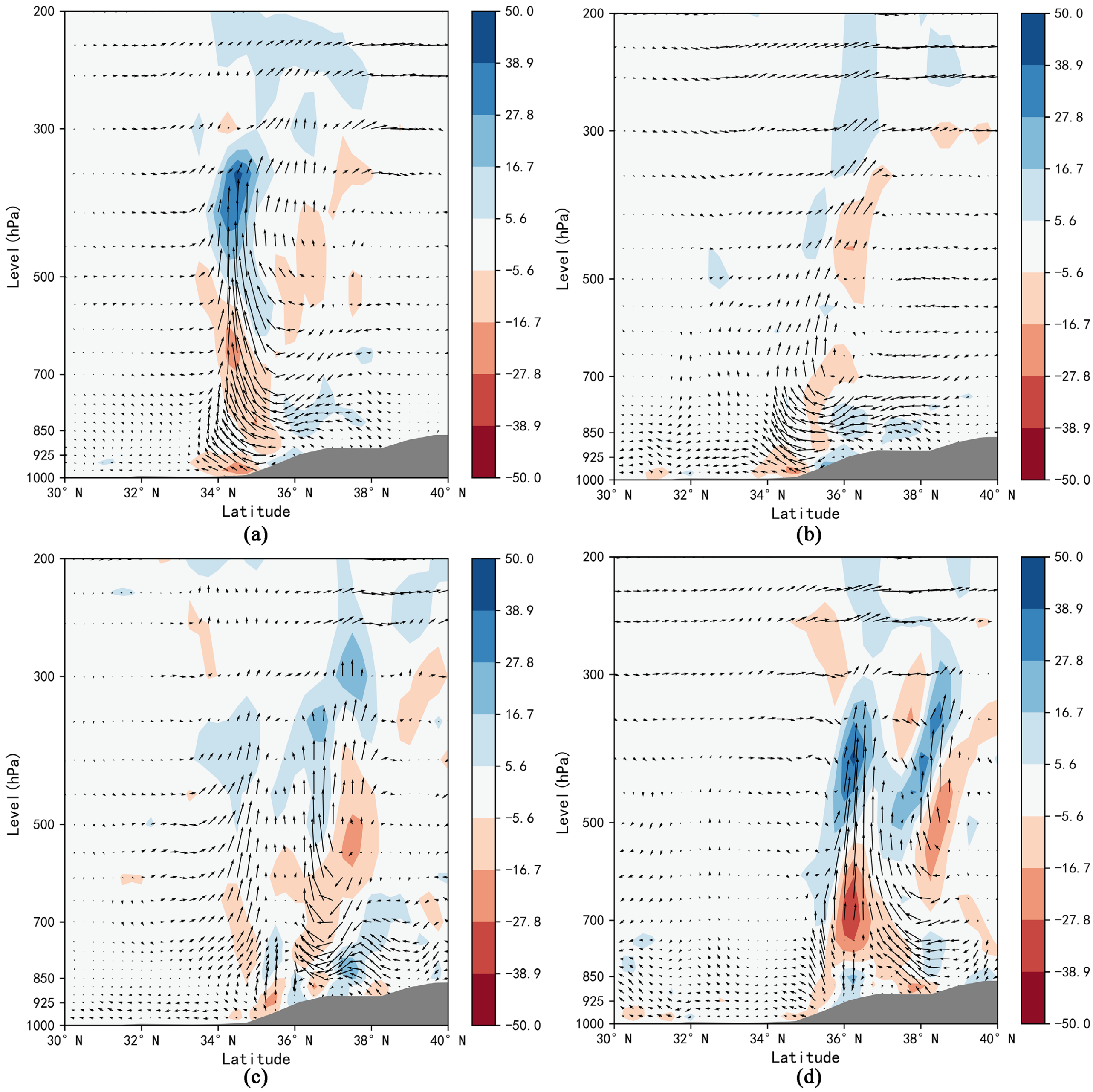

Figure 11. Vertical profiles of the scatter (filled color map in 10^{-5} s^{-1}) and meridional wind (in $m \cdot s^{-1}$) and vertical velocity (in 10^{-1} $Pa \cdot s^{-1}$) synthetic fields (arrows) along the center of heavy rainfall (113.5˚E) on July 2021: (a) at 08:00 on 20; (b) at 20:00 on 20 (c) at 08:00 on 21 (d) at 20:00 on 21.

and high-altitude dispersion with strong upward motion, combined with the water vapor flux (omitted) and the analysis of the aforementioned circulation situation, shows that the high-altitude and low-altitude configurations provide favorable power lifting conditions for the development of this rainstorm.

4. Summary

In this paper, the heavy rainfall process in Henan of the July 20, 2021 was first diagnosed and analyzed. Then the possible causes of the formation and development of this heavy rainfall were discussed.

1) The precipitation was of extraordinarily heavy rainfall level, mainly with Zhengzhou, Henan Province as the precipitation center and radiating to Jiaozuo, Xinxiang, Kaifeng, Xuchang, Pingdingshan, Luoyang, Luohe, etc. The precipitation started on the 19th and ended on the 21st. The cumulative precipitation in Zhengzhou area exceeded 500 mm in 48 hours, and the cumulative precipitation in the surrounding urban area of about 5000 square kilometers also reached more than 150 mm. The rain band in the precipitation process was first of the center-outward spreading type, then turned to the southwest-northeast direction, and finally showed a north-south direction.

2) The circulation situation formed by the short-term maintenance and strengthening of the WPSH and typhoon "In-Fa" and "Cempaka" is low in the south and high in the north, which is conducive to the transport of warm and humid airflow to northern China, especially Henan, and provides a continuous source of water vapor support for this rainstorm. The small high-pressure structure north of Henan formed by the less dynamic strengthening of the structure is conducive to the gathering of warm and humid air in the Henan area, coupled with the special topographic uplift of the south side of the Taihang Mountains makes the heavy precipitation center mainly distributed in the western part of Henan Province and the northwestern areas along the mountains.

3) Power conditions are an important reason for the formation and development of precipitation. The vertical structure of low-level convergence and high-level dispersion near Zhengzhou is conducive to the maintenance of latitudinal and longitudinal circulation, and the blocking and lifting effect of the terrain has formed a strong upward movement in Henan, providing favorable power lifting conditions for this rainstorm, especially the analysis of the vertical profile in the longitudinal direction, which shows that the strong upward movement area and the falling area and movement of the rainband There is a close connection between the fall zone and the movement of the rain band.

The July 20, 2021, rainstorm in Henan has important research significance and value, and the mechanism of its formation and development can be explored in depth in combination with numerical simulation afterwards.

Fund

This work is funded by the Sichuan Provincial Model Course on "Curriculum Civics and Politics"-Atmospheric Fluid Mechanics Project (2020KCSZ01) and the Undergraduate teaching Engineering of Chengdu university of Information Technology (JYJG2021034).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Ding, Y. (2019). The Major Advances and Development Process of the Theory of Heavy Rainfalls in China. *Torrential Rain and Disasters, 38,* 395-406.

Du, H., Donat, M. G., Zong, S., Alexander, L. V., Manzanas, R., Kruger, A. et al. (2022). Extreme Precipitation on Consecutive Days Occurs More Often in a Warming Climate. *Bulletin of the American Meteorological Society, 103,* E1130-E1145. https://doi.org/10.1175/BAMS-D-21-0140.1

Gao, W., Li, K., & Jin, H. (2020). Characteristics of Extreme Precipitation in Henan Province during 1960-2014. *Journal of Henan University (Natural Science), 50,* 253-261. https://doi.org/10.15991/j.cnki.411100.2020.03.001

Ji, C., & Li, S. (2021). Analysis on Extremity of the "7·19" Severe Rainstorm Process in Kaifeng. *Meteorological and Environmental Sciences, 44,* 53-62. https://doi.org/10.16765/j.cnki.1673-7148.2021.04.007

Khouakhi, A., Villarini, G., & Vecchi, G. A. (2017). Contribution of Tropical Cyclones to Rainfall at the Global Scale. *Journal of Climate, 30,* 359-372. https://doi.org/10.1175/JCLI-D-16-0298.1

Lei, L., Xing, N., Zhou, X., Sun, J., Zhai, L., Jing, H., & Guo J. (2020). A Study on the Warm-Sector Torrential Rainfall during 15-16 July 2018 in Beijing Area. *Acta Meteorologica Sinica, 78,* 1-17.

Li, G., Du, L., Zhao, H., Xu, Q., Wu, L., & Wang C. (2016). Multi-Scale Diagnosis of a Strong Precipitation Process in the North of He'nan. *Journal of Arid Meteorology, 34,* 828-835.

Li, H., Wang, X., Zhang, X., Lü, L., & Xu, W. (2018). Analysis on Extremity and Characteristics of the 19 July 2016 Severe Torrential Rain in the North of Henan Province. *Meteorological Monthly, 44,* 1136-1147.

Lin, Y. L., Chiao, S., Wang, T. A., Kaplan, M. L., & Weglarz, R. P. (2001). Some Common Ingredients for Heavy Orographic Rainfall. *Weather and Forecasting, 16,* 633-660. https://doi.org/10.1175/1520-0434(2001)016<0633:SCIFHO>2.0.CO;2

Si, F., Zhang, Y., Zhao, H. et al. (2021). Analysis on Formation and Extremity of the 9 July Extreme Torrential Rain in the North of Henan Province. *Meteorological and Environmental Sciences, 44,* 65-73. https://doi.org/10.16765/j.cnki.1673-7148.2021.01.008

Su, A., Lü, X., Cui, L. et al. (2021). The Basic Observational Analysis of "7·20" Extreme Rainstorm in Zhengzhou. *Torrential Rain and Disasters, 40,* 445-454. https://doi.org/10.3969/j.issn.1004-9045.2021.05.001

Su, A., Shi, D., & Ge, X. (2019). Numerical Simulation of the Influence from Urbanization and Orography on a Severe Rainfall Event in Zhengzhou. *Transactions of Atmospheric Sciences, 42,* 434-446. https://doi.org/10.13878/j.cnki.dqkxxb.20181116003

Wang, J., Wu, D., Wang, C. et al. (2022). Analysis on the Influence of Distance Typhoon on the Extreme Precipitation in July 2021 in Henan. *Meteorological and Environmental Sciences, 45,* 75-85. https://doi.org/10.16765/j.cnki.1673-7148.2022.02.008

Weisse, A. K., & Bois, P. (2001). Topographic Effects on Statistical Characteristics of Heavy Rainfall and Mapping in the French Alps. *Journal of Applied Meteorology, 40,* 720-740. https://doi.org/10.1175/1520-0450(2001)040<0720:TEOSCO>2.0.CO;2

Xi, S., Zhang, Y., & Zheng, S. (2021). Comparative Analysis of Two Heavy Downpour Events in Early Autumn over Henan Province. *Meteorological and Environmental Sciences, 44,* 48-58. https://doi.org/10.16765/j.cnki.1673-7148.2021.06.006

Zhang, B., Zheng, Y., Shen, F., Zeng, M., & Wang, Y. (2021). Characteristics and Simulation of a Torrential Rainstorm over Southern Jiangsu in 2017 Revealed by a High-Resolution

Numerical Model. *Journal of the Meteorological Sciences, 41,* 386-397.

Zhang, N., & Su, A. (2014). Influence of Topography on a Severe Rainfall Process in Western Henan Province. *Journal of Meteorology and Environment, 30,* 16-24.

Zhang, R., Tian, J., Chen, C. et al. (2022). Cause Analysis of the 20 July, 2021 Extreme Rainstorm Event in Zhengzhou. *Meteorological and Environmental Sciences, 45,* 52-64. https://doi.org/10.16765/j.cnki.1673-7148.2022.02.006

Zhang, W., & Cui, X. (2012). Main Progress of Torrential Rain Researches in North China during the Past 50 Years. *Torrential Rain and Disasters, 31,* 384-391.

Zhao, S., & Sun, J. (2019). Progress in Mechanism Study and Forecast for Heavy Rain in China in Recent 70 Years. *Torrential Rain and Disasters, 38,* 422-430. https://doi.org/10.3969/j.issn.1004-9045.2019.05.004

Zhou, X., Sun, J., Zhang, L., Chen, G., Cao, J., & Ji, B. (2020). Classification Characteristics of Continuous Extreme Rainfall Events in North China. *Acta Meteorologica Sinica, 78,* 761-777.