

Unveiling the differential effects of typhoon Doksuri and Khanun on the 2023 Beijing–Tianjin–Hebei extreme rainfall

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Abstract

A substantial number of severe convective storms caused flash flooding across Beijing–Tianjin–Hebei area(BTHA) from July 29th to August 1st, 2023. The prevailing view concerning the roles of the two typhoon, Doksuri and Khanun, posits that either both typhoons are of significant importance or the remnant of Doksuri play a predominant role.

However, there is a lack of definitive analysis and evidence to substantiate the specific differential impacts of these two typhoons on this particular event. This article reveals that both Typhoon Doksuri and Khanun play crucial roles in the transportation of water vapor. Typhoon Doksuri primarily exerts its influence on the southern region of BTHA, whereas Typhoon Khanun predominantly affects the northern region. Water vapor below 925 hpa plays a dominant role in the southern region. Further analysis indicates that the impact of Typhoon Doksuri on the southern region stems from the fact that the typhoon nearly dissipated on the 31st, with less water vapor reaching the northern region. Meanwhile, Typhoon Khanun intensified on the 30th and 31st, primarily influencing the northern region through the key water vapor channel(120–125°E;5–30°N). Consequently, the distinct water vapor sources influenced by the typhoons in these two regions determine their varied responses to global warming.

Introduction

The Northwest Pacific is the region with the most active typhoons in the world(Gu, Yining, et al. 2024,2025). Each year, typhoons, particularly those that make landfall, unleash sustained strong winds and torrential rainfall upon the affected areas, resulting in damage to buildings and other infrastructure, as well as causing casualties(Pérez-Alarcón, A. et al. 2023; Huang, C. et al. 2025). Moreover, the disasters and losses inflicted by typhoon rank highest among the most severe extreme events(Qin, L. et al. 2024; Jing, R. et al.2024). Occasionally typhoons occur in clusters, with two or more appearing simultaneously, leading to even more catastrophic disasters(Gray, W. M., 1979; Sun, Z. et al. 2009). For instance, during the extreme event in Zhengzhou, China, the combined water vapor transportation from Typhoon Cempaka and In-fa, significantly amplified the precipitation intensity, surpassing the cumulative impact of each typhoon acting alone individual.(Jie, Z. et al. 2024).`

From July 29th to August 1st, 2023(referred to as“23.7”), an extreme rainstorm struck the Beijing–Tianjin–Hebei area(BTHA), recorded rainfall totals > 1,000 mm over 3 days in a local region near the Taihang Mountains, in China (Fowler, H.J. **et al.2024**). It was observed that the “23.7”extreme rainstorm was characterized by prolonged duration, substantial accumulated rainfall and extensive coverage, displaying remarkable extremity. Beijing experienced its heaviest precipitation since record-keeping began more than over a century ago(Dajun Zhao et al. 2024).

Three primary factors contribute to this extreme event: the formation of a robust high-pressure dam by both the subtropical high and the Mongolian high pressure impeded the northward movement of the remnants of Typhoon Doksuri, leading to the stagnation of a significant amount of water vapor, the elevation of complex terrain between the Taihang and Yanshan mountain areas significant influence the

rainstorm, and the remnant of Typhoon Doksuri and Typhoon Khanun provided a sufficient and continuous supply of water vapor from low latitudes, which accumulated in the east region of the two Mountains area(Chen, T.et al.2024; Dajun Zhao et al. 2024; Jun Gu et al. 2025).

Previous research has predominantly focused on the first two factors, with comparatively limited exploration of the specific effect of typhoons. A key feature of this extreme event lies in the influence exerted by the two typhoons, the direct effect of the remnant of Typhoon Doksuri and the long-range water vapor transport associated with Typhoon Khanun. However, there remains a knowledge gap regarding the significant role these two typhoons play and their differing impacts on the event. This article addresses this issue through a series of sensitivity experiments.

Results

Characteristic of the 23.7 BTHA event

A substantial amount of research has been published on the characteristics of the 23.7 BTHA event. The entire precipitation area exhibits a banded pattern along the Tai hang-Yanshan mountain range. The maximum precipitation center is situated in front of mountainous region, with relatively less precipitation occurring in the plain areas. The simulation results align closely with the observations, though they slightly underestimate precipitation in the southern region. According to hourly precipitation statistics, this rainstorm is primarily characterized by long-duration and medium-duration precipitation(Tang et al. 2024).

Notably, this rainstorm formed two distinct precipitation center, one in the southern region, centered around Xingtai, in Hebei province, China and the other in the northern region, centered on the Beijing-Tianjin area. In terms of precipitation timing, the southern region predominantly experienced precipitation on the 29th and 30th, while the northern region mainly saw precipitation on the 30th and 31st. July 30th marks the overlapping precipitation period for both regions. Previous studies have primarily emphasized the significant impact of the remnants of the typhoon Doksuri and Khanun on the entire rainstorm events. However, the differential effects of these two typhoons during the distinct precipitation periods in the two regions have not been clearly distinguished in prior research.

Furthermore, it appears that the mechanisms underlying extreme precipitation in the northern region are fundamentally different from those in the southern region. The impacts of global warming also vary between these two regions. Zhao J. et al (2024) demonstrated that anthropogenic warming decreased extreme precipitation in the northern area while increasing it in the southern area, with both effects being primarily driven by dynamic factors. We further raise the question of why such difference exist, whether they are related to the nature of precipitation in these two regions, and what kind of correlation exists between these differences and the effects of the two typhoons.

The differential impacts of Typhoon Doksuri and Khanun

Hence, in this study, multiple sensitivity experiments are devised utilizing the WRF model to address these questions.

The entire precipitation region lies within the domain of 35° – 44° N, 110° – 120° E. To distinguish the differential impacts of the remnant of Typhoon Doksuri and Typhoon Khanun, we define two key subregions for water vapor transport: the Middle Area (MA), located at 30° – 35° N, 110° – 120° E, where moisture transport is primarily controlled by the remnant of Typhoon Doksuri; and the East Area (EA), situated at 30° – 35° N, 120° – 130° E, where water vapor transport is mainly influenced by Typhoon Khanun.

The purpose of differentiating the impacts of the remnants of Typhoons Doksuri and Khanun on this extreme rainfall event is achieved by separately halving the relative humidity (RH) in the Middle Area (MA; EXP1) and the East Area (EA; EXP2). Compared to the control experiment (CTL), EXP1 shows a substantial reduction in precipitation over the southern region of the Beijing–Tianjin–Hebei Area (BTHA), whereas precipitation in the northern region is less affected. In contrast, when RH in the EA is reduced (EXP2), the most significant precipitation decrease occurs in the northern BTHA, with a comparatively smaller reduction in the south. These two sensitivity experiments indicate that neither typhoon alone dominates the entire precipitation field of this extreme event. The remnant of Typhoon Doksuri primarily influences the southern BTHA, while Typhoon Khanun affects both southern and northern regions, with its dominant impact concentrated in the north.

Impact of the low level relative humidity(RH) and wind on the “23.7” event

Based on the aforementioned research, the precise extent of Typhoon Doksuri's influence on the precipitation over the southern Beijing-Tianjin-Hebei Area (BTHA) requires further quantification. A critical unresolved question is: What is the dominant vertical height of the water vapor source contributing to precipitation in the southern BTHA? To address this, we designed two sensitivity experiments in which the wind field and relative humidity (RH) in the Middle Area (MA) were separately halved below the 850 hPa and 925 hPa pressure levels, respectively.

The experimental results reveal a distinct vertical stratification in the impact of water vapor and wind field on precipitation. A reduction in RH below 925 hPa leads to a significant and pronounced decrease in precipitation across the southern BTHA (figure 3c). In contrast, additional reduction of RH below 850 hPa yields only a marginal supplementary decrease in precipitation (figure 3d). However, when the wind field below 925 hPa and 850 hPa or the wind field within all levels is reduced by half, only a limited reduction of precipitation occurs in both regions. These findings clearly indicate that water vapor originating from below 925 hPa is the primary contributor to precipitation in the southern BTHA, playing a dominant role in modulating

precipitation intensity and distribution.

Our results are further supported by the work of Chen Tao et al. (2024), who utilized ERA5 reanalysis data to demonstrate that during the precipitation event, the convergence center of the low-level wind

field and the peak of water vapor flux are concentrated between 950 hPa and 925 hPa. This alignment between our experimental findings and independent observational analysis strengthens the robustness of our conclusion, highlighting the critical importance of low-level water vapor in driving precipitation in the southern BTHA during this extreme weather event.

The main water vapor transportation channel of the 23.7 event

Based on the results above, it is evident that the primary areas affected by Typhoon Doksuri are in the southern region, while Khanun primarily affects the northern region. To address this question, further experiments were conducted. Three distinct areas were chosen: A (120-145°E, 5-30°N), B (125-145°E, 5-30°N), and C (120-125°E, 5-30°N). Initially, the relative humidity (RH) of areas A and B was reduced by half and one-fifth, respectively, to investigate the extent to which Khanun's water vapor transport influenced the 23-7 BTHA event. The results indicated that whether the RH of area B was reduced by half or one-fifth, the overall precipitation in the region decreased only slightly (Figure 4c, d). However, when the RH of area A was reduced by half or one-fifth, there was a significant decrease in precipitation in the northern region (Figure 4e, f). During this process, precipitation in the Beijing area almost vanished. This underscores the significance of the overlapping region, specifically the water vapor transport corridor (120-125°E; 5-30°N), for precipitation in the northern region.

To further emphasize the importance of the water vapor transport corridor (120-125°E; 5-30°N) for precipitation in the northern region, the RH within this corridor was reduced by half. The results revealed a precipitation pattern comparable to that observed in the experiments where the RH of area B was reduced by half or one-fifth (Figure 4b). This suggests that Typhoon Khanun's impact on the 23-7 BTHA event in the northern region is channeled through the water vapor transport corridor (120-125°E; 5-30°N).

The reason for the differential effects of typhoon Doksuri and Khanun on the BTHA region

From the research above, it is evident that despite the reduction in maximum wind speed and central pressure of Typhoon Doksuri between July 29th and 30th, the values remained firmly at approximately 10m/s and 998 hPa, respectively. However, from 18:00 on July 30th, the central pressure and brightness temperature increased to 1002 hPa and above minus 30°C, respectively (Figure 5a,b). Consequently, the entire remnant of the typhoon nearly dissipated, with minimal water transportation in the northern region. Simultaneously, Typhoon Khanun gradually intensified, with maximum wind speed and central pressure exceeding 45m/s and falling below 945 hPa, respectively (Figure 5b-f and Figure 1a). Consequently, water vapor, primarily driven by the lower tropospheric southeast jet stream originating from both the South China Sea and the strengthening Typhoon Khanun, converged in the northern area of BTHA, sustaining an extreme rainstorm.

Simultaneously, the brightness temperature was remarkably low, with minimum values below minus 60°C (Figure 5c,e), indicating active and continuous deep convective cloud systems. Wind profile radar

observations revealed a strong mesoscale easterly jet in the lower boundary layer, which enhanced convective precipitation to a maximum of 100mm/h on July 31st (Chen Tao et al., 2024).

Discussion

An unprecedented severe convective storm triggered flash floods in the BTHA region of China. Previous research has predominantly emphasized the effects of dual typhoons and the impact of overlapping water vapor transport, yet there is a notable absence of exploration into the differential effects of dual typhoons. This study demonstrates that both the remnants of Typhoon Doksuri and Typhoon Khanun played a pivotal role during the rainstorm. Specifically, the remnants of Typhoon Doksuri primarily affected the southern region of BTHA from July 29 to 30, 2023, while Typhoon Khanun intensified on July 30–31 and mainly impacted the northern region of BTHA.

Furthermore, multiple sensitivity experiments elucidate the reasons behind the differential effects of the two typhoons. The impact of the remnants of Typhoon Doksuri was primarily felt in the southern region of BTHA during July 29–30, and it weakened and nearly dissipated on July 31, 2023, with limited water vapor transported to the northern region of BTHA. Conversely, Typhoon Khanun intensified during July 30–31, 2023, transporting significantly more water vapor into the northern region of BTHA via crucial water vapor transport channels (120–125°E; 5–30°N).

Additionally, dual typhoons are the most common manifestation of typhoon clusters. It is imperative to investigate the differential effects of various typhoons on extreme processes. Moreover, this study identifies key water vapor transport areas (120–125°E; 5–30°N) influenced by Typhoon Khanun, which serve as narrow water vapor transport corridors facilitating typhoons' impact on the northern region of BTHA.

Given that the two regions were primarily affected by distinct typhoons, the southern region, located deep inland and primarily influenced by the remnants of Typhoon Doksuri, experienced warmer environmental conditions. Conversely, the northern region, primarily impacted by Khanun and receiving moisture from the ocean, tended to be cooler. This disparity may account for the differing responses of these two regions to global warming.

Methods

Model configurations

We utilized the Weather Research and Forecasting (WRF) model version 4.0 to investigate the differential effects of typhoons Doksuri and Khanun on the 23.7 BTHA event. The initial and lateral boundaries were derived from NCEP FNL (Final) Operational Global Analysis data, featuring a horizontal resolution of 1° and 34 vertical levels. The model top was set at 50 hPa. We employed a 108-hour simulation with double two-way interactive nest domains (D01 and D02), achieving horizontal resolutions of 9 km and 3 km, respectively, with corresponding grid points of (981×801) and (322×340). Our focus was solely on the

initial 72-hour simulation. The simulation commenced at 0000 UTC on July 29, 2023, with the outer domain centered at (38°N, 113°E). This domain primarily spanned the Bohai, Yellow, and East China Seas, encompassing the entirety of the rainstorm's progression, encompassing its development, intensification, and subsequent weakening phases. The WRF model incorporated various physical parameterization schemes, including the Thompson microphysics scheme, long- and shortwave radiative flux calculations utilizing the RRTM (Mlawer et al., 1997) and Dudhia (Dudhia, 1989) schemes, respectively. For the planetary boundary layer, we employed the ACM2 scheme, while the Monin-Obukhov scheme was utilized for the surface layer. Additionally, we incorporated the unified Noah land surface model. Notably, the Kain-Fritsch cumulus parameterization scheme was applied to D01, but not to D02.

Declarations

DATA AVAILABILITY

The FNL data and The ERA5 data are downloaded from the NCAR Geoscience data exchange <https://gdex.ucar.edu/datasets/d083002/> and the climate data store <https://cds.climate.copernicus.eu/>. The typhoon tracks data are from <https://tcdata.typhoon.org.cn/index.html>. The himawari-9 brightness temperature data are from <ftp.ptree.jaxa.jp/jma/netcdf/>. GPM IMERG7 product is used as the observed precipitation data and is from <https://gpm1.gesdisc.eosdis.nasa.gov/data/>.

CODE AVAILABILITY

The figures in this study were all plotted using the NCAR Commnad Language(NCL) as detailed in <http://www.ncl.ucar.edu/Applications/>. All codes are also available upon reasonable request from the corresponding author.

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Author Contributions

Luo San and Wang Junchao designed this paper and with Luo San being the author. Guiyang and Zhang Jinlong participated in the discussion and contributed to the completion of the article.

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Figures

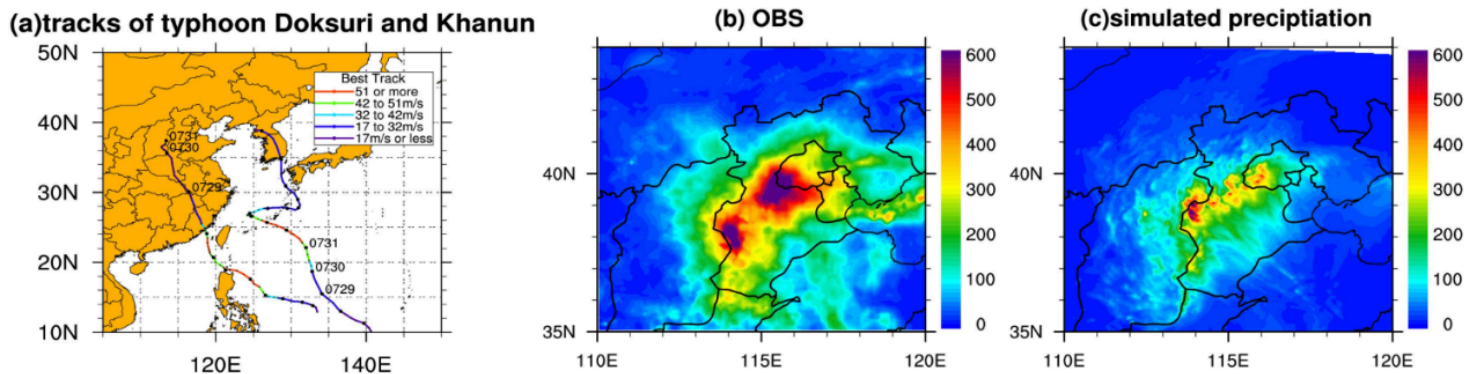


Figure 1

the tracks of the typhoon Doksuri and Khanun (a), and the observed accumulated precipitation (b) and the simulated accumulated precipitation (c) (shading; units: mm) between 00:00 UTC on 29 July and 00:00 UTC on 1 August, 2023.

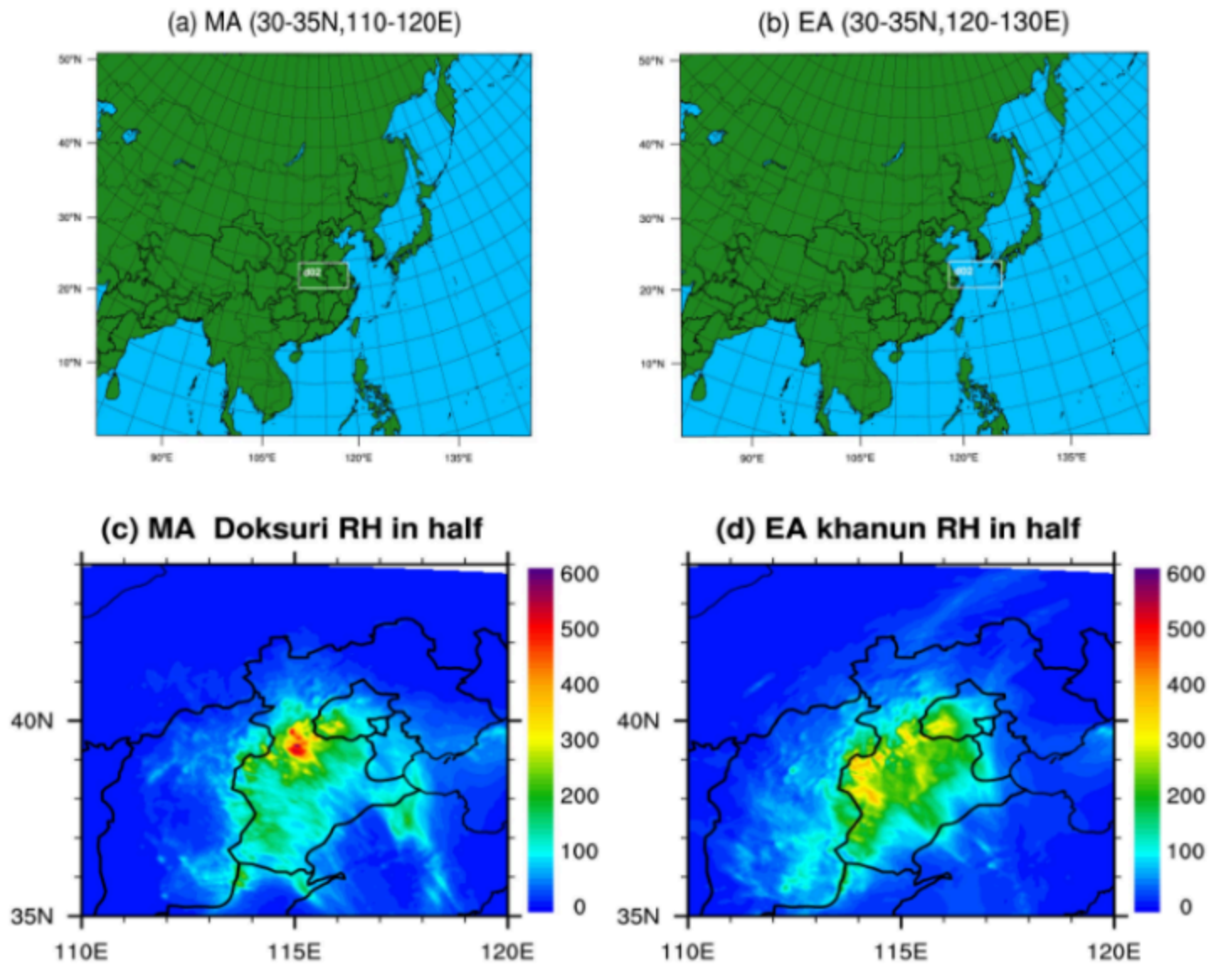


Figure 2

the different important water transportation channel windows and the impact of relative humidity from the two channels on the 23.7 BTHA event.

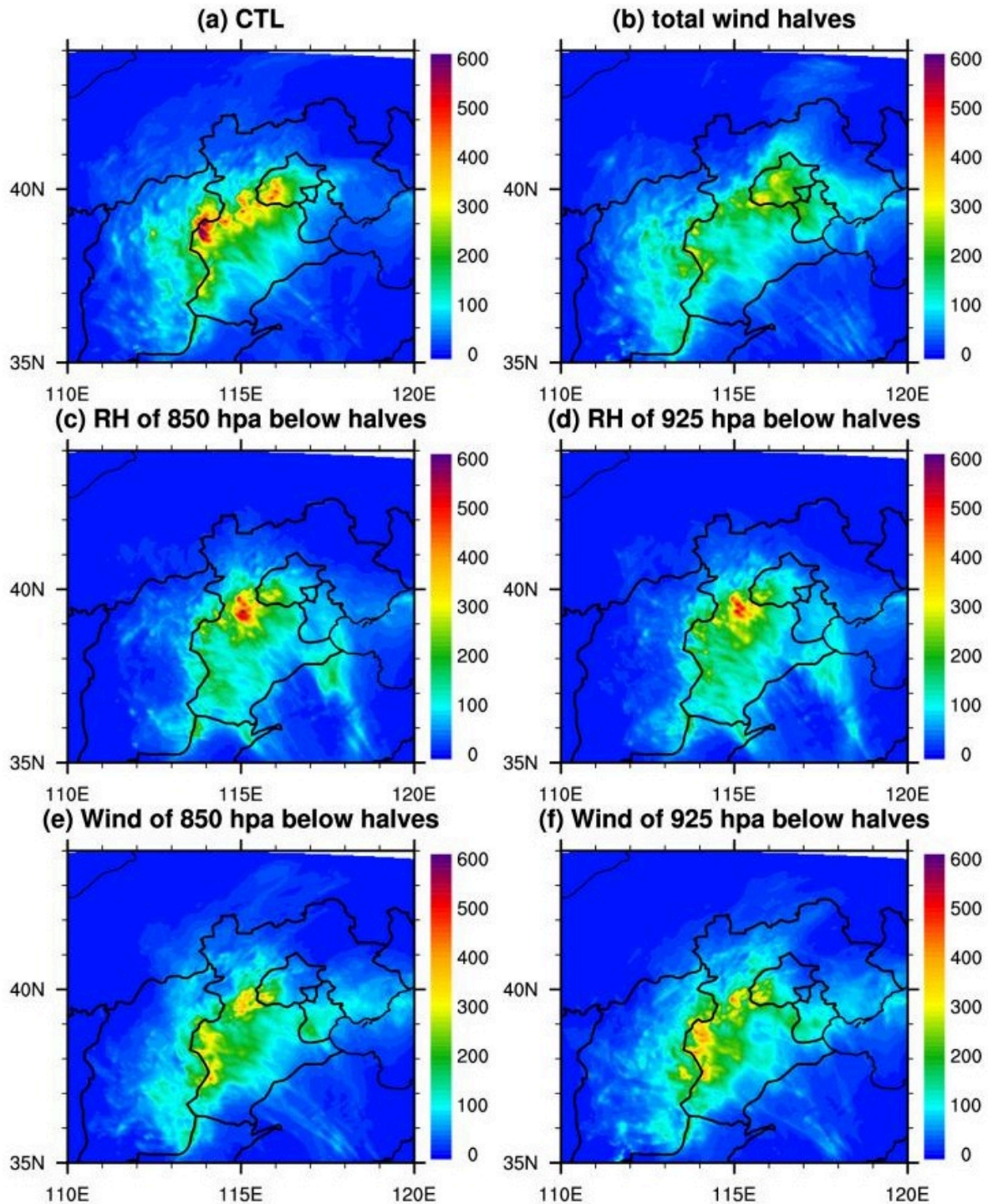


Figure 3

impact of low level relative humidity and wind below 850hPa and 925hPa, respectively.

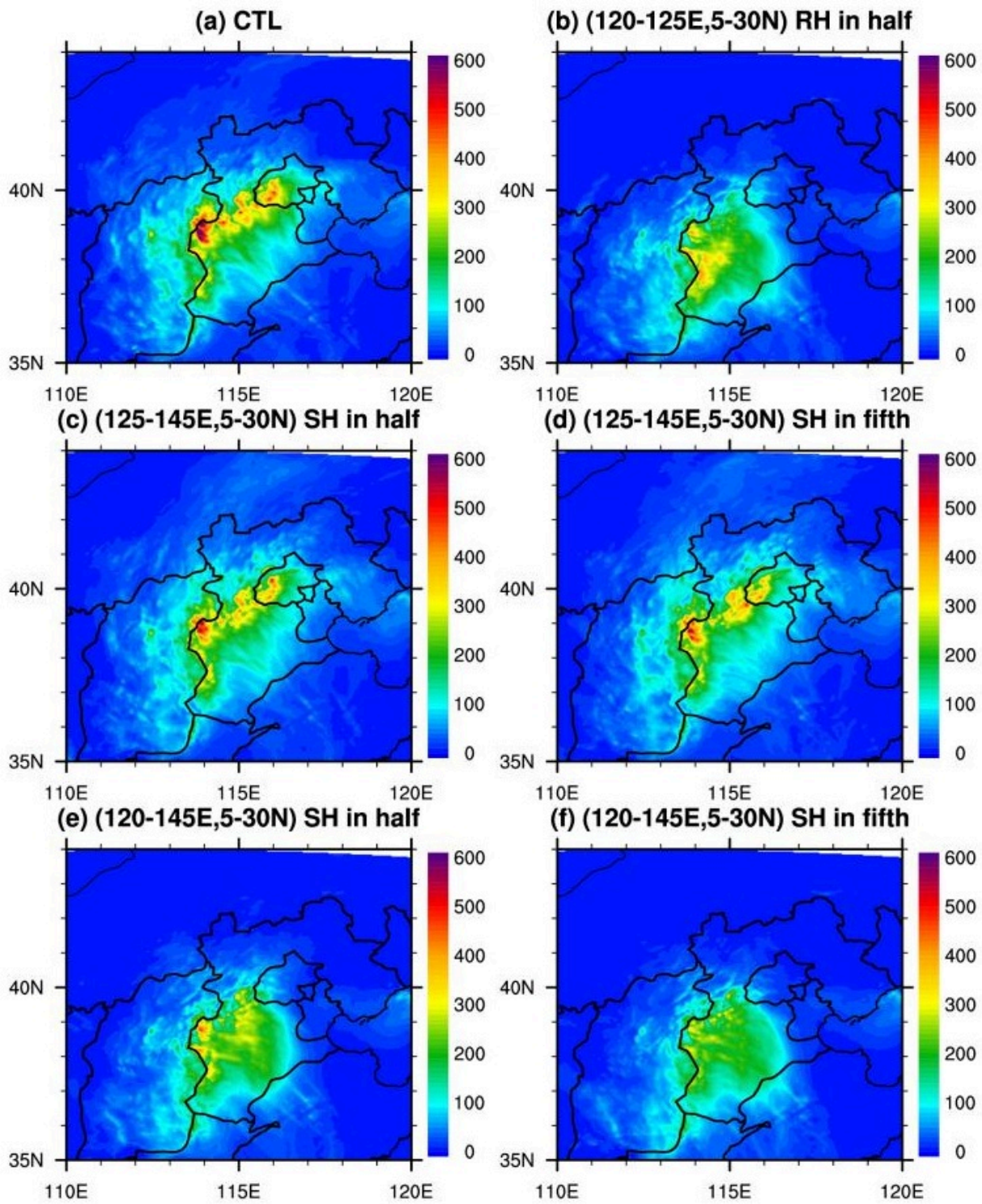


Figure 4

the important water vapor transportation channel of the 23.7 event

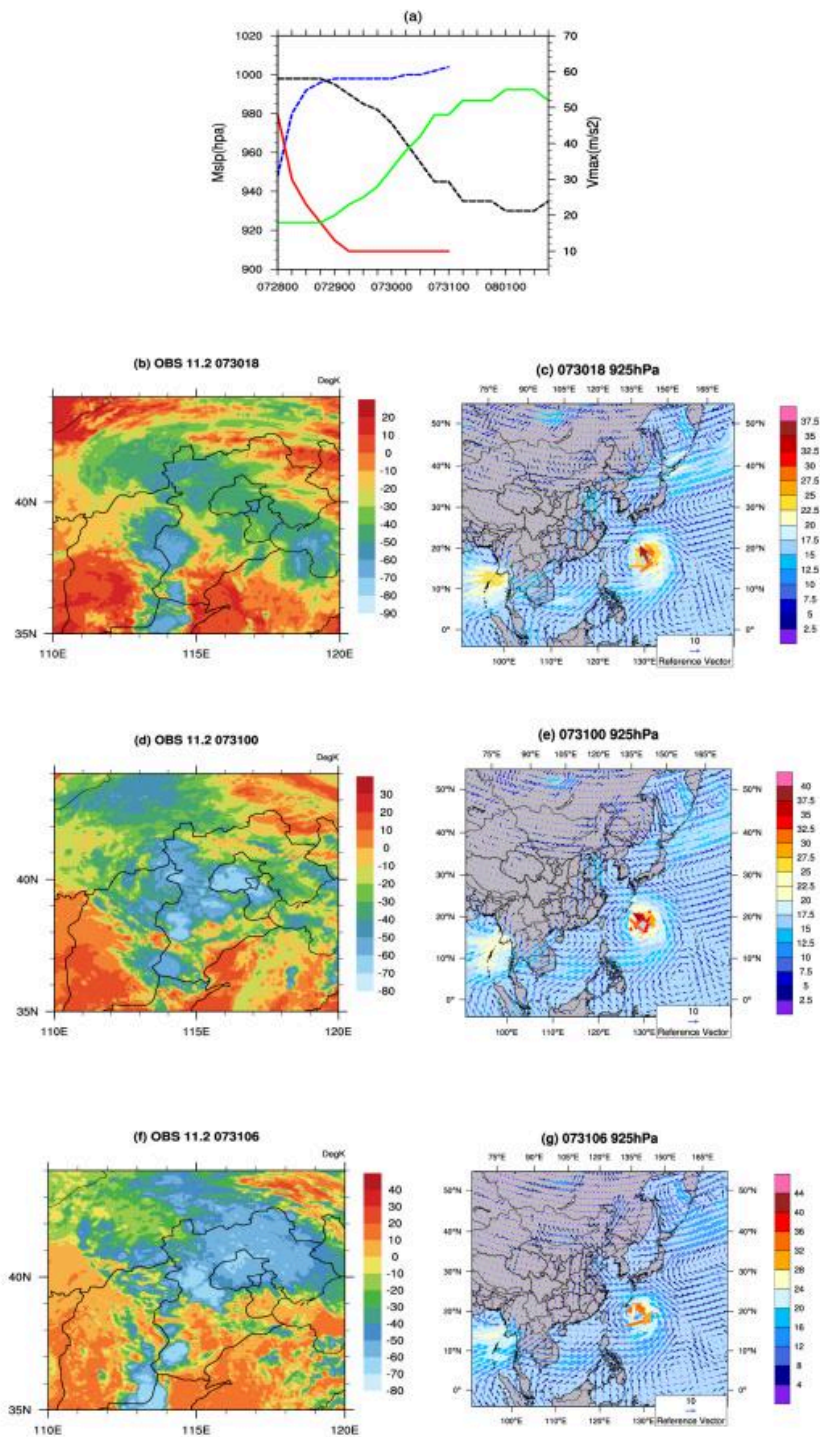


Figure 5

(a) evolution of the maximum wind speed, sea surface pressure and of the typhoon Doksuri and Khanun during the whole precipitation period; the spatial brightness temperature(b, d, f) and wind field(c, e, g) during the rainstorm.