Effects of the Tibetan Plateau and its second staircase terrain on rainstorms over North China: From the perspective of water vapour transport

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Funding information
The second pilot project the second Tibetan Plateau comprehensive scientific research, Grant/Award Number: I07-T01-2018-06/06-JH; Public Welfare Industry (Meteorology), Grant/Award Number: GYHY201406001; National Natural Science Foundation, Grant/Award Number: 91337000, 91644223 and 91437106; Ministry of Finance of China; Science development fund of the Chinese Academy of Meteorological Sciences, Grant/Award Number: 2018KJ019; Jiangsu province postgraduate research and innovation program project, Grant/Award Number: KYCX17_0869

The effects of the Tibetan Plateau (TP) and its second staircase terrain (i.e., the extension of the TP) on summer rainstorms over North China (NC) from the perspective of large-scale water vapour transport were investigated based on the frequency of summer rainstorms from 70 observational stations in NC and National Centers for Environmental Prediction reanalysis data from 1961 to 2010. Seven rainstorm cases over NC during 1981–2016 acquired from ERA-Interim reanalysis data and observational hourly precipitation data were selected. Two water vapour transport channels provided favourable backgrounds for rainstorms over NC. One channel flowed along the northern edge of the TP via westerlies. The other channel flowed along the eastern edges of the TP and its second staircase terrain accompanied with southerly monsoon airflow, with water vapour sources from the Bay of Bengal, South China Sea, and western Pacific. The abundant water vapour that was transported along the two channels not only offered a favourable moisture background for rainstorms over NC but also resulted in the development of water vapour flux vortices that supplied convergence conditions for rainstorms in situ. At low levels, water vapour transport mainly flowed along the eastern edge of the TP second staircase terrain. The results from the Weather and Research Forecasting model simulation of a randomly selected rainstorm case originating from the TP to NC confirmed the vital effect of the TP second staircase terrain on rainstorms over NC accompanied with water vapour transport.

KEYWORDS
North China, rainstorm, second staircase terrain, Tibetan Plateau, water vapour transport

1 INTRODUCTION

China is a large country with diverse and complex terrain. Plateaus in China include the Tibetan Plateau (TP), Inner Mongolian Plateau, Loess Plateau, and Yunnan-Guizhou Plateau, which form the three staircases in mainland China: the third staircase (terrain height: <800 m) comprising the plain located on the eastern region in China; the second staircase (terrain height: 800–3,000 m) with its average elevation at about 1,500 m, as the transition region between the TP and plains, comprising the Inner Mongolian Plateau, Loess Plateau, and Yunnan-Guizhou Plateau; and the TP in western China as the first staircase with its main body above 3,000 m. In the present study, the second staircase terrain refers to the extension of the TP, namely the TP second staircase terrain.
The TP accounts for about 25% of China’s total land area. As the highest plateau with the most complex terrain in the world, the TP has profound impacts on weather and climate in China and East Asia (Feng et al., 2014; Xu et al., 2014). The TP terrain modulates the monsoon climate in East Asia and distinguishes it from other areas of the same latitude (Wang et al., 2017). From the perspective of dynamic effects, as the “ridge of the world,” Yeh et al. (1957) found that the terrain of the TP had a distinct effect on the northern and southern branches of westerlies in winter. Based on numerical experiments, Wu et al. (2007) found that the TP forced the westerly jet to split into northern and southern branches and then merged east of the TP. When air flow is blocked, it can flow over or around the obstacle. Ding (1991) confirmed that the bypassing flow forced by the TP was dominant compared to the airflow climbing over the TP. In summer, the northwards propagation of the southerly monsoon water vapour may be influenced by TP terrain blocking (Chen et al., 2007). Xu et al. (2004) argued that the TP acts as a barrier to force water vapour from tropical oceans to flow along the eastern and southern flanks of the TP, providing favourable conditions for the Mei-Yu in the reaches of the Yangtze River and the Huai River.

Rainstorms in China are related to the distribution of the three staircase terrains of the TP, and rainstorm frequency shows an increasing trend from west to east (Zhao et al., 2016a). As a main region of China, North China (NC) includes the capital city of Beijing (~39°N, 116°E) and several of the most densely populated provinces (He and Zhang, 2010). Summer rainstorms in this area can cause major disasters (Zhao et al., 2014). For instance, NC suffered from an extreme rainstorm event in the summer of 2012, with the centre of the rainstorm event receiving 460.0 mm, and the 11 observational stations breaking historical records. An estimated 1.9 million people suffered from damage, with 77 people dead, and the direct economic loss was more than 10 billion Chinese RMB (Zhou et al., 2013). Huang et al. (2013) also noted that the “7.21” rainstorm event during 2012 in Beijing caused severe flooding within the urban area, resulting in major losses to life and property. The extreme rainstorm event that occurred on July 21, 2012 caused the most disastrous urban flooding in Beijing since 1950 (Chu et al., 2018). Therefore, it is important to research rainstorms over NC. Yang et al. (2013) argued that summer rainstorms in situ are mainly controlled by elevation. The TP topography enhanced the circulation coupling between the Tropics and subtropics, thus caused abundant tropical moisture to be transported northwards along the east TP, leading rainstorms over NC (Wu et al., 2012). In addition, the TP second staircase terrain (e.g., Yanshan-Taihangshan Mountain) has been suggested to induce the precipitation peak over NC (He and Zhang, 2010). The TP second staircase is confirmed to have a favourable role in rainstorms over NC through simulation (Liao et al., 2009). Liang et al. (2007) indicated that water vapour transport from the West Pacific through the South China Sea (SCS), and westerlies at mid-high latitudes have important roles in the occurrence of rainstorms over NC, whereas water vapour transport from the Bay of Bengal (BOB) somewhat enhances rainstorms over NC.

In light of these findings, the TP and its second staircase have a crucial role in rainstorms over NC. However, how the TP and its second staircase terrain influence rainstorms over NC remains unclear, and the role of water vapour transport in the effects of the TP and its second staircase on rainstorms over NC has not been clarified. Existing studies only concentrated on the dynamic effect of the TP without considering its extending areas. Therefore, in this study, we explored the dynamic effects of the TP and its second staircase terrain on summer rainstorms over NC from the perspective of water vapour transport.

2 | DATA AND METHODS

2.1 | Data

The data set employed in this study was the version 3.0 basic meteorology historic data set provided by National Meteorological Information Center (NMIC) of China Meteorological Administration, which consisted of 2,474 gauge stations with daily precipitation records during 1961–2016. This daily precipitation data set had been experienced quality control strictly including an extreme value check and a check of internal consistency by data providers (http://data.cma.cn/). Observational data of days with rainstorms (hereafter, rainstorm frequency) during June–August (1961–2010) at 601 rain-gauge stations throughout China were collected from the aforementioned version 3.0 basic meteorology historic data set to make sure no data missing. Here, rainstorm is defined as daily precipitation exceeding 50 mm (Li et al., 2017a; 2017b; Wu et al., 2018). The 601 stations are distributed throughout China and could be used to reflect the spatiotemporal characteristics of rainfall in the downstream regions of the TP over the central and eastern China, although they are relatively sparse over the TP. NC was defined as a rectangular area over 35°–45°N, 110°–120°E, in which 70 stations were evenly distributed (Figure 1). Reanalysis data including monthly wind and specific humidity acquired from the National Centers for Environmental Prediction (NCEP) with a horizontal resolution of 2.5 × 2.5° (Kalnay et al., 1996) during 1961–2010 were employed in this study (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html).

To reflect the influence of the TP and its second staircase on rainstorms over NC accompanied with water vapour transport, rainstorm cases over NC with the rainstorm process originating from the TP during 1981–2016 were selected. The hourly precipitation data were obtained from 2,413 observational stations with high quality control provided by the NMIC of China Meteorological Administration.
The wind fields and specific humidity with 6-hourly temporal resolution were acquired from the ERA-Interim reanalysis data (http://apps.ecmwf.int/datasets/), which is the global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (Dee et al., 2011). The ERA-Interim reanalysis data, the observational daily and hourly precipitation data were used to analyse the rainband distributions, their related circulations and water vapour flux vortexes during rainstorm processes over NC in detail. All the target rainstorms, their associated circulations and related water vapour flux vortexes strictly met the requirements of originating from the TP, moving eastwards, and reaching NC with achieving the rainstorm level synchronously. Finally, seven rainstorm cases over NC during 1981–2016 were selected. The periods of seven rainstorm cases included July 27–31, 1983, July 5–8, 1990, June 27–30, 1994, July 12–16, 1995, July 8–11, 2013, July 21–24, 2013, and July 17–21, 2016.

2.2 | Application of the Weather and Research Forecasting module

A rainstorm process over NC that originated from the TP running from 0000 UTC July 17, 2016 to 0000 UTC July 21, 2016 was selected from the seven rainstorm cases randomly. The Weather Research and Forecasting (WRF) Model version 3.4.1 (Skamarock and Klemp, 2008; Žabkar et al., 2015) was employed to simulate the influence of the TP second staircase terrain on rainstorms over NC based on this rainstorm process. The sensitivity test was designed by removing the TP second staircase terrain within the area of 103°–115°E, 32°–42°N, predominantly covering the Loess Plateau. Both the control and sensitivity tests were performed using 333 × 233 horizontal grid points with a 30-km horizontal grid resolution covering the whole East Asia area. The time step of the WRF model was set as 60 s. The output frequency of the WRF model was 1 hr. The model included 28 vertical levels, with the topmost layer set at 50 hPa. NCEP Final Operational Global Analysis data from the
Global Data Assimilation System with a horizontal resolution of 1 × 1° (https://rda.ucar.edu/datasets/ds083.2/) were used as the initial and boundary conditions in simulating this eastwards moving rainstorm case (Sun et al., 2013; Wu and Duan, 2015). The simulation time was from 1800 UTC July 16, 2016 to 0000 UTC July 23, 2016.

The WRF model was applied with combinations of different physical parameterizations, including microphysics, radiation, planetary boundary layer (PBL), land-surface model (LSM), and cumulus parameterizations. Yang et al. (2014) indicated that the Kain–Fritsch (new Eta) cumulus parameterization was more appropriate than others for simulating rainstorms over mainland China. The rainfall location and intensity simulated with the WRF Single-Moment 6-Class Microphysics Scheme (WSM6) were more similar to observed rainstorms over NC (Ma et al., 2012). Zhao et al. (2010) found that physical parameterizations, including the Kain-Fritsch cumulus scheme, Yonsei University PBL scheme, and Dudhia shortwave radiative scheme, could simulate rainstorms over NC very well. To simulate rainfall in the eastern area of China, the Dudhia option of the “shortwave scheme” and the Rapid Radiation Transfer Model (RRTM) option of the “longwave scheme” were also employed to calculate the atmospheric pressure short and longwave radiation, respectively (Wei et al., 2015). Tian et al. (2017) simulated rainfall in northern China with the Noah scheme as an LSM. In addition, the default “surface layer scheme” was applied in this study (Table 1).

### 2.3 Water vapour flux correlation vector calculation

To examine the large-scale water vapour transport facilitating rainstorms over NC, we investigated the correlation between rainstorm frequency over NC and total-column or single-layer water vapour transport fluxes. Equations 1 and 2 were used to calculate the total column vapour transport fluxes (Zhao et al., 2016a; 2016b),

\[
qu = \frac{1}{g} \int_{p_t}^{p_1} qu dp_v, \tag{1}
\]

\[
qv = \frac{1}{g} \int_{p_t}^{p_1} qv dp_v, \tag{2}
\]

where \(q\) is specific humidity, \(g\) is acceleration of gravity, \(u\) and \(v\) are the zonal and meridional wind speeds, respectively, \(p_s\) is surface pressure, \(p_t\) is the atmospheric pressure at 300 hPa, and \(qu\) and \(qv\) are the zonal and meridional water vapour fluxes, respectively.

Due to the even distribution of stations over NC, the regional mean rainstorm frequency over NC was identical regardless of re-gridding of the station data. The rainstorm frequency was first calculated for each station and then averaged across the region to derive the regional mean. Thus, the correlation between rainstorm frequency over NC and total column or single layer vapour flux was calculated (Zhao et al., 2018):

\[
R_u = \frac{1}{(n-1)} \sum_{i=1}^{n} (x_{ki} - \bar{x})(qu_i - \bar{qu}), \tag{3}
\]

\[
R_v = \frac{1}{(n-1)} \sum_{i=1}^{n} (x_{ki} - \bar{x})(qv_i - \bar{qv}), \tag{4}
\]

where \(R_u\) and \(R_v\) represent the correlation coefficients between the frequency of rainstorms and water vapour fluxes in the zonal and meridional components \(qu\) and \(qv\), respectively. \(x_{ki}\) is rainstorm frequency, \(\bar{x}\) is the multi-year mean rainstorm frequency, \(n\) is the number of years, \(qu_i\) and \(qv_i\) are the zonal and meridional water vapour fluxes, respectively, and \(x_{ki std}, qu_{i std},\) and \(qv_{i std}\) are the standard deviations of rainstorm frequency and zonal and meridional water vapour fluxes, respectively.

The correlation coefficient \(r\) (\(R_u\) or \(R_v\)) can be tested with Student’s \(t\) distribution with \(n - 2\) of freedom,

\[
t = r \sqrt{(n-2)/(1-r^2)}, \tag{5}
\]

where \(n\) is the number of years.

### 2.4 Water vapour flux vortex calculation

In this study, we considered the correlation between summer rainstorm frequency over NC and the vorticity of the summertime water vapour flux. The vorticity of water vapour flux is referred to as the water vapour flux vortex (\(\xi\)) and is calculated as follows:

\[
\xi = \nabla \times \mathbf{qV}, \tag{6}
\]

where \(\nabla\) denotes the gradient and \(\mathbf{qV}\) is the horizontal water vapour flux.

### 3 RESULTS AND DISCUSSION

#### 3.1 Water vapour transport pattern in summer over East Asia

Due to the dynamic forcing of the TP large terrain, regional lower tropospheric water vapour transport could flow along the TP (Wu et al., 2012). To examine the flow patterns of summer water vapour transport under the forcing of the TP large terrain, we calculated the water vapour transport flux below the average elevation of the TP terrain at about 600 hPa (Figure 2) with Equations 1 and 2. The water vapour flux field
was characterized by two channels along the TP (dashed purple arrows, Figure 2), with one tracing along the north and the other along the east of the TP. The two vapour transport channels merged over NC, where the confluence of the water vapour from the westerlies and tropical oceans provided favourable water vapour conditions over NC. Notably, there was a relatively large area of water vapour transmission flux over NC (purple solid circle, Figure 2).

3.2 Large-scale water vapour transport facilitating rainstorms over NC

Freychet et al. (2015) claimed that the monthly-mean water vapour flux bringing more low-level humidity from the south along the East Asian coast could provide a favourable background in frequency of extreme events over East Asian region during the East Asian summer monsoon. Especially in July–August, more water vapour from the south is transported into the north part of East Asian region. Thus, the linkage between summertime water vapour transport and the frequency of summer rainstorms over NC deserves to be investigated. Figure 3 shows the correlation vector map between the frequency of rainstorms over NC and the total column water vapour flux over East Asia in summer, representing the typical moisture and circulation backgrounds in favour of rainstorms over NC. The rainstorms had a close relationship with the Lake Baikal trough and associated cyclonic circulation. These circulation patterns reflected the dynamic effects of the westerlies to the north of the TP and the southerly flow to the east of the TP. There was a clear merging of the water vapour transport from the northern and eastern edges of the TP over NC (Figure 3). Interestingly, these two water vapour transport pathways were closely correlated with the flow along the northern and eastern edges of the TP. Not only was the structure of the cyclonic circulation of water vapour transport closely related to the upstream water vapour flow, but the southerly water vapour from tropical oceans including the SCS, western Pacific, and BOB.

The correlations between the frequency of rainstorms and the water vapour transport at 500, 700, 850, and 925 hPa are shown, respectively, in Figure 4a–d. At 500 hPa, we observed a typical cyclonic circulation over Mongolia, which strengthened the westerlies. Moreover, the correlation vector fields clearly showed correlation vectors along the eastern edge of the TP. Therefore, there should focus on the water vapour correlation vector channel along the northern edge of the TP and the other water vapour correlation vector from the SCS and the western Pacific that merge into one major channel along the eastern edge of the TP. The area over NC experiencing rainstorms occurred at the confluence zone of these water vapour transport channels (Figure 4a). At 700 hPa, the water vapour transport flowed along the northern and eastern edges of the TP. The sources of the water vapour transport included the westerlies, BOB, SCS, and western Pacific (Figure 4b). Differing from the 500 and 700 hPa layers, water vapour transport only occurred along the eastern edge of the TP at 850 hPa, as the topography located in the north TP blocked water vapour transport (Figure 4c). At 925 hPa, the correlative water vapour transport only traced along the eastern edge of the TP second staircase terrain, where the SCS and western Pacific merged into one major channel along the eastern edge of the TP second staircase terrain (Figure 4d).

3.3 Airflow facilitating rainstorms over NC

Two water vapour transport channels flowed along the northern edge of the TP via westerlies and along the eastern...
edges of the TP and its second staircase terrain originated from the BOB, SCS, and western Pacific. At lower levels, water vapour transport mainly flowed along the eastern edge of the TP second staircase. These two water vapour transport channels favoured rainstorms over NC. Freychet et al. (2015) also noted the intensification in frequency of summer rainstorms over East Asian region is associated with an increase in northwards wind over eastern China, which brings more water vapour to the north continent of East Asian region. The correlations between the frequency of summer rainstorms over NC and wind fields at different heights during 1961–2010 are shown in Figure 5. At lower levels, because the main body of the TP terrain blocked the eastwards water vapour transport, the zonal wind correlation with rainstorms over NC at 700 hPa was shown to clarify the west–east-oriented airflow channel. The most significant zonal wind correlation with rainstorms over NC was clearly observed along the northern edge of the TP (Figure 5a). Meanwhile, for the meridional component of the winds, the southerly monsoon airflow at 850 hPa that favoured rainstorms over NC was found to flow along the eastern edge of the TP (Figure 5b). The trajectories of airflow were consistent with the water vapour transport channels, which supported that the two water vapour transport channels at elevations lower than the TP had significant contributions to rainstorms over NC.

3.4 Water vapour flux vortex facilitating rainstorms over NC

The two aforementioned water vapour channels cultivated a favourable environment for rainstorms over NC. However, the question remained as to how the strong water vapour transport supports rainstorms over NC. Pan et al. (2008) found that sufficient water vapour transport induces a positive feedback between latent heat release and lower-layer positive vorticity system development. Wang et al. (2014) argued that the aggregation of water vapour is closely associated with convective system development, and further strengthens the convergence of rainstorms over NC. Chen et al. (2007) claimed that the strong southwesterly water vapour along the eastern area of the TP forms a local convergence zone to benefit the vortex induced by TP terrain blocking. Thus, we speculated a role of vortexes in rainstorms over NC accompanied with sufficient water vapour transport.

Water vapour mainly gathers at lower levels, while the main body of the TP terrain would block the north channel of water vapour transport. To explore how the two channels favour rainstorms over NC, Figure 6 shows the correlations between rainstorm frequency over NC and the vorticity of water vapour flux at 700 hPa in summer. There was a belt with a strong correlation along the northern edge of the TP that extended downstream. Another strong correlation area along the eastern edge of the TP showed a north–south-oriented belt. Interestingly, a close association was found between the two water vapour transport channels and the belt structures of water vapour flux vorticity. Figure 7 presents the distributions of vorticity anomalies of water vapour flux at 700 hPa during years with more frequent rainstorms (Figure 7a) and less frequent rainstorms (Figure 7b) over NC. In years with more frequent rainstorms (1963, 1964, and 1995), two belts with positive vorticity anomalies of water vapour flux were observed along the northern and eastern edges of the TP, which merged over NC. Meanwhile, in years with less frequent rainstorms (1968, 1983, and 2002), the two belts with positive vorticity anomalies of water vapour flux pointed towards the middle and lower reaches of the Yangtze River. These results support that the water vapour transport and water vapour flux vortexes have identical channels, and the water vapour flux vortexes can provide convergence conditions for rainstorms over NC.

3.5 Effect of the TP second staircase terrain on water vapour transport channels facilitating rainstorms over NC

Our results obtained that the climatological water vapour transport could flow along the northern edge of the TP and along the eastern edges of the TP and its second staircase terrain. As such, the water vapour transport channels not only supply the water vapour background for rainstorms over NC but also strengthen the convergence condition for rainstorms over NC via water vapour flux vortexes. Recent decades have shown rainstorms with higher intensities than earlier decades (Tu et al., 2010). Yu et al. (2010) found that the
rainfall intensity has enhanced over NC continually, although the rainfall amount and frequency have decreased markedly. Extreme rainstorm events have occurred frequently in recent years, such as the “7.21” rainstorm event during 2012 in Beijing. Thus, we further examined the effects of the TP and its second staircase terrain on water vapour transport facilitating rainstorm over NC based on several extreme rainstorm cases.

Seven typical eastwards moving rainstorm cases over NC with the rainstorm process originating from the TP in summer from 1981 to 2016 were selected. The water vapour flux composition fields of seven rainstorm cases at different layers were calculated for rainstorms over NC (Figure 8). Most water vapour was transported along the eastern edge of the TP second staircase terrain at 925 hPa, and the NC area was occupied with an anomalous cyclonic water vapour flux vortex (Figure 8a,b). Water vapour mainly gathers at lower levels, and the convergence of water vapour flux in summer could constitute a probable factor in the behaviour of summer extreme precipitation frequency over the north part of East Asian continent. The horizontal water vapour flux convergence is divided into two components: convergence \(-q \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)\) and horizontal water vapour advection \(-u \left( \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y} \right)\) (Chou and Lan, 2012; Freychet et al., 2015). The roles of two components at 925 hPa are also shown (red shaded areas in Figure 8a,b). The contributions of convergence component and advection component to the horizontal water vapour flux convergence were 79.1 and 20.9%, respectively, which demonstrated that the convergence component appeared to have a somewhat crucial role in strengthening water vapour flux convergence relative to the advection part.
Thus, the enhanced water vapour flux convergence along the eastern edge of the TP second staircase terrain favoured rainstorms over NC. Contrastingly, there were two water vapour transmission channels along the edges of the TP at 700 hPa (Figure 8c) and 500 hPa (Figure 8d). One channel was located to the north of the TP and the other to the east.

Notably, in the lower layer of 925 hPa, the water vapour transport facilitating rainstorms over NC only traced along the eastern edge of the TP second staircase terrain (Figures 4d and 8a,b). As such, we questioned whether rainstorms over NC could be affected by the TP second staircase terrain. Therefore, we examined one of seven eastwards moving rainstorm cases (see Figure 8) with the rainstorm process during July 17–21, 2016 and used the WRF model to simulate the influence of the TP second staircase terrain over 103°–115°E, 32°–42°N (red box, Figure 9) on rainstorms over NC. The rainfall intensity over NC was chosen to represent rainstorms in situ, and the daily rainfall amount over NC was selected to calculate rainfall intensity.

The rainstorm process originated from the northeast of the TP for the actual rainfall (Figure 10a) and in the control (Figure 10b) and sensitivity (Figure 10c) tests. Rainfall intensity was markedly greater in the sensitivity test (Figure 10c) than that in the control test (Figure 10b) on the first day. Because of the removal of the terrain, water vapour could reach the TP northeast rainfall area and accumulate water vapour (Figure 10c). On the second day, the rainfall area moved eastwards, and parts of the rainstorm area could arrive at NC. Both rainfall intensity over NC and water vapour transport towards NC in the control test (Figure 10e) were relatively larger than those in the sensitivity test (Figure 10f). On the final 2 days, the rainstorm process remained eastwards moving, and the rainfall intensity over NC and water vapour transport towards NC in the control test (Figure 10h.k) were substantially stronger than those in the sensitivity test (Figure 10i,l). Compared with the sensitivity test results, the simulations in the intensity and movement of rainstorms in the control test were more close to the observed results in the actual rainfall test during the whole rainstorm process. These results reveal that the TP second staircase terrain is crucial to rainstorms over NC and can force water vapour to move towards NC. Without the TP second staircase terrain, rainfall intensity over NC would be weakened.

To further examine the effect of the TP second staircase terrain on rainstorms over NC, the regional mean rainfall over NC on the second to fourth days of the rainstorm eastwards moving process is calculated. From the second to fourth days, the rainfall intensity was relatively reduced in the absence of the TP second staircase terrain (Figure 11). Table 2 presents the contribution of terrain to rainfall intensity over NC, which supports the crucial

![FIGURE 5](image1)  Correlation of summer rainstorms over NC with (a) zonal wind $u$ (unit: m/s) at 700 hPa and (b) meridional wind $v$ (unit: m/s) at 850 hPa during 1961–2010. The red (blue) shaded areas represent positive (negative) correlations exceeding the 90% confidence level. The grey area represents the terrain of the TP (unit: m). The blue box denotes NC. The green line represents the boundary line of 3,000 m.

![FIGURE 6](image2)  Correlation of summer rainstorms over NC (blue box) with the vorticity of the water vapour flux (unit: s$^{-1}$) at 700 hPa during 1961–2010. The coloured shading represents correlations greater than the 90% confidence level. The grey shading depicts the main body of the TP terrain higher than 3,000 m. The arrows indicate high-correlation channels.
influence of the TP second staircase terrain on rainstorms over NC.

Xu et al. (2002) proposed the “big triangle fan” conceptual model, in which water vapour transport from the north
and south of the TP have major contributions to rainstorms in the reaches of the Yangtze River. In this study, under the dynamic effects of the TP and its second staircase terrain, the southerly monsoon water vapour from the SCS, western

FIGURE 7 The vorticity anomaly of water vapour flux (unit: s\(^{-1}\)) at 700 hPa during summer in 1961–2010 with (a) more frequent rainstorms and (b) less frequent rainstorms over NC. The grey shading represents the main body of the TP terrain above 3,000 m. The blue box represents NC. The blue dots denote regions exceeding the 90% confidence level

FIGURE 8 Summertime water vapour flux composition streamlines (unit: g kg\(^{-1}\) m s\(^{-1}\)) of seven eastern moving rainstorm cases over NC originated from the TP at (a) 925 hPa, (b) 925 hPa, (c) 700 hPa, and (d) 500 hPa. The change in 925 hPa horizontal water vapour flux convergence (unit: g kg\(^{-1}\) s\(^{-1}\) 10\(^{-5}\)) is separated into its (a) convergence and (b) advection components. Red shaded regions denote positive horizontal water vapour flux convergence values (unit: g kg\(^{-1}\) s\(^{-1}\) 10\(^{-5}\)). The colours represent the magnitude of the water vapour flux (unit: g kg\(^{-1}\) m s\(^{-1}\)) at the respective layers and the grey shading is the terrain height (unit: m). The blue box denotes NC and the green lines outline the main body of the TP terrain above 3,000 m
Pacific, BOB transported northwards along the eastern edges of the TP terrain and its second staircase terrain, whereas the westerlies associated with water vapour traced along the northern edge of the TP terrain. The NC region was located at the confluence zone of the two water vapour transport channels (Figure 12), which provided the favourable water
vapour background, and convergence conditions for rainstorms over NC via water vapour flux vortexes. Notably, at lower layers, the TP second staircase terrain is critical to water vapour transport facilitating rainstorms over NC, where the east water vapour transport channel is more important.

### CONCLUDING REMARKS

We analysed the effects of the TP and its second staircase terrain on rainstorms over NC from the perspective of large-scale water vapour transport based on NCEP reanalysis data and the frequency of summer rainstorms from 70 observational stations provided by the NMIC during 1961–2010. The effects of the TP and its second staircase terrain on rainstorms over NC were further examined according to seven rainstorm cases from the period 1981–2016 and the WRF simulation of a randomly selected rainstorm case during 17–21 July, 2016. The main conclusions are as follows.

The water vapour transport was found to flow along the northern edge of the TP via westerlies and along the eastern edges of the TP and its second staircase terrain originating from the BOB, SCS, and western Pacific. The region in NC experiencing rainstorms was located at the confluence zone of the two water vapour transport channels. At lower levels, the water vapour transport mainly flowed along the eastern edge of the TP second staircase. The trajectories of airflow were consistent with the water vapour transport channels, including the westerlies along the northern edge of the TP and southerly monsoon flow along the eastern edges of the TP and its second staircase terrain.

There was a close association between the two water vapour transport channels and the belt structures of water vapour flux vorticity. Further analysis demonstrated that water vapour transport could favour rainstorms over NC through water vapour flux vortexes. The sufficient water

### FIGURE 11
Comparison of regional mean precipitation between the control and sensitivity tests on the second to fourth days (July 18–20, 2016) during the studied rainstorm case. The precipitation region is indicated by the blue dashed box in Figure 10e,f,h,i,k,l

### TABLE 2
Contributions from the terrain to rainstorms over North China (NC)

| Day  | Terrain (%) |
|------|-------------|
| Second | 3.5          |
| Third  | 18.6         |
| Fourth | 109          |

### FIGURE 12
Conceptual model of water vapour transport facilitating rainstorms over NC. In summer, the large terrains of the TP and its second staircase drive downstream rainstorms over NC via the typical water vapour transport and its vortex. The blue line and arrow represent water vapour flux vorticity and the coloured streamline arrows represent water vapour transport. The red ellipses highlight the water vapour sources from the ocean.
vapour transport along the two channels not only provided a sustainable water vapour background for rainstorms, but also promoted the development of water vapour flux vortexes, resulting in convergence conditions for rainstorms over NC.

Seven extreme rainstorm cases over NC were selected from 1981 to 2016. The water vapour transport flux composition fields of the seven rainstorm cases at different layers examined that the TP and its second staircase had a crucial role on rainstorm development over NC through modulating two water vapour transport channels. At the lower layer of 925 hPa, the water vapour transport only traced along the eastern edge of the TP second staircase terrain. The WRF model experiment was employed to confirm the vital influence of the TP second staircase terrain on rainstorms over NC. Overall, the TP and its second staircase terrain are the main drivers of rainstorms over NC.

The WRF experiment simulation of a randomly selected rainstorm case over NC originating from the TP showed that rainfall intensity over NC with the TP second staircase terrain was stronger than that without the TP second staircase terrain. The result supported the diagnosis results that the TP second staircase terrain favours rainstorms over NC. As a supplement to the simulation results in this study, more rainstorm cases would be simulated to analyse the variations in the maximum rainfall intensity and rainstorm location with the TP second staircase terrain or not. Based on more rainstorm cases, significance tests of the difference between the two channels not only provided a sustainable water vapour background for rainstorms, but also promoted the development of water vapour flux vortexes, resulting in convergence conditions for rainstorms over NC.

ACKNOWLEDGEMENTS
This work was supported by the Second Pilot Project the second Tibetan Plateau comprehensive scientific research (I07-T01-2018-06/06-JH); the Major Program of the National Natural Science Foundation (91644223); a Public Welfare Industry (Meteorology) special scientific grant (GYHY201406001); the Major Program of the National Natural Science Foundation (91337000, 91437106); the science development fund of the Chinese Academy of Meteorological Sciences (2018KJ019); research on the objective prediction of meteorological elements in the Tianjin intelligent network (20180411xxm01); and a Jiangsu Province Postgraduate Research and Innovation Program project (KYCX17_0869).

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How to cite this article: Zhao Y, Xu X, Zhao T, Yang X. Effects of the Tibetan Plateau and its second staircase terrain on rainstorms over North China: From the perspective of water vapour transport. *Int J Climatol*. 2019;39:3121–3133. https://doi.org/10.1002/joc.6000