Contribution of Thunderstorms to Changes in Hourly Extreme Precipitation over China from 1980 to 2011

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ABSTRACT: In many countries, thunderstorms are the main contributor to hourly extreme precipitation (HEP). Prior studies have shown that the number of thunderstorms decreased steadily in whole country of China; however, HEP has increased significantly in several areas over the past half-century. The role of thunderstorms in changes in HEP occurrence remains largely unknown in China. In this study, for the first time, we used continuous 32-yr records of hourly precipitation and thunder, and the fifth-generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5), to analyze changes in thunderstorms under various vertical wind shear (VWS) environments, and their contribution to HEP occurrence. The number of HEP events associated with thunderstorms (TD-HEP) increased significantly in southern China (SC) but decreased significantly in northeastern China (NEC) and east of the Tibetan Plateau (ETP). Weak VWS thunderstorms accounted for 69.1% of TD-HEP in SC. Changes in the most unstable convective available potential energy and precipitable water (PW) in SC favored an increase in weak-VWS thunderstorms, which resulted in an increase of 2.35 h per warm season in overall “station-mean” TD-HEP events from 1980 to 2011. As the major contributor to HEP in NEC, moderate VWS thunderstorms decreased by 0.37 h per warm season, due mainly to a reduction in PW, leading to a negative trend in TD-HEP events. Similarly, the decreasing TD-HEP occurrence on the ETP was due to a decrease of 1.12 h per warm season of moderate VWS thunderstorms. Studying the VWS environments of thunderstorms, and changes therein under a warming climate, can improve understanding of the changes in HEP in China.

KEYWORDS: Wind shear; Extreme events; Precipitation; Storm environments; Thunderstorms; CAPE

1. Introduction

Extreme precipitation changes in warmer climates have drawn much attention in research communities, as well as from decision-making entities worldwide. Many studies have addressed the number and intensity of extreme precipitation events at different temporal scales according to changes in temperature (Miao et al. 2016; Yu and Li 2012) and large-scale circulation (Ding and Chan 2005; Ng et al. 2021; Wang and Zhou 2005). Most continental extreme precipitation events are caused by severe convection accompanied by thunderstorms (Fujibe 1988; Schumacher and Johnson 2006; Xu 2020; Ye et al. 2017), which are mesoscale weather phenomena. For example, thunderstorms account for 70%–80% of the hourly extreme precipitation (HEP; >95th percentile rain rate) events over lower-elevation regions south of 38°N in China (Xu 2020). Therefore, understanding changes in thunderstorm events, and how they contribute to HEP in a warmer climate, is necessary to predict HEP behavior.

Many previous studies analyzed long-term trends in thunderstorms and HEP events separately. Using manual records, a significant decreasing trend of 2.82 days per decade was found in thunderstorm days from 1961 to 2010 across China (Q. Zhang et al. 2017). Similarly, other studies showed that daily summer thunderstorms were suppressed in central China (CC) from 1951 to 2005 (Yang et al. 2013). However, in southeastern China, thunderstorm days showed a significant upward trend of more than five days per decade in the warm season from 1990 to 2012 (Yang and Li 2014). The frequency of HEP events rose in the lower reach of the Yangtze River (LYR), and across southern China (SC) and northeastern China (NEC), from 1970 to 2019 (Ng et al. 2021). Therefore, trends in HEP and thunderstorms have not shown a consistent pattern, despite the strong contribution of thunderstorms to HEP.

Elucidating the reasons for changes in the frequency of thunderstorms and HEP requires both dynamic and thermodynamic research. Large-scale dynamic circulations that affect eastern China include the East Asia summer monsoon (EASM), Indian summer monsoon, and western North Pacific summer monsoon (Wang and Zhou 2005; You et al. 2011). The duration of the monsoon stages affects the frequency of extreme precipitation in China (Lau and Yang 1997; Ng et al. 2021; Zhang et al. 2004), while weakening of the EASM is considered to be strongly correlated with a decrease in the occurrence of thunderstorms (Q. Zhang et al. 2017). In a warmer climate, Earth’s atmosphere contains more water vapor (Lamb and Verlinde 2011, 231–234; L. Zhang et al. 2017), leading to more frequent and intense extreme precipitation and thunderstorms (Ma et al. 2017; Sun et al. 2007; Xu 2013). According to Xu (2020), stronger vertical wind shear (VWS), and a larger convective available potential energy

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CAPE, are conducive to thunderstorm development. CAPE and VWS have been considered together in analyses of severe thunderstorms in the United States and Europe (Taszarek et al. 2021). Phase 5 of the Coupled Model Intercomparison Project (CMIP5) also showed that a higher mean CAPE results in more intense thunderstorms in future climate projections for the tropics and subtropics in summer (Singh et al. 2017). However, the ways in which changes in VWS influence thunderstorms in a warming climate remain largely unknown.

VWS, as an important factor in the development of thunderstorms, has decreased in China during the past half-century because of the weakening of zonal mean zonal wind in the warming climate (Coumou et al. 2015). However, the ways in which changes in VWS influence thunderstorms in a warming climate remain largely unknown.

VWS, as an important factor in the development of thunderstorms, has decreased in China during the past half-century because of the weakening of zonal mean zonal wind in the warming climate (Coumou et al. 2015). Generally, the evolution of storms is dependent on VWS, which makes a key contribution to the organization and longevity of storms (Markowski and Richardson 2010; Taszarek et al. 2021). Single cells are normally associated with weak VWS, and are isolated and short-lived (lifetime of ~30–60 min). Multicell storms can be considered as clusters of single cells, which can be organized as meso-β- or meso-α-scale convective systems. Because of their ability to constantly regenerate themselves, multicell storms may last for hours and affect vastly larger areas than single cells. Supercell storms may have a lifetime of 1–4 h, and some have been observed to last for 8 h (Markowski and Richardson 2010; Weisman and Klemp 1984, 1986). Although the current radar observation system in China, which reveals the exact organization of thunderstorms, has been in operation for the past 15 years, its coverage is still too limited to study changes of the organization of thunderstorms from a climatological perspective. However, VWS may serve as an indicator of the organization of thunderstorms. Previous studies indicated a high prevalence of single-cell storms at low VWS, multicell storms at intermediate VWS, and supercell storms at high VWS (Weisman and Klemp 1984).

The above discussion shows that the long-term trends in HEP and thunderstorms, and the reasons mentioned, have been well studied on an individual basis; however, few studies have considered their combined effects, particularly in China. Considering thunderstorms as the main contributor to HEP, our study aims to classify and characterize HEP events and trends in the context of thunderstorm activity in China from 1980 to 2011.
2. Data and methods

a. Precipitation and thunder records

Datasets of hourly precipitation from 2435 stations and manually recorded surface weather information [including thunder (TD) records] from 2477 stations were released by the National Meteorological Information Center, China Meteorological Administration. Considering that manual recording of nighttime surface weather information had been phased out since 2012, we selected 1980–2011 as our study period. An hourly precipitation event was recorded when the accumulated precipitation was greater than 0.1 mm during each hour. For surface weather information, when TD is heard by professionally trained observers on duty at the station, the start and end times are recorded as one TD event if the time interval between two TD events is less than 15 min; otherwise, they are recorded as two events (Q. Zhang et al. 2017). If only one TD event is heard, the start time is recorded, whereas the end time is not. There are three categories of TD records: TD occurred, no TD occurred, and suspicious record.

The station data were subjected to quality control, and two datasets were separately screened for missing values and spatiotemporal inhomogeneity, with reference to Ng et al. (2021). In this study, observatories were not included if the site moved by more than 20 km or showed a change in elevation of more than 50 m during the study period. Stations with more than 80% complete hourly precipitation and TD datasets for the warm season (May–September) in each year were included in the study.

HEP events were defined at each station as precipitation greater than the 95th percentile of hourly precipitation (≥0.1 mm h\(^{-1}\)) in the warm season. The continuous rainy period from the hour with a precipitation rate ≥ 0.1 mm h\(^{-1}\) to the hour with a precipitation rate < 0.1 mm h\(^{-1}\) and at least one HEP event was defined as a distinct HEP process. To further improve the accuracy of TD data during HEP processes, we selected stations with <20% suspicious TD records in the HEP processes. A suspicious TD record during a HEP process was defined when the period from one hour prior to the end of the entire HEP process had no verified TD record but did have one or more suspicious records (i.e., lacked evidence proving that a TD had genuinely occurred during this period). Ultimately, 653 stations were selected to ensure data reliability (i.e., to provide a sufficient number of observations during 1980–2011).

b. Identification of HEP with thunder

To combine TD and HEP events, we defined a HEP process associated with TD as having at least one TD event during the period from one hour prior to the end of the entire HEP process. This HEP hour with thunder was defined as a TD-HEP event. Otherwise, it was defined as a HEP event without thunder (nTD-HEP; Fig. 1).

c. Reanalysis data and definition of environmental conditions

To understand dynamic and thermodynamic antecedents, we analyzed the fifth-generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5) (Hersbach et al. 2018a,b) to determine environmental conditions, including VWS [Eq. (1); Brooks et al. 2003; Xu 2013], the most unstable CAPE [MUCAPE; Eq. (2); Allen et al. 2011], and precipitable water [PW; Eq. (3); Luo et al. 2013; Xu 2013].

VWS is considered to be a proxy of a dynamic effect, defined as the difference between the upper- and lower-level wind fields. In this study, we calculated the most commonly
used VWS, namely the VWS between the ground ($V_{sfc}$) and an altitude of 6 km ($V_{6km}$):

$$VWS = |V_{6km} - V_{sfc}|.\quad (1)$$

Instability/updraft speed can be controlled by CAPE, which exerts a buoyancy force on rising air parcels (Diffenbaugh et al. 2013; Taszarek et al. 2021; Xu 2020). CAPE can be calculated by various methods, including lifting the parcel from various levels. However, CAPE is sensitive to fluctuations in the surface and boundary layer environment (Allen et al. 2011). To overcome this limitation, MUCAPE, which is a measure of the strength of updrafts, is used as a proxy of thermodynamic effects in this study. It lifts the parcel from the level of the maximum equivalent potential temperature (Colle et al. 2012):

$$MUCAPE = \int_{p_{mu}}^{p_{sfc}} R_d(T_{vp} - T_{we})d\ln p.\quad (2)$$

where $T_{vp}$ is virtual temperature of the specific parcel (K); $T_{we}$ is virtual temperature of the environment (K); $p_{mu}$ is pressure of the maximum equivalent potential temperature level (hPa); $p_{sfc}$ is pressure of the equilibrium level (neutral buoyancy; hPa); and $R_d$ is the gas constant parameter for dry air (287.05 J kg$^{-1}$ K$^{-1}$).

The term PW, which is defined as the total amount of water vapor in an air column, is used as another proxy of the thermodynamic effect of HEP. PW is one of the factors responsible for extreme precipitation (Kunkel et al. 2020). We calculated PW from the ground to 100 hPa:

$$PW = \frac{1}{\rho g} \int_{p_{sfc}}^{p_{100}} qdp,\quad (3)$$

where $q$ is the specific humidity, $\rho$ is the density of liquid water, and $g$ is the gravitational acceleration (9.8 m s$^{-2}$).

FIG. 3. Trends in the annual frequency of (a) hourly extreme precipitation (HEP), (b) thunder (TD), (c) HEP without TD (nTD-HEP), and (d) HEP with TD (TD-HEP) events at each station in the warm season (May–September) during 1980–2011. Black plus signs, red circles, and blue circles represent no trend, increasing trend, and decreasing trend, respectively. Stations with significant trends at the 95.0% confidence level are represented by large dots. The areas of central China (CC), the lower reach of the Yangtze River (LYR), northeastern China (NEC), east of the Tibetan Plateau (ETP), and southern China (SC) are outlined in black.
**d. Analysis methods**

Nonparametric estimation of Sen’s slope \((b)\) was performed to establish a trend (Sen 1968). A positive slope indicates increased frequency and vice versa (Figs. 3 and 4d–f). For trend analysis, the Mann–Kendall (MK) test was applied (Gilbert 1987, 209–213; Kendall 1975; Mann 1945). If Sen’s slope is positive and the \(P\) value of the MK test is smaller than 0.05, the increasing trend is significant. However, if the \(P\) value of the MK test is greater than or equal to 0.05, the increase is nonsignificant. If Sen’s slope is negative, the trend is decreasing. As such, there are five types of frequency changes: significant increase, significant decrease, nonsignificant increase, nonsignificant decrease, and no trend (Sen’s slope = zero). For spatial representation analysis, the regional average Mann–Kendall (RAMK) test and regional average Mann–Kendall bootstrap (RAMK-B) test were applied (Margaritidis 2021).

A two-sample Student’s \(t\) test (von Storch and Zwiers 2001, 99–127) was used to compare other pairs of means (Figs. 2 and 5–8; see also Table 2).

**3. Results**

**a. Characteristics of HEP and TD**

The annual frequencies of HEP and TD decreased from south to north China during 1980–2011 (Figs. 2a,b). The correlation coefficient between them was 0.76 \((P < 0.05)\). The spatial pattern of HEP frequency was similar to that found by Ng et al. (2021). We found that 63.2% of HEP events were associated with TD during the warm season in 1980–2011, as recorded by an average of 653 stations (Fig. 2c). Stations with a thunderstorm ratio (ratio of HEP events associated with TD) exceeding 70.0% were generally located in the plains and at low latitudes. In CC, the mean numbers of HEP and TD events in the warm season were only 6 and 48, respectively, which were the lowest values nationwide. The thunderstorm ratio was <45.0% in CC, which was a smaller contribution of TD to HEP events than in the rest of China.

The spatial distributions of trends in HEP and TD events were not consistent during the study period, although most HEP events were accompanied by TD. The frequency of HEP events mainly increased south of the Yangtze River (Fig. 3a). Among the 653 stations, 314 (48.1%) indicated an increase in HEP frequency, with 44 stations (6.7%) recording the largest increase (Fig. 3a). The spatial pattern of trends in HEP and TD events across China during a shorter period (1990–2011). In the present study, the “station-mean” percentage of TD with HEP was only 4.1%, and the decreasing TD trend across China was mainly caused by a decrease in nonextreme precipitation TD and TD without precipitation (not shown). However, we are interested in how thunderstorm behavior changes under extreme precipitation conditions.

To quantify the contribution of TD events to HEP, HEP events were categorized into those without (nTD-HEP) and those with TD. HEP and TD events were not consistent during the study period, although most HEP events were accompanied by TD. The frequency of HEP events mainly increased south of the Yangtze River (Fig. 3a). Among the 653 stations, 314 (48.1%) indicated an increase in HEP frequency, with 44 stations (6.7%) recording the largest increase (Fig. 3a). The spatial pattern of trends in HEP and TD events across China during a shorter period (1990–2011). In the present study, the “station-mean” percentage of TD with HEP was only 4.1%, and the decreasing TD trend across China was mainly caused by a decrease in nonextreme precipitation TD and TD without precipitation (not shown). However, we are interested in how thunderstorm behavior changes under extreme precipitation conditions.

**Table 2. Domain and correlation coefficients between trends in HEP and nTD-HEP (TD-HEP) in each region. Note: The \(P\) values for all correlation coefficients are <0.05.**

<table>
<thead>
<tr>
<th>Region</th>
<th>HEP</th>
<th>nTD-HEP</th>
<th>TD-HEP</th>
<th>TD-HEP weak VWS</th>
<th>TD-HEP moderate VWS</th>
<th>TD-HEP strong VWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>Central China</td>
<td>Southern China</td>
<td>Northeastern China</td>
<td>East of Tibetan Plateau</td>
<td>Lower reach of Yangtze River</td>
<td></td>
</tr>
<tr>
<td>Latitude</td>
<td>34.0°–40.0°N</td>
<td>19.0°–26.0°N</td>
<td>40.0°–50.0°N</td>
<td>26.5°–34.0°N</td>
<td>26.5°–32.0°N</td>
<td></td>
</tr>
<tr>
<td>Longitude</td>
<td>99.0°–115.0°E</td>
<td>107.0°–120.0°E</td>
<td>122.0°–133.0°E</td>
<td>103.0°–111.0°E</td>
<td>115.0°–125.0°E</td>
<td></td>
</tr>
<tr>
<td>Station amount</td>
<td>91</td>
<td>115</td>
<td>84</td>
<td>39</td>
<td>132</td>
<td></td>
</tr>
<tr>
<td>Correlation coefficient</td>
<td>0.67</td>
<td>0.23</td>
<td>0.36</td>
<td>0.35</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>Correlation coefficient</td>
<td>0.48</td>
<td>0.78</td>
<td>0.71</td>
<td>0.53</td>
<td>0.56</td>
<td></td>
</tr>
</tbody>
</table>
with TD (TD-HEP; see section 2b). The nTD-HEP increased in CC and south of the LYR (Fig. 3c). Among the 653 stations, 181 (27.7%) indicated an increase in nTD-HEP frequency, with 21 stations (3.2%) recording a significant increase ($P < 0.05$) and 138 (21.1%) indicating a decrease, with 9 stations (1.4%) recording a significant decrease ($P < 0.05$); 334 stations (51.1%) showed no trend. In CC, the spatial pattern of the frequency change in nTD-HEP was consistent with the overall trend in extreme precipitation. The correlation coefficient between the trend in HEP and nTD-HEP was 0.67 ($P < 0.05$); thus, the
trend in HEP for CC was dominated by nTD-HEP events. The spatial pattern of TD-HEP is more similar to the HEP frequency trend than to nTD-HEP; 269 (41.2%) indicated an increase in TD-HEP frequency, with 58 stations (8.9%) recording a significant increase \((P < 0.05)\); 161 (24.7%) indicated a decrease, with 17 stations (2.6%) recording a significant decrease \((P < 0.05)\); 233 stations (35.7%) showed no trend (Fig. 3d). In SC, NEC, and east of the Tibetan Plateau (ETP), there were consistent changes in the frequencies of HEP and TD-HEP events, with correlation coefficients of 0.78, 0.71, and 0.53, respectively \((P < 0.05)\); thus, TD-HEP events played a more important role in SC, NEC, and ETP than in CC. Spatial patterns of trends in nTD-HEP and TD-HEP events were also in agreement with HEP in the LYR, with correlation coefficients of 0.53 and 0.56, respectively \((P < 0.05)\), suggesting that changes in HEP frequency in the LYR were affected by both nTD-HEP and TD-HEP events. In summary, changes in the frequency of HEP were dominated by TD-HEP events nationwide, except in CC, which exhibited a lower thunderstorm ratio (<45%). The numbers of observation stations reporting changes of various types are listed in Table 1; the correlation coefficients are listed in Table 2.

b. Variation in TD-HEP among different VWS environments

Given the specific TD contribution to HEP events across China, we analyzed the causes of the frequency changes in TD-HEP events to shed light on the HEP trends from 1980 to 2011. In the following section, we mainly focus on the three regions where HEP frequency changes were dominated by TD-HEP: SC (19.0°–26.0°N, 107.0°–120.0°E; 115 stations), NEC (40.0°–50.0°N, 122.0°–133.0°E; 84 stations), and ETP (26.5°–34.0°N, 103.0°–111.0°E; 39 stations). These three regions had different TD-HEP frequency patterns, with SC showing increases at 89 stations (significant at 32) and NEC and ETP showing decreases at 34 (significant at 8) and 16 (significant at 4) stations, respectively (Fig. 3d). To verify the spatial representations, the RAMK and RAMK-B tests were applied (Margaritidis 2021). Both methods yielded results significant at the 95.0% confidence level in these three regions.

Because different types of convective systems are influenced by different environmental conditions, we first attempted to classify the TD-HEP data into three VWS types based on ERA5 data,\(^1\) that is, weak VWS (single-cell-like) thunderstorms with \(V < 10.0 \text{ m s}^{-1}\), moderate VWS (multi-cell-like) thunderstorms with \(V \geq 10.0 \text{–}20.0 \text{ m s}^{-1}\), and strong VWS (supercell-like) thunderstorms with \(V \geq 20.0 \text{ m s}^{-1}\) (Ding et al. 2016; Markowski and Richardson 2010); their spatial distributions and trends are shown in Fig. 4.

\(^1\) Sensitivity tests of various thresholds (8, 10, 12, 18, 20, and 22 m s\(^{-1}\)) for VWS were conducted. Similar results were obtained for all thresholds.

![Fig. 5. Station-mean frequencies (bars) and differences (dots) in weak (blue), moderate (green), and strong (red) VWS hourly extreme precipitation with thunder (TD-HEP) events in the first (1980–95; left bars) and second (1996–2011; right bars) periods in southern China (SC), northeastern China (NEC) and east of the Tibetan Plateau (ETP).](image-url)

Weak VWS TD-HEP events (Fig. 4a) occurred mainly over the south of Yangtze River (30°N); moderate VWS TD-HEP events (Fig. 4b) were more frequent in LYR, ETP, and NEC; and strong VWS TD-HEP events showed the lowest frequency overall (Fig. 4c), mainly occurring along the coast north of 30°N. The frequency trends of weak, moderate, and strong VWS TD-HEP events combined were found to influence overall TD-HEP event frequency. In total, 248 stations (38.0%) showed increasing trends in weak VWS TD-HEP events, with 93 (14.2%) of these showing a significant increase \((P < 0.05)\) (Fig. 4d; Table 1). Increasing trends were more prevalent in SC than in northern China. For moderate VWS TD-HEP, the numbers of stations showing increasing and decreasing trends were relatively similar [130 (20.0%) and 158 (24.2%), respectively]; among them, 16 stations (2.5%) showed a significant increase and 32 (4.9%) a significant decrease. Stations reporting a reduced frequency of TD-HEP events were concentrated in NEC, ETP, and the LYR (Fig. 4c; Table 1). The stations showing a decrease in strong-VWS TD-HEP events were mainly located in NEC and the LYR (Fig. 4f; Table 1).

To further understand TD-HEP frequency changes in SC, NEC, and ETP, TD-HEP events were divided into two 16-yr periods: 1980–95 and 1996–2011 (Fig. 5). SC had the largest proportion of station-mean weak-VWS TD-HEP events, at 69.1%, compared to ETP and NEC from 1980 to 2011 (Fig. 5). In contrast, NEC had the largest proportion of moderate and strong VWS storms, at 48.8% and 17.8%, respectively; weak and moderate VWS storms contributed 57.4% and 38.4%, respectively, to TD-HEP in ETP.
In SC, the station-mean frequency of TD-HEP events was approximately 2.35 h per warm season higher in the second than in the first 16-yr period, such that the frequency of weak, moderate, and strong VWS events changed significantly by 2.12, 0.32, and −0.09 h per warm season, respectively ($P < 0.05$). Thus, increases in weak VWS events dominated the TD-HEP increases in SC.

In NEC, the station-mean frequency of TD-HEP events was approximately 0.64 h per warm season lower in the second than in the first 16-yr period; this decrease was mainly due to a decrease in moderate VWS events by 0.37 h per warm season. The frequencies of weak and strong VWS events were 0.16 and 0.11 h per warm season, respectively. However, only moderate VWS TD-HEP events were reduced significantly ($P < 0.05$). Therefore, decreases in moderate VWS TD-HEP were the greatest determinants of TD-HEP decreases in NEC.

In ETP, the station-mean frequency of TD-HEP events decreased by approximately 0.98 h per warm season. Moderate VWS events decreased by 1.12 h per warm season, while weak and strong VWS events increased by 0.13 and 0.01 h per warm season, respectively. Only moderate VWS TD-HEP events showed a significant change in frequency ($P < 0.05$); thus, the decreasing trend was dominated by changes in moderate VWS TD-HEP events in both ETP and NEC.

We also carried out sensitivity tests, in which different VWS values/thresholds for the various thunderstorm types were investigated. The percentage of the different storm types varied among the VWS values/thresholds, but the overall differences in TD-HEP events from the first to second period did not (within the various VWS range within 2 m s$^{-1}$).

In summary, the frequency of changes in TD-HEP events in various regions of China differed among storm types. In SC, the increase in TD-HEP events was mainly caused by weak VWS events. Moderate VWS events were the main contributors to decreases in TD-HEP in NEC and ETP.

**c. Physical mechanisms underlying TD-HEP frequency changes**

Because changes in TD-HEP frequency can be influenced by both dynamic (VWS) and thermodynamic (MUCAPE and PW) factors, we examined the environmental conditions (VWS, MUCAPE, and PW) at each station during the warm season and compared them with conditions during the hour before a TD-HEP event (pre-TD-HEP hour) in SC, NEC, and ETP, to determine if the environmental conditions became more or less favorable for the occurrence of TD-HEP events during the study period. The environmental conditions at each station were approximated as the conditions at the nearest ERA5 grid. Hourly environmental conditions were calculated as the climatological background environment, and conditions for the pre-TD-HEP hour were calculated as the TD-HEP environment.

The probability density functions of VWS, MUCAPE, and PW for SC during 1980–2011 are shown in Figs. 6a–c. For context, the synergistic interactions between dynamic and thermodynamic factors are represented by the joint probability distributions of the VWS, MUCAPE, and PW in the climatological background environment (dashed contour) and the hour preceding the TD-HEP environment (solid contour$^2$), as shown in Figs. 6d and 6e.

SC was characterized by a weak VWS (Fig. 6a), high MUCAPE (Fig. 6b), and ample PW (Fig. 6c) during the warm season. The PW probability showed a peak around 40.0–55.0 mm (Fig. 6c). SC environments with VWS < 10.0 m s$^{-1}$ were collocated with environments with MUCAPE < 2000.0 J kg$^{-1}$ (Fig. 6d). However, at the pre-TD-HEP hour, VWS, MUCAPE, and PW values were higher than the background during 1980–2011, indicating that TD-HEP events required higher unstable energy and moisture, as well as more intense dynamic driving, compared with the climatological background (Figs. 6d,e).

To further analyze the physical mechanisms underlying frequency changes, we calculated differences in the probability of VWS, MUCAPE, and PW during the warm season between the first (1980–95) and second (1996–2011) periods (Figs. 6a–c), as well as frequency changes in VWS, MUCAPE, and PW from the climatological background environment and in the hour preceding the TD-HEP event in the second period (Figs. 6d,e).

We observed a distinct shift from strong/moderate to weak VWS (0–10.0 m s$^{-1}$; Fig. 6a); MUCAPE also shifted from high/moderate to low values (0–1000.0 J kg$^{-1}$; Fig. 6b). Shifts in the probability peak of PW to both sides in the second period indicated greater changes during more intense precipitation (Fig. 6c).

Regarding the climatological background, the frequencies showed a distinct shift from strong/moderate to low-VWS/MUCAPE environments (Fig. 6d) and shifted to both sides in PW environments (Fig. 6e). For TD-HEP events, the frequencies generally increased in single-cell-like events (Figs. 5 and 6d,e). Changes in joint environmental conditions showed that for weak VWS (<10.0 m s$^{-1}$), the probability of background VWS increased significantly, whereas the probability of MUCAPE increased at values < 1000.0 J kg$^{-1}$ and PW increased in the high-value range, accompanying increased joint frequency under weak VWS among TD-HEP events (Figs. 6d,e). These findings indicated that the increased frequency of TD-HEP events was influenced by both dynamic and thermodynamic effects (i.e., MUCAPE) under weak VWS. For moderate VWS, the slight increase in multicell-like TD-HEP event frequency was mainly due to the thermodynamic effect (i.e., PW), in association with a decrease in VWS within the 10.0–20.0 m s$^{-1}$ range and PW increased to >55.0 mm (Fig. 6c). In summary, the 2.12-h increase in weak VWS storm events was attributed to both thermodynamic and dynamic effects. A slight increase in moderate VWS TD-HEP events in SC was mainly attributed to thermodynamic effects.

Among the three regions, NEC had the strongest VWS (Fig. 7a), lowest MUCAPE (Fig. 7b), and smallest PW (Fig. 7c) in the environment background. The background VWS had a probability peak of 10.0–15.0 m s$^{-1}$, MUCAPE <

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$^2$ We convolved the two-dimensional (2D) data with a 5 × 5 kernel for data smoothing, since TD-HEP events occur rarely. The 2D convolution contains high-frequency components and enhances, i.e., smooths, the original data.
FIG. 6. Station-mean probability density functions (bars) of (a) vertical wind shear (VWS), (b) the most unstable convective available potential energy (MUCAPE), and (c) precipitable water (PW) during 1980–2011, and the differences therein (lines) between the first (1980–95) and second (1996–2011) 16-yr period in southern China (SC). (d) Joint probability distribution of the VWS (x axis) and MUCAPE (y axis) for background (dashed contour; %) and hourly extreme precipitation with thunder (TD-HEP; solid contour; %) events with 2% intervals during 1980–2011, and differences in the frequency of background (triangles) and TD-HEP (shading; h) between the first and second periods. (e) As in (d), but for VWS (x axis) and PW (y axis). In (a)–(c), significant differences at the 95.0% confidence level are indicated by solid circles. In (d)–(e), the x axis shows shear categories (<5.0, 5.0–10.0, 10.0–15.0,..., 35.0–40.0, and >40.0 m s⁻¹). Significant differences at the 95.0% confidence level are indicated by solid triangles (background) or dots (TD-HEP). Bold solid lines and bold dashed lines represent a joint probability distribution of approximately 1%. In (d), the y axis indicates MUCAPE categories (<500.0, 500.0–1000.0, 1000.0–1500.0,..., 3500.0–4000.0, and >4000.0 J kg⁻¹). In (e), the y axis indicates PW categories (<5.0, 5.0–10.0, 10.0–15.0,..., 75.0–80.0, and >80.0 mm).
and PW of approximately 10.0–25.0 mm (Figs. 7a–c). Similar to SC, MUCAPE (Fig. 7d) and PW (Fig. 7e) were higher than the background at the pre-TD-HEP hour, but the absolute values were lower than the corresponding values in SC. The probability of background VWS increased within the 0–15.0 and 30.0–40.0 m s$^{-1}$ bins in NEC during the second 16-yr period (Fig. 7a), whereas the probability of environmental MUCAPE (PW) decreased significantly within a range of 500.0–2000.0 J kg$^{-1}$ (20.0–40.0-mm bins) (Figs. 7b,c); this was a favorable environment for TD-HEP. For the climatological background, the frequency decreased in low MUCAPE and moderate PW environments (Figs. 7d,e), consistent with TD-HEP events. These results indicate that thermodynamic effects were the main drivers of lower TD-HEP event frequency, especially in PW, among the three storm types in NEC, where weak, moderate, and strong VWS made consistently negative contributions to TD-HEP events (Figs. 7d,e).

In ETP, the VWS (Fig. 8a) and MUCAPE (Fig. 8b) values were intermediate between those of the NEC and SC, and PW had a peak at approximately 30.0–40.0 mm (Fig. 8c). Similar to SC and NEC, the probabilities of MUCAPE (Fig. 8d) and PW (Fig. 8e) for the pre-TD-HEP hour were higher than the background values. Compared to the first period, the probabilities of VWS, MUCAPE, and PW shifted from high/moderate to low values during the second period (Figs. 8a–c), but these differences were not significant. For weak VWS, the background increased slightly in the second period (Figs. 8d,e) at MUCAPE < 1000.0 J kg$^{-1}$ and in most PW categories; this represented a favorable environment for single-cell-like storms in ETP. Therefore, both thermodynamic (MUCAPE and PW) and dynamic (VWS) effects drove increases in weak VWS TD-HEP event frequency. Similarly, for moderate VWS, the background MUCAPE (PW) decreased to <3000.0 J kg$^{-1}$ (25.0–65.0 mm), resulting in decreased TD-HEP frequency in the second period. However, because the absolute values of differences in VWS probability (Fig. 8a) were higher than the corresponding values of MUCAPE and PW (Figs. 8b,c), TD-HEP event frequency changes were influenced more by dynamic effects; the negative contribution of moderate-VWS dominated the changes in TD-HEP events in ETP.

In summary, VWS, MUCAPE, and PW work together to affect TD-HEP event frequency. Substantial changes in TD-HEP event frequency occurred in association with the favorable environments for such events of SC, NEC, and ETP. In SC, an increase in single-cell-like TD-HEP event frequency occurred due to weaker VWS and MUCAPE. The weaker VWS in the second period was mainly caused by a weakening of the $u$ wind at an altitude of 6 km (You et al. 2011; Zhang et al. 2020). The increase in multicell-like TD-HEP event frequency occurred primarily due to the favorable PW conditions. Dynamic and thermodynamic effects both play crucial roles in the TD-HEP events in SC. In NEC, PW within 20.0–40.0 mm among the three storm types represents the most favorable condition for TD-HEP; a background PW in this range was seen less frequently, perhaps because of summer monsoon weakening (Q. Zhang et al. 2017), resulting in decreased frequencies of all three TD-HEP types. Thus, thermodynamic effects and their changes exert an important influence on TD-HEP events in NEC. In ETP, dynamic effects were the main drivers of changes in TD-HEP event frequency, followed by thermodynamic effects (i.e., MUCAPE and PW). The $u$ and $v$ wind components at an altitude of 6 km were both weaker in ETP (data not shown), leading to a decreasing frequency of multicell-like storms and an increasing frequency of single-cell-like storms in the second period.

4. Discussion and conclusions

Using long-term manual TD records, the hourly precipitation data of 653 stations, and ERA5 reanalysis data for the period 1980–2011 (warm season), we examined the contribution of TD to HEP and the reasons for changes in TD-HEP event frequency in China. In total, 63.2% of the HEP events were associated with TD in the warm season. However, the changing frequency of HEP events was inconsistent with that of TD across China due to the decreasing frequency of non-extreme precipitation TD and TD without precipitation. Focusing on thunderstorm characteristics under HEP, TD-HEP trends dominated the variation in HEP frequency in SC, NEC, and ETP in the context of high thunderstorm ratio across China; therefore, we analyzed the causes of TD-HEP event frequency changes in these three areas.

TD-HEP events were divided into weak, moderate, and strong VWS types to determine the physical causes of changes in TD-HEP event frequency in SC, NEC, and ETP, respectively. SC showed the most increased TD-HEP event frequency, due to changes in the frequency of weak VWS events (69.1% of all TD-HEP events in SC) from the first (1980–95) to the second (1996–2011) 16-yr period. In ETP, although 57.4% of TD-HEP events were weak VWS environments, TD-HEP event frequency decreased overall due to the reduced frequency of moderate VWS storms that contributed 38.4% of TD-HEP events. In NEC, 48.8% of the TD-HEP events were moderate VWS environments, which was the main cause of the overall decrease in TD-HEP events.

To determine the physical mechanisms underlying changes in TD-HEP event frequency, we examined thermodynamic (MUCAPE and PW) and dynamic (VWS) factors. Changes in the environment conducive to TD-HEP events were the dominant contributors to variation in TD-HEP frequency. In SC, both thermodynamic and dynamic effects influenced TD-HEP event frequency. Under global warming, VWS weakens due to the weakening of zonal wind (Coumou et al. 2015), and CAPE increases mainly because of increased low-level specific humidity, which increases buoyancy above the level of free convection (Chen et al. 2020), and an increased PW (mainly governed by the Clausius–Clapeyron equation; Trenberth et al. 2003). The probabilities of VWS, MUCAPE, and PW were higher during the second than first 16-yr period in categories with the highest single-cell-like TD-HEP occurrence frequency. Thermodynamic effects (PW) favored a reduction in TD-HEP occurrence in NEC because of the weakening of summer monsoons (Q. Zhang et al. 2017), whereas the dynamical effect (VWS) was important in ETP.

Aerosols have also been proposed to affect precipitation and TD in China (Gao et al. 2016; Z. Li et al. 2016; Ma et al. 2017; Rosenfeld et al. 2007; Song et al. 2014; Wang et al. 2012).
Aerosol accumulation inhibits warm rain and promotes convective instability, which together promote the formation of convective clouds and TD (Fan et al. 2013; Rosenfeld et al. 2008; Yang and Li 2014). A previous study showed that the daytime aerosol extinction coefficient increased in the Pearl River Delta, decreased in NEC, and showed no significant change in southwestern China during the period investigated in this study (J. Li et al. 2016). This finding suggests that the

Fig. 7. As in Fig. 6, but for northeastern China (NEC).
changes in TD-HEP event frequency observed in SC and NEC in the present study may be associated with aerosols.

This work attempted to determine the reasons for changes in the frequency of different types of thunderstorms and has shed light on the thermodynamic and dynamic mechanisms underlying TD-HEP events (often studied separately, as TD and HEP events). However, due to the lack of long-term, high-resolution aerosol concentration data, the impact of aerosols on changes in TD-HEP event frequency remains unclear. Model simulations with full representation of

**FIG. 8.** As in Fig. 6, but for the area east of the Tibetan Plateau (ETP).
chemical processes may allow us to clarify the contribution of aerosols to variations in TD and HEP frequency in future studies.

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