Vol. 91: 83–96, 2023
https://doi.org/10.3354/cr01725

CLIMATE RESEARCH
Clim Res

Published September 21

Contribution to CR Special 36 'Observed changes in climate over Asia'

Spatial-temporal characteristics of tornadoes in China based on observational data of meteorological stations

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ABSTRACT: Tornadoes are the most destructive meso-small-scale strong convective weather on Earth. At present, however, the temporal change of tornadoes in a subcontinental region like mainland China is still controversial. Here, we report an analysis of the spatial-temporal pattern and long-term trend of tornadoes in mainland China from 1961 to 2013 based on a dataset of the national meteorological observational network. In total, 1082 tornado days were recorded by the national meteorological stations from 1961 to 2013, with an average occurrence frequency of 20.42 d yr^{-1}. Three high-frequency centers are concentrated in South China, East China, and Northeast China. Tornadoes mainly occur in the summer season, mostly in July and August. The annual mean tornado days in mainland China during 1961–1969 reached 43.89 d yr^{-1}, but the period 2010–2013 saw no tornadoes based on station records. There was a highly significant decreasing trend in annual total tornado days during 1961–2013, with a rate of −10.00 d per decade. The decreasing trend in summer was the most significant. We found that the decadal decrease in several atmospheric variables, including convective available potential energy, 0–6 km vertical shear, and low-troposphere relative humidity, is closely associated with the substantial decrease in the number of tornado days.

KEY WORDS: Tornado · Climatology · Spatial-temporal pattern · Trend · Mainland China

1. INTRODUCTION

The term 'tornado' refers to a violently rotating column of air from a cumulonimbus cloud to the surface of the earth. It is a type of severe convective weather that causes losses of lives and property (Simmons & Sutter 2012, Sun 2019). Average-sized tornadoes have a diameter between 150 and 600 m, but they can be as large as 1 km (Lutgens & Tarbuck 2013) and even as small as around 100 m (Sun 2019). The temporal scale of tornadoes can be as short as a few minutes (Sun 2019). Compared to North America, which experiences the most tornadoes in the world (Elsner et al. 2015), tornadoes in China are weaker and fewer in number (Zhou 2014). Nevertheless, with the rapid economic development and urbanization in China (Yang et al. 2021), tornadoes can cause large casualties and economic losses (Zhou 2014). For example, a tornado that happened on 23 June 2016 in Funing (Jiangsu Province) caused 99 deaths and severe property losses (Zhang et al. 2016). Therefore, it is necessary to understand the climatological characteristics and variability of tornadoes in mainland China (hereafter China) in order to reduce the damage caused by convective weather.

The study of severe convective weather depends on what data-collection system is present at the location and on the method and regulation of data collection (Brooks et al. 2003). The lack of uniformity in standards for tornado data collection between differ-

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ent countries makes it difficult to make comparisons across space and time (Brooks et al. 2003, Kunkel et al. 2013). Brooks et al. (2003) indicated that tornadoes are most common in central North America and in southern Brazil and northern Argentina. Zhou (2014) showed that tornadoes often happen in flat areas and that mountainous terrain is not favorable. The high-frequency areas of tornadoes in China are distributed in the Jianghuai Plain, South China, the Northeast China Plain, and the North China Plain (Fan & Yu 2015).

The Intergovernmental Panel on Climate Change (IPCC) has stated that the global climate has become successively warmer over the past 100 yr, especially in the last 4 decades, due to human influence. Human-induced climate change may have already increased the occurrences of some weather and climate extremes, such as heavy precipitation and extreme heat over most regions globally. Due to the short length of high-quality data records, however, the regional and global trends of severe convective weather like tornadoes are still unknown (IPCC 2021).

Observed trends of tornadoes are highly regionally dependent. The annual number of tornadoes remained relatively constant until the 1970s, after which, particularly during the 2000s, the number of tornado days decreased in the USA (Brooks et al. 2014, Elsner et al. 2015, 2019). In Europe, there was an increase in tornadoes from 1800 to 2014 (Antonescu et al. 2016, 2017). In China, some studies (Wang 1996, Zhou 2014, Feng 2016, Feng et al. 2017) indicated that tornadoes show a downward trend throughout the country. The data they used were mostly from the Chinese Meteorological Disasters Dataset, and the research period was generally short. Chen et al. (2018) investigated the tornado climatology and long-term change in China and showed that the tornado frequency seems to have increased. However, it is challenging to validate the trends in severe convective weather on regional scales partly because of insufficient observations and inhomogeneous records (Allen 2018). The different spatial variability of tornadoes indicates that local signals would contribute to both increasing and decreasing trends, and the global trend of tornadoes is uncertain (IPCC 2021).

Quantifying large-scale trends in tornadoes is challenging, mainly because of the locality and short life cycle of tornado events, and also the lack of high-quality observations. In spite of this, it is still valuable to use the existing long-time records from high-density observational networks to research the spatial-temporal pattern and changing trends of tornadoes in a sub-continental region like mainland China. This analysis will help clarify the causes of tornado occurrence and change, also providing climate information to allow decision makers to plan for better adaptation and risk management.

2. DATA AND METHODS

2.1. Data sources

Observation of tornadoes regularly occurs at meteorological observational stations by well-experienced and trained observers in China. It has been stipulated by the China Meteorological Administration (CMA) that if 1 or more tornadoes are observed at a station on a single day, it is recorded as a tornado day (Cui 2011). According to this stipulation, any tornadoes appearing out of observers' sights will not be recorded at the stations.

The tornado data set used in this study is derived from the China Daily Weather Phenomena Data released by the National Meteorology Information Center (NMIC), an ancillary institute of the CMA, which started in 1961 and includes a total of 2422 stations. The data set has been quality-controlled by the staff of the NMIC. Long and homogeneous data sets are fundamental to climate change research. The records of tornadoes from observational stations that we used are less extensive than those derived from other sources, but they are highly consistent and comparable through time, and thus the data could be used in analyses of the long-term trends in extreme weather events.

Homogeneity of the observational data may have been affected by station relocations, and possibly by the change in observers during the whole time period of the observations at the stations. However, the influence from these 2 factors should be negligible compared to that from atmospheric and environmental factors because tornadoes happen rarely around a station. The extreme rareness rules out any possibility to detect the breakpoints in the time series of tornadoes at a single station using the currently applied methods. On the other hand, the experience and training of observers would make the observations of tornadoes reliable. Therefore, the observation of tornadoes based on meteorological stations could be regarded as homogeneous and applicable in the analysis of climatology and climate change.

The thunderstorm and lightning data set from the same observational network as used in the present study is derived from the China Surface Severe Convection Weather Data set V1.0 released by the NMIC, which starts in 1954 (Zhao & Yu 2019). The data set has been quality-controlled, and it will be used to compare the changes in the small-scale extreme convection weather occurrences in the study region. In addition, the ERA5 reanalysis data (ERA5 monthly averaged data on pressure levels and single levels) are used to analyze changes in local environmental factors to examine their links with the tornado trends. The ERA5 reanalysis data were obtained from the European Centre for Medium Weather Forecasting (ECMWF; https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset). Convective available potential energy (CAPE) data are from ERA5 monthly averaged values on single levels. The relative humidity, temperature, and *u* and *v* wind data are from ERA5 monthly averaged records on varied pressure levels.

2.2. Selection of stations

The observation of tornadoes by meteorological observers at stations ceased in 2014. Therefore, the period 1961–2013 was selected for research in the present study. The distribution of all observational stations in the dataset is shown in Fig. 1a, and the distribution of stations with at least 1 tornado event recorded is shown in Fig. 1b. In total, 498 stations recorded at least 1 tornado event between 1961 and 2013 in China. They can be found in almost all provinces of the country, but mostly occurred in the eastern monsoon region.

Fig. 2a shows the 3 typical areas where tornado occurrences are more frequent. They are located in South China (16–24° N, 108–118° E), East China (27–34° N, 115–123° E), and Northeast China (41–49° N, 121–131° E). There are 52 stations in South China, 118 stations in East China, and 76 stations in Northeast China, which have records of at least 1 tornado occurrence in history. All national observation stations (n = 2422) were used in this work, but only 498 stations with at least 1 occurrence in the analysis period were applied to analyze the spatial-temporal characteristics of tornadoes in China. At the same time, the 3 areas with high-frequency occurrences were used to examine their spatial differences.

2.3. Methods

The total days of tornadoes at a station include all records from 1961 to 2013, and the annual mean days of tornadoes are the arithmetical means of the period. Because of its simplicity and intelligibility, ordinary least squares (OLS) is widely used to calculate linear trends in climatic variables. However, OLS is based on the assumption that the data follow a Gaussian distribution (Zhang et al. 2000). When the data do not have a Gaussian distribution, OLS is not suitable. Therefore, a modified Theil-Sen estimator (Sen 1968, Jassby & Cloern 2017) was used to calculate the linear trend in tornado days, and the significance of the linear trend was assessed using the Mann-Kendall test (Mann 1945, Kendall 1955). However, OLS and a 2-tailed simple *t*-test were still used to calculate the trend and significance of the regional environmental factors. Trends were considered statistically significant at the 95% ($p < 0.05$) confidence level. Spring is from March to May, summer is from June to August, autumn is from September to November, and winter

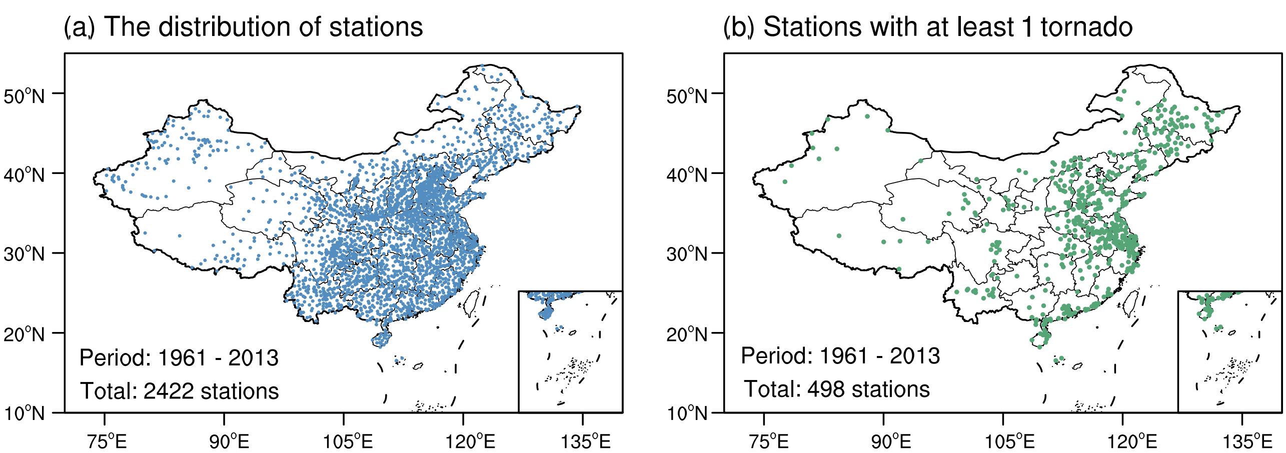

Fig. 1. Distribution of (a) all observational stations and (b) the stations with at least 1 tornado recorded between 1961 and 2013 in China

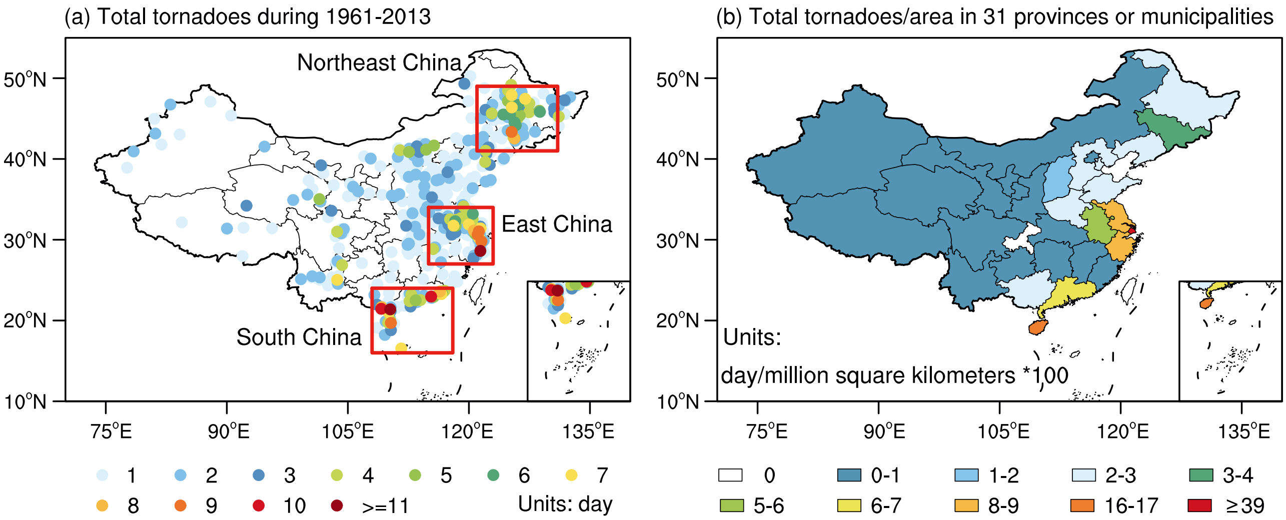

Fig. 2. Spatial distribution of the total tornado days during 1961–2013 in China. (a) Total tornadoes at stations; (b) total tornadoes in provinces or municipalities. The red squares indicate South China (16–24°N, 108–118°E), East China (27–34°N, 115–123°E), and Northeast China (41–49°N, 121–131°E)

is from December to February. Data were processed and figures generated using NCL 6.5.0 (https://www.ncl.ucar.edu/).

3. RESULTS

3.1. Spatial distribution

The spatial distribution of the total tornado days during 1961–2013 in China is shown in Fig. 2. From 1961 to 2013, 1082 tornado days were recorded, and the mean occurrence frequency of tornadoes in the country was 20.42 d yr^{-1} (Fig. 2a). Weizhoudao station in Guangxi Province had the most tornadoes, with 26 d in total. Three regions with high-frequency tornado occurrences are South China (215 tornado days), East China (286), and Northeast China (204). In these 3 regions, Guangdong, Jiangsu, and Heilongjiang provinces registered the most frequent occurrences of tornadoes during 1961–2013, reaching 120, 108, and 87 d in total, respectively. In terms of occurrences per unit area (d km^{-2}), however, Shanghai experienced the most tornadoes, followed in turn by Hainan, Jiangsu, Zejiang, and Guangdong Provinces (Fig. 2b). The inland arid regions and hilly areas of southern China saw the fewest occurrences of tornadoes per square kilometer. No tornadoes happened in Chongqing municipality based on the station records from 1961–2013.

The seasonal distribution of the total tornado days during 1961–2013 is shown in Fig. 3. In spring, 1 station (Xisha, Hainan Province) had 12 tornado days from 1961 to 2013, and all others saw at most 2 d in total. Summer experienced the most tornado days out of the 4 seasons, accounting for 72.6%, and Weizhoudao in Guangxi Province had the most tornadoes (22 d in total). Regarding the annual distribution, South China, East China, and Northeast China are also high-frequency centers in summer. In autumn, 5 tornado days were observed at Pinghu station, Zejiang Province. Few tornadoes happened in winter, with only 7 stations recording tornadoes. The total tornado days are summarized in Table 1.

The monthly total tornadoes in China and the 3 regions from 1961 to 2013 are shown in Fig. 4. July showed highest number of days, accounting for 31.8%, followed by August, with these 2 months accounting for more than 55% of the annual total in China. The 3 regions all recorded the most tornadoes in July (Fig. 4b). It is also notable that tornadoes hap-

Table 1. Total tornado days during 1961–2013 in China and the 3 high-frequency regions (units: day)

Area	Total	Spring	Summer	Autumn	Winter
China	1082	122	785	166	9
East China	286	13	216	56	1
South China	215	42	135	37	1
Northeast China	204	20	160	20	4

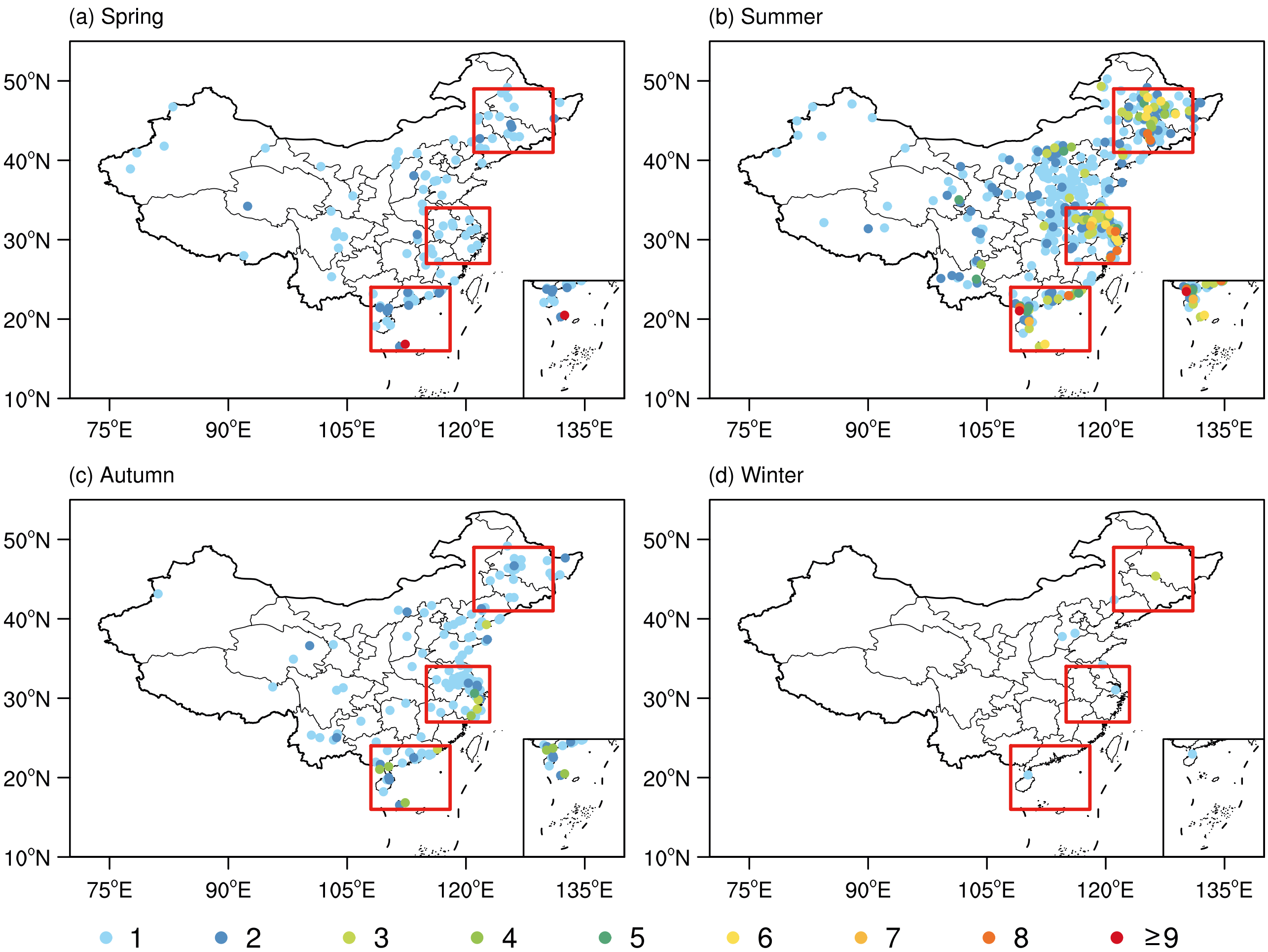

Fig. 3. Seasonal spatial distribution of the total tornado days during 1961–2013 in China: (a) spring; (b) summer; (c) autumn; (d) winter. The red squares indicate South China (16–24°N, 108–118°E), East China (27–34°N, 115–123°E), and Northeast China (41–49°N, 121–131°E)

pened earlier in South China than in other regions, with 13 tornadoes in total in April. In East and Northeast China, fewer tornadoes occurred in April. No tornadoes occurred in January, and only 1 tornado was recorded in December. The earliest occurrence date (month-day) of a tornado was 1 February (1983,

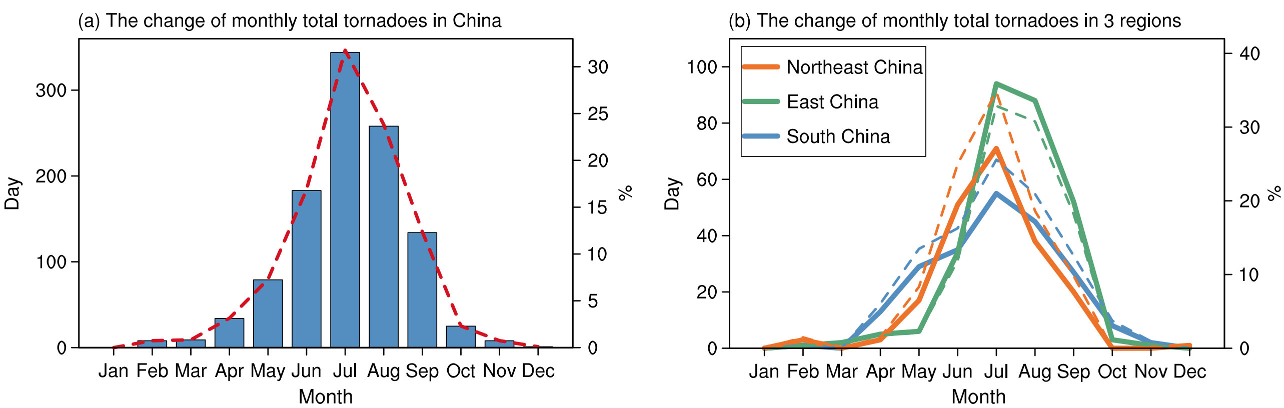

Fig. 4. Monthly total tornadoes in (a) China and (b) the 3 high-frequency regions from 1961 to 2013. The bars in (a) and the solid lines in (b) indicate total tornado days in every month. The dashed lines show the percentages

Table 2. Earliest and latest occurrence date (month-day) of tornadoes during 1961–2013 in China and the 3 high-frequency regions

Area	Earliest date	Station	Latest date	Station
China	2-1 (1983)	54617 (Xiancheng, Hebei)	12-20 (1977)	54132 (Qinglongshan, Inner Mongolia)
East China	2-10 (1962)	58462 (Songjiang, Shanghai)	11-10 (1972)	58214 (Huoqiu, Anhui)
South China	2-22 (1966)	59754 (Xuwen, Guangdong)	11-12 (1968)	59647 (Weizhoudao, Guangxi)
Northeast China	2-13 (1972)	50955 (Shuangcheng, Heilongjiang)	12-20 (1977)	54132 (Qinglongshan, Inner Mongolia)

Xiancheng station, Hebei Province) and the latest occurrence was 20 December (1977, Qinglongshan station, Inner Mongolia Province). The earliest and latest occurrence dates of tornadoes in China and the 3 regions are shown in Table 2.

3.2. Temporal variations

The change in annual total tornado days from 1961 to 2013 in China is shown in Fig. 5a. The tornado days decreased significantly, with a trend of −10.00 d

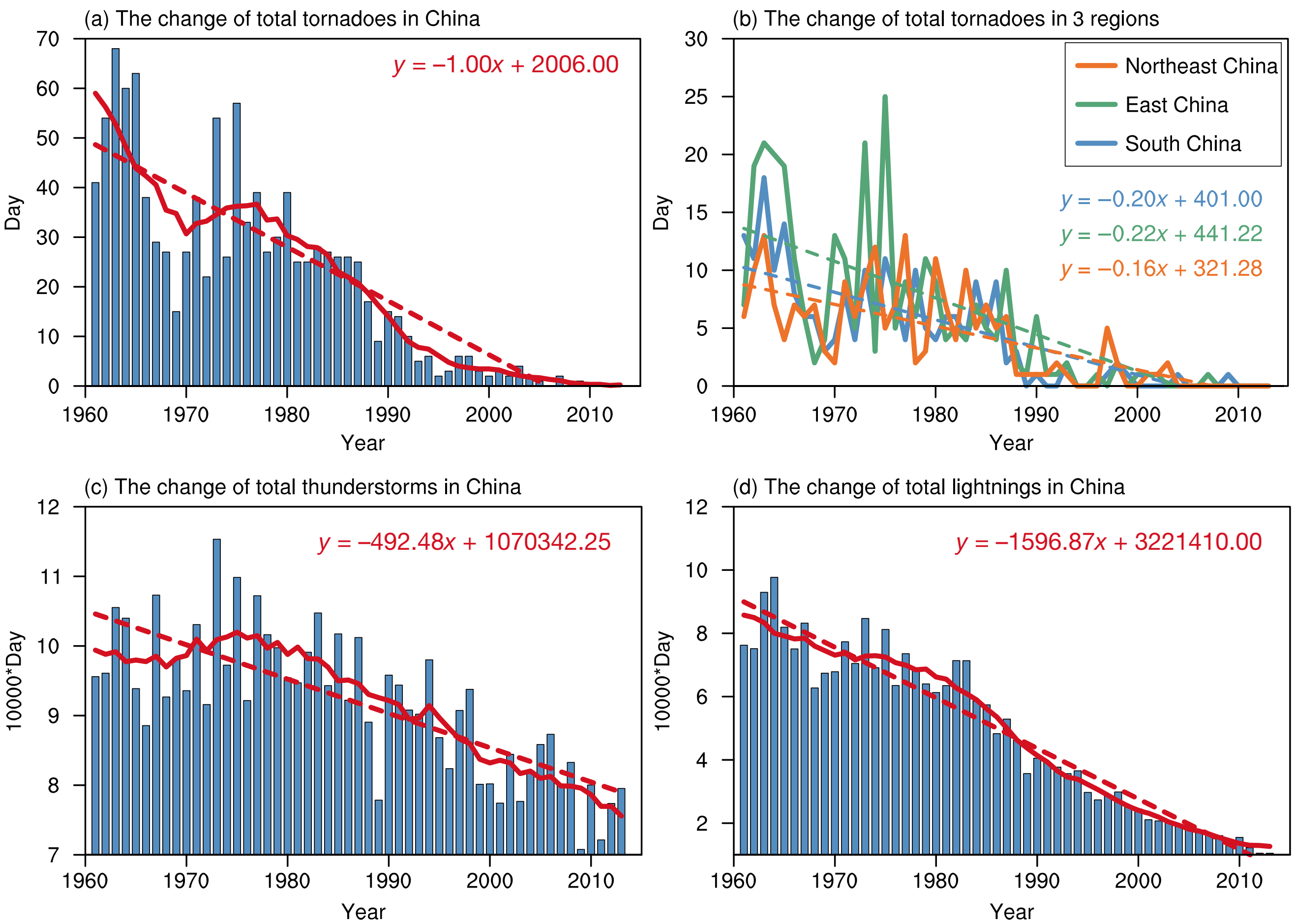

Fig. 5. Change in (a) total tornadoes, (c) total thunderstorms, and (d) total lightnings in China and (b) change in total tornadoes in the 3 high-frequency regions from 1961 to 2013. The blue bars in (a) and the solid lines in (b) are total tornadoes in every year. The dashed lines show the linear regression trends. The red line in (a) is the 9-point moving average. The formulas are the fitted equations

per decade, which passes the significance test at the 95% confidence level. In 1963, the occurrence of tornado days reached 63 d in total, but far fewer tornadoes were observed after the mid-1990s. The large decrease happened after the mid-1980s.

All of the 3 high-frequency regions showed significant decreasing trends (Fig. 5b). The downward rates per decade were −2.00 d in South China, −2.22 d in East China, and −1.60 d in Northeast China, all of which were significant. After the late 1980s, the annual total tornadoes became extremely rare in each of the 3 regions.

Table 3. Trends in total tornadoes recorded in different seasons during 1961–2013 in China and the 3 high-frequency regions. An asterisk (*) indicates that the trends are statistically significant at the 95% ($p < 0.05$) confidence level

Area	Year	Spring	Summer	Autumn	Winter
China	−10.00*	−0.99*	−7.38*	−1.36*	0
East China	−2.22*	0	−1.64*	−0.36*	0
South China	−2.00*	−0.38*	−1.11*	0	0
Northeast China	−1.60*	0	−1.26*	0	0

The annual total thunderstorm and lightning days, which are also considered meso-small-scale strong convective weather, also decreased from 1961 to 2013 in China (Fig. 5c,d). The mechanisms and factors influencing the changes in tornado occurrence may be similar to those of thunderstorms and lightning events. The similarly high decreasing trends of thunderstorm and lightning days in China also imply that the decrease in tornadoes in the country as reported herein is reasonable.

The total tornado trends in China and the 3 high-frequency regions in different seasons from 1961 to 2013 are shown in Table 3. The decrease trend is the most significant in summer, followed by autumn. The change in tornadoes in winter is not significant mainly due to the extremely small sample size. In South China, the decreasing trend in spring is also significant compared to the other regions, probably due to the fact that tornadoes are more likely to occur in this season in South China than in East and Northeast China.

Fig. 6 shows a comprehensive temporal pattern of the total tornado days from 1961 to 2013 in China and the 3 regions. The characteristics of seasonal and decadal variations as described above, including the high-frequency occurrence in summer especially in July and the remarkable reduction from the mid-1980s to 2013, can be more clearly seen from Fig. 6. Since 2010, the 3 high-frequency regions have registered no tornadoes.

3.3. Links between changes in tornado occurrence and regional environmental factors

Conditionally unstable stratification, sufficient moisture in both low and middle levels of the atmosphere, and strong vertical shear are suitable conditions for severe convective weather to occur (Antonescu et al. 2017, Tochimoto & Niino 2018). Tornadoes are more likely to form when there is a large CAPE and a deep-tropospheric wind shear (Brooks et al. 2003, Xue et al. 2021). Abundant moisture conditions at low levels can lead to a lower lifting condensation level that is favorable to the occurrence of tornadoes (Feng 2016). Lower-troposphere stability (LTS) presents the thermodynamical state of the troposphere (Wood & Bretherton 2006). It is defined as the difference in the potential temperature between the free troposphere (700 hPa) and the surface (LTS = $\theta_{700\ hPa} - \theta_{1000\ hPa}$) (Slingo 1987).

Romero et al. (2007) examined the relationships between tornadoes and multiple sets of environmental parameters in Europe, and found that CAPE, low-level moisture, and wind shear have better correlations with tornadoes. Wang (1996) analyzed the conditions of tornado occurrence in the Pearl River Delta in spring and revealed that the high temperature and humidity at the lower level, and the unstable potential at the middle and lower level, are both favorable for the formation of tornadoes. Feng et al. (2012) indicated that tornadoes decreased significantly during 1980–2009 and the 0–6 km vertical shear may have been the main reason for the decline in East China.

In this study, we used CAPE, the 0–6 km vertical wind shear, the relative humidity at 925 hPa, and LTS to examine their links with the decreasing trends of tornadoes in China. China has a vast territory, and climate varies greatly in different regions, which makes identifying the causes of the small-scale severe convective weather variations in different regions difficult (Feng 2016). The following analysis focuses on the 3 high-frequency regions (South China, East China, and Northeast China).

The number of tornado days decreased significantly after the late 1970s and especially the late 1980s in China (Figs. 5 & 6). The quality of the reanalysis data also improved after 1979 because of the integration of more observations and the improve-

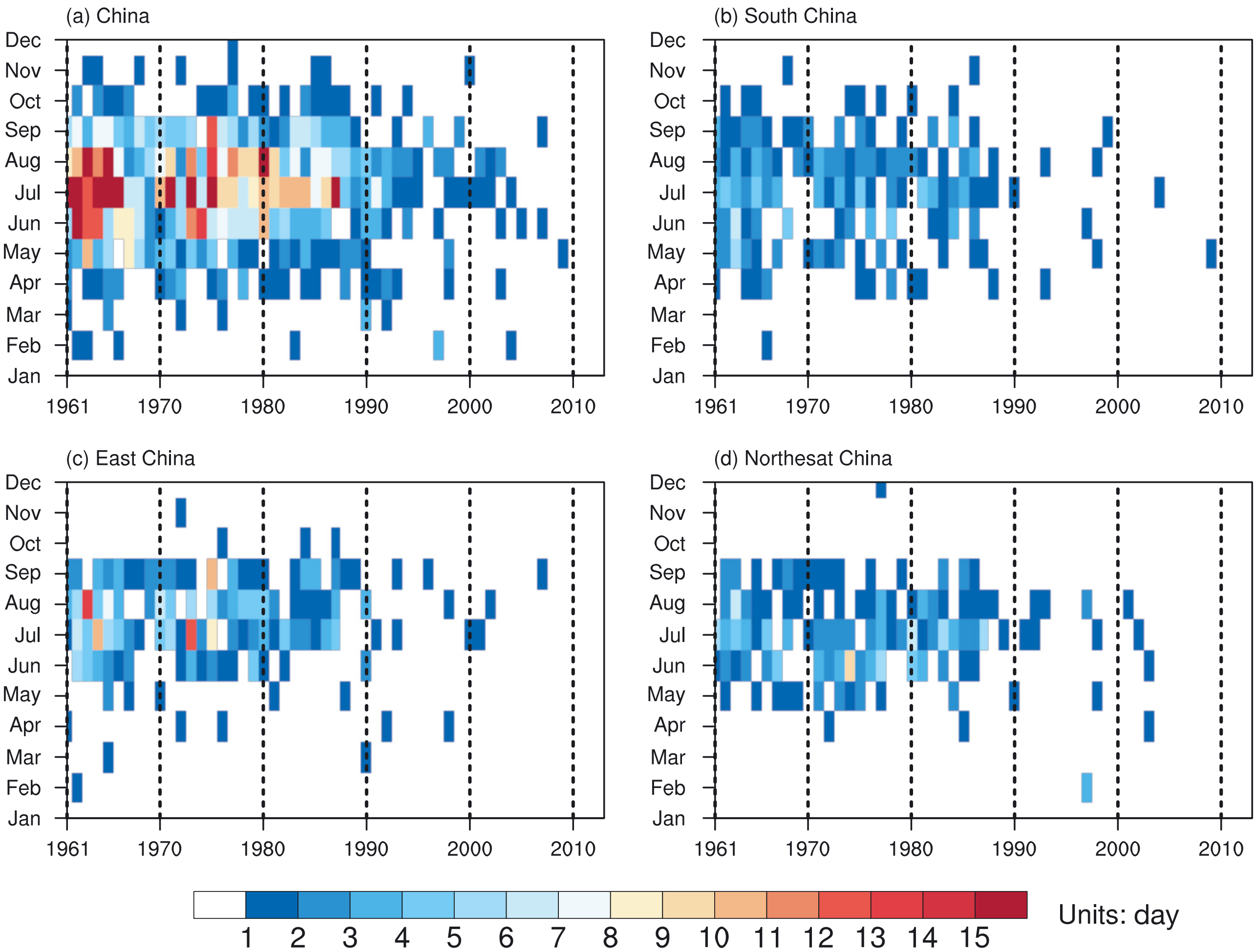

Fig. 6. Month-year profile of the total tornado days from 1961 to 2013 in (a) China and the 3 high-frequency regions: (b) South China, (c) East China, and (d) Northeast China

ment of assimilation methods and models (Zhou et al. 2018). Therefore, the reanalysis data from ERA5 during 1979–2013 were selected for the analysis.

Fig. 7 shows the changes in the environmental factors from 1979 to 2013 and their correlations with tornado days. CAPE decreased significantly in South China (Fig. 7a) and had a positive correlation with the occurrence of tornadoes (Fig. 7b). This means that the decrease in CAPE may have affected the change in tornado occurrence in South China. In East and Northeast China, however, the correlations between CAPE and tornado occurrence were generally negative, probably indicating a dominant effect of other environmental factors on the trends of the extreme weather in other parts of the country.

The 0–6 km vertical shear also decreased significantly in South and East China (Fig. 7c). There was a generally significant positive correlation of the 0–6 km vertical shear with the tornado occurrence, and the decrease in 0–6 km vertical shear is larger and more significant in East and South China (Fig. 7d), indicating that the decrease in the 0–6 km vertical shear may have been one of the important causes for the observed drop in tornado days, especially in East and South China.

For relative humidity at 925 hPa, the 3 regions all showed a significant decrease (Fig. 7e). However, the correlations between relative humidity and tornado days were not consistent across the regions, with most of the grids in North and East China showing a significant negative correlation (Fig. 7f). Once again, the inconsistence implies the complexity of the influence of large-scale environmental conditions.

The significant decreases in LTS were also found in East and Northeast China (Fig. 7g). East China saw a larger and more significant decrease. However, the LTS showed a negative correlation with the tornado occurrence in most grids, especially in Northeast China (Fig. 7f). It is likely that LTS had some influence on the observed change in tornadoes in East China,

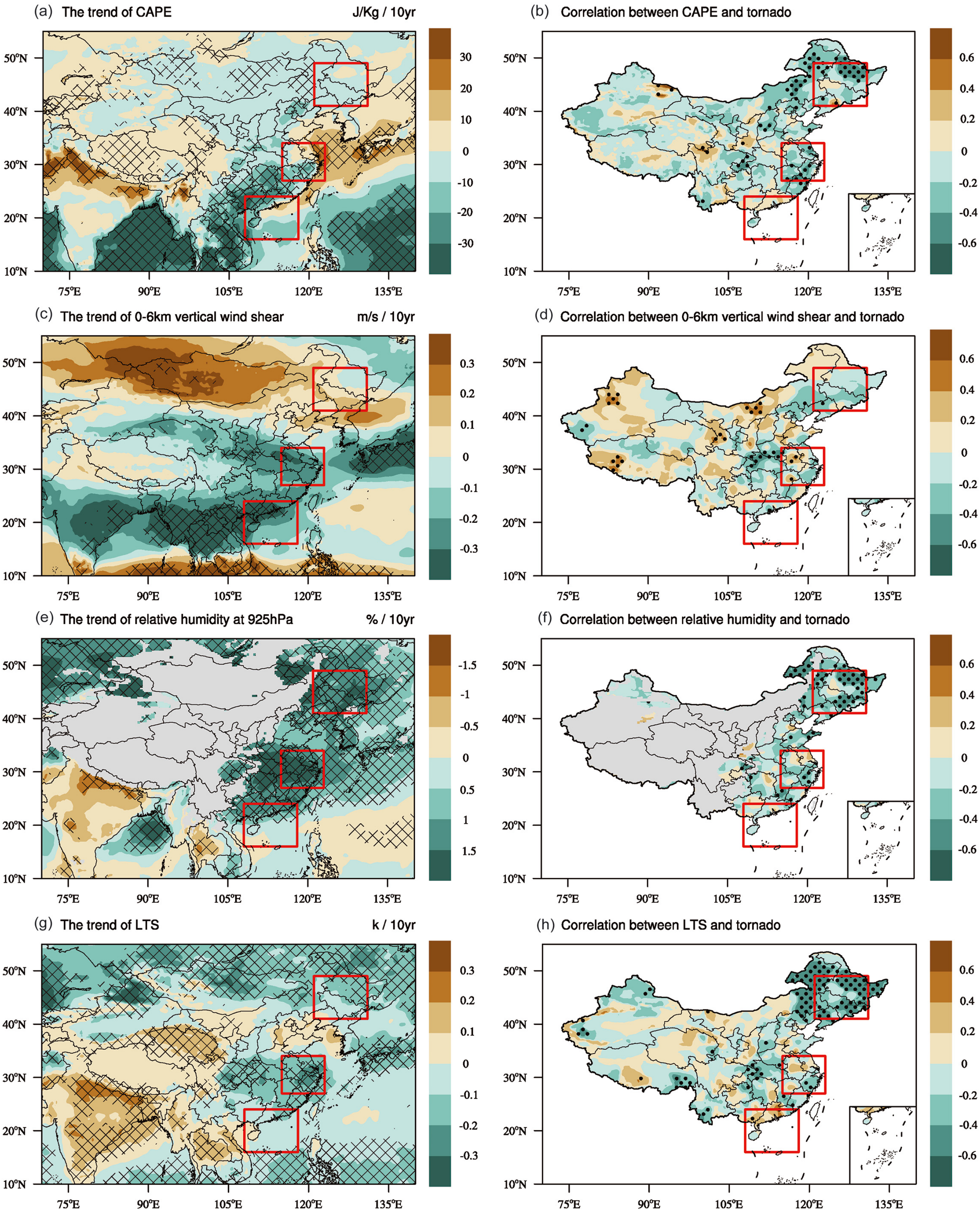

Fig. 7. Trends in (a) convective available potential energy (CAPE), (c) the 0–6 km vertical wind shear, (e) the relative humidity at 925 hPa, and (g) lower-troposphere stability (LTS) during 1979–2013 and the correlations with tornadoes for (b) CAPE, (d) 0–6 km vertical wind shear, (f) relative humidity at 925 hPa, and (h) LTS. Black cross-hatched areas in (a, c, e, g) indicate that the trends are statistically significant at the 95% ($p < 0.05$) confidence level. Black dots in (b, d, f, h) indicate that the correlations are statistically significant at the 95% ($p < 0.05$) confidence level. The red squares indicate South China (16–24°N, 108–118°E), East China (27–34°N, 115–123°E), and Northeast China (41–49°N, 121–131°E). The grey-shaded areas in (e) and (f) indicate heights lower than 925 hPa

and to a lesser extent in South China, but it may have exerted only a weak effect in Northeast China.

The calculation of simple correlations may be problematic, because tornadoes occurred significantly less frequently during the last 2 decades, with some years experiencing no tornadoes in the 3 regions. In order to further examine the possible effect of regional environmental factors on changes in tornado occurrence, we selected the 3 stations with the most frequent occurrences for each of the 3 regions (South China: Stns 59647, 59981, and 59650; East China: Stns 58752, 58665, and 58464; and Northeast China: Stns 54164, 54266, and 50750) to compare the differences in regional environmental factors between the sub-periods 1979–1989 (more tornadoes) and 2003–2013 (fewer tornadoes). The regional environmental factors were calculated by choosing the nearest grid points to the stations. The results are shown in Fig. 8.

In South China, the CAPE was larger during 1979–1989 than during 2003–2013 (Fig. 8a). The decrease in CAPE is closely related to the decrease in the tornado occurrence in South China. At the same time, the 0–6 km vertical shear also decreased significantly in South China (Fig. 8b). In East China, the relative humidity at 925 hPa and LTS also decreased significantly (Fig. 8g,h), which is highly consistent with the decrease in the tornado occurrence. In Northeast China, CAPE (Fig. 8i), relative humidity (Fig. 8k), and LTS (Fig. 8l) all showed a significant downward trend, indicating that they may have played a role in the observed decrease in tornadoes.

Although the changes were inconsistent across the 3 regions, the environmental factors at the representative stations generally experienced a significant decrease over recent years compared to the previous period (Fig. 8). This is consistent with the regional average trends in the environmental factors shown before, indicating that 1 or more of the environmental factors may have affected the long-term change in tornado occurrence in different parts of China by modifying the background atmospheric condition.

4. DISCUSSION

Compared to the USA, where tornadoes can occur every month and most are recorded in May (Brooks et al. 2003), the tornadoes that happen in China are much smaller in number, do not happen in January, and most frequently appear in July. According to the US National Oceanic and Atmospheric Administration (NOAA), more than 60 000 tornadoes were recorded in the USA from 1950 to 2016 (NOAA 2016). This may be because the observational network in the conterminous USA is denser than that of mainland China, and more tornadoes can be spotted. Geographical conditions are also favorable for the formation and development of tornadoes in the vast plains east of the Rocky Mountains.

The results reported here are basically consistent with those shown in previous studies. Feng et al. (2017) used data from the Chinese Meteorological Disasters Yearbook from 2004 to 2012 to analyze the climatological characteristics of tornadoes in China, and they identified 3 centers of tornado occurrences (Guangdong and its adjacent regions, Jiangsu and its adjacent regions, and Northeast China), and the tornadoes mainly happen in summer and spring. Wang et al. (2015) indicated that Northeast China is one of the major centers of tornadoes in China. They analyzed in detail the environmental characteristics of tornado generation in this region, showing the close association of extreme weather with the Northeast China cold vortex. These findings of tornado climatology are consistent with the results of our study. The data we used in this study are the observational records from meteorological stations and cover a much longer period than those used by Feng et al. (2017).

Fan & Yu (2015) used the data from the Handbook of China Meteorological Disasters and other relevant documents from 1961 to 2015 to analyze the spatial-temporal characteristics of tornadoes, finding a total of 165 records of major events, most of which occurred in the plain regions, with higher frequency in the Jianghui Plain, South China, the Northeast China Plain, and the North China Plain. These results are also similar to those of our study. Fan & Yu (2015) estimated that in total, about 1055 tornadoes happened in China during 1961–2010, which is also close to the result of 1082 from 1961 to 2013 shown in the present paper.

In the present study, we used a relatively high-density dataset of 2422 stations to analyze the trends of tornado days in China from 1961 to 2013. The results show that the total tornado days have a steady and significant decreasing trend with a rate of −10.86 d per decade. Feng et al. (2017) used the data of the Chinese Meteorological Disasters Yearbook from 2004 to 2012 to analyze changes in tornado occurrence, indicating that the tornado days in China significantly decreased after 2008, but the decreasing trend was not calculated due to the short time period. Fan & Yu (2015) showed a higher frequency of tornadoes during the period 1986–1990, and a decrease after that period, but the decreasing trend was not

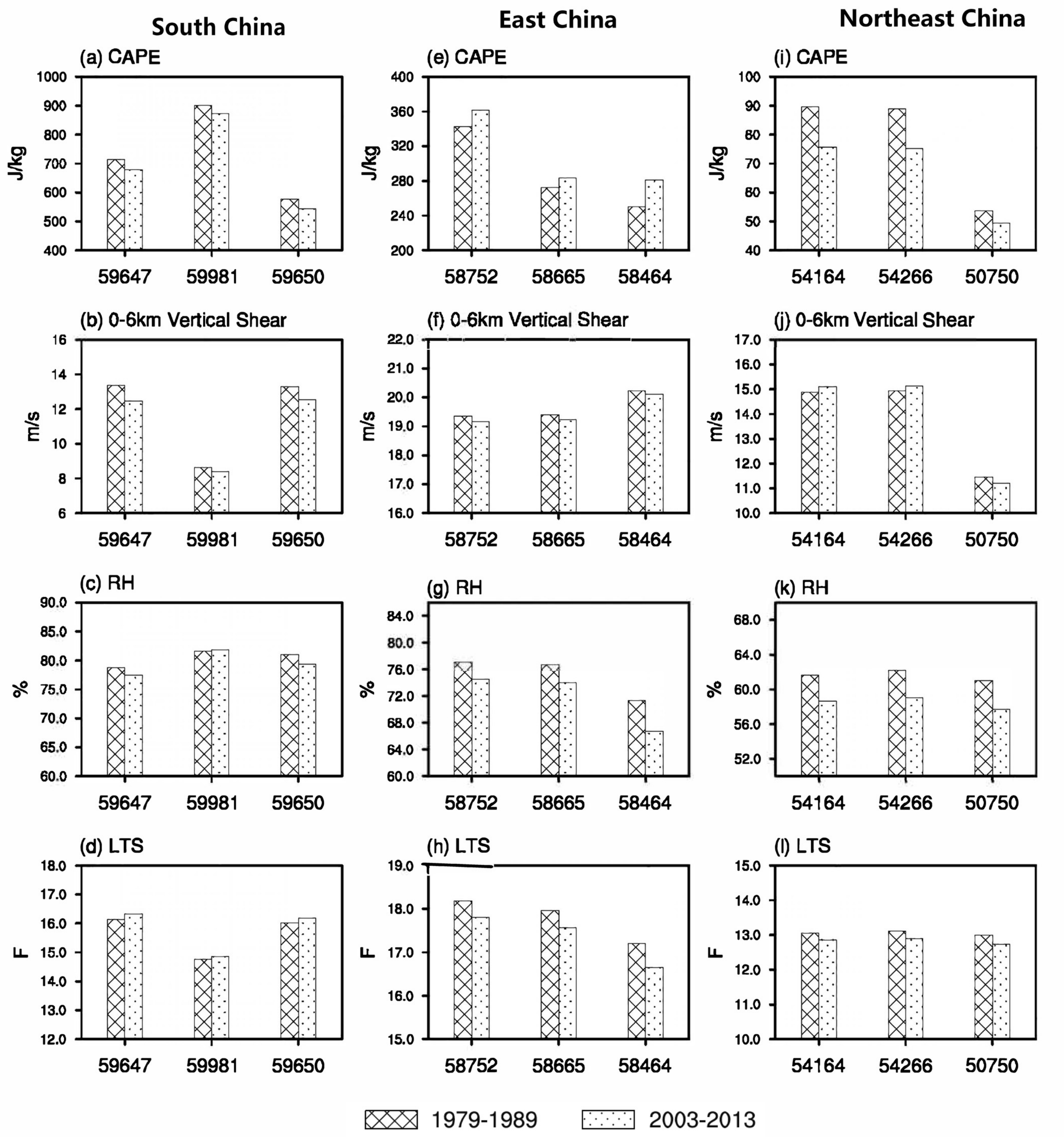

Fig. 8. Difference in environmental factors — (a,e,i) convective available potential energy (CAPE), (b,f,j) 0–6 km vertical wind shear, (c,g,k) relative humidity (RH) at 925 hPa, and (d,h,l) lower-troposphere stability (LTS, in degrees Fahrenheit) — between 1979–1989 and 2003–2013 for the 3 stations with the most frequent occurrence of tornadoes in the 3 representative regions of China

calculated. Some analyses of local and regional changes in tornadoes in China generally indicate a significant decrease from the 1950s to the early 2000s (Ren et al. 2010), which is quite consistent with the results shown in the present paper.

Other meso-small-scale strong convective weather like thunderstorm and lightning days were reported to decrease from 1961 to 2013 almost everywhere in China (Xue et al. 2021). To some extent, this phenomenon affirms the reliability of the data series and the results shown in our analysis because they usually occur in similar large- to meso-scale circulation conditions, with tornadoes being formed in more extreme situations. The mechanism and factors influencing changes in tornadoes may also be similar to those of thunderstorm and lightning events.

Chen et al. (2018) investigated the climatology and changes in tornadoes in China, showing an increasing trend in tornado occurrence. This may be because the data they used in their analysis came from the Collection of Meteorological Disasters in China, a combination of the Climate Impact Assessment in China and the Yearbook of Meteorological Disasters in China, and the data of meteorological stations only covered the eastern part of China. The recording start date of different tornado sources is variable. With increased public awareness, and more attention to the development of tornado databases by national meteorological services, tornadoes are reported and recorded more frequently (Antonescu et al. 2016). The datasets developed through meteorological disaster monitoring and climate impact assessment thus may have a temporal bias toward a more frequent occurrence more recently. They could not be used to research the long-term trends of tornado occurrence. However, the results of climatological characteristics of tornadoes in China reported by Chen et al. (2018) are useful. We used observational records from national stations. The records report far fewer tornadoes than those derived from other sources, but they are highly consistent and comparable through time, and thus the data could be used in analysis of the long-term trends in extreme weather events.

The occurrence of tornadoes in China showed a significantly decreasing trend after the mid-1980s, and such a significant decreasing trend has also been found in other regions of the world, including the USA (Brooks et al. 2014, Elsner et al. 2015, 2019). The trends in tornadoes from different regions are briefly summarized in Table 4. In the present study, we have shown that the decreasing trends in the 3 high-frequency regions in China may have been closely associated with the different effects of the regional environmental factors. The root causes of the atmospheric condition change are beyond the scope of this study; more research is needed in the future. However, it would be interesting to know whether or not the regional environmental factors that may have led to a decrease in China also changed in the regions of the world that have shown downward trends in tornado occurrence since the mid-1980s.

With rapid urbanization, the physical properties of the underlying surfaces have changed a lot (Yang et al. 2021), including an increase in surface friction and aerosols around the observational stations. Schenkman et al. (2014) indicated that surface friction affects the occurrence of tornadoes. The increased concentration of aerosols reduces the total and direct solar radiation reaching the surface, and thus weakens the surface heating and local air convection. It is possible that the significant decline in tornadoes at the national meteorological stations may be at least partly caused by rapid urbanization and the remarkable increase in aerosol concentrations in the monsoon region of eastern China in the last 4 to 5 decades. This issue requires further investigation in future work.

The data of tornadoes that we used in the present study are only the records of tornadoes that happened at the meteorological stations. In fact, many tornadoes do not happen near the stations. This may affect the estimates of total tornadoes, leading to an underestimate, but may not affect the analysis results of seasonal and decadal variations. We also collected data of tornadoes from the Yearbook of Meteorological Disasters in China from 2003 to 2019. Table 5 shows that tornado records from the yearbook are much larger than those observed at

Table 4. Trends in tornadoes reported in previous studies for different regions of the world

Region	Data source	Period	Trend	Source
China	The Handbook of China Meteorological Disasters	1961–2010	Decrease	Fan & Yu (2015)
China	The Chinese Meteorological Disasters Yearbook	2004–2012	Decrease	Feng et al. (2017)
China	Collection of Meteorological Disasters, Climate Impact Assessment, Yearbook of Meteorological Disasters, and meteorological station data	1948–2012	Increase	Chen et al. (2017)
China	Yearbook of Meteorological Disasters	2004–2011	Decrease	Zhou (2014)
USA	The US Storm Prediction Center	1954–2013	Decrease	Elsner et al. (2015)
USA	US National Oceanic and Atmospheric Administration	1954–2013	Decrease	Brooks et al. (2014)
Europe	European Severe Weather Database	1950–2015	Decrease	Antonescu et al. (2016a)

Table 5. Comparison of tornado records between the Yearbook of Meteorological Disasters in China and the national meteorological observation stations (units: days). A slash (/) indicates no observations

Year	Yearbook of Meteorological Disaster records	Meteorological station records
2003	98	4
2004	69	2
2005	106	1
2006	82	0
2007	59	2
2008	81	0
2009	38	1
2010	47	0
2011	35	0
2012	47	0
2013	45	0
2014	21	/
2015	26	/
2016	23	/
2017	18	/
2018	22	/
2019	16	/

the meteorological stations during the same time period. However, both records present a decreasing trend during 2003–2019, indicating that days of tornadoes in China are indeed decreasing, and the decrease during the longer time period of 1961–2013 is credible.

Finally, from 2010 to 2013, no tornado has been registered at stations in China (Fig. 6). This does not mean that no tornadoes touched down in the country; rather, it simply means that no tornadoes were observed near the observational stations. Table 5 indicates that tornadoes happened in China after 2013, but the number significantly decreased. The apparent decline in tornadoes makes those that happen right near the observational sites rarer. The manual observation of tornadoes by meteorological observers at stations was stopped in 2014. After that time, there are no similar observations of tornadoes available at the stations, making the update of the observational data series in China impossible, although a renewed occurrence of extreme weather events after 2013 is assumed to be likely based on the news reports.

5. CONCLUSIONS

Based on the observational data during 1961–2013, the spatial-temporal pattern of tornado variations and trends in China and the possible environmental factors are analyzed. The main conclusions are as follows:

(1) From 1961 to 2013, a total of 1082 tornado days occurred in China, with a frequency of 20.42 d yr^{-1}. Three high-frequency centers are located in South China, East China, and Northeast China.

(2) Summer experiences the most tornado days among the 4 seasons, and July is the month with the most tornadoes of the year. The earliest occurrence date was 1 February (1983), and the latest date was 20 December (1977).

(3) The tornado days decreased significantly with a trend of −10.00 d per decade during 1961–2013. No tornadoes were recorded during 2010–2013. All 3 high-frequency regions experienced a significant decline, with a rate of −2.00, −2.22, and −1.60 d per decade in South, East, and Northeast China, respectively. The decreasing trend was most significant in summer compared to the other seasons.

(4) The decrease in tornadoes can be associated with the change in regional atmospheric conditions, in particular with the decreases in CAPE (or the increase in LTS), the 0–6 km vertical shear, and the low-troposphere relative humidity in the 3 high-frequency regions.

Acknowledgements. This study was financially supported by the National Key R&D Program of China (2018YFA 0605603), the Second Tibetan Plateau Scientific Expedition and Research (STEP) program (2019QZKK0105).

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Editorial responsibility: Eduardo Zorita, Geesthacht, Germany
Reviewed by: T. W. Moore and 3 anonymous referees

Submitted: November 10, 2022
Accepted: August 17, 2023
Proofs received from author(s): September 19, 2023