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Key Points:

- The results confirm the highly significant decreasing trend of frequency of thunderstorm and lightning during 1961~2013
- The decrease of geopotential height difference, the weakening of westerly jet strength and the decline of zonal wind have influence
- CAPE, relative humidity and 0–6 km vertical wind shear have a significant positive correlation with change of thunderstorm and lightning days

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The Trends of Warm-Season Thunderstorm and Lightning Days in China and the Influence of Environmental Factors

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Abstract Previous studies indicated that numbers of meso-micro scale severe convective weather exhibited a significant decrease over China's mainland in the past decades. However, the possible mechanism of the decrease has not been well understood. This paper analyzes the changes in frequency of thunderstorm and lightning days using an updated data set of denser national observational stations and theirs links to the atmospheric circulation and regional environmental factors. The results confirm the highly significant decreasing trend of frequency of thunderstorm and lightning days during 1961–2013, with the decreasing rates of −2.6 days/10 years and −6.5 days/10 years in the warm season, respectively. The decrease of geopotential height difference between south and north, the weakening of westerly jet strength at 200 hPa and the decline of zonal wind speed of high level are found to be the direct reasons for the wide-spread decrease of thunderstorm and lightning days across the country. Meanwhile, there is a significant positive correlation between thunderstorm days and convective available potential energy (CAPE), indicating a reduction of potential atmospheric instability accompanying the decline of thunderstorm days especially in the south of China. The decrease in the relative humidity at the lower troposphere, the weakening of 0–6 km vertical wind shear and the accompanying slackening of actual convective activity, may have also contributed to the downward trends of the severe convective weather. Our analysis shows a strong link of the decreasing thunderstorm and lightning days to the long-term changes of the atmospheric circulation and environmental factors. Further investigation is needed to examine what have driven the changes of the environmental factors over the time period.

1. Introduction

Severe convective weather like thunderstorms and the lightning (TSL hereafter) have astonishing destructive power, often causing serious damage to buildings, crops, automobiles and so on, resulting in heavy economic losses (Bouwer & Laurens, 2011; Mohr et al., 2015). In recent years, the economic losses caused by TSL are huge in countries and regions of mid-to-low latitude. For example, the annual mortality rate caused by TSL is about 0.3 per million people in China from 1998 to 2004 (Mei et al., 2007), corresponding to an annual death toll of 420 across the country. Furthermore, with the development of science and technology, electronic products are used more and more widely. TSL can not only damage electronic facilities by direct impact, but also impose high impulse overvoltage on insulators which leads to a major public hazard in the electronic age (M. Ma et al., 2008). Therefore, a systematic and in-depth understanding of TSL including their changes over time and the possible influential factors are of great significance.

The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2013) indicates that the global climate is undergoing a significant warming in the past 100 years. Global warming can alter the surface radiation balance, atmospheric circulation and water cycle, and can also cause extreme weather events change. For instance, the observed frequency and intensity of heavy precipitation and heat wave have increased significantly in China (Committee on China's National Assessment Report on Climate Change, 2006; IPCC, 2013). However, the trends of smaller scale extreme weather events, including TSL, are not so well understood, mainly due to the lack of high-quality and high-resolution observations

(IPCC, 2013). The events often occur in spatial scales within tens of kilometers, which are quite different from the global and regional changes in other extreme weather and climate processes that are typically within thousands of kilometers (Q. H. Zhang et al., 2017).

The changes of TSL under the warming climate attract great attention (Brooks et al., 2014; Field, 2012; Parry et al., 2007). At present, however, the estimates on the long-term trends of TSL days vary spatially, with different research areas even showing opposite trends (Araghi et al., 2016; Changnon & Changnon, 2001; Enno et al., 2013; Kunkel et al., 2013; Pinto et al., 2013; Tuomi & Mäkelä, 2009). Bielec (2001) indicates that there is no significant change in the frequency of thunderstorms in Poland during the twentieth century. Changnon and Changnon (2001) report a significant positive trend in the west but downward trend in the east over the United States from 1896 to 1995; the same conclusion has been reached by Kunkel et al. (2013). Tuomi and Mäkelä (2009) see no clear trend in days of thunderstorms from 1998 to 2007 in Finland. Brooks (2013) points out that CAPE increases under the global warming background, which causes the frequency of severe thunderstorms to rise, based on observation and model data. Pinto et al. (2013) indicates that there is a significant positive trend of thunderstorm frequency after 1951 in three cities in the southeast of Brazil. Araghi et al. (2016) also reports an upward trend in thunderstorms in Iran during the 50 years of 1961–2010. Taszarek et al. (2020) shows that the trends of severe thunderstorm environments in the United States and Europe are different in a warming climate.

In China, however, most of the previous researches suggest that days of TSL decrease significantly. Although M. F. Zhang and Feng (1998) indicate an increase in days of thunderstorms during 1961–1980, Chen et al. (2009), Ren et al. (2012), Q. H. Zhang et al. (2017) and Xue et al. (2019) all report a generally significant decline in days of TSL in some areas of China or in the country on a whole. Chen et al. (2009) suggests that thunderstorms in China decreases from 1951 to 2005 except for the insignificant increase in the Tibet Plateau. Q. H. Zhang et al. (2017), applying a data set of over 500 observational stations, analyzes the long-term change in total number of severe weather days including thunderstorms, and shows that the days of thunderstorms in China decreases about 50% from 1961 to 2010.

To understand the possible influential factors of the observed change in severe weather days is of a great challenge (Q. H. Zhang et al., 2017), partly because the trends of environments supportive of TSL are unclear and not all of them follow the expectations under the climate warming (Taszarek et al., 2020). The temperature in the low troposphere and the water vapor content generally increase, while TSL have a distinct regional characteristics of change (Araghi et al., 2016; Changnon & Changnon, 2001; Chen et al., 2003; Enno et al., 2013; Kunkel et al., 2013; Pinto et al., 2013; Tuomi & Mäkelä, 2009; Q. H. Zhang et al., 2017; Xue et al., 2019). Q. H. Zhang et al. (2017) suggests that the decreasing trend of thunderstorms in China is at least partly induced by rapid social and economic development and population growth. They also show a strong correlation of the decrease of thunderstorms with the weakening of East Asian summer monsoon. Xue et al. (2019) supposes that the long-term decline of TSL may have been caused partially by the urbanization process around the observational stations.

Obviously, two questions still remain with the change of TSL in China mainland: (a) is there a robust trend in the region on a whole if a data set from higher density observational network is used for analysis? (b) if so, what the possible influential factors of the observed change?

This paper presents an analysis of the changes in TSL in China mainland and their links to the atmospheric circulation and regional environmental factors over the last decades based on datasets of more than 2,300 (1,737 after screening) stations and global reanalysis. The new analysis results would help in answering the two questions raised above.

2. Data and Methods

2.1. Data Sources

Observation of TSL is regularly operated at meteorological observational stations by well trained and experienced observers in China. It has been stipulated that, if one or more thunderstorms or lightning are observed at a station on one day, they are recorded as a thunderstorm or lightning day. Thunderstorms are

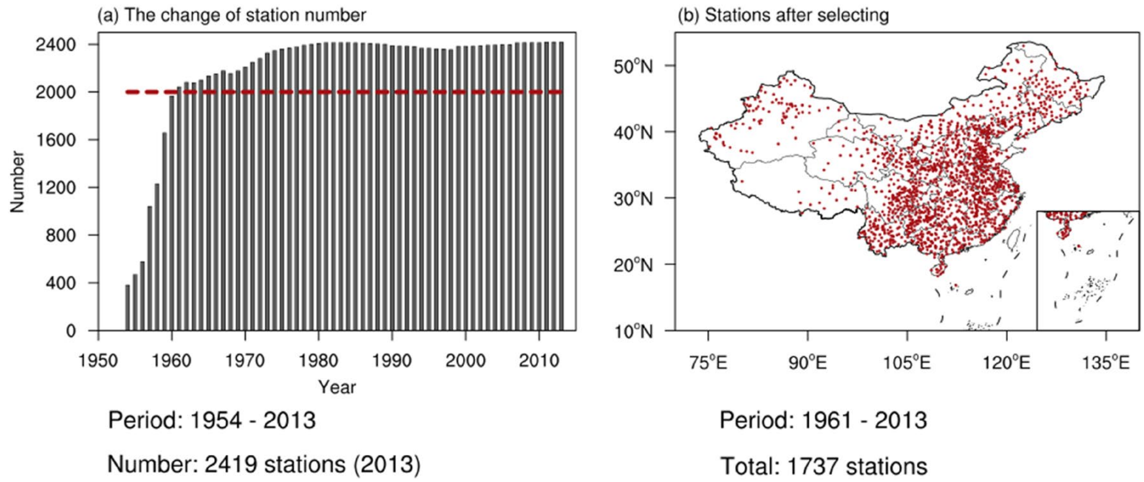

Figure 1. Number of observational stations from 1954 to 2013 (a) and the spatial distribution of the stations selected for use from 1961 to 2013 (b).

manifested as lightning with thunder. Sometimes, only thunder is heard without seeing lightning. Lightning refers to the light while the thunder is not necessarily heard (Zhao & Yu, 2019).

The TSL data set used in this study is derived from the China Surface Severe Convection Weather Data set V1.0 recently released by the National Meteorology Information Center (NMIC), China Meteorological Administration (CMA), which starts in 1954 including statistics of days with TSL at most 2,419 stations in the year 2013 (Zhao & Yu, 2019). The data set has been quality-controlled and homogenized, and it will be used for analysis of the change in days of TSL. The ERA5 reanalysis data (ERA5 monthly averaged data on pressure levels and single levels) are used to analyze the change of large scale atmosphere circulation and severe weather indices in order to examine the links of the TSL trends with the atmospheric and environmental factors. The ERA5 reanalysis data are obtained from European Center for Medium Weather Forecasting (ECMWF).

2.2. Selection of Stations

The observation of TSL by meteorological observers was stopped in 2014, and it has been replaced since then by autonomous observation with Lightning Locating System (LLS). The annual number of observational stations is shown in Figure 1a. There are relatively few stations in the early period, and since 1961 there have been more than 2000 observational stations. Therefore, the period from 1961 to 2013 is selected as the research period in this study. On this basis, the data are selected according to a strict criterion in which no missing record during the 53 years in the warm season (From April to October) is allowed. If a station has missing data during this period, this station will be discarded.

There are total 1,737 observational stations selected for use. The spatial distribution of the 1,737 stations is shown in Figure 1b. There is a better spatial coverage of stations over China mainland except for the western part of the Tibet Plateau and small areas of the northwestern China. Overall, the quantity and quality of the data are substantially improved as compared to the previous studies.

2.3. Methods

The spatial distribution of the stations is uneven and the density in the east is obviously higher than that in the west (Figure 1b). In addition, China mainland is large enough to include the regions of different latitudes from tropical to rigid temperate zones that the area of the grids in different latitude is varied. In order to reduce the influence of uneven distribution of stations and the effect of the latitude difference, the weighted averaging method of grid boxes (Jones & Hulme, 1996) is adopted to calculate the country-average time series. The time period of 1981–2010 is considered as the climate reference period when calculating anomalies of TSL days. The steps are as follows:

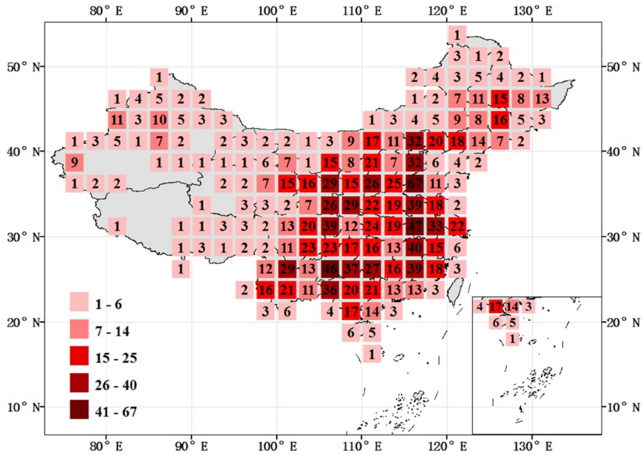

Figure 2. The spatial distribution of stations and gridded boxes with observations. Color boxes and the values within them indicate the number of stations. And there are totally 163 grids in China mainland.

1. The anomaly value of TSL days at each station is calculated
2. The research area (China mainland) is divided into 2.5*2.5 equal latitude and longitude grids
3. The mean value of the anomalies of all stations in one grid is calculated
4. The mean value of the grid multiplied by the cosine of the latitude of the center point (as weight) is calculated
5. All the grid values are weight-averaged to obtain the country average anomalies of TSL days

The formula for the weighted averaging method of grids is as follows:

$$\overline{Y_k} = \frac{\sum_{i=1}^{m}\left(\cos\theta_i\right) \times Y_{ik}}{\sum_{i=1}^{m}\cos\theta_i}$$

where $\overline{Y_k}$ is the regional average value of the research area (China mainland) in year k, $i = 1, 2, 3, ..., m$ (m is the number of grids), Y_{ik} is the mean value of grid i in year k, θ_i is the latitude of the center in grid i.

The number and distribution of all the grids with data after gridding into 2.5*2.5 are shown in Figure 2. There are totally 163 grids in China mainland, with the largest number of stations in any grids reaching 67 stations. A few grids in the west of the Tibet Plateau have no stations.

Ordinary Least Square (OLS) is used to calculate linear trend, and the significance of the linear trend is judged using the Mann-Kendall test. A trend is considered statistically significant if it is significant at the 95% ($p < 0.05$) confidence level, and highly significant if it is significant at the 99% ($p < 0.01$) confidence level. However, the significance is examined by using the 2-tailed simple t-test method when discussing the correlation between two factors.

We divide correlation coefficients into five levels to judge the degree the significance of two factors (https://www.andrews.edu/~calkins/math/edrm611/edrm05.htm). Correlation coefficients between 0.9 and 1.0 indicate variables which can be considered very highly correlated (V); correlation coefficients between 0.7 and 0.9 indicate variables which can be considered highly correlated (H); correlation coefficients between 0.5 and 0.7 indicate variables which can be considered moderately correlated (M); correlation coefficients between 0.3 and 0.5 indicate variables which have a low correlation (LO); and correlation coefficients less than 0.3 have little if any linear correlation (LI).

Considering that TSL mostly happen in the warm season (from April to October) in China, with the TSL days during the seven months accounting for about 92% of all year round (Xue et al., 2019), we choose to focus on the warm season as the research period of a year, but also examine the trends of the TSL in each season (spring, summer and autumn) and all year round. Spring is from March to May, summer from June to August, and autumn from September to November.

3. Results

3.1. Spatial and Temporal Characteristics

The spatial distribution of the average thunderstorm days in the warm season, the change of thunderstorm day anomaly for grids and the country-averaged thunderstorm day anomaly in the warm season, are shown in Figure 3. From April to October, the mean occurrence frequency of thunderstorm days is 37.3 days/yr. The warm season mean thunderstorm days decrease obviously with the increase of the latitude (Figure 3a). The south and southwest China are the center of the thunderstorm days. The southeast of the Tibet Plateau and the Yunnan-Guizhou Plateau of Southwest China also witness more frequent occurrence of thunderstorm days, which is significantly higher than other regions in the same latitude. In regions north of the Yangtze River, the average occurrence of thunderstorms does not change significantly with the latitude,

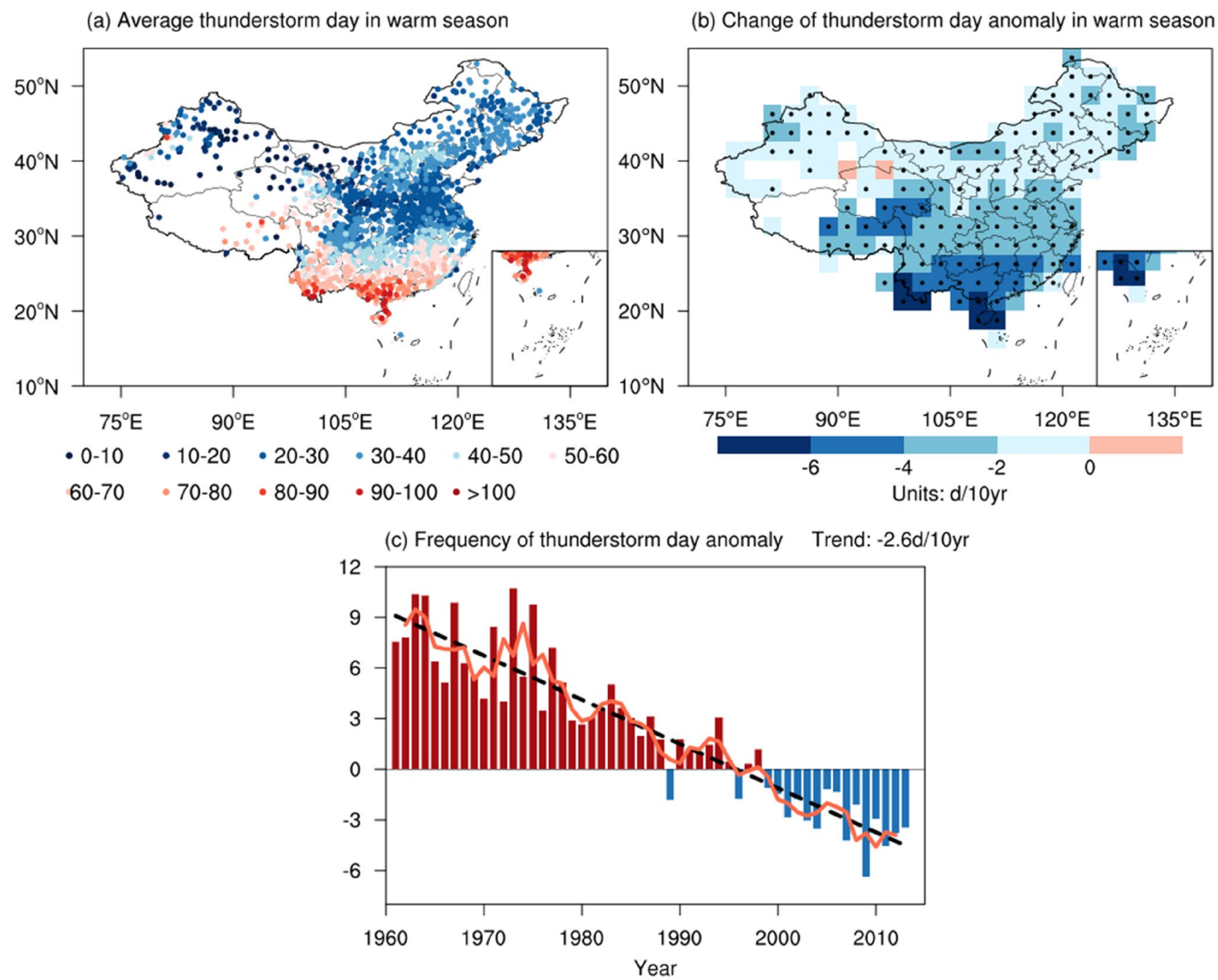

Figure 3. The spatial distribution of average thunderstorm days (a), trends of average thunderstorm day anomaly for grids (b) and the country-averaged thunderstorm day anomaly series (c) in the warm season during 1961–2013. Black points in Figure 3b represent grids with trends statistically significant at the 95% ($p < 0.05$) confidence level. The dashed black line in Figure 3c represents linear regression and the orange curve represents the tri-slip average. The time period of 1981–2010 is considered as the climate reference period.

with the ranges from 10.0 days/yr to 20.0 days/yr. The arid region of Northwest China has the lowest occurrence of thunderstorm days.

Among 163 grids, there are 161 grids (98.8%) with negative trends in the warm season from 1961 to 2013, and 89.4% pass the significance test. Therefore, the annual thunderstorm days in the warm season show a significant downward trend in the most parts of China mainland (Figure 3b). The central and eastern part of the Tibet Plateau, Southern China and Southwestern China experience a larger and more significant decrease than the other parts of China mainland, with the trends in these regions surpassing −4.0 days/10 years. However, there is a less obvious rising trend in some areas of the northwest China. There are only two grids with positive trends, accounting for 1.2% of the total. In China mainland on a whole, average thunderstorm days decrease with a trend of 2.6 days/10 years in the warm season from 1961 to 2013, which is highly significant (Figure 3c). The obvious reduction begins after 1975 with the most tremendous drop occurring after the 2000s.

Figure 4 shows the spatial distribution and long-term change of lightning days in the warm season from 1961 to 2013 over China mainland. The mean occurrence frequency of warm season lightning days is

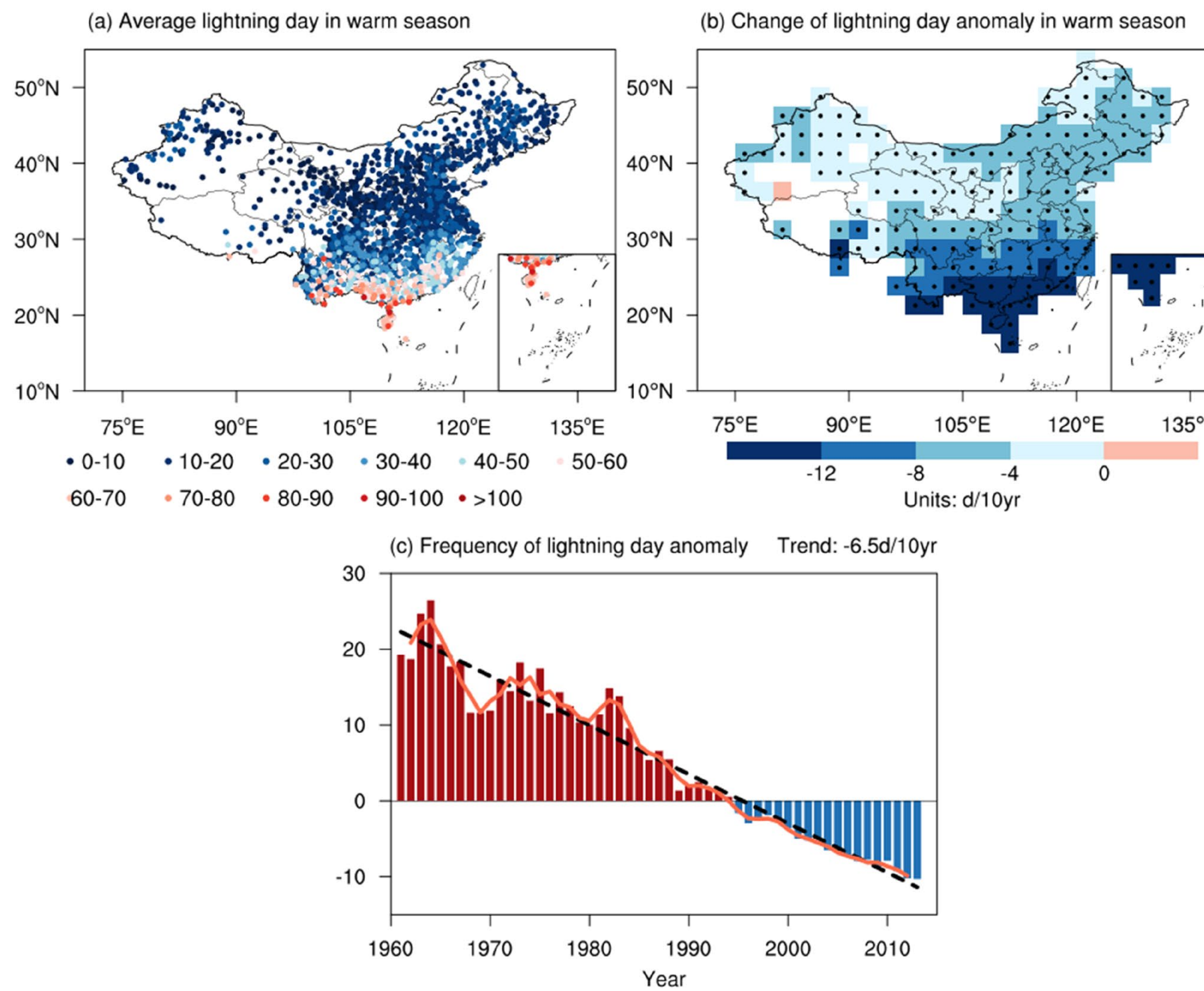

Figure 4. The same as Figure 3, but for lightning days.

21.4 days/yr. Generally, the spatial distribution of mean lightning days is similar to that of the thunderstorms, but the Tibet Plateau is no longer one of the high frequency (Figure 4a). The mean lightning days also decrease with the increase of latitude.

Among 163 grids, there are 162 grids (99.4%) with negative trends, most of which pass the significance test (Figure 4b). South China experiences the most significant downward trend at the rate of less than −12.0 days/10 years. In the past five decades, the country average lightning days significantly decrease with the rate of −6.5 days/10 years (Figure 4c). Although lightning and thunderstorms often occur at the same time and the spatial distribution is also similar, the decline of lightning days is larger and more significant.

Table 1
The Trends of Thunderstorm and Lightning Days From 1961 to 2013

Period	Thunderstorm	Lightning	Unit
Year	−2.7[a]	−6.6[a]	d/10 years
Warm season	−2.6[a]	−6.5[a]	d/10 years
Spring	−0.6[a]	−1.1[a]	d/10 years
Summer	−1.7[a]	−4.1[a]	d/10 years
Autumn	−0.4[a]	−1.3[a]	d/10 years

[a]denotes the trends are statistically significant at the 95% (99%) significance level.

The trends of the country-averaged warm season thunderstorm and lightning day anomalies from 1961 to 2013 described above are summarized in Table 1. They all decrease significantly and pass the significance test at the 99% ($p < 0.01$) confidence level. The largest seasonal decrease appears in summer, and the downward trends of thunderstorm and lightning day anomalies reach −2.7 days/10 years and −6.6 days/10 years respectively.

3.2. The Links of TSL Changes With Atmospheric Circulation and Regional Environmental Factors

Previous researches indicate that the weak precipitation decreases, but the extreme intense precipitation shows an increasing trend in most part of China (D. Li et al., 2016; Liu et al., 2005; Ren et al., 2016; Wen et al., 2015). The TSL belongs to the micro-small scale convective weather and always occurs together with the abrupt heavy precipitation (Chen et al., 2009). However, the convective weather phenomena show significant decrease trends during the last 50 years over China mainland, which is in contrast to the increase of other intensive weather events like extreme intense precipitation. Obviously, the reasons for the decrease of TSL are well worth further investigation.

The occurrence, development, disappearance and long-term change of the weather systems breeding TSL are not only related to the background of the large-scale circulation (Dong et al., 1999; Pinto et al, 2015; Yu et al., 2016; Q. H. Zhang et al., 2017), but also to atmospheric temperature, water vapor, and unstable conditions (Johns & Doswell, 1992; Taszarek et al., 2020; Q. H. Zhang et al, 2017; Zou et al., 2018). Meanwhile, the sharp decrease of the TSL days in China during the past five decades also coincides with the rapid global warming and regional scale environment changes such as air pollution and land use and cover change (Q. H. Zhang et al., 2017; Xue et al., 2019). Although the occurrences of TSL are usually related to meso-micro weather systems, they also happen accompanying large-scale circulation abnormality (Q. H. Zhang et al., 2017). It is necessary, therefore, to discuss the possible effect of large-scale circulation and regional environmental factor changes on the observed decrease in TSL days.

The days of TSL decrease mostly obviously after 1979 in the warm season (Figures 3 and 4). The quality of the reanalysis data after the mid-1970s have also been improved because of the integration of more observations and the improvement of models and the assimilation methods (Zhou et al., 2018). Therefore, the ERA5 reanalysis data from April to October during 1979–2013 are selected to examine the possible links of the decreases of TSL days to atmospheric circulation and regional environmental factors in China mainland.

3.2.1. Atmospheric Circulation

Synoptic scale disturbances play a key role in generation and evolution of storms (Archer & Caldeira, 2008; Yu et al., 2016). The upper air jet stream, for example, is important because synoptic scale disturbances occurred in the core zone of the jet-stream wind speed can cause variations in generating and developing conditions of storms (Archer & Caldeira, 2008). Song and Webster (1990) indicate that the intensity of the westerly jet stream is closely related with convective activity, and Dong et al. (1999) shows that local convection is more likely to happen when the zonal westerly wind stronger. So it is necessary to discuss the effect of large-scale circulation changes on the observed decrease in TSL days.

In the following analysis, the period of 1979–1999 is chosen as the positive anomaly phase, and the period of 2000–2013 as the negative anomaly phase. The mean value of the geopotential height at 500 hPa and the wind at 200 hPa during 1979–2013 in the warm season are shown in Figure 5a. The differences (The mean value of 2000–2013 subtracts the mean value of 1979–1999) of the geopotential height at 500 hPa and the wind at 200 hPa between the two phases in the warm season are calculated, with the results shown in Figure 5b.

From the mean of geopotential height at 500 hPa and the wind at 200 hPa (Figure 5a), geopotential height is relatively higher in the south of China and lower in the north of China. At 200 hPa, it is prevailing westerly wind in the warm season in most part of China. From the distribution of geopotential height differences at 500 hPa (Figure 5b), it is obvious that there is a significant rise in the area from the Baikal Lake to Northeast China. Corresponding to the change, there is an anticyclonic anomaly in this area which controls most of Northern China and eastern Mongolia. That means that there is an abnormal easterly wind in a zone where the westerly jet stream at 200 hPa (35–45ºN) prevails. The existence of the abnormal easterly wind causes the weakening of westerly jet stream which is not conducive to high-altitude divergence. In contrast, there is a negative difference of geopotential height in the area from Yunnan to Hainan in Southern China.

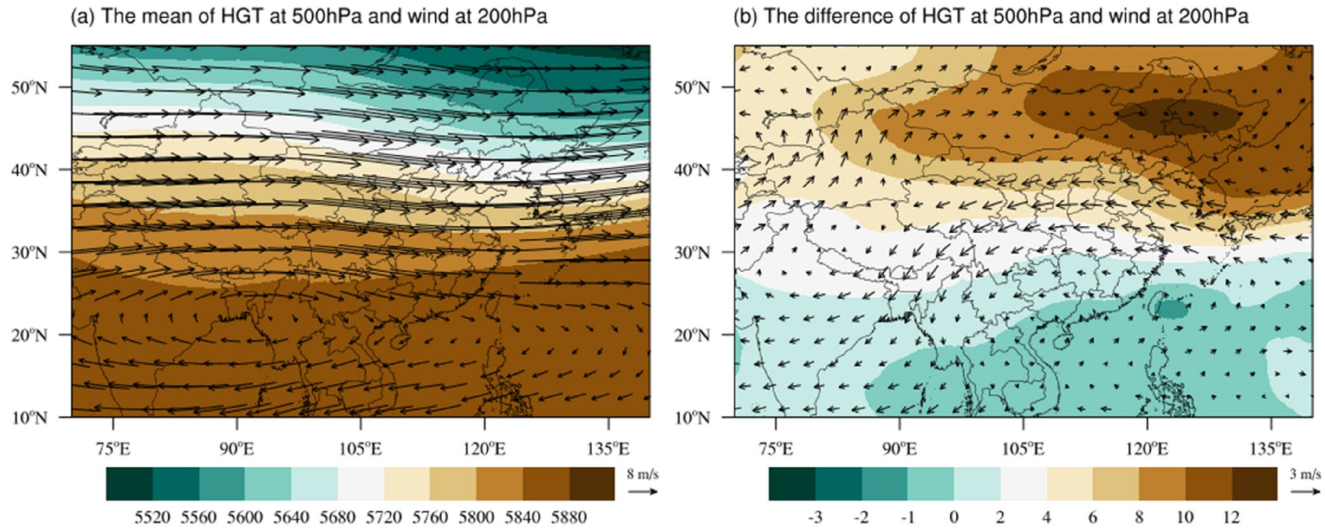

Figure 5. The mean (a) and difference (b) of geopotential height at 500 hPa and wind at 200 hPa from April to October during 1979–2013. The mean value is the average in the warm season during 1979–2013, and the difference is that the mean value during 2000–2013 subtracts the mean value in the warm season during 1979–1999.

It means that, in the second period, the geopotential height in the north becomes relatively higher, while in the south it becomes relatively lower than that in the first period. That makes the geopotential height difference between the south and the north smaller, which is not in favor of cold air burst toward south (X. L. Ma, 2019).

The decrease of geopotential height difference between the south and the north and the weakening of the westerly jet stream affect the changes of the zonal wind at high level. There is a good positive correlation between thunderstorm days and zonal wind speed of 500 hPa, especially in the areas from the southeast coast to Yunnan and from the Tibet Plateau to Inner Mongolia (Figure 6). The correlations between lightning days and zonal wind are even more significant and those of most parts between 30 and 45ºN past the significant test at the 95% significance level. In China mainland as a whole, the correlation coefficient of zonal wind at 500 hPa with thunderstorm days reaches 0.53, and that with lightning days reaches 0.51 (Table 2). The zonal wind at high level atmosphere decreases in most parts of China mainland during 1979–2013, and the southeast coast area and the central China decreasing more significant, which may also have contributed to the decrease in TSL frequency.

In summary, the decrease of geopotential height difference between the south and the north, the accompanying weakening of the westerly jet stream and zonal wind speed of high level atmosphere, may have affected the generation and development of TSL activities in China mainland during the past 50 years. However, more research is needed to examine the specific dynamic mechanism and if other large-scale atmospheric circulation factors are playing an important role.

3.2.2. Regional Environmental Factors

The ingredient-based approach can be used to identify the bounding distribution of the environmental factors to severe convective weather (Doswell et al., 1996; Johns & Doswell, 1992; Taszarek et al., 2020). According to this approach, there are four relevant factors (the conditional instability, the low-level moisture, the initiating mechanism and the vertical shear). CAPE is the physical quantity used to measure instability of the atmosphere, which can provide an estimate of the vertically integrated buoyancy leading to a rising air parcel (Taszarek et al., 2020). The higher the value of CAPE, the more unstable the atmosphere will be, and the convective motion is easier to occur. Therefore, CAPE would have an obvious effect on the occurrence of TSL.

Figure 7a shows that CAPE undergoes a significant decline in most parts of China's mainland from 1979 to 2013, especially in the area from the southeastern coastal zone to Yunnan province, where the reduction

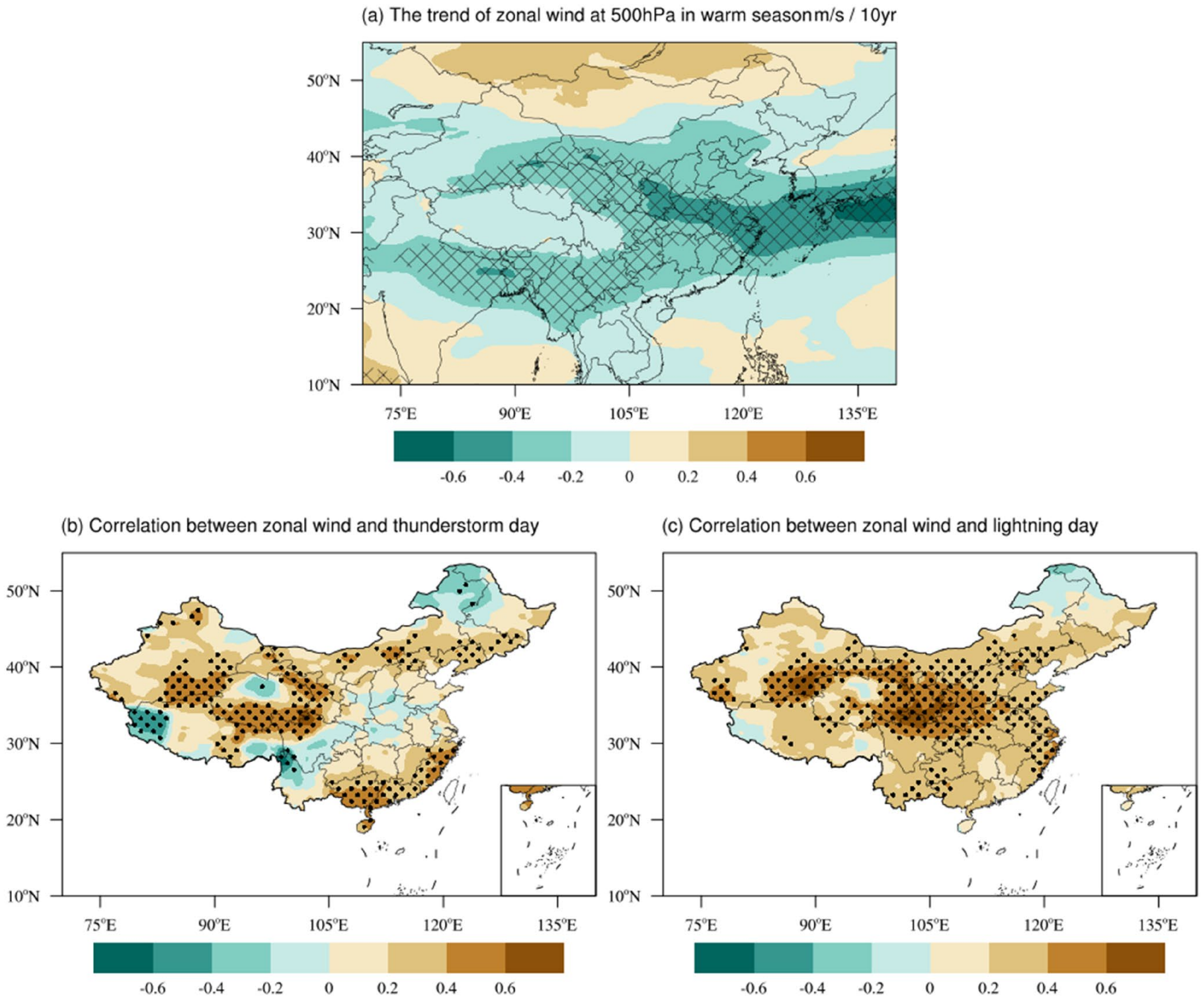

Figure 6. The trend of zonal wind at 500 hPa from April to October during 1979–2013 (a), the correlation coefficients of zonal wind with thunderstorm days (b) and lightning days (c) and their significance. Black mesh area in Figure 6a and black point in Figures 6b and 6c respectively indicate that the trend and correlation are statistically significant at the 95% ($p < 0.05$) confidence level.

Table 2
The Trends and Correlations in the Warm Season (From April to October) During 1979–2013

Name	Trend	Unit	Correlation with thunderstorm	Level	Correlation with lightning	Level
Thunderstorm	−2.5[a]	d/10 years			0.91[a]	V
Lightning	−6.9[a]	d/10 years	0.91[a]	V		
Zonal wind at 500 hPa	−0.2[a]	m/s/10 years	0.53[a]	M	0.51[a]	M
CAPE	−4.6[a]	J/kg/10 years	0.58[a]	M	0.27	LI
Relative humidity at 850 hPa	−0.6[a]	%/10 years	0.56[a]	M	0.51[a]	M
0–6 km vertical wind shear	−0.2[a]	m/s/10 years	0.48[a]	LO	0.49[a]	LO

[a]denotes the trend and correlation are statistically significant at the 95% ($p < 0.05$) significance level. Correlation is regarded very high, high, moderate, low, and little when they reach 0.9~1.0, 0.7~0.9, 0.5~0.7, 0.3~0.5 and 0~0.3.
Abbreviations: H, high; LI, little; LO, low; M, moderate; V, very high.

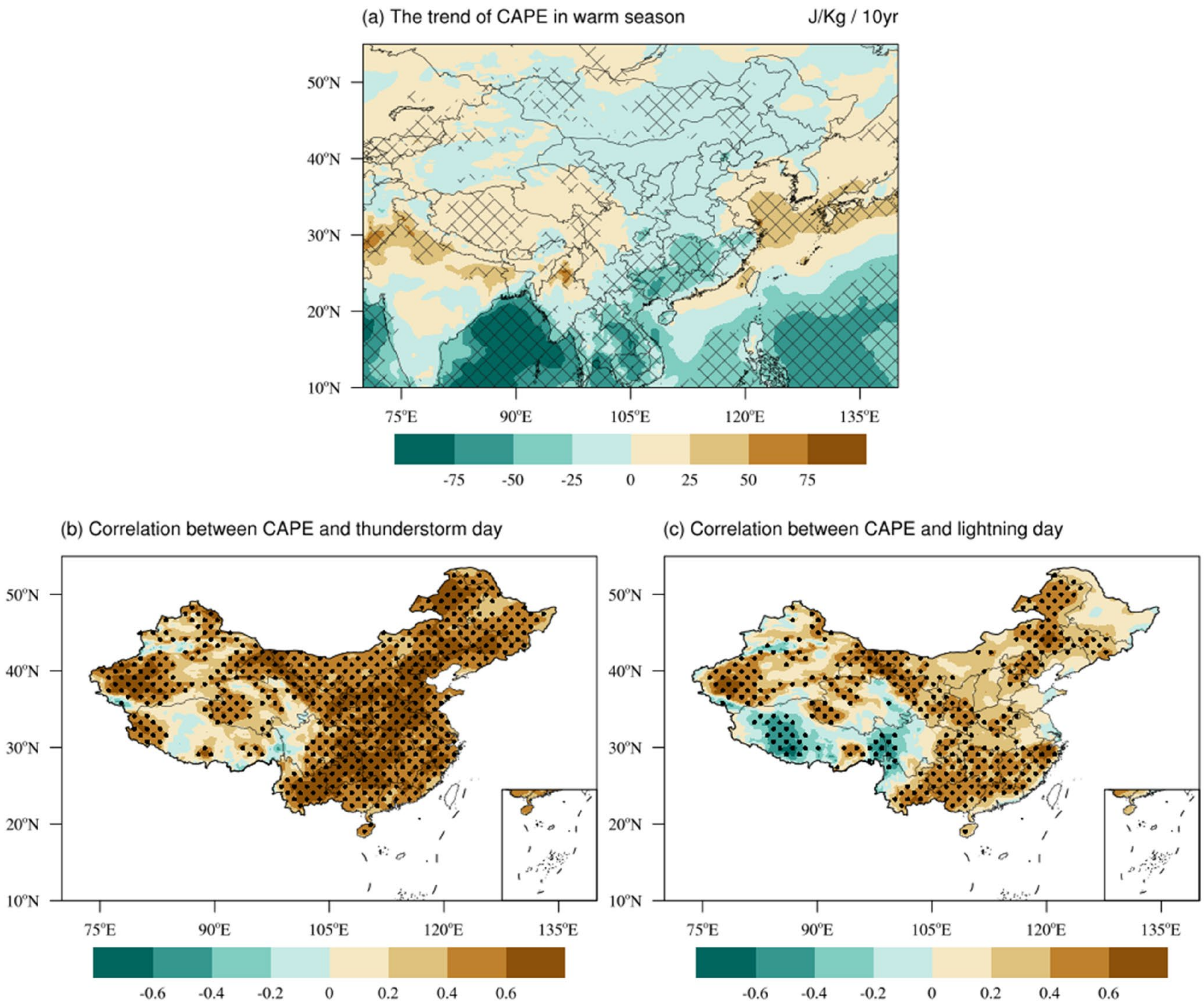

Figure 7. The same as Figure 6, but for convective available potential energy from April to October during 1979–2013.

trend can reach less than −25 J/Kg/10 years. The spatial distribution of the correlation and significance of CAPE with TSL days are shown in Figures 7b and 7c. There is a significant positive correlation between CAPE and thunderstorm days, with the correlation coefficients reaching above 0.40 in most parts of China. Most of them are statistically significant at the 95% confidence level. The positive correlation between CAPE and lightning days is not as significant as thunderstorm days, but more than half of the correlations are still statistically significant.

The decrease of CAPE is well consistent with the downward trend of thunderstorm and lightning days. In the whole study region, the correlation coefficient of CAPE with thunderstorm days can reach 0.58, and that with lightning days is 0.27 (Table 2). Thunderstorms have a better correlation with CAPE than lightning, and the correlation passes the significance test. Therefore, the change of thunderstorm days, and in a less extent lightning days, is significantly related to that of CAPE.

The low level moisture is also an important factor of the ingredient-based approach which is significant to indicate the occurrence of severe convective weather (Doswell et al., 1996; Johns & Doswell, 1992; Taszarek et al., 2020). According to Westermayer et al. (2017), the decreasing of low and mid-level relative humidity can lead dry air entrainment into a developing updraft, which may result in a degeneration of thunderstorms or a worsening condition for the initiation of thunderstorms even if amply CAPE is available.

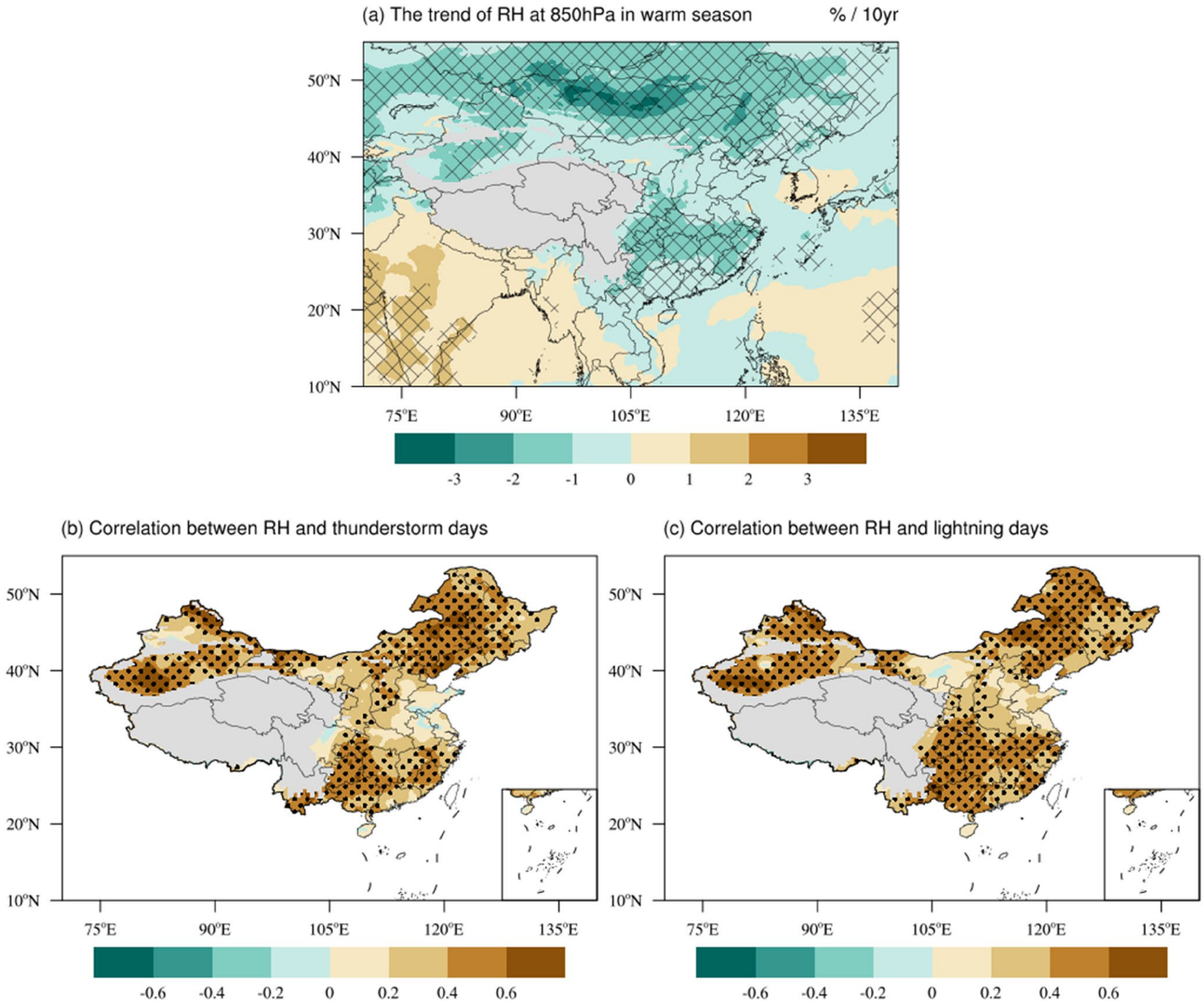

Figure 8. The same as Figure 6, but for relative humidity at 850 hPa from April to October during 1979–2013. And the shadow means the height less than 850 hPa.

Here the relative humidity at 850 hPa is used to examine the relationship with TSL reduction. Figure 8a shows that, in most parts of China mainland, the relative humidity at 850 hPa presents a decrease trend. In the southeast coast and Northeast China, the decreasing trend is more than 2%/10 years. There is a significant positive correlation of the TSL days with the relative humidity at 850 hPa in most parts of the study region (Figures 8b and 8c). Except for Shandong and Henan provinces, the correlations generally pass the significance test at the 95% confidence level. In the whole region, the correlation coefficient of the relative humidity with thunderstorm days can reach 0.56, and that with lightning days are 0.51 (Table 2). They all pass the significance test at the 95% confidence level. This indicates that the decreasing of the relative humidity at the lower troposphere may have a significant effect on the reduction of TSL days over the last decades.

The vertical wind shear is also an important factor of the ingredient-based approach, which can govern the organization of updrafts and is conductive to form long-lived storm modes like supercells producing severe weather including TSL (Antonescu et al., 2020; Gatzen et al., 2019; Guastini & Bosart, 2016; Smith et al., 2012; Thompson et al., 2012). It has been demonstrated that the likelihood of severe convection increases along with the increasing of the vertical wind shear (Allen et al., 2011; Brooks et al., 2003;

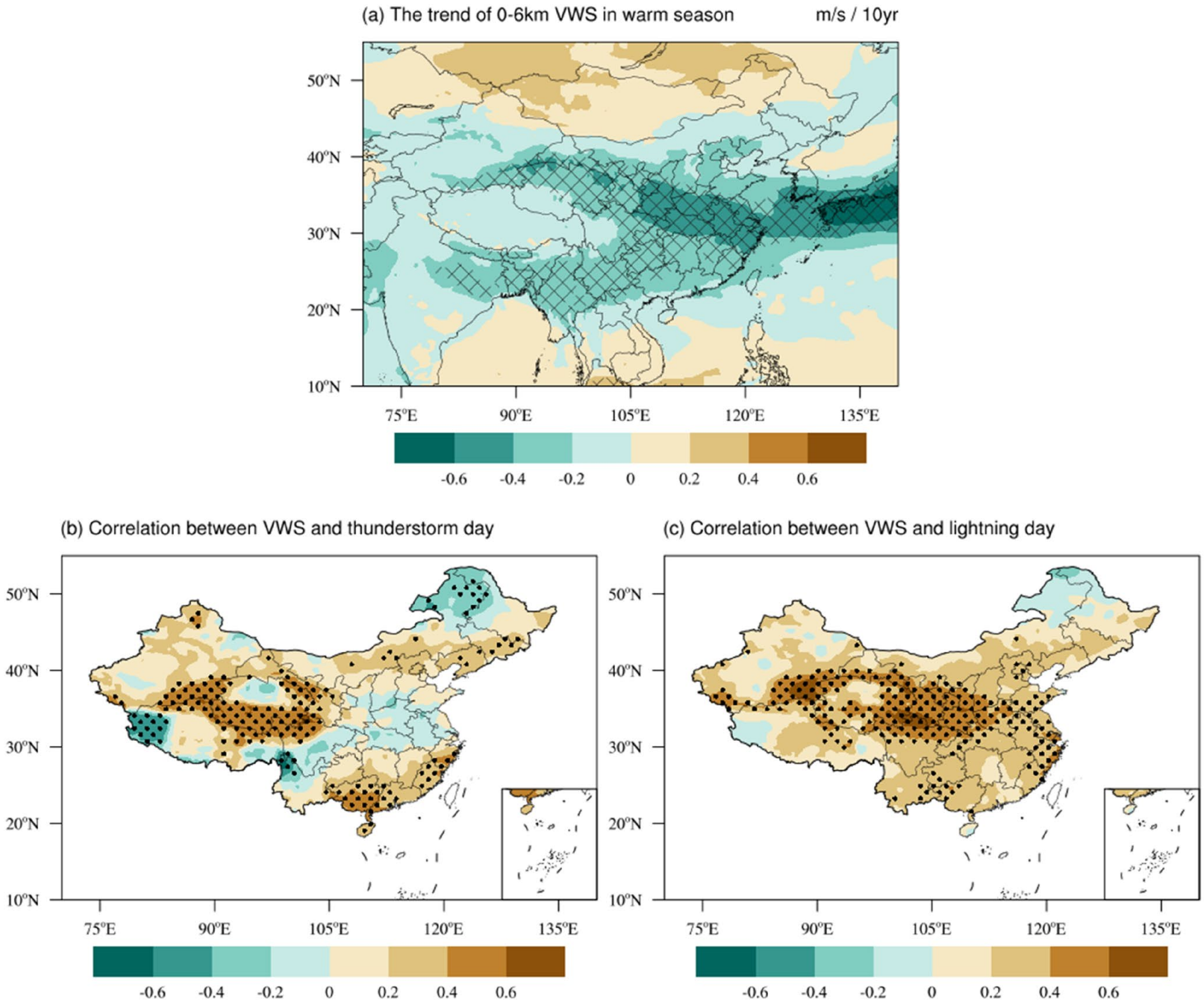

Figure 9. The same as Figure 6, but for 0–6 km vertical wind shear from April to October during 1979–2013.

Brooks, 2013; Taszarek et al., 2017; Weisman & Klemp, 1982). The 0–6 km vertical wind shear is more capable of producing TSL in the United States and Europe (Taszarek et al., 2020), and it should be also a causal element to affect the changes of TSL at a similar latitude in China. We analyze the change in 0–6 km vertical wind shear and its relationship with TSL reduction.

Figure 9a shows that, in most parts of China mainland, the 0–6 km vertical wind shear presents a decrease trend. There is a significant positive correlation of the lightning days with the 0–6 km vertical wind shear in most parts of the study region (Figure 9c), and those of most parts between 30 and 40ºN past the significant test at the 95% significance level. In China mainland as a whole, the correlation coefficient of the 0–6 km vertical wind shear with thunderstorm days reaches 0.48, and that with lightning days reaches 0.49 (Table 2). The distributions of the trend and the correlation of the 0–6 km vertical wind shear with TSL days are similar as the zonal wind at 500 hPa.

The 0–6 km vertical wind shear decreases in most parts of China mainland during 1979–2013, which may have contributed to the decrease in TSL frequency. According to the calculation method of the 0–6 km vertical wind shear (the vector difference between surface and 6 km above ground level after interpolation to the height profile), and the fact that the change of wind speed at high level in China mainland basically reflects the change of zonal wind speed (A. Y. Zhang et al., 2009), it seems reasonable to deduce that the

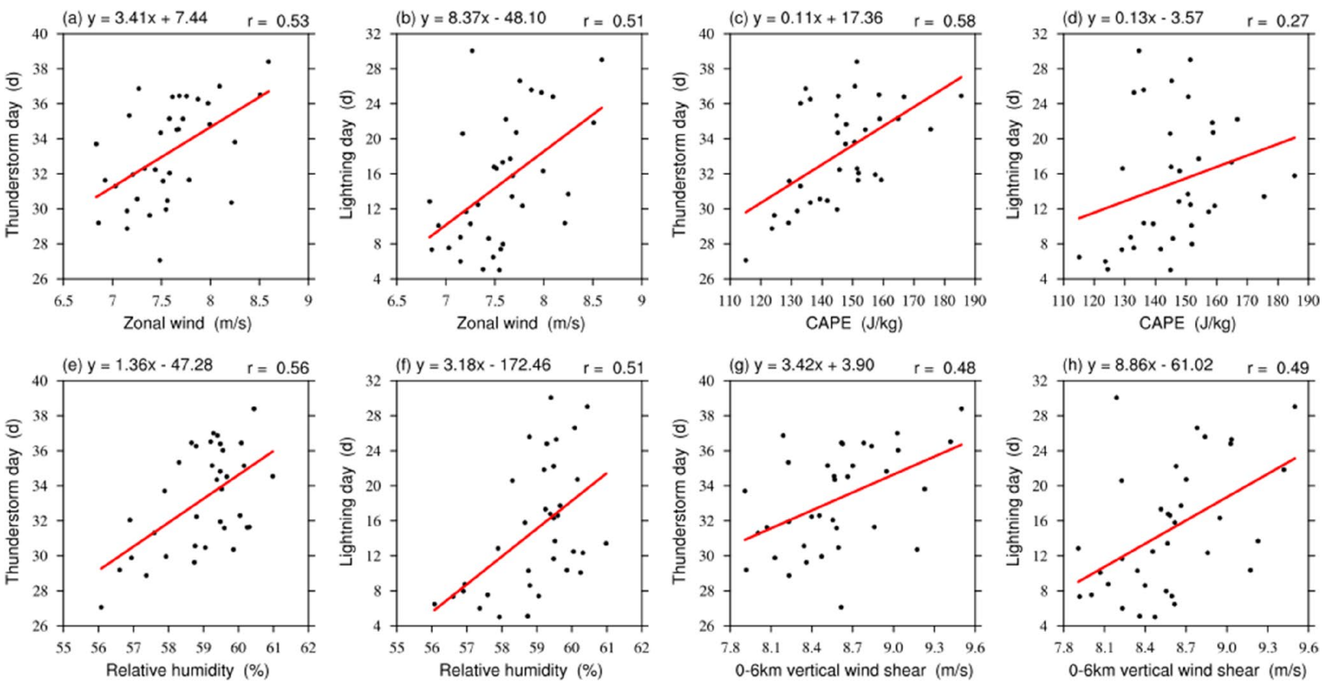

Figure 10. The correlations of physical factors with the country average thunderstorm and lightning days from April to October during 1979–2013. The red lines present fitted line and the dark spots indicate the average values of the warm season in every year. And the values of r in the top left corner indicate correlation coefficients.

decreasing of the zonal wind at high level leads to the downward trend of the 0–6 km vertical wind shear and the resulting decrease of TSL days.

The trends of the above physical factors and their correlations with TSL days from April to October during 1979–2013 are summarized in Figure 10 and Table 2. The correlation between thunderstorm and lightning days can reach 0.91, which means that they often occur at the same time and place. The zonal wind at 500 hPa, CAPE, the relative humidity at 850 hPa, and the 0–6 km vertical wind shear are all positively correlated with TSL days, and they also have the same decreasing trends with the TSL days.

The schematic diagram of the mechanism for how the decrease of TSL days is linked to atmospheric condition and regional environmental factors is shown in Figure 11. In view of the atmospheric condition, the

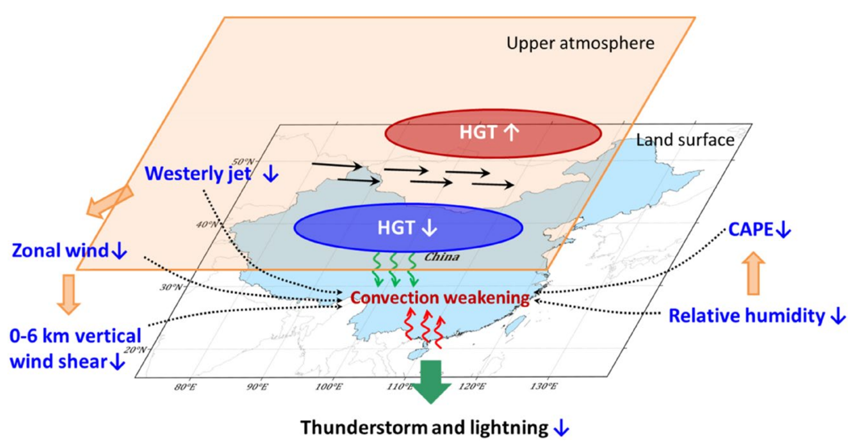

Figure 11. The schematic diagram of the mechanism for the decrease of thunderstorm and lightning days over China mainland. The blue words present environmental factors, HGT indicates geopotential height, the up arrows indicate increase, the down arrows indicate decrease and the orange arrows indicate promotion.

decrease of geopotential height difference between the south and the north and the weakening of the westerly jet stream and zonal wind speed of high level atmosphere may have been the important background of the observed decrease of TSL days. Among the regional environmental factors, the decreasing trends of the CAPE, low-level relative humidity and 0–6 km vertical wind shear may have been contributed to the decreasing of TSL days. At the same time, the decreasing of the zonal wind at high level leads to the weakening of the 0–6 km vertical wind shear. The decrease of TSL days may have been the result of a combined influence of all the atmospheric and environmental factors. However, how they work together and which one is the most important factor are still unclear, and more work is needed to examine the relative contribution of the factors and the underlying causes by combining observational data and climate model.

4. Discussion

It is important to understand the long-term change of the micro scale severe convective weather events and the possible influential factors based on reliable and persistent observations. The trends of the TSL days have received attention from around the world. However, the estimated trends are very inconsistent or even opposite to each other. It is thus worth examining what changes on earth occurs for the convective weather in a subcontinental region like China mainland under the background of global warming.

In this study, we use a newly developed and continuous data set of 1,737 stations from 1961 to 2013 to examine the trends in TSL days of the warm season and their possible association with changes of atmospheric circulation and environmental conditions. The analysis shows that both thunderstorm days and lightning days have steady and significant decreasing trends with the rates of −2.6 days/10 years and −6.5 days/10 years respectively from April to October in the past five decades.

This finding of thunderstorm day change is consistent with Q. H. Zhang et al. (2017) who uses a subset (∼580 stations totally) of the 1,737 stations. They find that the average number of the thunderstorm days decrease in the national observational stations in China from 45 days in 1960s to about 34 in 2010 with the trend of −2.8 days/10 years. This value is very close to the result of our research. In addition, the decreasing trend of thunderstorm days are also reported in almost all the regional researches in China mainland (e.g., Chen et al., 2009; Z. R. Li et al., 2005; Xu & Yang, 2001). However, we also find an even larger and more significant decreasing trend of lightning days, which was not mainly analyzed in Q. H. Zhang et al. (2017). Our results thus robustly affirm the highly significant decrease in the severe weather events over the last decades in China mainland.

Q. H. Zhang et al. (2017) also discusses the possible causes of the decrease of thunderstorm days, and they indicate that the overwhelming reduction of thunderstorm frequency over China is strongly related to the weakening Asia summer monsoon, which makes the weakening of dynamic forcing and the decreasing of moisture supply. In this study, we examine the possible environmental influential factors of the TSL change. We find that, during the period of 1979–2013, the decrease of the geopotential height difference between the south and north of China mainland, the mid-latitude westerly jet stream, the zonal wind speed of high level, the mid to lower layer vertical wind shear and the CAPE, are all closely associated with the reduction of TSL days on varied extents, which indicates that the stagnated dynamical condition of the atmosphere may have been one of the direct factors for the observed decline of TSL frequency in the study region (Figure 11). Meanwhile, there is also a significant positive correlation between TSL days and the 850 hPa relative humidity. The drop of the relative humidity in the low troposphere may have been caused by the surface and low-layer atmospheric warming in some extent (Ding & Ren, 2008), but it in turn results in a progressively unfavorable condition to the occurrence of the TSL weather in the country.

Except for the atmospheric and environmental factors discussed above, the convective inhibition (CIN), the temperature lapse rate between 700 and 500 hPa, the vertical velocity at 500 hPa, and the specific humidity at 850 hPa and 925 hPa are also examined, according to the ingredient-based approach (Doswell et al., 1996; Johns & Doswell, 1992; Taszarek et al., 2020). The associations of TSL days with the CIN, the temperature lapse rate, and the vertical velocity are not significant in the country as a whole. Obviously, there is a mixed signal here, and further investigation is still needed. It is also found that the absolute moisture or specific humidity at 850 hPa and 925 hPa has a non-significant trend, and the relative humidity at 500 hPa also decreases, in the warm season during the period of 1979–2013.

This paper does not go further to examine the underlying causes of the weakened dynamical condition of atmosphere during the analysis period. However, the heterogeneous surface air warming between high and low latitudes under the back ground of global warming is a confirmed fact, which might have been an important driver of the stagnated mid-latitude westerly flow and jet stream as found in this study, and as frequently reported stilling of near-surface wind across China mainland and other regions (Ding & Ren, 2008; Jiang et al., 2010; Mcvicar et al., 2008; Ren et al., 2005; A. Y. Zhang et al., 2009). Another major candidate underlying driver would be the increase of aerosols in atmosphere of East Asian region (Qian et al., 2003). It has been confirmed to cause the decrease of solar radiation over the last decades in China mainland (Qian et al., 2003; Ren et al., 2005; Yu et al., 2013). The reduced solar radiation has led to the wide-range diming and the largely weakened increasing trend of maximum/daytime temperature in China mainland since 1950s (Committee on China's National Assessment Report on Climate Change, 2007; Ren et al., 2005), and it may also have caused the decrease in the CAPE as indicated in this study.

The climatological characteristics between thunderstorm days and lightning days are similar, but there is a difference between them in the Tibetan Plateau, where there is a higher frequency of thunderstorm days than that of lightning days. The causes for this difference are complex and difficult to explain at present. It is possible that the relatively lower altitude of cloud base in the plateau region causes less frequent lightning activities to be observed, though thunder and lightning always occur at the same time in the thunderclouds. There is a limitation for the human observation of lightning. The very low altitude of cloud base in the Tibetan Plateau may block observers' view, or may make observers hear the thunder more easily, leading a relatively less record of lightning. Besides, it is found that −10°C temperature level is where the charge-separation process is the most efficient (Rakov & Uman, 2003). When the altitude of the −10°C temperature level is lower than 1.8 km, the thunderclouds exhibit relatively weaker or no lightning activity (Michimoto, 1993). The altitude of cloud base, and also the −10°C temperature level, is always lower in the Tibetan Plateau, and this may cause a less lightning activity, and a larger difference between the observed frequencies of thunder and lightning.

With the construction of the Lightning Locating System (LLS), the manual observations of TSL have been canceled by CMA since January 2014. The merged data suffer from inhomogeneity because the autonomous observations by LLS are very different from manual records (Huo et al., 2018). There is an urgent need to measure and compare the data from LLS and manual observations to find the appropriate adjustment method. Some studies examined this relationship, but all of them were focused on local scale or separate stations (Huo et al., 2018; Wang et al., 2015; Zhong et al., 2010), with less value of reference for adjusting the national data set. Therefore, the update of the data set has to be done in the future.

Understanding the exact physical mechanism and cause of TSL decline are still a challenge. It is partly because the knowledge of complex physics process is incomplete (Q. H. Zhang et al., 2017) and the high density, high temporal resolution and longer time period observations of TSL are still lacking. Although some possible influential factors of the rapid decrease of TSL days are presented in this study, it is beyond our current study to pinpoint which factors are more important and how they interact with each other. More importantly, it is unclear what are the underlying causes of the observed changes in the atmospheric and environmental processes. Aerosols emission and air pollution in East Asia may have been a candidate, and large-scale climate warming and the multi-decadal oceanic variability may have been the other root causes. Obviously, more researches are still needed to tackle these questions.

5. Conclusions

Based on the observational data from NMIC from 1961 to 2013, long-term changes of TSL days and the possible environmental drivers over China mainland are analyzed. The main conclusions are as follows.

1. TSL days have significant decreasing trends in the past 50 years from April to October, with the rate of −2.6 days/10 years and −6.5 days/10 years respectively. In most parts of China mainland, the significant decrease trends are detectable, but the south of China experiences the most significant downward trend
2. The decrease of the geopotential height difference at 500 hPa between south and north, the westerly jet stream at 200 hPa, and the zonal wind speed at 500 hPa, may have been the direct atmospheric factors of the decrease of TSL days over China mainland during the past 50 years

3. CAPE, relative humidity at the lower troposphere and 0–6 km vertical wind shear also experiences a significant decrease in most parts of China mainland, and they have a significant positive correlation with TSL days, indicating that the relative poverty of moisture, the weakening of vertical wind shear and increase of atmospheric stability may have contributed to the decrease of the TSL

Data Availability Statement

The thunderstorm and lightning grid data used in this study are derived from the China Surface Severe Convection Weather Data set V1.0 released by the National Meteorology Information Center, China Meteorological Administration (Zhao & Yu., 2019), which can be found at https://zenodo.org/record/4020185#.X1hsgdS-uUk (https://doi.org/10.5281/zenodo.4020185). ERA5 reanalysis data is obtained from European Center for Medium Weather Forecasting (https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset).

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