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Changes of climate extremes of temperature and precipitation in summer in eastern China associated with changes in atmospheric circulation in East Asia during 1960–2008

LI Juan[1,3], DONG WenJie[2*] & YAN ZhongWei[1]

[1] *Key Laboratory of Regional Climate-Environment for East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China;*
[2] *State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, China;*
[3] *Graduate University of Chinese Academy of Sciences, Beijing 100049, China*

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Climate extremes and changes in eastern China are closely related to variations of the East Asian summer monsoon and corresponding atmospheric circulations. The relationship between frequencies of temperature and precipitation extremes in China during the last half century is investigated using Singular Value Decomposition analysis. During 1980–1996, there was a typical pattern with fewer hot days and more precipitation extremes in the northern part of eastern China, and more hot days and fewer precipitation extremes in the southern part. This geographic pattern tended to reverse after 1997, with fewer hot days and more extreme precipitation days south of the Yangtze River and vice versa to the north. Differences in atmospheric circulation between the former and latter periods are presented. We conclude that a mid-level anomalous high/low, upper-level anomalous easterlies/westerlies over the north/south of eastern China, a weakened East Asian summer monsoon and associated upper-tropospheric center of cooling (30°N, 110°E) are all favorable for the changes in frequencies of temperature and precipitation extremes.

climate extremes, daily temperature and precipitation observations, Singular Value Decomposition, interdecadal changes in atmospheric circulation

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Temperature and precipitation are two of the most frequently used variables to describe climate in a region such as eastern China. Changes of temperature and precipitation in the country have been extensively studied in recent years. The average temperature in the entire country has been increasing, especially since the 1980s. Warming has been prominent in northern China, while temperature decreases occurred in summer near the middle reaches of the Yangtze River and parts of central China [1]. A decreasing trend of annual precipitation was observed from the southern part of northeast China to the mid-lower Yellow River and upper Yangtze River valleys. Increasing precipitation was found in the northwest, northern part of northeast China, and southeast China, mainly south of the mid-lower Yangtze River [2]. In particular, summer precipitation in eastern part of the country changed abruptly in the late 1970s, resulting in the so-called Yangtze-River-flooding-and-North-China-drought pattern [3,4]. The rain belt has moved southward since then. A new decadal climate period may have emerged since the late 1990s, with more flooding south of the Yangtze and more drought in North China during summer [5–8]. As for climate extremes, there were increases in frequencies of extremely high temperature days across the whole country, except southern North China [9,10]. This frequency increase became more pronounced in the 1980s. Annual frequencies of extreme precipitation events increased in most of the

*Corresponding author (email: dongwj@bnu.edu.cn)

southeast and northwest, but decreased in central, north, and northeast areas [11,12]. Many climatic indices exhibited abrupt climatic changes during 1960s, around 1980 and in the 1990s [4,13,14]. However, most previous works have analyzed extremes of temperature and precipitation separately.

The relationship between precipitation and temperature has been an interesting topic in the context of global warming. Climate models and satellite observations both indicate that the total amount of water in the atmosphere would increase at a rate of 7% per Kelvin of surface warming [15]. Lenderink and Meijgaard [16] reported that hourly precipitation extremes increased twice as fast with rising temperatures, as expected from the Clausius-Clapeyron equation, when daily mean temperatures at a station in the Netherlands exceeded 12°C. Tropical observations reveal a distinct link between rainfall extremes and temperature, with more/less frequent heavy rain events during warm/cold periods [17]. Liu et al. [18] found that the upper 10% of extreme precipitation intensified by about 95% for each degree Kelvin increase in global mean temperature. However, there are different regional patterns because of various regional climatic characters. Yan [19] found that annual precipitation amounts in northern China were closely related to a regional temperature gradient between southern and northern China, at interannual to interdecadal timescales. Qian et al. [20] indicated that decreasing rain days (especially light rain events, i.e. those <1 mm/d) in China were related to a large-scale warming environment. A weakened thermal gradient between southern and northern China was linked to decreasing/increasing probabilities of summer precipitation in northern/southern China [21].

To further understand the relationship between temperature and precipitation at regional scale, we investigate potential links between changes of climate extremes of temperature and precipitation in eastern China, where the well-known South-flooding-and-North-drying pattern has intensified [3,22], and the corresponding atmospheric circulation changes during the past half century.

1 Data and methods

1.1 Data

A homogenized temperature dataset developed by Li and Yan [1] was used, which includes daily temperature records from 1960–2008 at 549 stations in mainland China. Daily precipitation records from 1960–2008 were obtained from the Chinese Meteorological Information Center. Stations with missing codes for more than 10 days in summer (June–August) in any year were excluded. Consequently, 595 stations were chosen for analyzing precipitation changes.

Monthly mean data of sea level pressure (SLP), geopotential height, horizontal and vertical wind and specific humidity were acquired from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset, to investigate the large-scale circulation associated with regional climate change.

1.2 Methods

Two percentile-based extreme indices were defined, similar to those in previous works [23,24]. For a given station, a daily maximum temperature is defined as an extreme if it exceeds the 95th percentile threshold of a set of daily records, including those observed on the same calendar day and 10 neighboring days (5 before and 5 after that day) from 1960–2008. Similarly, an extreme of daily precipitation for a given calendar day at a station is defined if it exceeds the 90th percentile of a set of daily precipitation records, including those on the same calendar day and eighty neighboring days (40 before and 40 after that day) from 1960–2008. The smaller percentile for precipitation relative to that for temperature was used in part because there are much fewer observations of daily precipitation. The Singular Value Decomposition (SVD) method [25] is used to reveal possible relationships between different climate variables. This method describes not only the principal features of variations in each variable, but also the main time-space structure of correlation between two fields. The Kriging method [26] is used for spatial interpolation of the SVD result, from stations to grids. Then, we apply this method to areas within the Chinese mainland.

2 Results

2.1 Relationship between frequencies of temperature and precipitation extremes

The first SVD mode of the frequencies of summer temperature and precipitation extremes in China for the period 1960–2008 accounts for 37.3% of the total square covariance (significant at the 0.95 confidence level). The correlation coefficient between the two field expansion coefficients is 0.88. Heterogeneous correlation patterns of the frequencies of temperature and precipitation extremes in the first SVD mode are shown in Figure 1(a) and (b), respectively. Areas with significant correlation coefficients (at the 0.95 confidence level) are outlined by bold lines. These patterns suggest that when extremely high temperature days are less frequent than usual during summer in the northern part of eastern China and more frequent in its southern part, extreme precipitation days are more frequent than usual in northern but less frequent in southern China. This indicates a negative correlation between the frequencies of temperature and precipitation extremes in the eastern part of the country. There is an abrupt change in the time coefficients of both fields around 1997 (Figure 1(c)), implying that the corresponding geographic patterns turned around that year. The time coefficients changed from a positive phase during

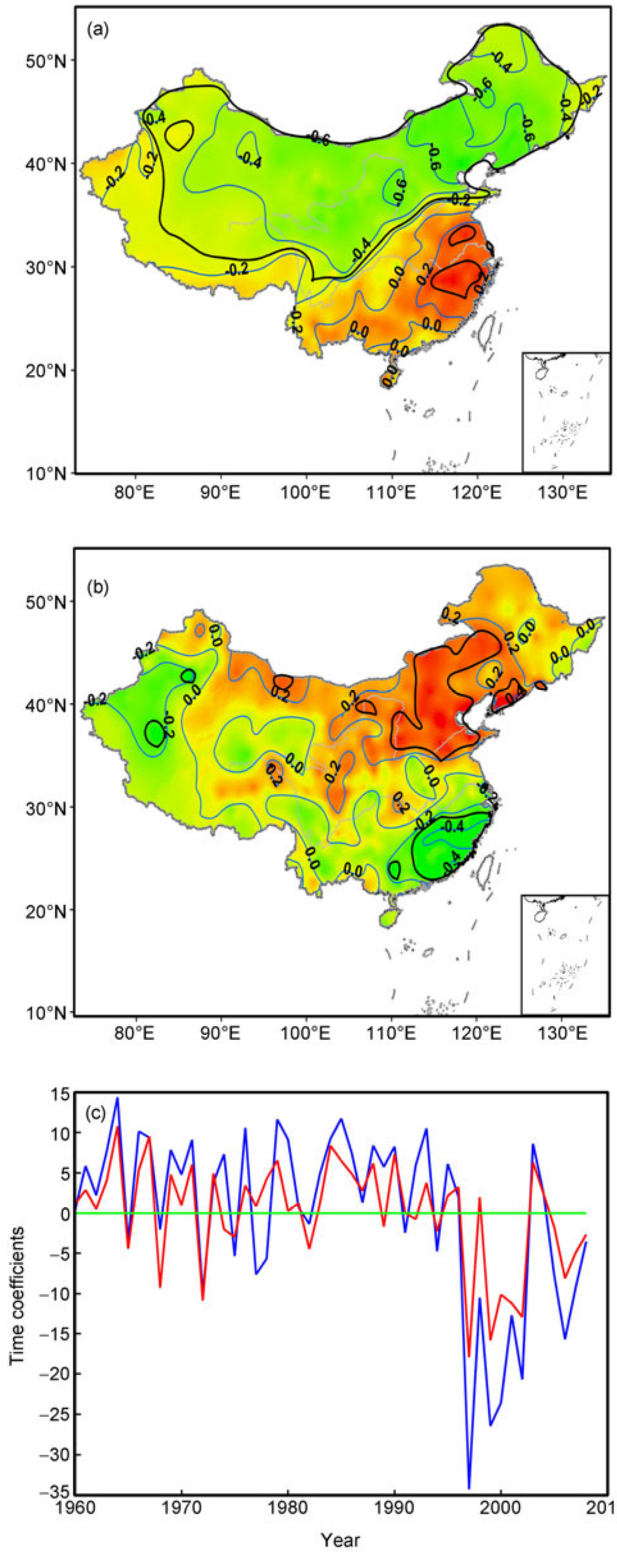

Figure 1 Heterogeneous correlation patterns for the first SVD mode of summer extremely high temperature days (a); summer extreme precipitation days (b); and their corresponding time coefficients (c). Areas with correlation coefficients significant at the 0.95 confidence level are enclosed by thick black lines. In the time coefficients diagram, blue lines represent extremely high temperature days expansion coefficients, red lines represent extreme precipitation days expansion coefficients, and green line represents zero value.

1980–1996 to a negative one during 1997–2008. This indicates more extremely high temperature days and fewer extreme precipitation days during summer in northern China, and the opposite pattern in southern China, since 1997. The jumps around 1996–1997 were also detected by many precipitation and temperature indices in recent studies [7,13,27–29].

To help understand the results, we used the Rotated Empirical Orthogonal Function (REOF) method (figures not shown). The results support the SVD analysis. However, the results using SVD place greater emphasis on the coexisting change in frequency of extremes between temperature and precipitation. The extremely high temperature days decreased where extreme precipitation days increased, and vice versa. With regard to the SVD results, the subsequent analysis focuses on interdecadal changes between 1980–1996 and 1997–2008.

2.2 Associated changes in atmospheric circulation

Changes of temperature and precipitation are closely related to those of atmospheric circulation. Specific extreme temperature or precipitation events are directly caused by unusual weather fluctuations. However, seasonal mean circulation anomalies provide a climatic background for the daily extreme events. From the standpoint of climatological statistics, extreme events are closely associated with seasonal means [14,30]. Therefore, in this section we investigate interdecadal differences of large-scale atmospheric circulation, to comprehend the coexisting changes in frequency of temperature and precipitation extremes discussed above.

Interdecadal differences of atmospheric circulation between 1997–2008 (Phase II) and 1980–1996 (Phase I) are illustrated in Figure 2, to understand the changes of temperature and precipitation extremes. There is anomalously high SLP (Figure 2(a)), which corresponds to an anomalous anticyclonic circulation at 850 hPa (Figure 2(b)) over northern East Asia. The wind vector at 850 hPa indicates anomalous easterlies over northern China. This suggests that the anomalous continental anticyclone (centered in Mongolia) or high pressure systems in summer play a role in increasing occurrences of extremely high temperature days in northern China, since this weakens southward cold flow in the region. Meanwhile, low-level divergence is unfavorable for rainfall, leading to less frequent extreme precipitation days in the north. There are negative pressure anomalies at sea level and an anomalous cyclonic circulation at 850 hPa in southern China. Anomalous low-level convergence primarily over southern China is favorable for rainfall and hence low temperature there. The wind vector at 850 hPa shows anomalous northerlies across southern China, indicating weaker summer monsoons [31,32]. Weaker East Asian summer monsoons are unfavorable for precipitation in northern China, as they keep the rain belt over the southern part of the country [33]. The East Asian monsoon weakened significantly beginning in 1978, and weakened further in the

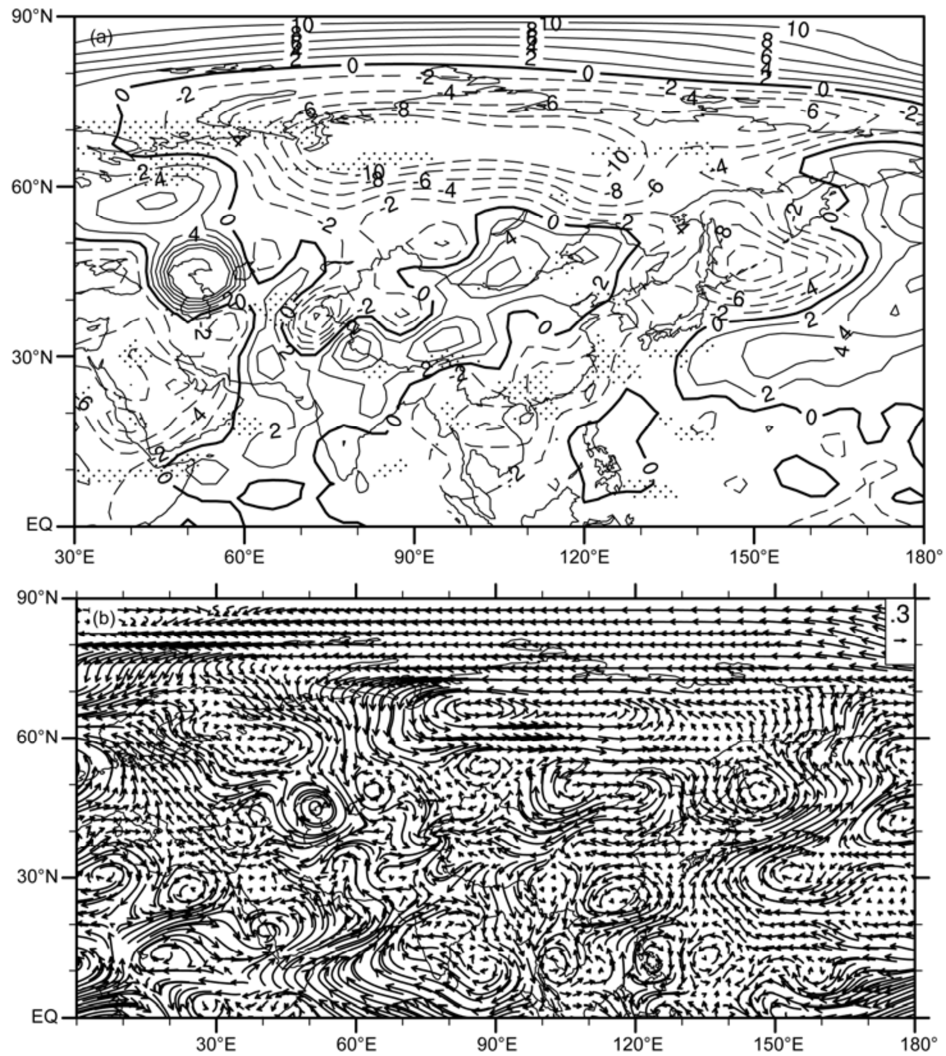

Figure 2 Interdecadal difference (Phase II minus Phase I) of sea level pressure (Pa) (a) and 850 hPa horizontal wind (m/s) in summer (b). Shaded area indicates that the anomaly exceeded 95% significance level.

early 1990s [4]. Figure 2(b) suggests that the East Asian summer monsoon circulation became weaker between 1980–1996 and 1997–2008. It is clear that this weakening East Asian summer monsoon is important to the interdecadal change in temperature and precipitation extremes of eastern China.

Figure 3(a) shows the difference of geopotential height at 500 hPa between 1997–2008 and 1980–1996. Positive anomalies are found to the north of 30°N, and negative ones to the south of 30°N in eastern China. The anomalous high in northern China favors sinking air motion and adiabatic warming, while the anomalous low in southern China favors ascending air motion and rainfall. As seen in Figure 3(b), in the upper troposphere over eastern China (200 hPa), there are anomalous easterlies favoring convergence to the north of 30°N, and anomalous westerlies favoring divergence to the south of 30°N. A center of interdecadal cooling at 300 hPa is around 30°N over eastern China (Figure 3(c)). This leads to anomalously low geopotential heights in the upper troposphere, and consequent strengthening/weakening of the westerlies to the south/north of 30°N in China. The upper-tropospheric cooling weakened the northward progression of westsoutherly monsoon winds, contributing to the weakening of the East Asian monsoon system [34]. Yu et al. [3] found a prominent upper-tropospheric center of cooling around 40°N in eastern China, between 1958–1979 and 1980–2001. Compared with our results (Figure 3(c)), the cooling center tended to move southward during recent decades, accompanying the southward migration of the monsoon rain belt. The low-level anticyclonic circulation of the cooling center was enhanced, weakening the summer monsoon and increasing rainfall in this area. The atmospheric circulation changed greatly after 1997, in a manner favorable for the interdecadal overturning of climate extremes in eastern China.

Figure 4 indicates anomalous ascending air motion to the south of 30°N, and sinking motion to the north of 30°N in eastern China. This is consistent with the aforementioned

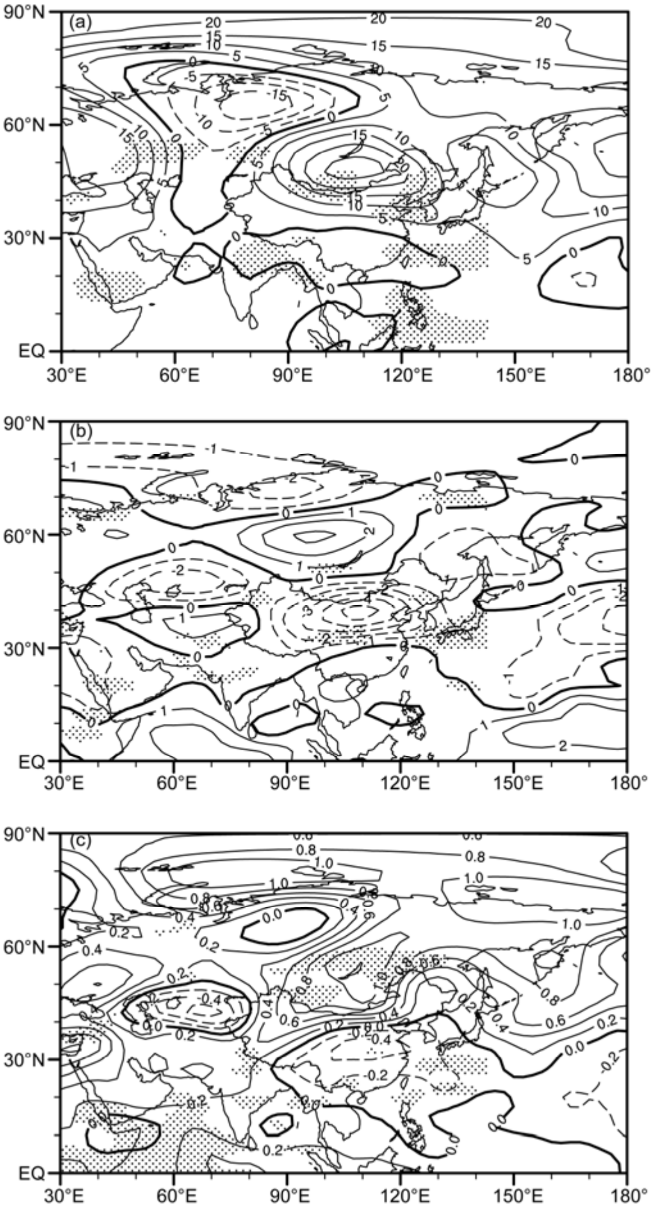

Figure 3 As in Figure 2, but for 500 hPa geopotential height (m) (a), 200 hPa zonal wind (m/s) (b) and 300 hPa air temperature (°C) (c).

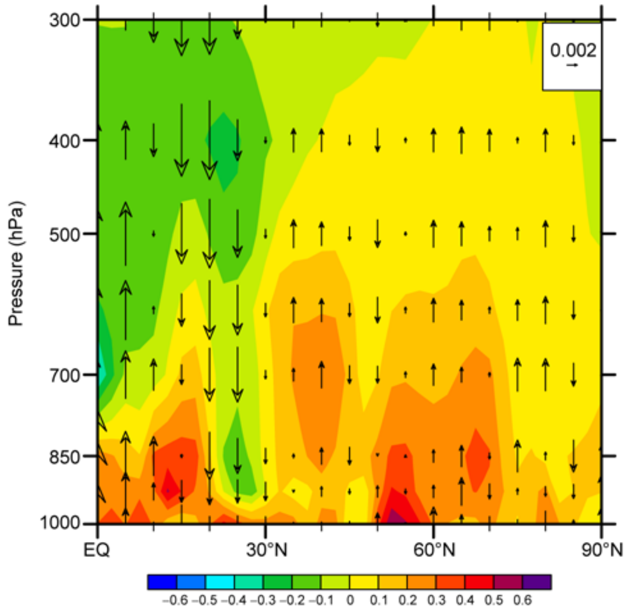

Figure 4 Meridional-vertical cross sections of interdecadal difference (Phase II minus Phase I) in vertical wind (Pa/s) and specific humidity (g/kg), averaged over 110°–120°E.

changes at different tropospheric levels. All these changes in atmospheric circulation are consistent with the changes of surface climate extremes in eastern China. Figure 4 also shows that lower-tropospheric specific humidity in eastern China increased from Phase I to Phase II, except for a small region south of 30°N. Enhanced humidity is likely a consequence of the significant warming in the region, whereas precipitation changes are prone to variations in atmospheric circulation.

3 Discussions and conclusions

The present study illustrates the relationship between changes of temperature and precipitation extremes in eastern China during the last half century, and variations in atmospheric circulation over East Asia. The main results are summarized as follows.

(1) Over the last five decades, there were opposite changes of temperature and precipitation extremes in eastern China. There was an interdecadal change around 1997, since then extremely high temperature days increased and extreme precipitation days decreased in the northern part of eastern China; the opposite changes occurred in the southern part.

(2) Associated interdecadal changes in atmospheric circulation were revealed. An anomalous continental high (centered over Mongolia) at 500 hPa weakened southward cold flow and favored sinking air motion and adiabatic warming. An anomalous low (over southern China) at 500 hPa favored ascending air motion and convection. Meanwhile, at 200 hPa, anomalous easterlies/westerlies favoring convergence/divergence intensified sinking/ascending air motion to the north/south of 30°N. A weakening summer monsoon, with its warm and moist airflow, remained south of 30°N in eastern China. These were major factors in the greater numbers of extremely high temperature days and fewer extreme precipitation days in North China, and the opposite pattern in the southern part of eastern China.

It is notable that because of the accompanying cooling center (centered at 30°N, 110°E) at 300 hPa, the upper-level westerly jet stream was strengthened/weakened to the south/north of 30°N in China, and the lower-level anticyclonic circulation was strengthened. This further weakened the East Asian summer monsoon. These changes are consistent with coexistent transformations of the frequency of extremely high temperature and extreme precipitation in eastern China.

An interesting topic remains open. As many works have indicated, certain Asian summer monsoon indices changed dramatically in the early 1990s. The present paper, as well as several previous studies cited herein, focused on the abrupt change in the mid-late 1990s indicated by surface climate observations. Two reasons are easily perceived for the discrepancy of the time of climatic jump among the different variables. First, statistical results are uncertain, especially for non-stationary time series like those of climate [35]. Second, climate change may be identified earlier by some variables than others, especially within analyses of climate extremes. This is partly because extremes are directly related to unusual weather phenomena, whereas conventional climate elements are expressed in terms of monthly or seasonal means. The link between changes in regional climate extremes and those in large-scale and mean climate, such as in atmospheric circulation patterns, is deserving of further study.

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