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Changes in Climate Regionalization Indices in China during 1961–2010

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ABSTRACT

The regionalization of climate in China is based on a three-level classification in terms of lasting days for accumulated temperature (AT), aridity index, and July mean temperature. Based on daily meteorological observational data from 756 stations, trends and interdecadal variation in indices for classifying temperature zones, moisture regions and climatic sub-regions in the period 1961–2010 are discussed. Results reveal that the nationwide AT $\geqslant 10^\circ$C (AT10) and its lasting days are basically increasing, while aridity in northern Xinjiang is decreasing. The increasing trend of July mean temperature in North China is found to be notably larger than in South China. In terms of their national averages, a marked step increase of AT10 and its lasting period, as well as July mean temperature occurred around 1997, while the aridity index presents no such clear change. By comparing regionalization areas for 1998–2010 with those for 1961–97, it is found that the semi-humid, semi-dry and dry regions in the sub-temperate zone, as well as the humid region in the middle subtropical zone, have experienced substantial shrinkage in terms of area. In contrast, the areas of semi-dry and dry regions in the warm temperate zone, as well as the humid region in the south subtropical zone, present drastically increasing trends. Owing to the influence of such step changes that took place in 1997, that particular point in time should be given close attention in future studies regarding the regionalization of climate in China.

Key words: climate regionalization, climate trends, interdecadal variation

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1. Introduction

Owing to its wide latitudinal coverage, large variation in distances from the ocean and complex topography, China is a country whose regions are characterized by a diverse range of climatic conditions. Conducting climate classification over China based on sufficient understanding of the distribution of climatic features lays the foundation for the allocation and planning of agricultural production. It also helps to take advantage of climatic resources and avoid negative influences of unfavorable climatic conditions.

Heat and moisture conditions are key factors for plant growth, and should be taken into account when defining climatic regions. Zhu (1930) published the first regional climate map of China, in which the country was divided into eight regions on the basis of temperature, precipitation, weather systems and natural landscape features: South China; Central China; North China; Northeast China; the Yunnan–Guizhou Plateau; grassland; Tibet; and the Mongolia–Xinjiang regions. Tu (1936) modified the previous work, and Lu (1945) later divided China into 10 regions in terms of the growth characteristics of crops, before Tao (1949) and Yao (1951) took monsoon features into account and incorporated these into the map. In the late 1950s, the Natural Division Committee of Chinese Academy of Sciences (1959) divided China into 8 first-class regions, 32 second-class regions, and 68 third-class regions in terms of accumulated air temperature $\geqslant 10^\circ$C (AT10) and annual mean aridity as the heat and moisture indices, respectively. Two decades later, based on data from the period 1951–70, the China Meteorological Administration (CMA, 1979) carried out climate classification using the same indices mentioned above. Qiu (1980) proposed using "lasting days", during which period the mean temperature steadily exceeds 10°C to replace AT10, which may have enormously different effects in various regions. Shortly after, Chen (1982) indicated that using lasting days $\geqslant 10^\circ$C would better reflect the distributional features of horizontal and vertical zonality of climatic zones. Since then, climate classification has basically been using lasting days $\geqslant 10^\circ$C to denote heat conditions, along with the gradual introduction of a three-level climate classification scheme consisting of divisions for temperature zones, moisture regions and climate sub-regions (CMA, 1994, 2002; Zheng et al., 2010). In addition, many scholars (Mitchell, 1976; Ayoade, 1977; Ding et al., 2007; Kang et al., 2007) adopted mathematical methods such as clustering analysis and principal component analysis (PCA) in climate classification studies.

Generally, early studies depicted the average conditions of regional factors while interannual and interdecadal vari-

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ations of these factors were rarely discussed. Although heat resources and arid conditions in China have been investigated in various aspects (Yang et al., 2002; Ma et al., 2005; Ma and Fu, 2007; Miu et al., 2009), the three-level indices for dividing temperature zones, moisture regions and climate sub-regions should also be systematically discussed, owing to the fact that different combinations of heat and moisture conditions can lead to changes in a wide variety of climatic resource types. The purpose of this paper, therefore, is to analyze long-term trends and interdecadal variations in climate zoning indices such as AT10 and its lasting days, aridity and July mean temperature. Variation in area of the synthetic climate regions is also analyzed.

2. Data and methods

2.1. *Data*

A dataset of daily data from 756 stations along with detailed metadata covering mainland China for the period 1961–2010 is used in this study. In this dataset, data for surface air temperature, precipitation, relative humidity, sunshine duration, maximum and minimum temperature, and wind velocity are included. It was provided by the Climate Data Center (CDC) of the National Meteorological Information Center, China Meteorological Administration (CMA), and the daily data have been subjected to quality control procedures of the CDC, meaning they are of the highest quality for climate studies in China (Zhai and Pan, 2003, Zhai et al., 2005). Considering the continuity of the data from 1961 to 2010 and making full use of the data, 553, 532 and 565 stations were selected to calculate AT10 and its lasting days, aridity, and July mean temperature, respectively.

The first critical step in calculating AT10 and its lasting days is to determine the start and end dates, which are generally computed by means of the five-day moving average method (Wang, 1982). Once identified, the accumulated temperature and total number of days between the start date and end date are respectively defined as the AT10 and its lasting days. Secondly, annual mean aridity (K) is denoted by annual mean potential evapotranspiration (E) divided by annual total precipitation (P) (i.e., $K = E/P$). Potential evapotranspiration is calculated by the radiation-modified FAO–Penman–Montein model (Allen et al., 1998). Many studies (e.g., Mao et al., 2000; Yin et al., 2010) have applied this model and concluded that this method is more suitable for use in China compared with other models. Finally, the average temperature for July is calculated.

2.2. *Methods*

2.2.1. *Time series homogenization method*

A method developed by Easterling and Peterson (1995), called the E–P procedure, was applied to detect and adjust inhomogeneities in climatological time series of AT10 and its lasting days, as well as July mean temperature. Before the homogenization procedure, reference time series were created. Taking AT10 for example, the average AT10 of the four adjacent stations around candidate ones were used as the reference series. Then, the candidate AT10 and the reference AT10 acted as the input of the E–P program. Using this method, a difference time series was created by subtracting the candidate AT10 from the reference AT10, and basically, the regression analysis and non-parametric statistics were used.

Results of the E–P procedure are presented in Table 1. It can be seen that 212 stations for AT10 were evaluated to be inhomogeneous. Among them, 143, 52 and 17 stations were identified with one, two and greater than two discontinuities, respectively. For lasting days of AT10, there were 141 inhomogeneous stations, of which 90, 37 and 14 stations were detected with one, two and greater than two discontinuities, respectively. The most inhomogeneous stations were found in the index of July mean temperature. Among the 337 inhomogeneous stations, 172, 113 and 52 stations were detected with one, two and greater than two discontinuities. The bias values calculated from the difference series, using a window method, were applied to adjust the identified discontinuities.

2.2.2. *Regionalization method*

The lasting days of AT10 were adopted to divide the temperature zones, and the annual mean aridity served as a moisture index to divide the humidity regions. Additionally, considering the influence of non-zonality on climate characteristics, July mean temperature was used to classify the climate sub-regions, as in Zheng et al. (2010). It should be noted that the "edge-tropical", "middle-tropical" and "equatorial tropical" climate zones illustrated by Zheng et al. (2010) are collectively called "tropical zones" in the present study due to their small spatial coverage. The details of the thresholds for the above three indices are given in Tables 2–4.

2.2.3. *Algorithm for area estimation*

The method of effective grid area described by Zou and Zhai (2004) was adopted to calculate the areas of all the

Table 1. Results of the E–P procedure.

Index	Number of homogeneous stations	Number of inhomogeneous stations		
		With one discontinuity	With two discontinuities	With greater than two discontinuities
AT10	341	143	52	17
Lasting days of AT10	412	90	37	14
July mean temperature	228	172	113	52

Table 2. Criteria of temperature zones

Temperature zone	Number of days with temperature over 10°C
Cold temperate	< 100
Sub-temperate	100–170
Warm temperate	170–220
North subtropical	220–240
Middle subtropical	240–285
South subtropical	285–365
Tropical	365–366

Table 3. Criteria of moisture regions.

Moisture region	Annual aridity (mm mm^{-1})
Humid	$\leqslant 1.0$
Semi-humid	1.0–1.5
Semi-arid	1.5–4.0
Arid	$\geqslant 4.0$

Table 4. Criteria of climate sub-regions.

Climate sub-region	Jul mean temperature (°C)
Ta	$\leqslant 18$
Tb	18–20
Tc	20–22
Td	22–24
Te	24–26
Tf	26–28
Tg	$\geqslant 28$

different types of climate regions. The area for each box is $S_g = xyscos\phi$, where x and y are the horizontal resolutions of latitude and longitude respectively, and s is the approximation of area with a $1^\circ \times 1^\circ$ grid in the equatorial zone; namely, 110.0 km $\times$ 110.0 km. ϕ is the center latitude of the grid. The effective grid area of a certain climate type is $S_E = AS_g$, where A is calculated by the ratio of the station number of a certain climate type to the total number of stations in the grid. Consequently, the total area of the particular climate type over all of China is equal to the accumulated area of all the effective grids of the same type.

2.2.4. *Other methods*

In addition to the methods discussed above, statistical methods including linear regression analysis, the running t-test, statistical t-test, and a 21-point binomial filter were also adopted (Jones et al., 1999; Wei, 1999).

3. Changes in climate classification indices

3.1. *Heat indices*

3.1.1. *Trends of AT10 and its lasting days*

The trend pattern of AT10 over all of China during the past 50 years resembles that of its lasting days (Figs. 1a, b). In most areas of China, the two variables are both increasing. The most obvious increases, where the trends > 75°C d (10 yr)$^{-1}$ and > 2.5 d (10 yr)$^{-1}$ respectively, are found in the Yellow River basin, the middle and lower reaches of the Yangtze River basin, along the southern coast, in Yunnan, in the southeast of the Tibetan Plateau, and in parts of Northeast China. The number of stations with the trends of AT10 are significant at the 0.05 level is larger than that of stations where the trends of lasting days are significant at the same level. Earlier studies also reported that the increase in AT10 and its lasting days in the east of China is higher than that in the west (Miu et al., 2009).

Variation in the start and end dates of the period in which air temperature exceeds 10°C exerts a great influence on the seeding and growth of thermophilic crops. Except in the west, the north of northeast China, Guizhou, and parts of Hainan, the start dates of the majority of areas are earlier (Fig. 1c). Among those areas where start dates are getting earlier, the most notable changes, > 1.5 d (10 yr)$^{-1}$, are found in Heilongjiang Province, across from the Yellow River and Huaihe River basins to the lower reaches of the Yangtze, along the southern coast, and in the southeast of the Tibetan Plateau. Regarding end dates, these are generally becoming delayed. The obvious delays, > 1.5 d (10 yr)$^{-1}$, are found north of the Yellow River, in East China, and in Yunnan Province.

From the above discussion, it can clearly be seen that both start dates becoming earlier and end dates being delayed have led to the trends of increasing AT10 and its lasting days during the past 50 years. Additionally, amplitudes of mean temperature, calculated by dividing AT10 by its lasting days, show nationwide increasing trends. The most evident increases are found north of 35°N. To the south of 35°N, the increases in southern and eastern coastal regions, as well as in the provinces of Hainan and Yunnan, are also prominent. Thus, it can be seen that the increases in mean temperature amplitudes over 10°C have also contributed to the trends of increasing AT10.

3.1.2. *Step change in AT10 and its lasting days*

In this part, the interdecadal variation of AT10 and its lasting days during the past 50 years is explored. Under the background of global warming, most areas of China have experienced marked increases in annual average temperature since the 1980s (Ren et al., 2005). However, the question of whether AT10 and its lasting days present the same interdecadal features as mean temperature remains unclear.

The latitude–time profiles for lasting days $\geqslant 10$°C at 85°E, 95°E, 105°E, 115°E and 125°E (Fig. 2) show that the heat factor in most areas of China has increased drastically since the 1990s, especially in the north of Xinjiang, in the southeast of the Tibetan Plateau, in the northwest of Jiangsu, in the south of the area of Hetao (the "great bend" of the Yellow River), in the northeast of Inner Mongolia, and in the south of Northeast China. This is also true for AT10. Based on the running t-test method, the time series on average over China (Fig. 3) indicate that AT10 and its lasting days display an abrupt change in 1997; the averages before and after are,

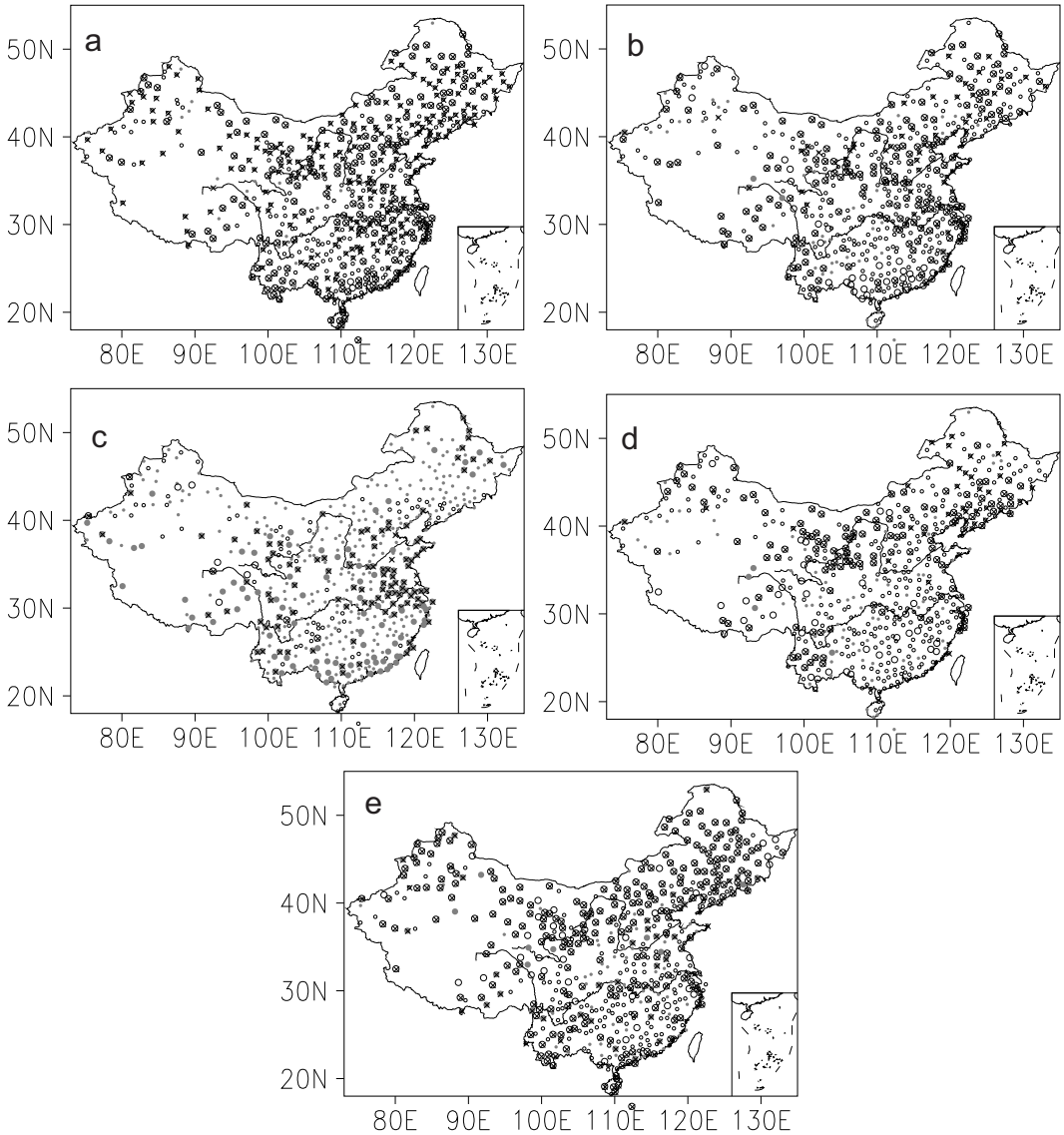

Fig. 1. Linear trends of (a) AT10, (b) lasting days, (c) start dates, (d) end dates, and (e) mean temperature amplitudes during 1961–2010. Increasing (decreasing) trends are respectively represented by empty (solid) dots, while the large and small dots respectively stand for the absolute values greater and less than (a) 75°C d (10 yr)$^{-1}$; (b) 2.5 d (10 yr)$^{-1}$; (c, d) 1.5 d (10 yr)$^{-1}$; and (e) 0.1°C (10 yr)$^{-1}$. Those trends significant at the 0.05 level are marked by a cross.

respectively, 196 d and 3956°C d and 205 d and 4220°C d. The AT10 and lasting days do not display similar interdecadal characteristics as annual average temperature, and the reason may be that the variation in AT10 is affected by the characteristics of seasonal temperature variations and the large-scale increase in winter is invalid to the increase of AT10 (Sha et al., 2002).

Based on Table 2, the locations of each boundary during the period before and after 1997 are provided in Fig. 4. Note that, considering the lack of meteorological stations in the Tibetan Plateau region, particularly in the west, and its distinct physical geography and climate characteristics, a discussion of boundary variations across the Tibetan Plateau are beyond the scope of this paper. Furthermore, the discussion below regarding area coverage will also exclude this region. Figure 4 shows that the boundaries of temperature zones present marked variation. In eastern China, all the boundaries, especially that between the northern and southern subtropical zones, display a northward movement. The most obvious boundary oscillation can be seen in the middle reaches of the Yangtze River. The location of the boundary dividing the warm temperate zone and the northern subtropical zone shows marked northward and northwestward movement in the south of the North China Plain and the northwest of the Yunnan–Guizhou Plateau, respectively. However, the location of the boundary dividing the middle temperate zone and the warm temperate zone shows obvious northeastern and northwestern oscillation in Liaoning Province and the

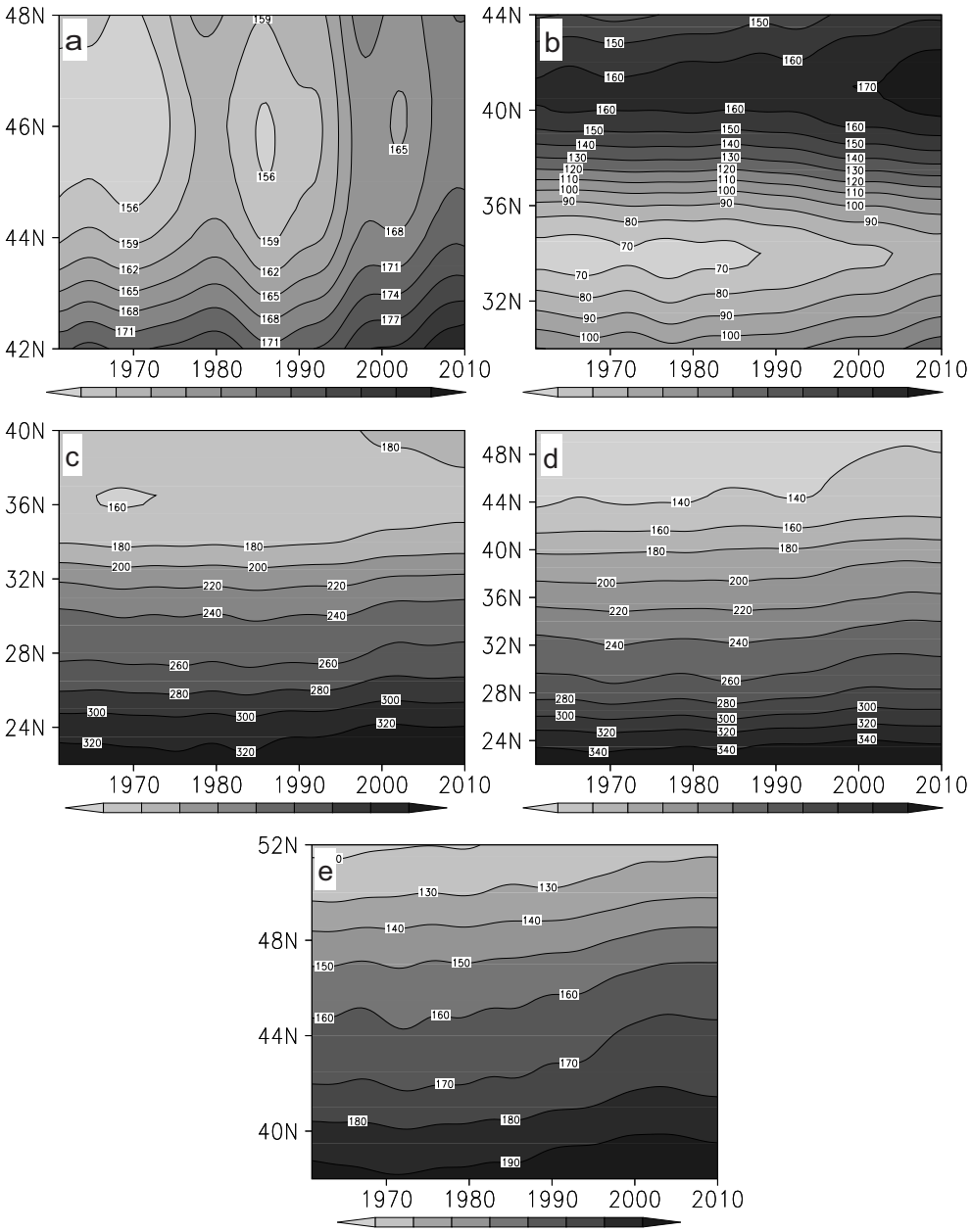

Fig. 2. Latitude–time profiles of lasting days $\geqslant 10°$C processed by the 21-point binomial filter method at (a) 85°E; (b) 95°E; (c) 105°E; (d) 115°E; and (e) 125°E.

area of Hetao. The most notable movement in the area of Hetao is in accordance with its relatively larger increase after 1997. Boundary movement in Northwest China—most areas of which present warm temperate or sub-temperate climate—is less obvious compared with that in eastern China, indicating that the increase of AT10 and its lasting days in the northwest is weaker. By calculating the variation in area around 1997 of each temperate zone (Table 5), it can be seen that the cold temperate and sub-temperate zones decrease by 0.41×10^7 hm^2 and 4.63×10^7 hm^2, respectively. Meanwhile, the warm temperate, subtropical and tropical zones all increase. The relatively larger increases in area are found in the warm temperate and southern subtropical zones, respectively reaching 1.77×10^7 hm^2 and 1.8×10^7 hm^2.

3.2. *Aridity index*

3.2.1. *Trends in aridity index*

Trends in annual aridity during the studied period exhibit distinct spatial distributions over China (Fig. 5a). Statistically significant decreasing trends are found in northern Xinjiang with a magnitude of 1 mm mm^{-1} (10 yr)$^{-1}$, indicating that the extent of drought this area is becoming weaker—a result that is consistent with studies by Yang et al. (2002), Ma and Fu (2007) and Wei et al. (2009). In addition, the regions extending from the Yellow and Huaihe river basins to the southern coast present decreasing trends with a weaker

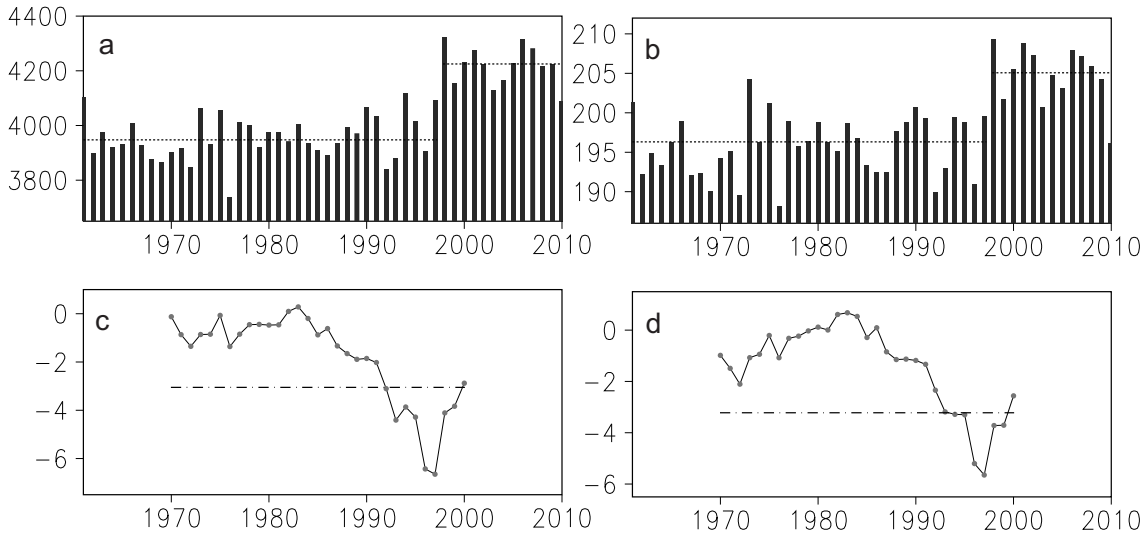

Fig. 3. Time series of (a) AT10 and (b) lasting days on average over China and (c, d) their moving *t*-test results. In panels (a) and (b), the averages during the periods before and after the step change year are shown by short dashed lines. The dot-dashed lines in panels (c) and (d) represent the critical value at the 0.01 significance level (units: days).

Table 5. Variations in area of the integrated sub-regions around 1997 (units: 10^7 hm^2).

Temperature zone	Moisture region	Climate sub-region							
		Total area	T_a	T_b	T_c	T_d	T_e	T_f	T_g
Cold temperate	Humid	0.19/0	0.19/0						
	Semi-humid	0.23/0.10	0.23/0.10						
	Semi-dry	0.45/0.35	0.45/0.35						
	Dry								
Sub-temperate	Humid	0.67/0.99	0.23/0.41	0/0.13	0.18/0.18	0.26/0.27			
	Semi-humid	**4.88/3.01**	1.59/0.77	1.38/0.93	1.67/1.09	0.23/0.22			
	Semi-dry	**8.30/7.07**	0.70/0.77	**2.12/0.53**	2.25/2.72	3.23/3.04			
	Dry	**7.67/5.81**	**1.97/0.57**	1.59/1.57	1.94/1.18	2.16/2.14	0/0.35		
Warm temperate	Humid	0.72/0.58		0.08/0.10	0.14/0	0.49/0.47			
	Semi-humid	2.67/2.17	0.28/0.56	0.22/0.22	0.79/0.39	0.48/0.45	0.90/0.55		
	Semi-dry	**7.96/9.31**		0.19/0.36	0.59/0.68	**3.95/2.70**	**1.96/4.65**	1.27/0.91	
	Dry	**9.42/10.48**		0/0.77	0.79/0.21	2.68/2.33	3.37/3.72	2.58/1.98	**0/1.46**
North subtropical	Humid	0.64/0.74		0/0.08	0.23/0.14	0.28/0.51		0.14/0	
	Semi-humid	1.69/1.70	0.14/0	0/0.14		0/0.10	0.20/0.59	1.35/0.87	
	Semi-dry	1.90/1.69	0.14/0	0.14/0	0/0.14			1.61/1.55	
	Dry	0.12/0.88					0/0.57	0/0.19	0.12/0.12
Middle subtropical	Humid	**10.15/9.01**			0.66/0.52	0.54/0.69	1.11/1.18	**3.74/2.63**	4.10/3.99
	Semi-humid	2.15/2.99		0.40/0.43	0.14/0.29		0.14/0.20	1.26/1.69	0.21/0.38
	Semi-dry	0/0.44	0/0.14					0/0.30	
	Dry								
South subtropical	Humid	**10.55/12.35**		0.22/0	0.40/0.44	0.68/0.99	1.57/1.05	2.01/2.09	**5.67/7.78**
	Semi-humid	1.96/1.96		0.26/0.11	0.58/0.84	0.14/0.23	0.09/0.09	0.44/0.29	0.45/0.39
	Semi-dry	0.31/0.31				0.22/0.22			0.09/0.09
	Dry								
Tropical	Humid	0.23/1.05					0/0.44		0.23/0.61
	Semi-humid	0.62/0.46							0.62/0.46
	Semi-dry	0.15/0.15							0.15/0.15
	Dry								

Note: average areas before and after 1997 are separated by "/"; blank spaces indicate that sub-regions of the identified type did not exist during the past 50 years; numbers in bold denote that the absolute values of the changes in areas are larger than 1.0 hm^2. Seven temperature zones , four humidity regions and seven climate sub-regions are divided. Specially, the seven climate sub-regions are marked by T_a–T_g.

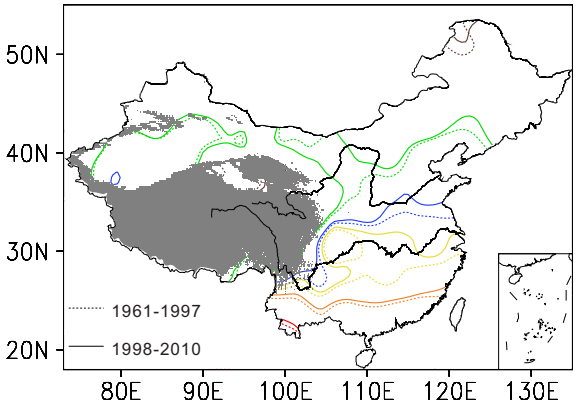

Fig. 4. Changes in boundary locations for classifying temperature zones around 1997 (brown, 100; green, 170; blue, 220; yellow, 240; magenta, 285; red, 365) (units: d).

magnitude. All other areas basically present increasing trends. The aridity index adopted in this study is determined by annual precipitation and potential evapotranspiration. Thus, whether or not these two dominant factors have caused changes in the annual index deserves further discussion.

As Fig. 5b shows, strong decreases in potential evapotranspiration are found in the northwest, in the south of the North China Plain, and in the west of Liaoning Province, with the most marked magnitude of 10 mm (10 yr)$^{-1}$ and the weaker decreases being found in the middle and lower reaches of the Yangtze River and the region to the south of the Yangtze River, respectively. Meanwhile, potential evapotranspiration in Yunnan Province, in the area of Hetao, and in the northern part of Northeast China displays an increasing trend. Figure 5c shows that increasing trends in annual precipitation are found in areas extending from the Yangtze River–Huaihe River basin to the South China coast and Hainan. Particularly, the increasing trends in those regions extending from the east to the south coast, in Hainan Province, over the middle and lower reaches of the Yangtze River, and to the south of the Yangtze River reach 10 mm (10 yr)$^{-1}$. Meanwhile, decreasing trends, exceeding 20 mm (10 yr)$^{-1}$, are found over the Liaodung Peninsula, Hexi Corridor, Shandong Peninsula, Yellow River region, south of Sichuan Province, and east of Yunnan Province. Thus, it can be seen that trends in annual precipitation over eastern China take on a "southern flood–northern drought" pattern, while those in the west present markedly increasing trends. To summarize, the decrease in potential evapotranspiration and increase in precipitation in Northwest China, over the Yangtze River–Huaihe River basins, over the middle and lower reaches of the Yangtze River, and to the south of the Yangtze River, both relieve the extent of drought, while adverse variations of both these two variables aggravate the occurrence of drought in the south of the area of Hetao.

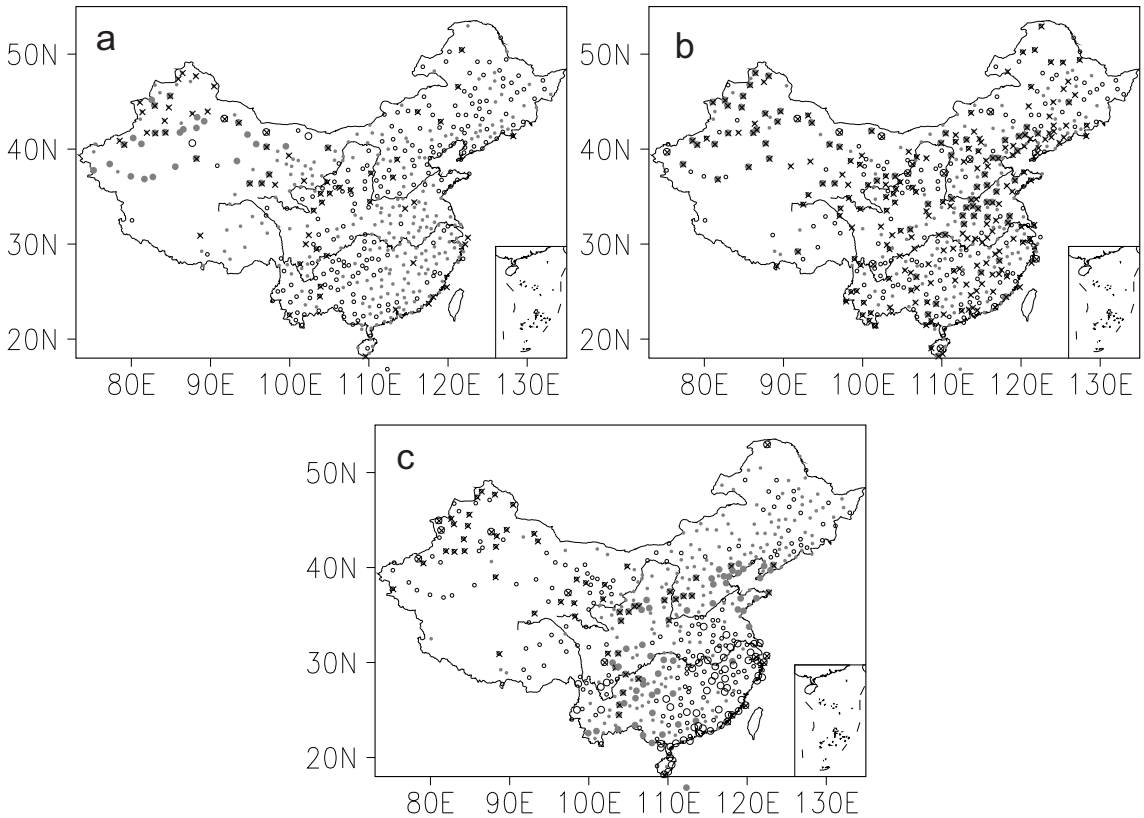

Fig. 5. Trends in (a) annual aridity, (b) potential evaporation, and (c) precipitation during 1961–2010. As in Fig. 1, the large and small dots represent the absolute values greater and less than (a) 1 (10 yr)$^{-1}$ and (b, c) 20 mm (10 yr)$^{-1}$.

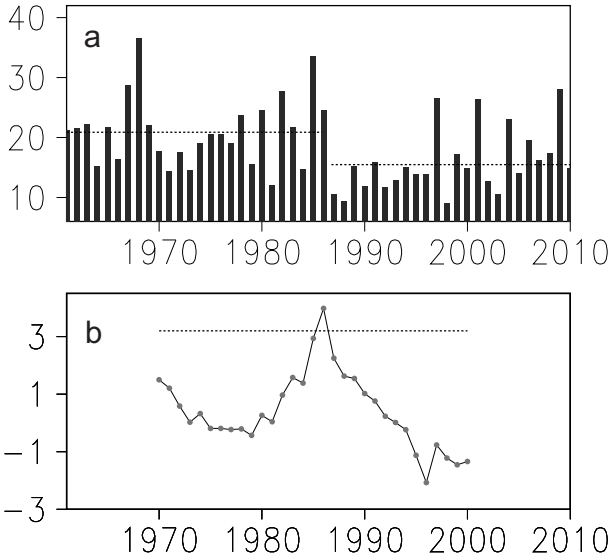

Fig. 6. The same as Fig. 3, but for annual aridity of northern Xinjiang (northern Xinjiang covers an area north of 40°N and west of 95°E).

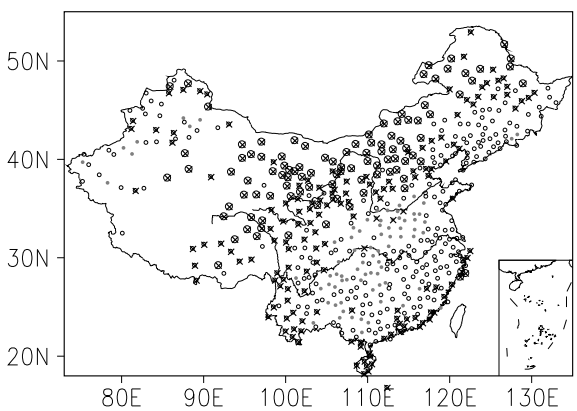

Fig. 7. Trends in July mean temperature during 1961–2010. As in Fig. 1, the large and small dots represent the absolute values greater and less than 0.3°C (10 yr)$^{-1}$.

3.2.2. *Interdecadal variations in annual aridity index*

Latitude–time profiles (not shown) of annual aridity at around 85°E, 95°E, 105°E, 115°E and 125°E reveal that there are obvious interdecadal variations in the north of Xinjing Province, northwest of Gansu Province, northeast of Inner Mongolia, and north of Northeast China. The index in the north of Xinjiang Province has become smaller since the 1980s, while that in the northwest of Gansu Province became relatively larger during the period 1985–2000. Annual aridity in the northeast of Inner Mongolia has become greater since 1995, while in the north of Northeast China it was relatively greater during 1960–80 and after 1990. Thus, it can be seen that the interdecadal variations over China display distinct spatial differences.

By normalizing the annual aridity index, it is also possible to examine the nationwide average moisture characteristics. The results (not shown) reveal that the annual average aridity presents relatively smaller values from the mid-1980s to the late 1990s, and relatively larger values in the most recent 10 years. However, overall, the interdecadal variation is fairly unremarkable.

During the past 50 years, annual aridity in northern Xinjiang has taken on a notable decreasing trend. In order to conveniently discuss the variations in aridity of this region, the areas north of 40°N and west of 95°E are defined as northern Xinjiang. Figure 6 illustrates that the index presents a marked abrupt change around 1986; the values before and after that year are 21 mm mm^{-1} and 16 mm mm^{-1}, respectively. This interdecadal variation is consistent with the conclusions of Wang et al. (2004) based on data from 1961 to 2000.

By analyzing the time series of areas of each aridity region (not shown), it can be seen that the area of arid regions presents a jump during the 1990s (i.e., expanding in the most recent 10 years), while the areas of humid, semi-humid and semi-arid regions do not demonstrate any apparent interdecadal variation.

3.3. ***The climate sub-regions index***

3.3.1. *Trends in July mean temperature*

The spatial distribution of trends in July mean temperature in the past 50 years shows that the indices in most areas are increasing (Fig. 7). The strong increase trends, exceeding 0.3°C (10 yr)$^{-1}$, are found in Inner Mongolia, Gansu, Qinghai, and along the eastern coast, indicating that the increase in the north is stronger than in the south. Based on the *t*-test, those increases significant at the 0.05 level are found in the northwest, over the Yellow River basin, the north of Northeast China, the southeast of the Tibetan Plateau, in Yunnan, along the East China coast, and the South China coast. However, stations in the south of Shaanxi, Henan and Hebei display decreasing trends.

3.3.2. *Step change in July mean temperature*

As shown in Fig. 8, July mean temperature on average over China presents an abrupt change in 1996. For convenience, 1997 can be reasonably taken as the transition point for AT10 and its lasting days. Based on Table 4, the variations in location of each boundary around 1997 are provided in Fig. 9, and the results show that, in the east, there is more or less a northward shifting for each boundary. In particular, the most obvious northward movement is found in East China (28°C isogram). In the northwest, the areas circled by the 18°C, 20°C and 22°C isograms are decreasing, while those circled by the 24°C, 26°C and 28°C isograms are increasing, denoting an increasing trend in July mean temperature. By calculating the variation in area of each climate sub-region (Table 5), and taking 1997 as the transition point, it can be seen that average areas with a July mean temperature of $\leqslant$18°C, 18°C–20°C, 20°C–22°C, 22°C–24°C and 26°C–28°C decrease by 2.25×10^7 hm^2, 1.21×10^7 hm^2, 1.56×10^7 hm^2, 0.95×10^7 hm^2 and 1.89×10^7 hm^2 respectively, while those with a July mean temperature of 24°C–26°C and $\geqslant$28°C increase by

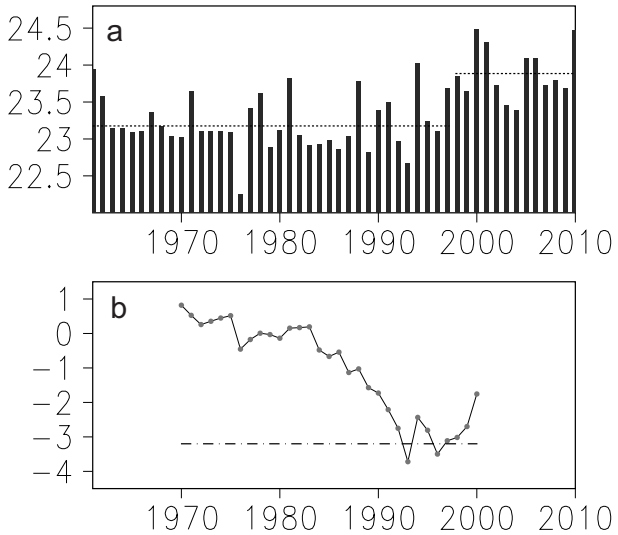

Fig. 8. The same as Fig. 3, but for July mean temperature.

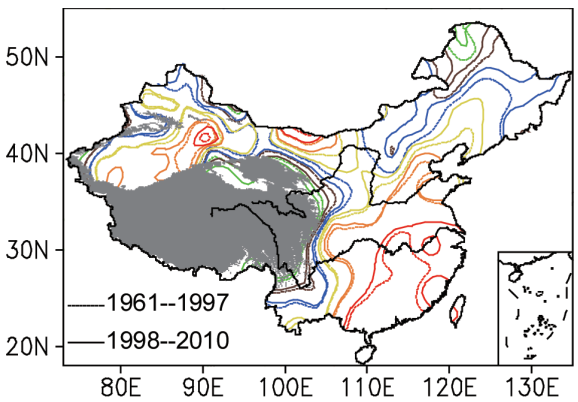

Fig. 9. Changes in boundary locations for July mean temperature around 1997 (brown, 18; green,10; blue, 22; yellow, 24; magenta, 26; red, 28) (units: °C).

4.05×10^7 hm^2 and 3.81×10^7 hm^2, respectively.

4. Changes in the spatial coverage of integrated sub-regions before and after 1997

Heat and moisture conditions are both major factors affecting the growth and production of crops, and thus their different characteristics and features are important in determining planting patterns. The above results show that, in terms of their nationwide average, AT10 and its lasting days, and July mean temperature, both present a jump point around 1997, while the aridity index does not exhibit such a step change. Consequently, in this section, the variations in area of the integrated sub-regions before and after 1997 are discussed.

As shown in Table 5, the areas of humid, semi-humid and semi-arid regions in the cold temperate zone are decreasing, which is consistent with the decrease in the total area of the cold temperate zone. Areas of semi-humid, semi-arid and arid regions in the sub-temperate zones present distinct decreasing trends, with the relatively obvious decreases being found in the Tb climate sub-region of the semi-arid region (1.59×10^7 hm^2) and the Ta climate sub-region of the arid region (1.4×10^7 hm^2). As for the warm temperate zone, the areas of humid and semi-humid regions decrease, while the areas of semi-arid and arid regions increase; the largest increase (1.35×10^7 hm^2) is found in the semi-arid region. July mean temperature in the semi-arid region of the warm temperate zone is mainly 22°C–26°C, while that in the arid region of the warm temperate zone is mainly 22°C–28°C. Meanwhile, in the warm temperate zone, the areas of Tb and Tg climate sub-regions in the arid region increase from non-existence to 0.77×10^7 hm^2 and 1.46×10^7 hm^2, respectively. As for the north subtropical zone, the variation in the arid region is most obvious, with the area increasing by 0.76×10^7 hm^2. In terms of the middle subtropical zone, the humid region demonstrates a decreasing area of coverage, with the most notable decrease (1.11×10^7 hm^2) being found in the Tf climate sub-region. Meanwhile, the semi-humid and semi-arid regions in the middle subtropical zone increase. Regarding the south subtropical zone, the humid region presents a stronger increasing trend, with its area of the Tg climate sub-region increasing by 2.11×10^7 hm^2. Finally, with respect to the tropical zone, the area of the humid region increases and that of the semi-humid region decreases, while that of the semi-arid region presents no obvious change.

5. Conclusions and discussion

The trends and interdecadal variations of the temperature zones, moisture regions and climate sub-regions in China during the past 50 years have been discussed. Basically, the AT10 and its lasting days both present increasing trends over the country. The drought in northern Xinjiang has weakened, while the linear trends in all other areas are not significant. The increasing trend in July mean temperature in the north is more notable than in the south. On a national average, the AT10 and its lasting days and July mean temperature all display a step change around 1997, while the aridity index does not present such a clear change. Northern Xinjiang has become wetter since 1986. The average areas of the sub-regions of the integrated regionalization after 1997 are distinct from those before 1997. Consequently, the jump point of 1997 should be given close attention.

Climate change can exercise a great influence on climate resources, especially in terms of agricultural production and planting systems in China. Under the background of global warming, there is a corresponding northward-heading planting boundary for wheat, rice and corn. As an example, Li and Wang (2010) showed how the rice-growing area has expanded in Heilongjiang Province. For dry-farming regions, the area suitable for planting is expected to expand due to climate warming; however, it is also greatly affected by moisture conditions (Zhang et al., 2008). As for Central and East China, climate warming could improve growing conditions

and benefit rice production, while a wetter climate would be harmful for production (Xu et al., 1999). Therefore, all agricultural regions should be adjusted, with scientifically-based and practical cropping systems established according to local changes in conditions.

Exploring the possible reasons or mechanisms behind changes in regional climate can inform future predictions, and thus allows proper and reasonable planning for agriculture to be conducted. Theoretically, climate warming is expected to increase AT10 and its lasting days. Specifically, as discussed in section 3.1.1, both start dates becoming earlier and end dates becoming delayed contribute to the increasing trends of AT10 and its lasting days. Furthermore, enhanced amplitudes of average temperature during periods when mean temperature steadily exceeds 10°C are also beneficial to increases in AT10. It has been found that a prolonging of the higher temperature period but not the lower temperature period has enhanced the amplitudes of average temperature. Accordingly, it is very likely that an extension of the summer period has made a major contribution, and such speculation is supported by a recent study conducted by Yan et al. (2011). Their results showed that a change point for warming occurred in the 1990s (1994 and 1997) for summer—a result that is quite consistent with the abrupt point in 1997 identified for AT10 and its lasting days, as well as July mean temperature in the present study. This implies that a prolonging of the summer period has exerted a significant influence on increases in AT10 and its lasting days. Additionally, previous research has indicated that human activity has a significant impact on the local environment. In particular, urbanization has altered weather and climate phenomena in and around urban areas (Balling and Brazel, 1987; Baik et al., 2001; Ren et al., 2010; Huang et al., 2011). Accordingly, the problem of how deeply urbanization affects climate regionalization still needs further study.

Factors influencing dry and wet climate changes are more complex. Although such changes can also be explained as being related to global climate warming (Shi et al., 2003), factors impacting regional climate are also important and deserve to be studied in depth. Analyses have shown that both the decrease in potential evapotranspiration and increase in precipitation have led to the wetting trend in northern Xinjiang. Wind speed, sunshine duration, temperature, relative humidity and other elements can affect potential evapotranpiration. Indeed, some previous studies have indicated that sunshine duration and wind speed are both principle factors affecting potential evapotranspiration in China; for example, in northern China, a reduction in wind speed has been found to be the main reason resulting in decreases of potential evapotranspiration in the warm temperate zone (Xie and Wang, 2007; Yin et al., 2010). Likewise, there have been many studies published on the mechanisms of precipitation changes in northern Xinjiang. Shi et al. (2003), Li et al. (2003) and Zhao et al. (2006) indicated that variation in general circulation is conducive to a decrease in northerly wind and an increase in southerly wind. As a result, moisture from the Indian Ocean and western Pacific can be transported to the north more smoothly. Enhanced water vapor convergence in the west is another important element (Chen and Dai, 2009). Wei et al. (2009) indicated that atmospheric heat source over the Tibetan Plateau has impacted upon precipitation changes in northwestern China. Obviously, a comprehensive analysis of the possible causes of changes in potential evapotranpiration and precipitation is needed in order to understand aridity variation in Northwest China. In addition, whether or not such changes are due to interannual variability or long-term change also warrants further study.

Finally, climate regionalization for the Tibetan Plateau has not been discussed in the present study owing to a lack of sufficient data. The Tibetan Plateau covers a vast geographic area, accounting for one quarter of China's total territory, and its topography and climatic features are complex. Yet, with the exception of Zhao et al. (2002), who discussed variation in its heat indices, there have been few studies conducted regarding changes in climate resources over this region. As is known, moisture conditions also greatly affect the growth of crops and plants. Hence, in order to provide a reference base for planting system designs and ecosystem protection on the Tibetan Plateau, the characteristics of changes in its heat and moisture resources, as well as its climate classification, are worthy of investigation.

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