Spatial–temporal variation of temperature over China during 1961–2009

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Abstract The spatio-temporal variation of temperature is one of the basic signals for climate change. Analysis of its detailed distribution is useful for humans to adapt the ongoing and coming climate change. In this study, monthly mean temperature during 1961–2009 in China was used and processed by the classical Mann Kendall (MK) test. A Significant Year was defined as: (a) the time of break point for the temperature series, or (b) the time of 95% confidence level for the temperature series with monotonic trend. The rate of temperature changes before and after the Significant Year, and the trend magnitude were discussed. Our analysis shows: (a) all four annual regional average temperatures over China were decreasing before the 1970s, slightly or significantly; (b) the Tibetan Plateau and southwest Yunnan were the most significant warming areas during 1961–2009; and (c) the warming in northern China is much more significant than in the south, and the east coastal area was getting warmer more rapidly than the neighbouring interior.

Key words average temperature; Mann-Kendall test; spatial and temporal distribution; China

1 INTRODUCTION

Temperature is the most direct indicator of climate change. The change of temperature influences hydrological factors, such as streamflow and evapotranspiration. Hence, it is vital to analyse the spatial–temporal variation of temperature when assessing the change of local water resources (Hao *et al*., 2006, 2007). There are many studies of temperature changes over China. Tu (1984) and Chen *et al*. (2010) report that, in China, except for the Northeast and northern Xinjiang, the basic pattern of temperature change over the past century is in accordance with that of the Northern Hemisphere. That is, a warm period from the 1900s until approximately 1945, followed by a cold period until the 1970s, and then another warm period. Yu (2000) shows that temperature change in China is not as significant as for the North Hemisphere. Ding & Dai (1994) obtained similar results, and they also undertook specific exploration into the temperature changes over Southeast China. Ban *et al*. (2006) did a similar analysis for Southwest China. Ding & Dai (1994) also discussed the influence of urbanization to the observed temperature changes. Shi *et al*. (1994) analysed the main characteristics of regional meteorological elements, including air temperature and precipitation, for the different decades in the last century. Chen *et al*. (1998) argue that temperature increases in China mainly happened over the regions north of 35°N, with Xinjiang and north Heilongjiang as the most significant warming areas. The areas between 23°N and 35°N and east of 100°E, however, were actually cooling during the past half century (Chen *et al*., 1998). Qin (2005) agreed with Chen's results and reported that North China is indeed the main warming area in the past 50 years; furthermore, he calculated the increasing rate of temperature and pointed out that in the northern part of the Northeast, Inner Mongolia, as well as some western basins, the temperature increase rate was as high as 0.8°C per 10 years.

Most of the studies above focused on the overall trend of the temperature and do not contain detailed information. This may lead to a misunderstanding of regional climate trends. This paper aims to provide a more detailed and comprehensive depiction of the spatial–temporal variation of monthly temperature in China during 1961–2009. We use the newest temperature data provided by the China Meteorological Administration CMA (http://cdc.cma.gov.cn/) from more than 700 stations over China.

2 METHODOLOGIES

The linear trend assessment is important for time series analysis. Hess reviewed the method for linear trend detection (Hess *et al*., 2001). The classical Mann Kendall test was used to examine the possible trends and abrupt change points in the average monthly temperature time series. This method was first mentioned by H. B Mann in 1945 (Mann, 1945), and since M. G Kendall's improvement (Kendall & Gibbons, 1962) it has become one of the most widely-used methods for trend detection in time series analysis (WMO, 1988).

In this method, the null hypothesis H_0 for the test is that there is no significant trend in the time series consisting of *n* independent random samples that all comply with a normal distribution. The alternative hypothesis test is double-tailed. The statistic *S* is given by:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(x_j - x_k) \tag{1}$$

where:

$$\mathrm{sgn}(x_j - x_k) = \begin{cases} +1, (x_j - x_k) > 0 \\ 0, (x_j - x_k) = 0 \\ -1, (x_j - x_k) < 0 \end{cases} \tag{2}$$

S is normally distributed with:

$$E(s) = 0 \tag{3}$$

$$V(s) = \frac{n(n-1)(2n+5)}{18} \tag{4}$$

When $n > 10$, the test statistic *Z* of the standardized normal distribution can be calculated as:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}, S > 0 \\ 0, S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}}, S < 0 \end{cases} \tag{5}$$

A positive value of *Z* indicates an increasing trend and *vice versa*. Given a significance level *α*, if $Z \geq Z_{1-\alpha/2}$ then the null hypothesis will be rejected; that is to say, there exists a significant increasing (decreasing) trend in the target time series. If this method is used to detect abrupt change(s), the trend existed in the time series will be represented by another series UF_k rather than *Z* (Fu *et al*., 1992); UF_k is calculated as follows:

$$S_k = \sum_{i=1}^{k} \sum_{j=1}^{i-1} \alpha_{\mathrm{ij}} \quad (k = 1, 2, \ldots, n) \tag{6}$$

where:

$$\alpha_{\mathrm{ij}} = \begin{cases} 1, x_i > x_j \\ 0, x_i > x_j \end{cases} \tag{7}$$

then:

$$UF_k = \frac{|S - E(S_k)|}{\sqrt{Var(S_k)}} \quad (k = 1, 2, \ldots, n) \tag{8}$$

where $E(S_k) = k(k+1)/4$ and $Var(S_k) = k(k-1)(2k+5)/72$.

In order to qualify the trend magnitude, the Theil-Sen approach (TSA) was employed (Kumar *et al*., 2009). The TSA slope β is given by:

$$\beta = Median\left[\frac{(X_j - X_i)}{(j-i)}\right] \quad \text{where } \ i < j < n \tag{9}$$

A positive β indicates the increasing rate of the trend, and a minus value indicates the decreasing rate (Xu *et al*., 2002). The unit of β here is °C/year.

The Mann-Kendall method can also be applied in change-point detection. However, it is not effective enough if there are more than one change-points in the time series (Fu *et al*., 1992). An important work in change point detection is to set a confidence level and make sure the detected change-point can surpass this level. The most-used confidence levels are 90% and 95%. Temperature is relatively steady compared with other meteorological elements in long time periods, and considering the time span we chose, it is unlikely to be able to determine a significant change-point that is highly reliable (Jiang *et al*., 2004). While it is believed the trend of the observed temperature time series is not monotone (Chen *et al*., 1998; Jiang *et al*., 2004; Wang *et al*., 2009), and different parts of China may have different patterns in the trend of temperature evolution. This makes it necessary to use alternative statistics to indicate any change in the monotone series.

Calculation results show that there are only two types of trends here: slight decrease then increase, or continuous increase. We arrive at such conclusions not only in terms of the Four Geographic areas of China, but also from the statistical results of all the 730 stations. For the first situation, we call it a "mixed" trend, while the second type is called "monotone" or "monotone-like". If a mixed type of trend exists, we determine the time when the shift occurs; if it is monotone or monotone-like, we establish the time when the trend becomes significant. Here we define the time when the UF_k series first surpasses the confidence level as Significant Year (SY) to represent the transfer time of different trends or the significant trend happens. For example, the SY of regional monthly average temperature of Qinghai-Tibet is round about 1968.

3 *Z* SPATIAL DISTRIBUTION

The *Z* values of the Mann-Kendall test for 730 stations seasonal and annual temperature series of for 1961–2009 were calculated and interpolated via the ordinary kriging method. The results are shown in Fig. 1.

In spring season (MAM), most of China has a warming process. The most significantly warming areas include most parts of Eastern China and Northern China and the southeastern part of Northwestern China. The warming trends in northern Xinjiang, most of Southwest and Southern China do not surpass the confidence level of 95%. However, the results show that all other areas have a significant warming trend in spring with a confidence level of 95%.

Compared to spring, there are fewer areas with significant warming trend in summer (JJA). Heilongjiang, Jilin, Inner Mongolia, Beijing, Tianjin, most of Northwest China, Qinghai-Tibet Plateau, southwest Yunnan as well as parts of the Southeast coastal areas have significant warming trends. All other places, however, can not pass the confidence test of 95%. An interesting finding is the significantly cooling area with its centre in the border area of the central provinces Henan, Shannxi and Hubei.

Autumn (SON) temperatures increased significantly (SON). Unlike summer, most parts of China were warming in autumn over the last 50 years, and most of this warming process is reliable. Among those warming areas, the northeast Qinghai-Tibet Plateau is the most significant place. Only quite small parts, such as some sections of mid-South China and the Southwest can not pass the confidence test, and so very few parts were cooling and they can almost be ignored.

Similar to autumn, winter (DJF) was getting warmer nation-wide. Monthly average winter temperatures in the North coastal area, Qinghai-Tibet Plateau and west Yunnan show the most significant increase. Parts of Southwestern China like Sichuan, Chongqing, Guizhou and Guangxi can not surpass the confidence test, and some were even cooling.

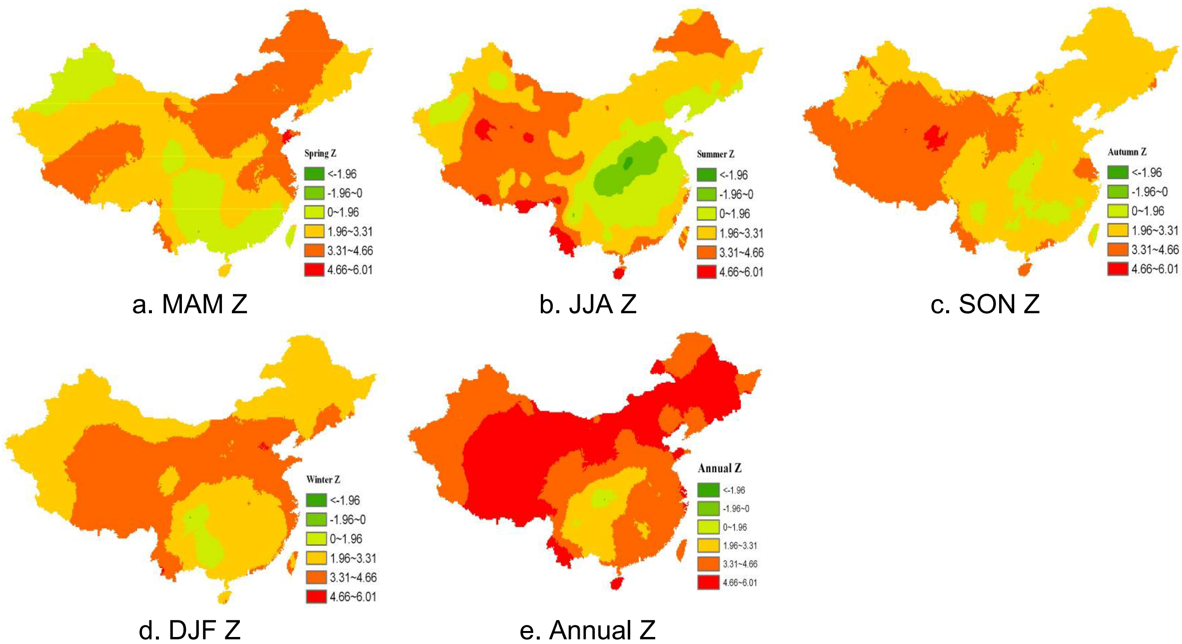

Fig. 1 *Z* value spatial distribution for annual and seasonal temperature over China.

The *Z* distribution for annual temperature shows that most of China was warming and the results are significant at a higher confidence level than for any single season; this is especially obvious for the Qinghai-Tibet Plateau, mid-east of the Northwest, the Northeast and southwest Yunan. A *Z* value greater than 1.96 can be regarded as significant at a confidence level of 95%. *Z* values for those regions are commonly higher than 5, thus it is almost certain that these regions were getting warmer in terms of annual temperature between 1961 and 2009. In the Yangtze River Basin, Wuhan and its surrounding area have significant warming trends, while neighbour areas, Chongqing and east Sichuan province, are the only places with a cooling trend.

It is a common pattern that Northern China and the coastal areas have more significant warming trends than Southern China and its neighbouring inland area. There is an overall increasing trend in both seasonal and annual temperatures over China in the past 50 years. The warming magnitude and span of annual temperature are much greater than seasonal temperatures. Northern China has warmed more rapidly than Southern China. Average temperatures in Qinghai-Tibet Plateau and southwest Yunnan have the most significant increases at both annual and seasonal time scales.

4 SY DETERMINATION

It is useful to determine the SY values of stations and to analyse their temporal and spatial distribution. For regional mean temperatures, we calculated the average temperature UF_k series for the four geographical regions. As shown in Fig. 2, SY of the South and Qinghai-Tibet occurs in 1970 or so, which means their trend is mixed with a decrease and an increase; neither should be neglected. The North and Northwest regions have similar trends, though we see decreases in the first several years of the records. The trends are insignificant to bring about a SY. The real SY happened after 1990, when the increasing trend is significant. The statistics of all 730 stations are listed in Table 1.

It is clear that there are two main peaks in the SY distribution, and the year of 1981 divides them into these two groups. Judging from the station and regional Mann-Kendall test results, the group before 1981 likely indicates a significant decreasing trend in the 1960s or 1970s, and the group after 1981 possibly indicates a lasting increasing trend without significant decrease since 1961.

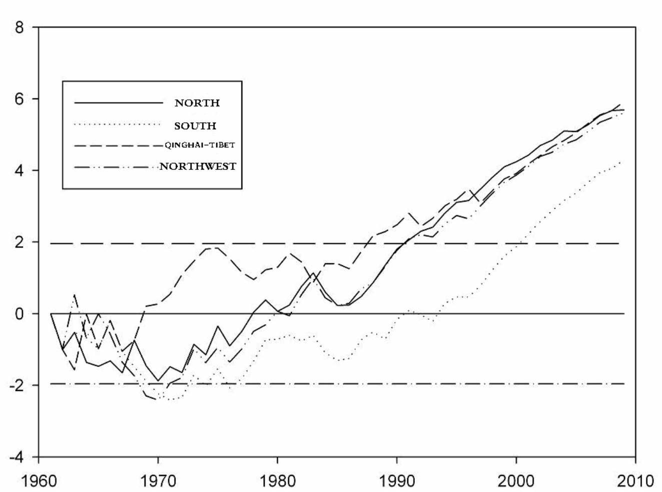

Fig. 2. The M-K test results of the annual temperature.

Table 1 Statistical characteristics of annual and seasonal SY.

	Annual	MAM	JJA	SON	DJF
MEAN	**1981**	**1993**	**1982**	**1988**	**1988**
SEM	0.519	0.495	0.556	0.536	0.497
MEDIAN	**1977**	**1998**	**1979**	**1991**	**1991**
MODE	**1964**	**2001**	**1964**	**1971**	**1964**
SD	14.012	13.361	15.011	14.47	13.432
VAR	196.341	178.511	25.321	209.386	180.422
SKW	0.26	–0.977	0.362	–0.154	–0.622
SES	0.09	0.09	0.09	0.09	0.09

SEM is Stand Error Mean; SD is Standard Deviation; VAR is Variance; SKW is Skewness; SES is Standard Error of Skewness.

Specifically, the distributions of annual and JJA (summer) Z are comparatively uniform and alike, even though two SY values of annual average make up more than 10% of all the annual SY values, respectively. The Mean and Median value of annual and summer SY values are quite alike as well (Table 1). Compared to annual and JJA, the other three seasons have more SYs than later than 1981. This verifies the last conclusion that unlike the summer and annual temperatures, spring, autumn and winter temperatures increased steadily over the past 50 years.

The spatial distribution of annual SY values in Fig. 4 indicates some cluster features: SY values in the Yangtze River and Yellow River basins are commonly earlier than 1981; Northeast, Northwest, Southwest and far Southern China have most SY values after 1981. The middle and eastern part of China, therefore, did not become warmer in the last 50 years. Instead, they have significant cooling trends prior to 1981.

5 MAGNITUDE DISTRIBUTION

The TSA slopes of annual temperatures, i.e. β to indicate the trend magnitudes, were calculated for three periods: 1961–1981, 1982–2009, and 1961–2009, respectively. Figure 5 presents the results of β in °C/year.

The β values are all positive during 1961–2009 over China. Most of the maximum values are found in the northern areas of the Northeast, mid-east part of Inner-Mongolia, Beijing, Tianjing, northeastern Qinghai-Tibet Plateau, and the north of Xinjiang. β values in these areas are as great as 0.40–0.50 °C/10 years, making them the most significantly warming areas in China during

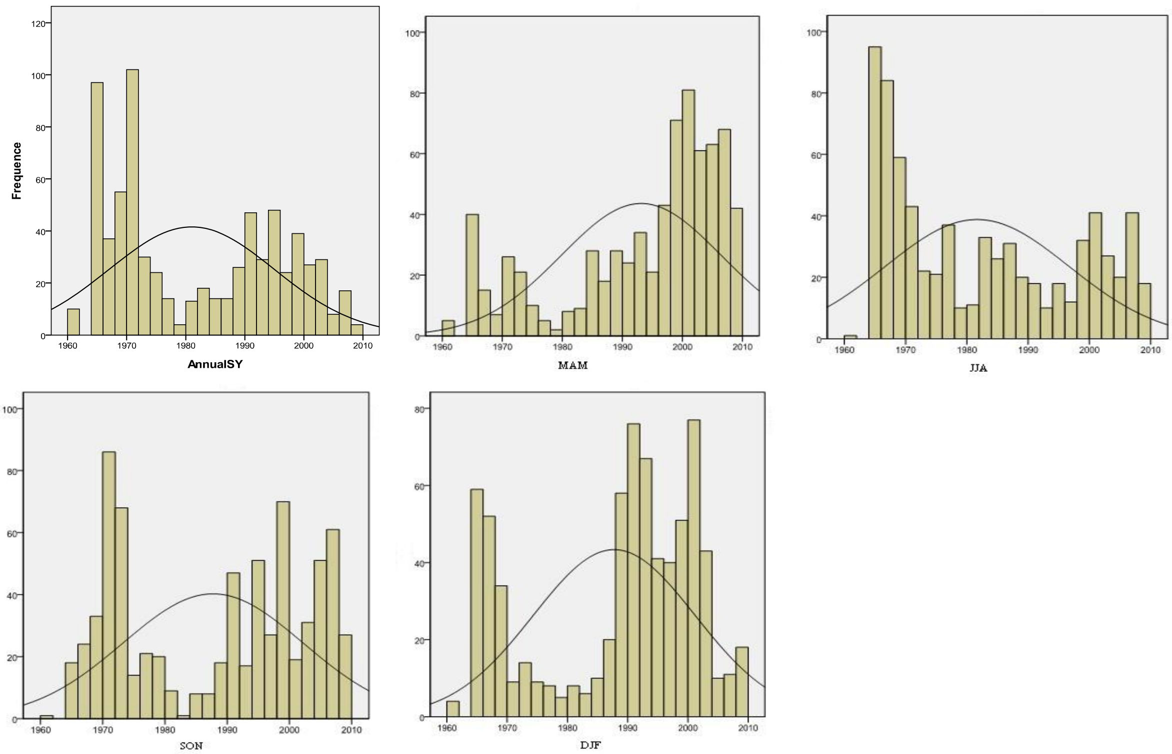

Fig. 3 Frequency distribution of the Significant Years of the annual and seasonal temperatures. The vertical axis (frequency) indicates the number of stations that have specific SY.

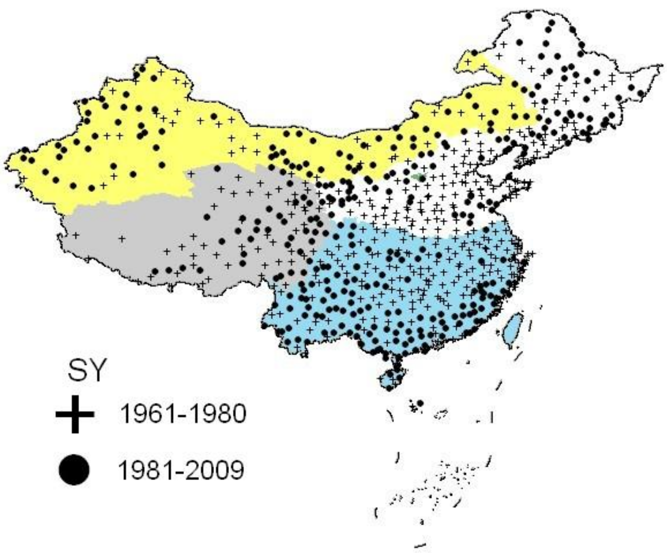

Fig. 4 Spatial distribution of annual SY (crosses stand for SY prior to 1981, circles stand for SY after 1981; in the base map, the shading distinguishes Northern China, Southern China, Northwest China and Qinghai-Tibet).

1961–2009. On the contrary, in the southwestern areas, such as Sichuan, Guizhou, Guangxi and Chongqing, the β values are no more than 0.14°C/10 years, although they are all positive. The coastal areas, such as Jiangsu, Zhejing and Guangdong, have greater β values than the neighbouring inland region, like Anhui and Hunan. Whether this has anything to do with urbanization is still uncertain and requires more research.

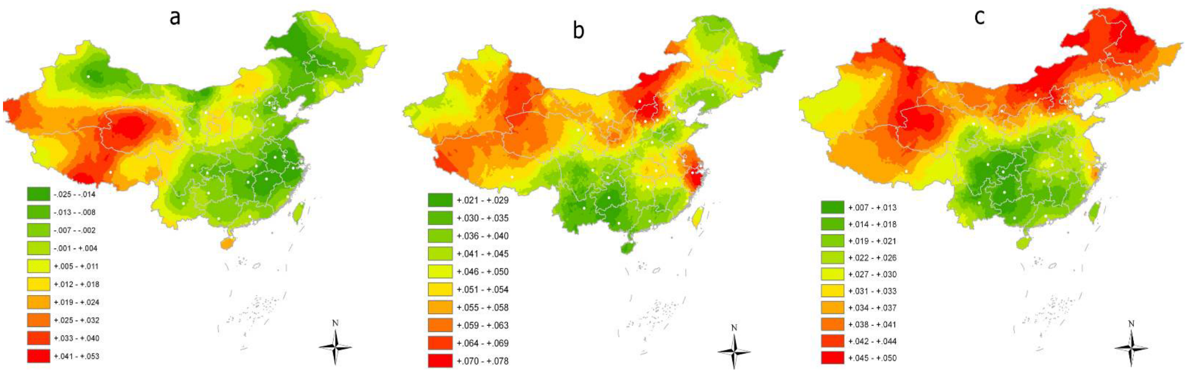

Fig. 5 Annual temperature changes, β in °C/a: (a) 1961–1981; (b) 1982–2009; and (c) 1961–2009.

The values are negative over a large percentage of China, but the Qinghai-Tibet Plateau might be warming at a rate as fast as 0.41–0.53°C/10-years. The major cooling areas are along the middle and lower reaches of the Yangtze River and the Northeast, where the decreasing rates are as great as 0.14–0.25 °C/10year. Temperatures all around China rebounded strongly during after 1981. In particular, increasing rates in parts of Zhejiang, Jiangsu, North China (especially the adjacent areas of Shanxi, Hebei and Inner Mongolia) are astonishing, 0.69–0.78°C/10 year. Even the least significant warming area, seen in parts of Guangxi and Guizhou, have rates greater than 0.21°C /10 year (see Fig. 5).

6 CONCLUSIONS

In the past 49 years, temperature in China has increased extensively. The temporal and spatial distributions of monthly and seasonal temperature trends are different. Comparatively, summer (JJA) has the least increase, while winter (DJF) has the largest increase. For yearly temperature, different patterns of seasonal temperatures may affect each other; a very significant decrease in one season may be offset by a significant increase in another season.

Average temperature over the Qinghai-Tibet Plateau (the Asian water tower), has increased in the past 49 years. This should draw attention when considering the possible consequences of snow and ice melt and glacier retreat to the local and regional energy and water cycle, as well as ecological security. North China has warmed faster than South China, if this trend continues in future, it would be wise to rethink the infrastructure building criteria for drought adaptation and water supply insurance in North China. Similarly, the Southeast Coastal areas have become warmer than their adjacent inland regions. Whether this can be explained by urbanization deserves more discussion.

The reason for setting a Significant Year (SY) is to describe the complex spatial and temporary distribution of different trends over time more effectively, and help to determine a proper divide if the trend is not continuous or changes over time. With the use of SY description, we successively determined the temporary similarity of annual and summer temperature variation. It is also an important reference to choose 1981 as the break point of trend calculation and periods.

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