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Regional differences in the timing of recent air warming during the past four decades in China

WANG ShaoPeng[1,2], WANG ZhiHeng[1], PIAO ShiLong[1] & FANG JingYun[1*]

[1] *Department of Ecology, College of Urban and Environmental Sciences, and Climate Change Research Center, Peking University, Beijing 100871, China;*
[2] *School of Mathematical Sciences, Peking University, Beijing 100871, China*

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Global surface temperature has dramatically increased in the past decades. It is critical to evaluate such a change using appropriate approaches. The previous studies for assessment of the change usually used overall trends of temperature series (i.e. slopes of simple linear regression of temperature versus year based on a least-square analysis) for entire study period. Temperature trends, however, differ among different periods, i.e. there are often breakpoints in the temperature series. Therefore, the overall linear trend of a temperature series may conceal some of the temporal characteristics of the temperature change. To precisely characterize the temporal and spatial patterns of air temperature change in China, we analyze the annual mean temperature series between the year of 1961–2004 for 536 meteorological stations across China, using piecewise linear regression approach. We found remarkable breakpoints in the annual mean temperature during the study period across the country. The annual mean temperature started to increase in 1984 at a rate of 0.058°C/a at the country level. The year when warming started appeared to be gradually later from the north to the south: temperature increased since the 1970s in the north (north of 40°N), and did not rise until the 1980s in most areas of the south (south of 40°N), with warming starting in 1983 in the Tibetan Plateau. The trends in annual mean temperatures showed a large spatial heterogeneity across China: a relatively small rising with a rate of 0.025–0.05°C/a in the Sichuan Basin, Central China and South China; the greatest increase in some parts of northwest China (i.e. Xinjiang) with up to a rate of 0.1°C/a; and rising at a rate of >0.05°C/a for most regions of the country. The feedbacks of cold waves and snow may be responsible for such regional differences in the timing and rates of warming in China.

piecewise linear regression, breakpoint, the timing of warming, regional differences, Tibetan Plateau

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In the last two decades, changes in global climate, especially temperature, have received widespread attention and become a central issue in the field of environmental sciences [1]. Many observations and simulations have been performed to explore the temperature change and its influence on ecosystems [1–8]. In previous studies, a common method to evaluate the rate of temperature changes is to fit an overall linear model for the study period using ordinary least-square (OLS) regression [1,6,8]. According to the Third and Fourth Assessment Report by the Intergovernmental Panel on Climatic Change (IPCC), the global mean surface temperature had increased by 0.6 (0.4–0.8)°C from 1901 to 2000 and 0.74 (0.56–0.92)°C from 1906 to 2005, respectively [1,9]. Temperature trends, however, always exhibit temporal variations, i.e. they differ among different periods. By analyzing the global mean temperature series over the period of 1880–1997, Karl et al. [10] found that remarkable breakpoints existed in the temperature series, suggesting that an overall linear rate is insufficient to characterize the low frequency behaviors of temperature changes. Therefore, new approaches are needed to evaluate the temporal characteristics of temperature changes.

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*Corresponding author (email: jyfang@urban.pku.edu.cn)

Additionally, temperature changes are not spatially homogeneous [1]. It has been indicated that the increasing rates of temperature on terrestrial surface are higher than those on oceanic surface [1]. Moreover, the rates of warming tend to enhance towards high latitudes in the Northern Hemisphere [1]. Located in the eastern part of Eurasia, China contains diverse landforms, including the highest plateau (i.e. Tibetan Plateau) and many mountain ranges, which result in dramatic and complex climatic variations in China [11]. In addition, because the territory of China is influenced by several different airflows, especially by the monsoons, different regions show obviously different response sensitivities to global warming [12]. Many studies had been conducted by Chinese scientists to examine the temperature change in China and its regional patterns [6–8,12–15]. It was shown that during the past half century, the surface air temperature had increased by 0.026°C/a in eastern China and 0.018°C/a in western China [8], while it increased by 0.02–0.03°C/a in northern China and less than 0.01°C/a in southern China [6]. Most of these studies focused on the spatial pattern of the overall increase rates or abrupt change of temperature during a particular period [6,12,15]. However, there have been little discussions about the geographic patterns in the timing of recent air warming, which will improve our understanding of the warming process in China.

In this paper, based on the annual averaged surface air temperature data from 536 stations across China from 1961 to 2004, we analyzed the temporal variations of temperature change in China during the past four decades using a piecewise linear regression approach. To investigate the spatio-temporal characteristics of annual mean temperature change across the country, we applied the algorithm for each station and explored the spatial pattern of breakpoints in temperature series as well as change rates before and after breakpoints.

1 Data and methods

1.1 Data source and preprocessing

The data of diurnal mean temperature recorded in 1951–2004 at 679 meteorological stations in China are obtained from the Chinese National Meteorological Center. The stations are nearly uniformly distributed across the whole country except in the Tibetan Plateau and central Taklimakan Desert. The average distance between stations is about 86 km. Considering that some stations have relatively short recording duration or contain largely incomplete records, we executed strict data filtration to ensure the reliability of our analysis using two criteria: (1) because of much less numbers of available stations and much more missing data before 1960, we conducted our analysis for the period of 1961–2004; and (2) to improve the accuracy of data, the stations with missing records of >10 days were omitted. We hence obtained data of diurnal temperature series from 536 stations from 1961 to 2004 to perform following analyses, among which 435 (81%) stations had complete records.

For the missing data, we did not make corrections because of the extremely low missing proportions (<0.1%) for all stations. For each station, we calculated monthly mean temperature by averaging the recorded diurnal temperature in the month, and then mean annual temperature (MAT) by averaging the obtained monthly data. The country-averaged MAT was finally derived from the average of 536 stations.

It should be noted that we did not make homogeneity adjustment for the temperature series. Although some non-climatic factors, such as relocation of stations and equipment updating, may cause inhomogeneity in temperature series [16–18], the effects may take place at a local scale but not at the country-scale [17]. In addition, the previous approaches for homogeneity adjustment are all based on spatial smoothing algorithms, which may eliminate real local variations in the temperature trends. Moreover, these homogeneity adjustment methods need to be further improved and unified, because the adjusted results are sensitive to some subjective factors, such as the use of different methods or statistics, and the number of reference series [17–19]. Therefore, we did our analyses based on original series rather than homogenized data.

1.2 Statistical analyses

Piecewise linear regression (PLR) approach was used to explore temporal variations in the trend of temperature changes during the past four decades in China. PLR is a method to solve the problem of heterogeneous trends in time series, which was originated from statistics [20–22]. It was first proposed by Page [20] to test whether several samples were from the same population, given no grouping information. Quandt [21,22] developed the theory into two-stage linear models, and provided algorithms for parameter estimation and statistical testing. In the past decades, theories of the piecewise linear regression have been applied in many fields [23–26]. Generally, two forms of piecewise linear models can be applied for different problems: (1) no continuity restriction at breakpoints; and (2) continuous at each breakpoint. The former has been widely used to detect temporal inhomogeneity in meteorological data [16,18,27,28], while the latter is useful for determining the boundary along environmental gradients [29–31]. In recent years, the latter model has also been used to examine transition of trends in long time-series climatic data [10,32].

The PLR method attempts to detect (one or more) potential breakpoints and fits linear trends before and after each breakpoint. The optimal solutions for the model are the breakpoints and phase slopes that minimize the residual sum of squares. Specifically, for the continuity-restricted PLR model with only one potential breakpoint (BP), the value of *BP* which minimizes the following error function is regarded as the breakpoint [31,32].

$$Q(BP;a,b_1,b_2)=\sum_{i=1}^{n}\left[y_i-a-b_1t_i-b_2\max(t_i-BP,0)\right]^2, \quad (1)$$

where y_i is a time series (dependent variable); t_i is the time (independent variable); and *BP* is the potential breakpoint. The parameters to be estimated are intercept a and two slopes b_1 and b_2.

With the continuity-restricted PLR model, we estimated the breakpoints and trends (slopes) of two phases separated by the breakpoints in the MAT series (1961–2004) for the whole country and for all 536 stations. In our calculations, two restrictions were made for our data: (1) because of the short time span (44 years) in this study, we assumed that only one breakpoint existed in each series; and (2) to ensure that two divided series were both longer than 10 years so that they were long enough to reflect valid trends, the breakpoint was restricted in the period of 1970–1995. In addition, to compare with the phase change rates, we calculated the overall rate of temperature change during the whole study period (i.e. 1961–2004) using ordinary linear regression, which was called overall changing rate (OCR) or overall increasing rate (OIR) of temperature below.

To present the spatial patterns of the breakpoints of 536 stations, we conducted spatial smoothing analysis to eliminate the noises of individual stations. Green & Silverman[33] developed several algorithms for spatial smoothing, among which the Thin Plate Spline (TPS) method was most commonly used. To conduct a TPS smoothing, a penalty function is firstly defined as eq. (2) [33]:

$$S(g)=\sum_i\left[Y_i-g(z_i)\right]^2+\alpha\cdot\int\left(g_{xx}^{"2}+g_{xy}^{"2}+g_{yy}^{"2}\right)\mathrm{d}x\mathrm{d}y, \quad (2)$$

where $z_i=(x_i, y_i)$ refers to the spatial coordinates, α is the smoothing parameter, and the thin plate spline function g is constructed as

$$g(z)=\sum_{i=1}^{n}\delta_i\cdot\frac{1}{16\pi}\left|z-z_i\right|^2\cdot\log\left(\left|z-z_i\right|^2\right)+a_1x+a_2y+a_0. \quad (3)$$

In eq. (2), the first item is the residual sum of squares, while the second item represents the roughness penalty. The TPS algorithm derives the optimal parameter solutions for eq. (3) by minimizing $S(g)$ under known α, which could be estimated by cross validation. In this study, we applied the TPS method to conduct spatial smoothing to clarify the geographic patterns of the breakpoints. Tps function in the R package "fields" (http://www.image.ucar.edu/Software/fields) was used, with α estimated by cross validation [34].

To investigate the significance of trends transition, Shea & Vecchione [30] proposed a synthetic method based on the following three steps: (1) examining whether the residuals are random or (nonlinear) correlated with the independent variable; (2) defining a loss function to measure the differences between ordinary regression and PLR; and (3) comparing the slopes before and after breakpoint. However, this method was complicated and hard to realize. Therefore, we simplified the method and examined the significance using the following two steps. Firstly, an *F* statistic was constructed for hypothetical testing [18,31]:

$$F=\frac{(\mathrm{RSS_{sl}}-\mathrm{RSS_{pl}})/1}{\mathrm{RSS_{pl}}/(n-3)}. \quad (4)$$

$\mathrm{RSS_{sl}}$ and $\mathrm{RSS_{pl}}$ are residual sum of squares from ordinary linear regression and PLR, respectively, and n is the length of time series. The F statistic follows $F(1, n\text{-}3)$ distribution under the null hypothesis H_0: no breakpoint exists. Lund and Reeves [18] proposed a modified statistic, $F_{\max}$, because the algorithm for detecting breakpoints is associated with issue of extreme-value statistics. However, testing the significance of the smoothed breakpoints can avoid this problem. Therefore, F, instead of $F_{\max}$, was used in our analysis, and the significance was given under a significance level of 0.05. Secondly, the slopes of the two phases of a temperature series before and after the breakpoint were compared, and if any transition between significant increase (significant positive slope), significant decrease (significant negative slope), and insignificant change (insignificant slope) happened, the breakpoint was considered to be significant. Here, the significances of two phase slopes were tested by *F* test [35].

2 Results and discussion

2.1 Trends of country-averaged MAT

During the period of 1961–2004, overall increasing rate of country-averaged MAT was 0.027°C/a ($P<0.01$) (Figure 1). However, a significant breakpoint was identified in 1984 (Figure 1), which is consistent with the timing of trends transition achieved by moving average method in previous studies [7,14,36]. The trend of country-averaged MAT was insignificant before 1984, with an increasing rate of 0.001°C/a ($P=0.87$), while it increased rapidly after 1984 at a rate of 0.058°C/a ($P < 0.001$), which was more than twice of the OIR and resulted in a total increase of 1.2°C during the past two decades. Therefore, OIR significantly underestimated actual warming rate after the mid-1980s and covered the rapid warming process in recent twenty years in China.

2.2 Geographic patterns of the warming time of mean annual temperature

PLR analysis detected significant breakpoints in MAT series for 478 (89%) out of all 536 stations (Figure 2). The stations with insignificant breakpoints were mostly located

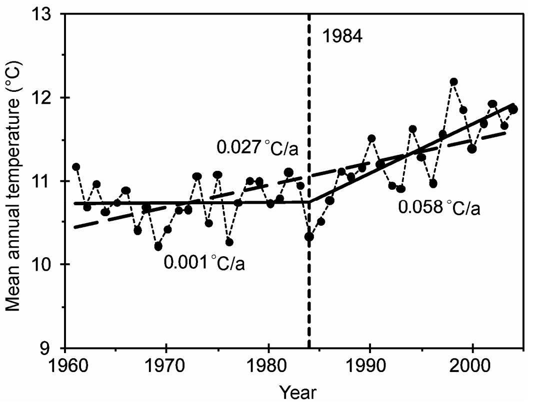

Figure 1 The country-averaged mean annual temperature in China during 1961–2004. The dashed and twofold line represent the overall rate (0.027°C/a) and rates (0.001°C/a and 0.058°C/a) for the two phases, respectively. Vertical broken lines show the occurrence year of breakpoint (1984).

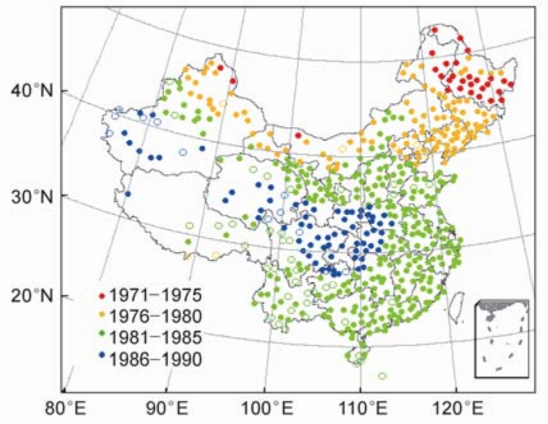

Figure 2 Occurrence time of breakpoints in mean annual temperature series for 536 stations. The occurrence time of breakpoints is divided into four time periods, 1971–1975, 1976–1980, 1981–1985, and 1986–1990 illustrated by different colors. Stations with insignificant breakpoints are represented in hollow.

in western China and the Tibetan Plateau. Figure 3 illustrated the patterns of temperature change rates before and after breakpoints. Temperature at most (81%) of the stations did not change (increase or decrease) significantly before the breakpoints (Figure 3(a)). Only a few stations in north and southeast Tibetan Plateau showed slight warming trends, and a few in Sichuan Basin and middle-lower Yangtze Basin showed slight cooling trends. In contrast, after the breakpoints, most (93%) stations saw significant warming trends (Figure 3(b)). The averaged increase rate of temperature was 0.056°C/a, which was more than twice of the averaged OIR (0.026°C/a). Moreover, the rates of temperature increase after the breakpoints varied geographically. In particular, the rates were relatively low (0.025–0.05°C/a) in Sichuan Basin, Central and South China, but higher (>0.05°C/a) in North and East China (Figure 3(b)). In Northwest China, the rates of temperature increase at some stations were even up to 0.1°C/a, e.g. Hotan and Minfeng stations (both 0.1°C/a) in Xinjiang and Mangya station (0.15°C/a) in Qinghai. The transition, from insignificant change before breakpoint to significant increase after breakpoint, suggested a start of warming (warming time) in most areas of China.

The time of the breakpoints varied greatly across the country, suggesting that the warming in different regions started in various years (Figures 2 and 3). In particular, warming first started in the northern part of Northeast China (Heilongjiang and northeastern part of Inner Mongolia) and Altay Mts. in Xinjiang in 1971–1975, and then moved towards the south. In the southern part of Northeast China, west Inner Mongolia, and north Xinjiang, warming started in 1976–1980, while it started in 1981–1985 in East, South and Southwest China, and in the Yellow River Basin. The latest warming began in 1986–1990 in Central China, northern parts of the Tibetan Plateau, and Taklimakan Desert, where the warming was later by 10–15 years than in north China. As a whole, the warming started from the north towards the south, and from the coast towards the inland. Such a geographic pattern of warming time is consistent with the previous findings on the timing of temperature abrupt change [12,15].

Previous studies suggested that temperature started to increase in the 1960s in the Tibetan Plateau, much earlier than in other regions of China, and therefore temperature changes in the plateau had been considered as a signal of global warming [37,38]. By analyzing the time series of region-averaged MAT for 33 stations across the Tibetan Plateau (Qinghai and Tibet) during the past four decades, however, we found that a significant breakpoint was in 1983 (Figure 4). This suggests that temperature started to increase in 1983 in the Plateau: temperature did not change significantly (P=0.254) before 1983 and increased significantly after 1983 at a rate of 0.047°C/a (P<0.001). This is to say, the warming in the Plateau delayed by c.a. ten years compared with that in northern China (Figure 2). Recently, Ding et al. [15] reported a similar finding to ours.

The regional differences in the timing of recent air warming probably reflect different sensitivities of the different regions to climatic change. Some relevant factors can accelerate or decelerate the process of temperature change, thus leading to an asynchrony of temperature change in different regions [15,39]. A recent study [39] showed that the frequency of cold waves from Siberia began to decrease slightly in the late 1960s, but decreased remarkably since the late 1970s. This declining cold wave frequency, together with its mutual feedbacks with the Siberian high, the winter monsoon, and air temperature, may cause a warming much earlier in northern China than in other regions. In addition, another feedback process, i.e. the positive feedback of “snow-albedo”, proposed by Ding et al. [15], could also influence the geographic pattern of warming time, especially in northern China and the Tibetan Plateau. Ding et al. [15]

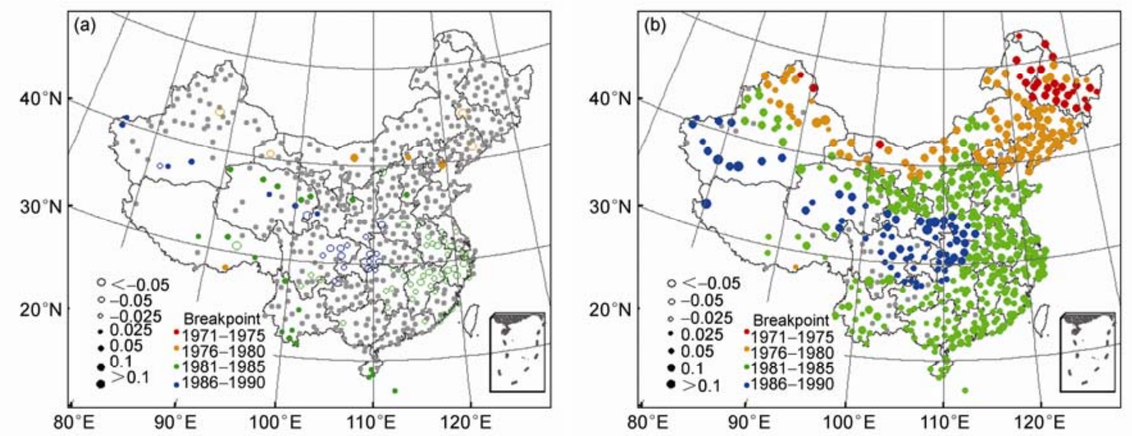

Figure 3 Changing rates of temperature for two phases: (a) before breakpoints; (b) after break points. The size of points represents the magnitude of change rates, while the colors indicate the occurrence time of breakpoints, except the gray color which implies insignificant trends.

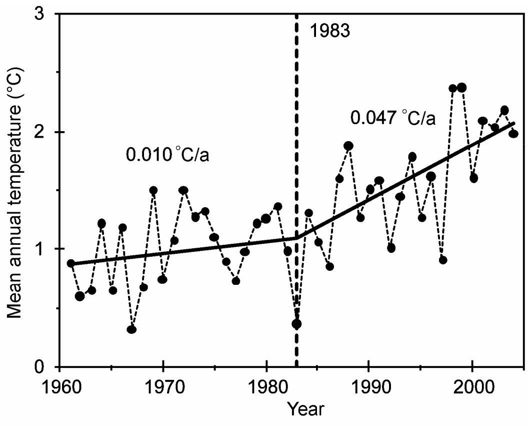

Figure 4 Region-averaged mean annual temperature in the Tibetan Plateau (Qinghai and Tibet, including 33 stations) during 1961–2004. The vertical broken lines show the occurrence year of breakpoint (1983), and the twofold line represents the trends in temperature change for the two phases.

found that in northern China snow melting could lead to a decrease of albedo, and thus to an increase of illumination absorbing, which could subsequently contribute to earlier timing and larger rates of warming. In contrast, the snow in the Tibet had increased since the 1980s, which tended to delay the warming process [15]. Although these two feedback processes could both contribute to the regional differences in the timing of recent air warming in China, further validations on the mechanisms are still needed in the future.

3 Conclusions

Piecewise linear regression approach has been increasingly used for the studies on climate change in recent years. By applying this approach for 536 meteorological stations across the country, we analyzed the changes of mean annual temperature from 1961 to 2004 and investigated the geographic patterns in the timing and rates of recent air warming in China. Our results indicated that a significant breakpoint took place in 1984 for the changes of the country-averaged temperature during the study period in China. The temperature did not change significantly before 1984, but dramatically increased after 1984, with a rate of 0.058°C/a. The OIR, which was calculated based on classic ordinary least-square regressions, observably underestimated the rate of temperature increase during the past twenty years by 0.03°C/a. Our analyses also suggested that the warming in different regions were not synchronous. The year when warming started appeared to be gradually later from north to south: warming started in the 1970s in the north (north of 40°N), while it did not begin until the 1980s in most areas of the south (south of 40°N). The feedback effects of cold wave and snow may contribute to the regional differences in the timing of recent air temperature rising.

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