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Full Length Research Paper

Statistics-induced data from meteorological station characteristics of air temperature variation in Sichuan-Chongqing for about 50 years

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This paper characterizes the spatial features and trends of temperature change during 1960 to 2009 using the daily temperature data of 48 stations in Sichuan-Chongqing and 47 stations close to Sichuan-Chongqing from 691 national meteorological stations adopting the GIS spatial analysis function and the linear trend method. The results showed that firstly, the annual mean temperature change of Sichuan-Chongqing presented different spatial unconventionally sensitive areas due to local complex terrain patterns. Typically, Sichuan basin was the cooling center and the Southwestern Sichuan became warming center. In the past 50 years, the change of annual mean temperature showed a U-pattern including the rapid cooling period of 1960s, the relative stability period of 1970s to 1980s and the obviously warming period of 1990s to 2000s. Secondly, the interdecadal change of seasonal temperature in Sichuan-Chongqing strongly fluctuated. The warming rate was more significant in spring and autumn than that in summer and winter. Specifically, in spring, the temperature change of inner Sichuan basin was generally stable, but fluctuated greatly in the boundary of Sichuan basin. In summer, the temperature change of Sichuan-Chongqing showed a weakened cooling trend, and a significantly warming trend in autumn and a gradually warming trend in winter. Thirdly, the temperature change of Sichuan-Chongqing was significantly controlled by the large temporal-scale. The trend of temperature change showed a remarkably difference among annual, decade, accumulated decade and season. The annual mean temperature did not change significantly (in a warming rate of 0.173°C/10a) in the past 50 years. However, the temperature change showed a fluctuant pattern, with a cooling trend, a stable trend, and a warming trend associating with time process, regardless of interdecades, accumulated interdecades and seasons. Fourthly, the mutation of annual mean temperature change in Sichuan-Chongqing occurred about 1974. The change of annual mean temperature presented an overall cooling trend before 1974 and a fluctuated warming trend with dentate-like patterns after 1974.

Key words: Sichuan-Chongqing, temperature change, spatial-temporal distribution, station statistics.

INTRODUCTION

The fourth IPCC report showed that the linear warming trend of global mean temperature (0.74°C) during 1906 to 2005 was 0.14°C higher than that given in the third IPCC report (0.6°C) during 1901 to 2000 (IPCC, 2007). Certainly, temperature change presented clear regional differences due to the effects of geographical location, undulant terrains and complex land surface processes (Du et al., 2004; Piao et al., 2011). Even the cooling center occurred in local areas where temperature change was the opposite as global warming trend (Chen and Chen, 2003; Liu et al., 2009). Sichuan-Chongqing, Southwest China was one of the typical anomalous areas against global warming (Ban et al., 2006; Zheng et al., 2008). Presently, it has become a key area that the research of short-term climatic change focused on. Sichuan-Chongqing (26 to 34°N and 97 to 110°E) located in the transition zone of Qinghai-Tibet plateau and eastern Great Plains, with an area of 56.63×10^4 km^2.

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Complex terrains, as plateaus, mountains, basins and hills from west to east could be seen. The types of climate involved western plateau climatic zone and eastern basin humid subtropical climatic zone. The temperature change presented the particularity with an annual mean temperature of -5 ~ 18°C due to the effects of tropical and, subtropical monsoon, plateau driving force and thermal activities. At the macro level, the climatic change of Sichuan-Chongqing was affected by the East Asian monsoon and the Indian monsoon (Han et al., 2010) but also by the role of the Tibetan Plateau circulation, at the micro level, it is influenced by the more complex factors including altitude, topography, roughness and other causes due to special location, roughness terrains and complex land surface processes.

Nowadays, many literatures were interested in the temperature change of Sichuan-Chongqing. Bai (2006) found that there was a negative correlation between monthly mean temperature and altitude and latitude, while the change of monthly mean temperature was in a weak trend along longitude in Sichuan. Qin et al. (2005) obtained that the cooling trend was obvious during 1960 to 2000 in Sichuan basin. Li and Xie (2001) stated that there was a temperature mutation from warm to cold in Sichuan basin in the mid-1970s. Chen et al. (2004) suggested that south of 35° N and east of 100° E was a cooling region from 1950s to 1990s, and the cooling center was the Sichuan basin with the highest cooling rate of 0.2°C/10a.

Afore-mentioned results indicated that Sichuan-Chongqing was a typical cooling region against the global warming trend. However, the existing literatures on its temperature change at seasonal and its decadal scale was not yet in-depth understanding. And they were still unclear to identify the decadal turnings and regional distributions of temperature change. Consequently, the minute features of temperature change still were not obtained in Sichuan-Chongqing. Hence, further research was needed to make clear the trajectory of temperature change. In this study, the spatial-temporal features of temperature change in Sichuan-Chongqing were characterized by GIS spatial analysis function and linear trend method using daily temperature data nearly 50 years.

The main objective of this paper was to provide scientific evidence to appropriately develop and use regional climate resources in Sichuan-Chongqing.

MATERIALS AND METHODS

Data description

48 stations in Sichuan-Chongqing and 47 stations close to Sichuan-Chongqing, from 691 national meteorological stations were chosen as the referenced sites. And the temperature data of 95 stations were tested for validity by Standard Normal Homogeneity Test (Alexandersson, 1986; Alexandersson and Moberg, 1997).

Consequently, 11 invalid stations were removed including 5 stations (Sichuan-Chongqing) and 6 stations (around Sichuan-Chongqing) as shown in Figure 1. The daily temperature observation data from 1951 to 2009 were provided by National Meteorological Information Center. Some missing data were replaced by the data from the near meteorological stations. There was too much missing information on the temperature records in 1950s. Thus, the temperature data of 1960 to 2009 were chosen as the main observation data so as to ensure the integrity and continuity of temperature series.

Data treatment

1. The long time series of annual and seasonal (spring, summer, autumn and winter) mean temperature were established in Sichuan-Chongqing. The range of four seasons was defined as follows, spring (March, April and May), summer (June, July and August), autumn (September, October and November), and winter (December, January and February). The arithmetic mean method was adopted when seasonal, annual, decadal and interdecadal mean temperature was calculated based on daily observation data.
2. In this study, the linear trend analysis method was adopted to calculate the rate of temperature change. The linear trend of temperature change was measured by least squares method. The correlation (r) between time and temperature was used to show whether the liner trend was significant or not. If r passed the reliability test, the linear trend was considered as statistically significance and vice versa:

$$Slope = \frac{n \times \sum_{i=1}^{n} i \times T_i - (\sum_{i=1}^{n} i)(\sum_{i=1}^{n} T_i)}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

Where $Slope$, the increase of annual mean temperature in the calculated year is calculated by linear regression between time and annual mean temperature. $n \times Slope$ is the increase (decrease) of multi-annual mean temperature. T_i is the annual mean temperature and n is the number of the calculated year.
3) Characteristics of temperature change were analyzed by cubic polynomial curve fitting.

RESULTS AND DISCUSSION

Total spatial features of temperature change nearly 50 years

As shown in Figure 2, the tendency of annual mean temperature in Sichuan-Chongqing coincided with the contour lines in the past 50 years. Mountain and plateau of Northwest Sichuan near Qinghai Province was the coldest region with multi-annual mean temperature below 0°C. And the center of Sichuan basin was the warmest region with multi-annual mean temperature above 18°C. The linear relationship between annual mean temperature (y) and altitude (x) was presented in the following, y = -0.0016x + 16.346. The correlation coefficient r was 0.8309 and the mean decline rate was 0.16°C/100 m. The boundary of annual mean temperature was Longmen

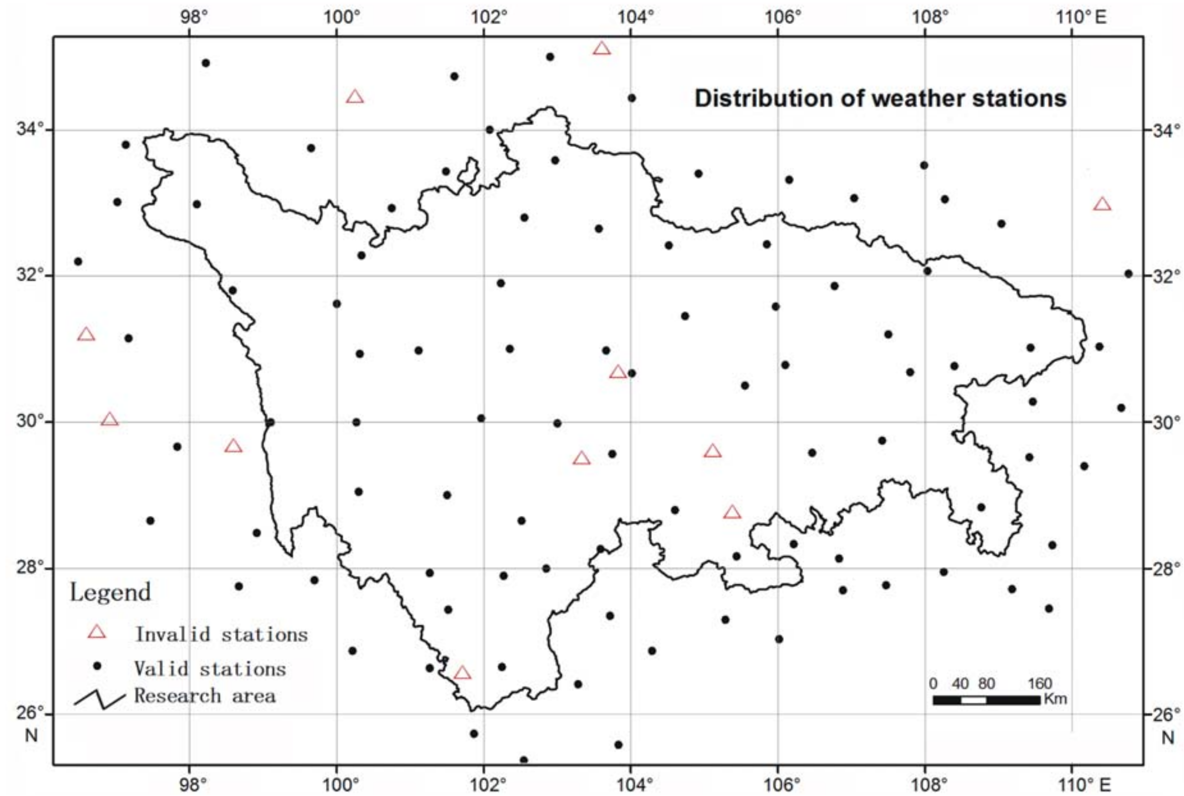

Figure 1. The distributions of weather stations in research area.

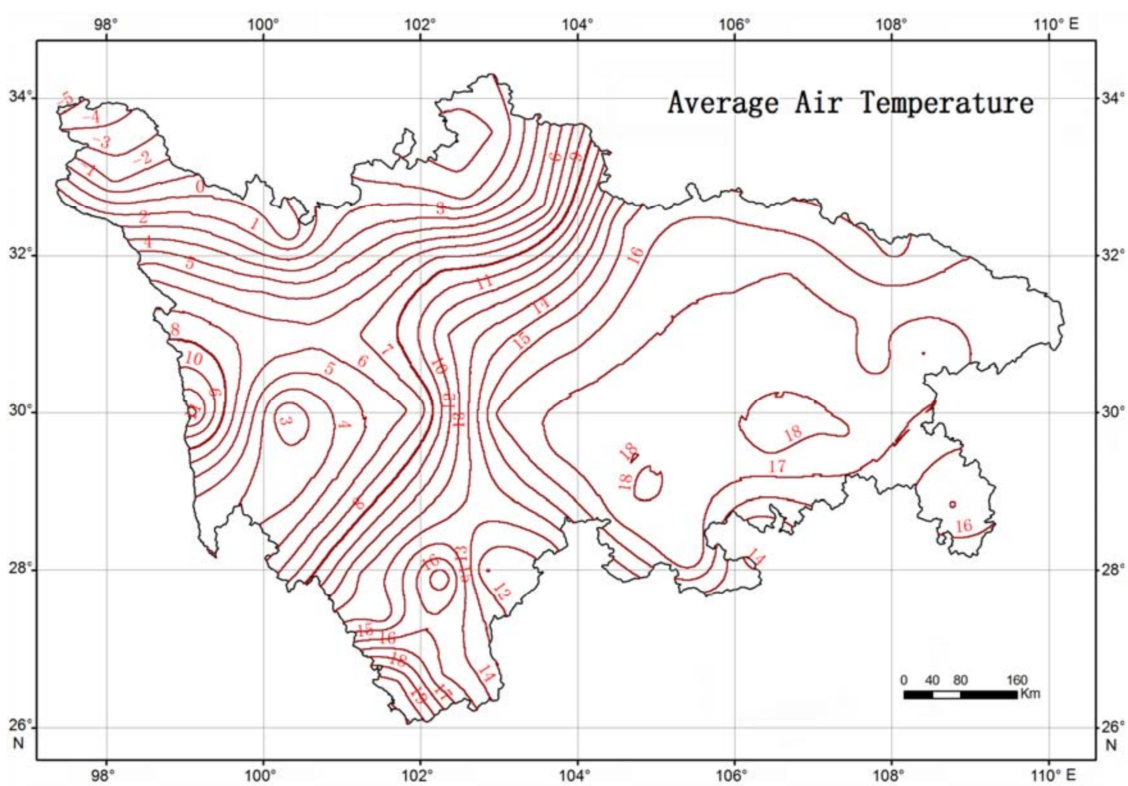

Figure 2. The annual mean temperature contours during 1960-2009.

Mountain and the Yalong River. It was below 10°C in the west of the boundary and above 12°C in the east of the boundary. The reversed tendency of temperature change showed a heavy negative correlation with huge terrain which the altitude of western Sichuan-Chongqing is relative higher and the east lower. In addition, annual mean temperature increased rapidly in western mountain and plateau areas, where it was more sensitive to warming. This result was associated with the findings described by Ge et al. (2010). Moreover, in the comparison of the contour map of annual mean temperature before 1970 and the temperature change trend in Figure 2, there was a warming trend in northwestern Sichuan and 0°C isotherm shifted to the northwest. And annual mean temperature in southwestern Sichuan and Sichuan basin was generally lower than that before 1970.

The temperature change generally presented a cooling trend during 1960s to 1970s, comparing with the differences between interdecades. The cooling range, with 0 ~ 0.5°C/10a occurred in center of Sichuan basin, mountain areas of southwestern Sichuan and plateau areas of northwestern Sichuan. The boundary of temperature change was Qionglai Mountains during 1970s to 1980s. A cooling trend in basin and hilly, eastern Qionglai Mountains was observed with the dropping scope of 0 ~ 0.5°C/10a. This result was contrary to those findings described by Du et al. (2009) who observed annual mean temperature increasing over the Nujiang River Basin during 1971 to 2008. And a warming trend in western Sichuan plateau, western Qionglai Mountains was measured with the climbing range of 0 ~ 0.5°C/10a. The temperature change of Sichuan-Chongqing generally showed a warming trend during 1980s to 1990s except for the northwestern Sichuan near Tibetan areas with a slightly cooling trend. Especially, a significant warming trend happened in Chengdu metropolitan area and Southwestern Sichuan adjacent to Yunnan Province with the range of 0.5 ~ 1.5°C/10a. During 2000s, annual mean temperature suggested a more warming trend compared with that of 1990s. A significant warming trend occurred in Chengdu metropolitan area, Fengjie, Wanzhou and the junction of Yunnan Province, and Sichuan Province and Guizhou Province with the scope of 0.5 ~ 1.5°C/10a. Aforementioned findings accorded with the features of the variability of local temperature due to the effects of complicated terrain.

The temperature change trend of Sichuan-Chongqing presented unconventional sensitive areas at spatial patterns nearly 50 years (Figure 3). Sichuan basin was the cooling center especially in Bazhong, Langzhong and Nanchong. The warming center was Southwestern Sichuan adjacent to Yunnan Province where showed the most significant warming trend, and seasonal temperature gradually increased. The winter temperature change of western Sichuan plateau was the most significant with the warming rate of 0.2°C/10a. Aerosol was accumulated in the center of Sichuan basin due to the role of around landforms (Zhao et al., 2008). And it affected the radiative processes (Zhao et al., 2006) which lead to a significant cooling trend. In spring, the temperature change of inner Sichuan basin was generally stable. And that of the boundary of the Sichuan basin showed a fluctuation situation. Specifically, the temperature change of southwestern Sichuan presented a warming trend with the maximal warming rate of 0.6°C/10a. And that of mountain areas of southern Sichuan and northern Sichuan showed a cooling trend with the maximal cooling rate of 12.2°C/10a. A standard deviation of the temperature change was 0.185. In summer, the temperature change of Sichuan-Chongqing generally showed a warming change (0 ~ 0.2°C/10a), and was divided into three areas, that is, the slow cooling area of central Sichuan basin, the relative stable area of western Sichuan plateau and the slightly warming area of external western Sichuan plateau. In particular, the warming trend of southwestern and northwestern Sichuan was significant with the variability of 0.4 ~ 0.8°C/10a. There was a slowly cooling trend in eastern Sichuan with the cooling rate of 0 ~ 0.2°C/10a. And the standard deviation of the temperature change was 0.017.

In autumn, the temperature change was in a warming trend. Its spatial patterns showed a significant linear feature. The mountains around Sichuan basin and the border of western Sichuan plateau were slowly warming areas. And the temperature change of the inner Sichuan basin and the western Sichuan plateau was generally in a stable state. In winter, the features of temperature change were in an obvious difference between East and West of Sichuan-Chongqing. It ran in opposite directions from Longmen Mountain. Western Sichuan plateau, the west of Longmen Mountain suggested a quick warming area with the warming rate up to 0.97°C/10a. Central Sichuan basin, the east of Longmen Mountain indicated a slow cooling area. Afore-mentioned findings were not associated with those results found by Ren et al. (2005) in Southwestern China as a whole from 1952 to 2004. Concretely, in Southwestern China, spring and summer temperature generally showed some cooling trend especially spring with the obvious cooling trend. And four seasonal temperatures were in significant warming trend in southern Yunnan Province.

Spatial variabilities of interdecadal seasonal temperature

The interdecadal trends of temperature change in spring, autumn and winter were significant especially in spring. Generally, it was in accordance with that of China and of the northern Earth in which the warming rate was the most significantly in 1990s. In the past 50 years, the interdecadal trends of seasonal temperature change presented a strong fluctuation. Its trend delayed compared with that in China during the corresponding period. Overall, it in spring and winter was prominent in 1960s and 1980s, whereas it was insignificant in summer

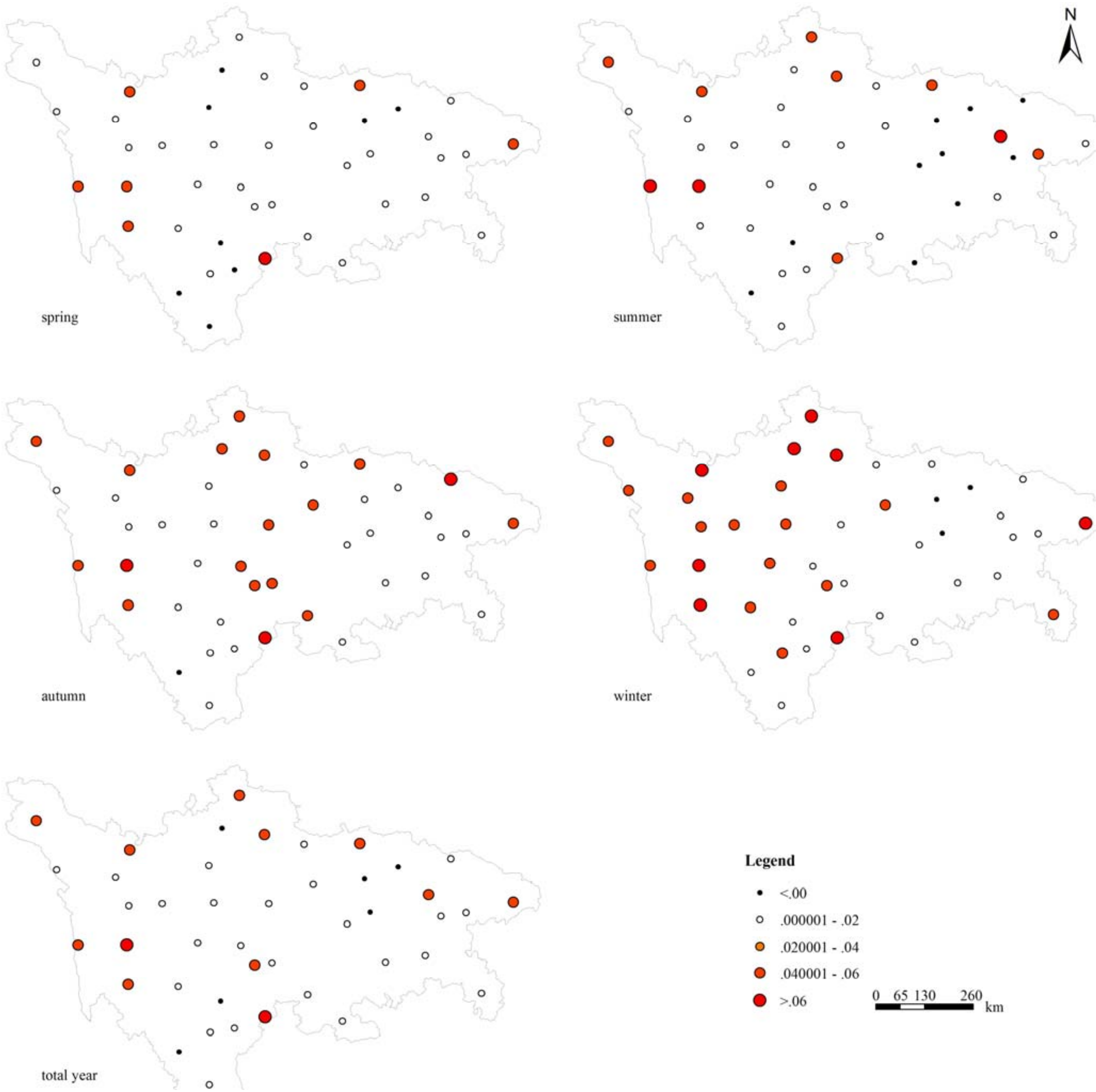

Figure 3. Spatial variabilities of air temperature for four seasons in Sichuan-Chongqing in the past 50 years.

and autumn. In 1970s, it was more obvious in autumn and winter than that in spring and summer. In 1990s, it presented obviously in spring and autumn, and it was not pronounced in summer and winter. In 2000s, it in spring showed a significant trend while an unapparent change in other three seasons.

The interdecadal variation of seasonal temperature change was largely obvious (Figure 4). In spring, the temperature change fluctuated strongly. The temperature of western Sichuan plateau showed a significant warming trend, whereas, in central Sichuan basin, it fluctuated frequently. Mountain body in the east of western Sichuan plateau impacted significantly on the spatial variation of spring temperature change. Western Sichuan plateau as a whole was in a warming state especially at the junction of Sichuan Province, Yunnan Province and Tibet Municipality where the interdecadal trend of spring mean temperature was in a remarkably warming scenario.

In central Sichuan basin, it was in an obviously fluctuated state, with a frequent up-and-down parabola

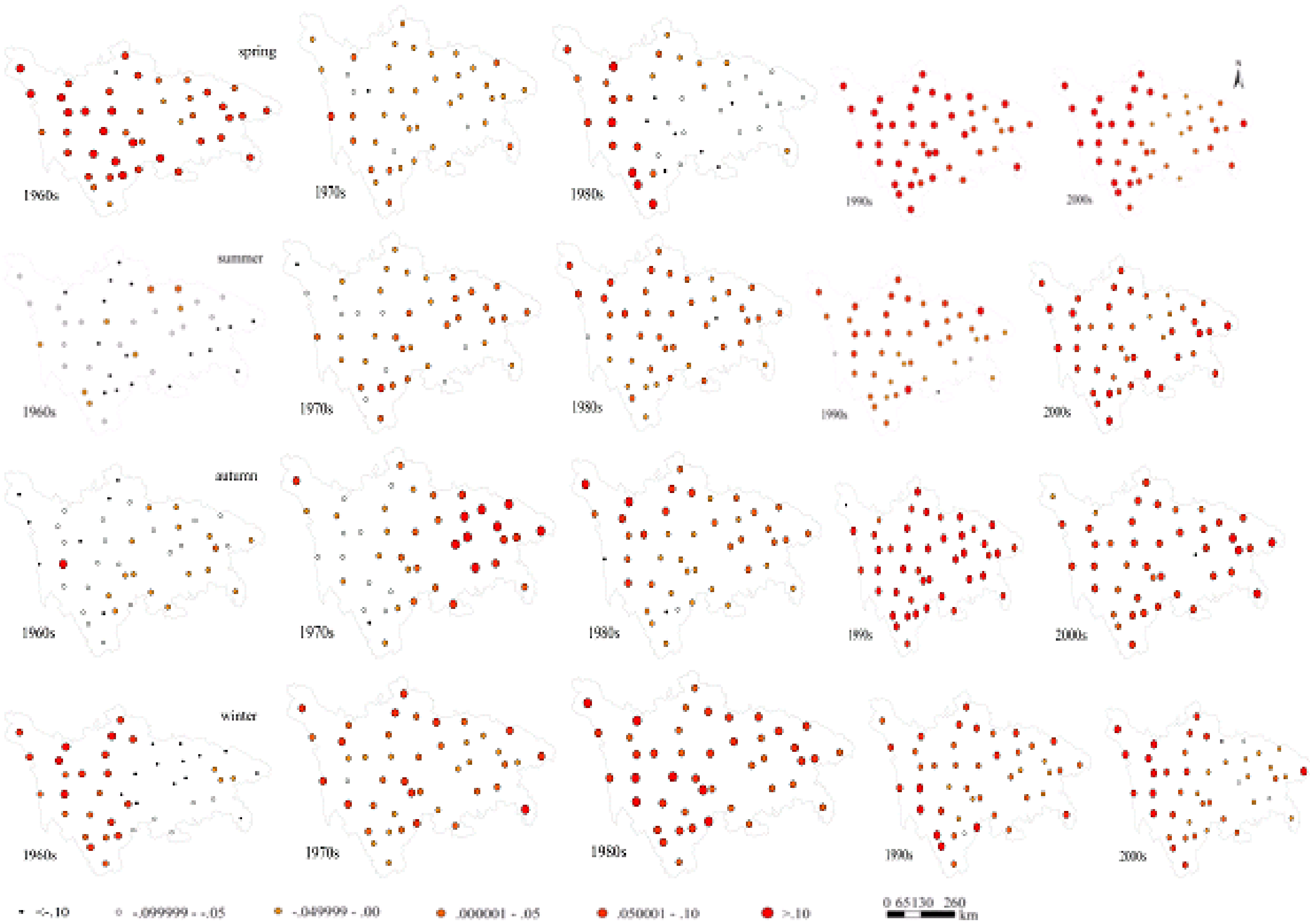

Figure 4. The spatial variabilities of seasonal mean temperature in Sichuan-Chongqing in the past 50 years.

type. In a word, there was a warming trend in spring in 1960s and 1990s especially in 1990s. The trend of temperature change between western Sichuan plateau and Sichuan basin in spring was generally similar in other four decades except for that in 2000s with an opposite result. A reverse finding was obtained by Ren et al. (2005) in Southwestern China. In summer, the interdecadal cooling trend was gradually weakened. Especially, since 1990s, summer mean temperature began to rise up. As a whole, it presented three phases: a basically cooling term throughout the 1960s and 1970s, a transition period from cooling to warming during 1980s and a generally warming stage since 1990s. Hence, 1980s could be regarded as a transition point of summer temperature change from cooling to warming. The interdecadal variation of summer temperature change was relatively small due to daily lowest temperature slowly climbing. At the same time, it presented strong local features at spatial patterns. The summer temperature of western Sichuan plateau showed a significant warming trend, especially since 1990s with an increasingly strongly warming state. In central Sichuan basin, it presented a warming trend with the warming rate above 0.5°C/10a. In 2000s, it in other areas presented a warming trend except that in Chengdu metropolitan area. Those results were reverse with the findings of Zhang et al. (2006) in Southeastern China.

The interdecadal trend of autumn temperature change was clearly warming especially in 1990s. It presented strong fluctuations: An obviously cooling trend was in 1960s. In 1970s and 1980s, a generally cooling trend still occurred in most of the Sichuan-Chongqing areas. A warming trend was observed since 1990s while a relative slowly warming trend occurred in 2000s. Namely, in autumn, a transitional period from cooling to warming occurred in 1990s. Moreover, autumn temperature change showed a regional regularity. The cooling trend in 1960s and the warming trend in 1990s and 2000s were all over the Sichuan-Chongqing. But, in 1970s and 1980s, the warming trend appeared in Sichuan basin. And the warming trend of Sichuan basin delayed than that in western Sichuan plateaus. In Sichuan basin and its east, autumn min-temperature being clearly increased during 1986 to 2006 with the warming rate up to 0.55°C/10a resulted in an obvious warming autumn since mid-1980s. In western Sichuan plateau, it increased monotonously in 1960s and largely contributed to the warming autumn since 1970s.

In winter, a warming trend of interdecadal temperature was generally observed especially since 1970s. In detail, winter mean temperature was the coldest in 1960s but presented gradually the warming trend. It was up to the warmest in 1980s.

The warming range in 1990s was as similar as that in 2000s which showed a slightly warming trend compared with that in 1980s. In addition, the interdecadal change of winter temperature showed significant regional heterogeneity. In western Sichuan plateau, there were two mutation points which occurred in 1970s and 1980s, respectively, and it lasted a warming trend since 1980s. In Sichuan basin and its east, it presented a generally cooling trend in spite of a down-up-down fluctuation compared with that of western Sichuan plateau. Moreover, two mutations occurred in 1980s and 1990s, respectively, with a last cooling trend. This finding was similar with the suggestion of Li et al. (2007), but was contrary with the result described by Pan (2006).

Patterns of temperature change at multi-temporal scales

Figures 5, 6 and 7 were the fitting graph of mean temperature at seasonal, annual, decadal and accumulated decadal scale, respectively. The trend of temperature change presented obvious differences at multi-temporal scales. The multi-annual mean temperature was 12.0°C (Figure 5a). Moreover, interannual trend of temperature was not significant. The highest value was 13.75°C in 2009 and the lowest value was 11.16°C in 1968. The trend of annual mean temperature change was calculated by the fitting of 5-year moving average, linear regression and cubic polynomial fitting. As shown in Figure 5a, it showed a warming trend in the past 50 years with the warming rate of 0.173°C/10a.

In the past 50 years, the cooling range was relatively weak while the heating trend was relatively strong. Annual mean temperature reached a min-value in 1980s. In the reference of Figure 6a, it can be seen that it was lower than multi-annual mean temperature, although it indicated a warming trend since 1982. And since 1985, it gradually increased up to multi-annual mean temperature. Ban et al. (2006) found a similar result of the warming trend after 1980s in southwestern China. As shown in Figure 5b, the interdecadal variation of annual mean temperature was obvious in the past 50 years. Concretely, it experienced a rapid cooling period in 1960s with a change rate of -0.848°C/10a. And it was a relatively stable period during 1970s to 1980s. A rapid warming period was observed since 1990s especially after 2000 with a warming rate of 1.124°C/10a. That is, there was a generally cooling trend during 1960s to mid-1980s and a clear warming trend since late 1980s. At the same time, the linear trend at multi-temporal scales intersected around 1974. Before the intersected point, it showed a cooling trend and a fluctuated warming trend after the intersected point. This result suggested that the turning point of annual mean temperature change occurred about 1974 (Figure 6).

Zhao et al. (2008) found that the temperature of Sichuan-Chongqing was unconventionally cold in 1976. Moreover, annual mean temperature showed a cooling trend in 1960 to 1969, 1960 to 1979 and 1960 to 1989, while a warming tend after 1960 to 1999. This result suggested that a turning point happened in 1989. Before the turning point, annual mean temperature was in a slight warming trend, and after the turning point, a rapid warming trend occurred. In addition, according to decadal mean temperature, a finding could be drawn out that annual mean temperature during 1960 to 1990 was in a slight cooling trend and the lowest 11.74°C occurred in the late 1980s. Namely, it was in a stable cold period during 1960 to 1990 and in a gradually warming period after 1990.

The change of seasonal mean temperature in spring and autumn contributed more for annual mean temperature rising than that in summer and winter (Figure 7). In 1960s, it generally showed a rapid cooling trend especially in summer with the cooling rate of 1.412°C/10a. Moreover, a relative stable cooling trend happened in spring and autumn with the cooling rate of 0.59°C/10a and 0.634°C/10a, respectively. A slight warming trend occurred in winter with the warming rate of 0.405°C/10a.

The seasonal temperature change smoothly fluctuated during 1970s to 1980s.

In 1970s, it slowly declined in spring and summer and slowly rose in autumn and winter. In 1980s, it showed a warming trend except that in spring with a cooling trend. In 1990s to 2000s, seasonal mean temperature change suggested a rapid warming trend, particularly, with the warming rate of 0.84°C/10a and 1.056°C/10a in spring, 0.676°C/10a and 0.811°C/10a in autumn, respectively. From the aforementioned results, it can be seen that the warming rate of spring and autumn in 1990s was more significant than that in 2000s. But, the warming rate of summer and winter in 1990s was less obvious than that in 2000s. This result was inconsistent with the observation of Huang and Hu (2006) towards Southern China.

Conclusions

The temperature change of Sichuan-Chongqing was generally in a gradual warming trend in the past 50 years

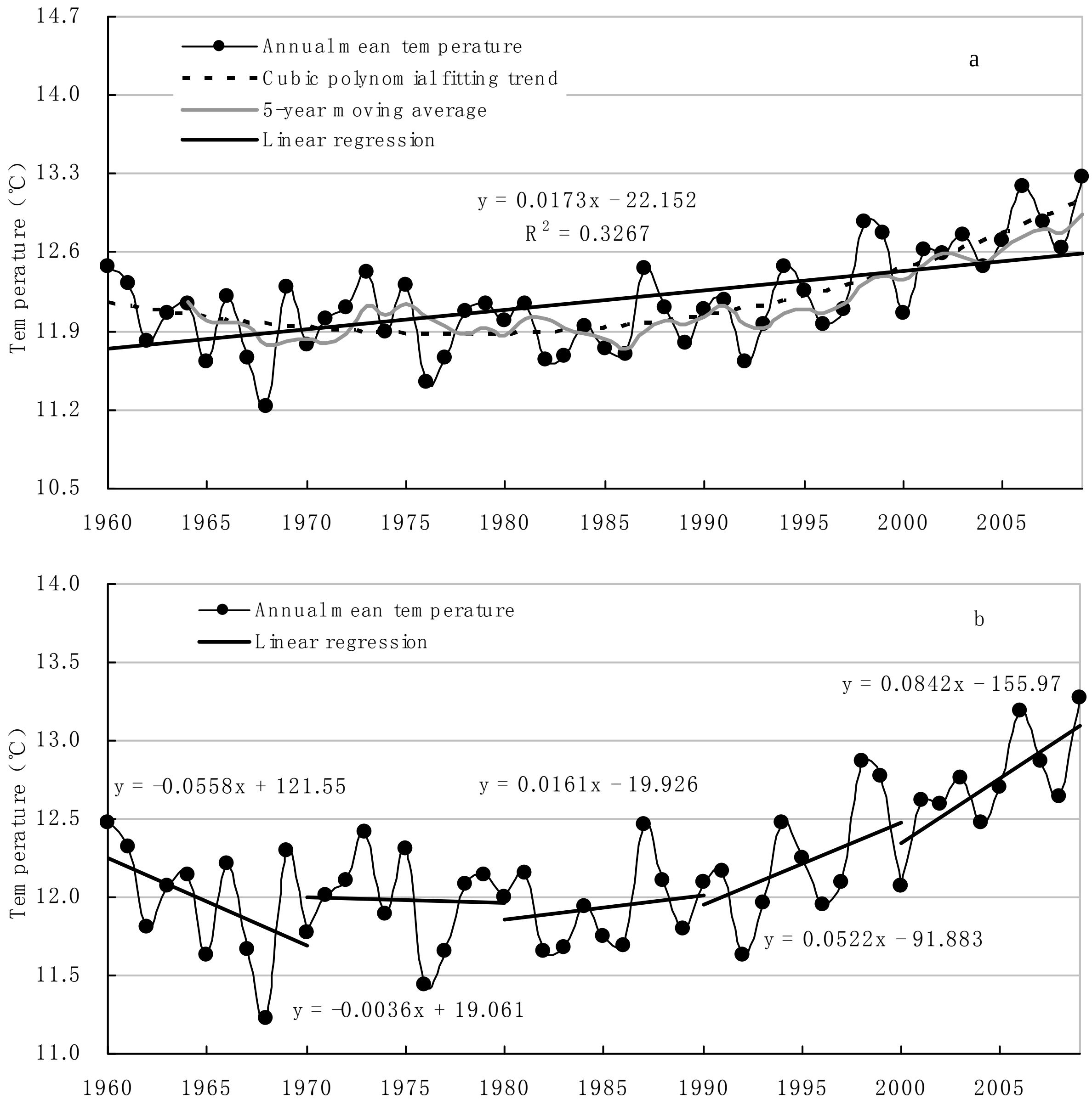

Figure 5. The change of annual mean temperature and its fitting trend in Sichuan-Chongqing in the past 50 years.

with the down-and-up fluctuation. On one hand, the temperature variation showed largely different between southwestern Sichuan, western Sichuan mountains and plateau, and Sichuan basin and its east due to the effects of complex landforms. On the other hand, it presented similar trends as a whole on the condition of the large time scale and complex variations for different cases at the small time scale. Hence this paper found:

1. The change of multi-annual mean temperature was reverse in west and east of Longmen Mountain and Yalong River. And it presented complex local features due to relief diversity. In the past 50 years, annual mean temperature was lower than 10°C west of the boundary and above 12°C east of the boundary. Sichuan basin became the cooling center, and Southwestern Sichuan, near the Yunnan Province became the warming center. Moreover, it showed a U-pattern, that is, a rapid cooling period in 1960s, a relative stable period during 1970s to 1980s and a significant warming period during 1990s to 2000s.

2. The interdecadal trend of seasonal mean temperature strongly fluctuated. And it was in accordance with the warming trend in 1990s of the northern Earth. Moreover, the warming rate was more significant in spring and autumn than that in summer and winter during the past 50 years. Specifically, in spring, the temperature change of inner Sichuan basin was generally stable, but fluctuated

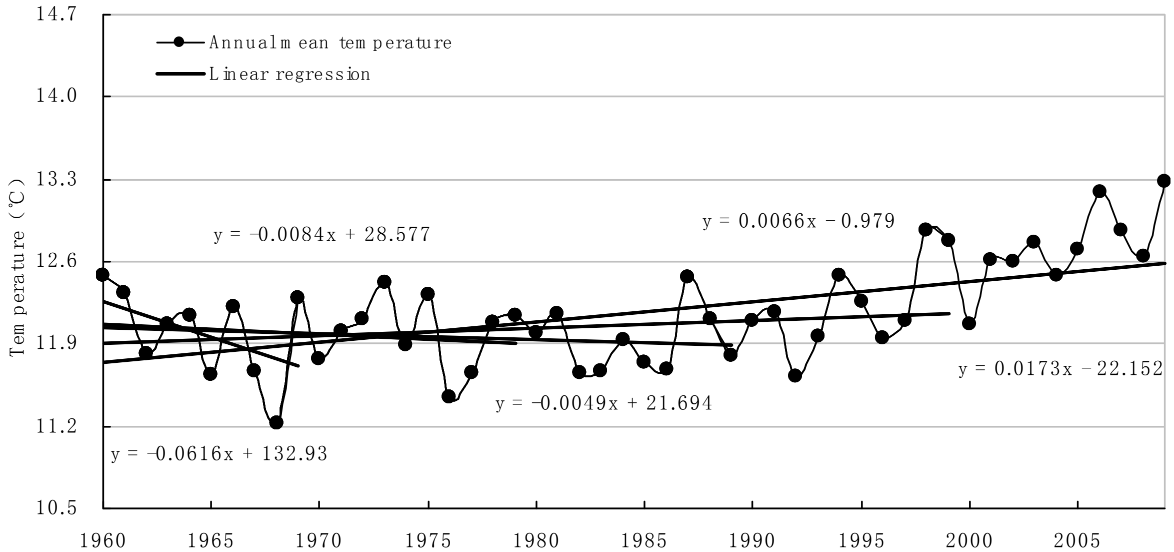

Figure 6. Fitting trends of annual mean temperature during different stages.

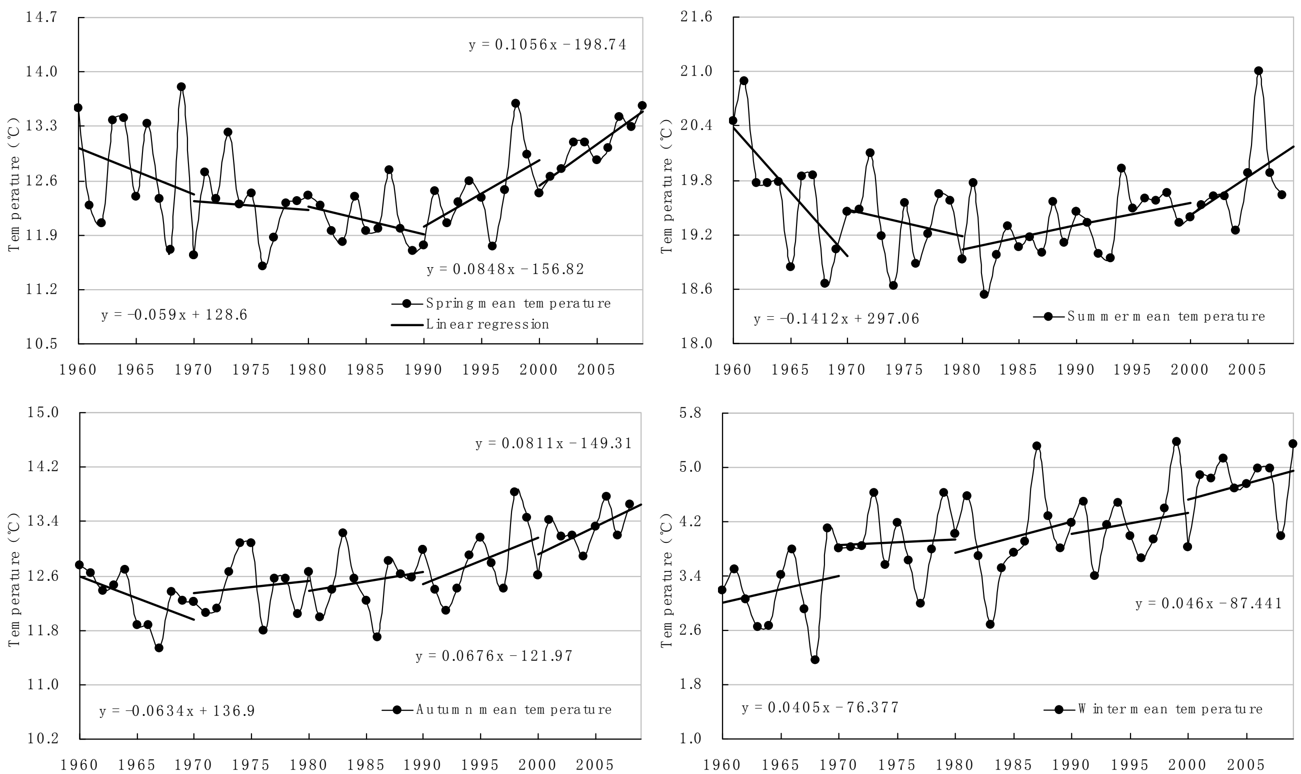

Figure 7. Seasonal changes in mean temperature and its decadal fitting trend in Sichuan-Chongqing in the past 50 years.

greatly around Sichuan basin. In summer, it showed a weakened cooling trend, and a significant warming trend in autumn and a gradual warming trend in winter all over the Sichuan-Chongqing.

3. The temperature change significantly was controlled by the large time-scale. The fitting trend of mean temperature change at annual, decadal, accumulated decadal and seasonal scale was in pronounced differences. The interdecadal variations of annual mean temperature were not obvious with a warming rate of 0.173°C/10a. The mean temperature change showed a fluctuant state with a cooling trend, a stable trend and a warming trend

regardless of interdecades, accumulated interdecades and seasons.
4. The mutation of annual mean temperature occurred in 1974 and 1989. Concretely, the change of annual mean temperature presented an overall cooling trend before 1974 and a fluctuated warming trend after 1974. And it began a warming trend at accumulated decadal scale after 1989, while presented a cooling trend before 1989. This finding indicated another mutation that happened in 1989.

The aforementioned findings were obtained using statistics-induced data from national meteorological station. This study did not include local meteorological station data due to data availability. Thus, the results were slightly different if based on the data both from national and local meteorological station. However, the general trend of temperature change was similar in the past 50 years regardless of using the data from national or local meteorological station. The following interest of this study will further research the temperature change with the increase of local meteorological station data. Moreover, to minimize the effects of complex landform on temperature change, this study only analyzed the temperature data by statistical method, and did not adopt the spatial interpolation analysis, which did also contribute the differences from other studies. And the trend of temperature change was in significant different at annual, decadal, accumulated decadal and seasonal scale, respectively. Hence, the data of the last 10 years was merely used to analyze the trend of temperature change, and its finding, with a warming rate of 0.842°C/10a possibly exaggerated the trend of climate change. In addition, this study only obtained the basically features of temperature change in the past 50 years.

The effects of typical geographic factors on the trend of temperature change as complex terrains, latitude and longitude were not analyzed. Future research will focus on temperature change trend with altitude, latitude, longitude and their coupling nearly 50 years.

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