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Observed trends of heating and cooling degree-days in Xinjiang Province, China

Fengqing Jiang · Xuemei Li · Binggan Wei · Ruji Hu · Zhen Li

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Abstract Global warming has the potential to impact various aspects of human society such as agriculture, construction, transportation, water resources management, power generation, and phenology. The impact on energy, especially energy consumption for heating and cooling of buildings, is very important. These influences are different in terms of space and time due to spatial and temporal variations of temperature. In this study, daily data of minimum and maximum temperature of 51 stations for 1959–2004 were used to detect annual and seasonal variations of heating and cooling degree-days in Xinjiang, China, by using the Mann–Kendall trend test and linear regression techniques. The results indicate that: (1) taking 18°C as the base temperature, annual mean heating degree-days (HDD) ranged between 2,700 and 7,973°C, and annual mean cooling degree-days (CDD) (the base temperature is 24°C) ranged between 0.4 and 792°C. CDDs are relatively low in Xinjiang; (2) autumn, winter, and annual HDDs show significant decreasing trends. Annual CDD at 23 out of 51 stations present significant increasing trends, while no remarkable positive trends can be observed at the other stations; and (3) with respect to spatial variations, Xinjiang was characterized by significant decreasing annual, winter, and autumn HDDs, and it was particularly true for the northern Xinjiang. The annual and summer CDDs in the western parts of northern Xinjiang (the edges of the Tarim Basin and the Turpan-Hami Basin) were characterized by significant increasing trends. However, no fixed spatial patterns can be identified in the variations of annual and summer CDDs. The results of this study could be useful for energy management in Xinjiang and are also helpful for better understanding of impacts of global warming on energy consumption in other countries of the world.

F. Jiang (✉) · X. Li · B. Wei · R. Hu · Z. Li
Xinjiang Institute of Ecology and Geography,
Chinese Academy of Science,
818 South Beijing Road,
Urumqi, Xinjiang 830011, China
e-mail: jiangfengqing18@yahoo.com.cn

F. Jiang · X. Li · B. Wei · R. Hu
Key Laboratory of Oasis Ecology and Desert Environment,
Xinjiang Institute of Ecology and Geography, CAS,
Xinjiang, China

1 Introduction

Global warming and its effects on human society is a matter of general concern (IPCC 2001; Zhang et al. 2008). Temperature variations can directly affect agriculture, construction, transportation, water resources, power generation, and phenology, particularly energy consumption for heating and cooling of buildings (Sen and Kadioglu 1998; Kadioglu and Sen 1999). These impacts, however, vary from place to place due to spatial and temporal variations of temperature. The energy consumption for heating and cooling buildings mainly hinges on temperature changes. Many studies have indicated considerable impacts of temperature changes on energy consumption in buildings (e.g., Yan and Chen 1994; Sailor and Munoz 1997; Chen and Huang 2000; Chen and Hong 2000; Zhou 2000; Cartalis et al. 2001; Matzarakis and Balafoutis 2004; Lam et al. 2004; Liu et al. 2005; Christenson et al. 2006).

Degree-day, which is a truncation of daily temperature series at a constant level, i.e., base temperature, is usually accepted as an index of energy consumption for heating and cooling of the buildings (e.g., Matzarakis and Balafoutis 2004; Lam et al. 2004; Chen and Huang 2000). Increasing temperature may imply a decrease in heating degree-days

(HDD) and an increase in cooling degree-days (CDD), and vice versa. However, it is a qualitative evaluation method. Therefore, quantitative assessment is usually necessary to reflect the energy demand of heating or cooling for buildings based on daily temperature observations due to the unique role of HDD and CDD in regional energy management.

Xinjiang, an autonomous region located in northwest China, covers about 1,600,000 km^2 with two vast deserts lying between three high mountains stretching across the north, the middle, and the southern parts of the study region. Xinjiang is sensitive to temperature changes. Our temperature analysis indicates that the diurnal temperature ranges between 11 and 16°C and annual temperature between 30 and 70°C. The mean annual maximum temperature ranges between 36 and 45°C and mean annual minimum temperature between –20 and 40°C. Most regions in Xinjiang have freezing temperature in winter and high temperatures in summer, thus heating (cooling) is necessary in winter (summer). Residential energy consumption, including heating and cooling, accounts for about 17.78% of the total energy consumption in Xinjiang (XUARBS 2007). Under current global warming trends, we are unsure of the extent to which temperature variability may affect energy consumption for building heating or cooling in the Xinjiang region. The answer may depend on better understanding of trends of HDDs and CDDs in this region (Kadioglu et al. 2001). Despite comprehensive studies elsewhere (Thom 1952; EL-Shaarawi and AL-Masri 1996; Sen and Kadioglu 1998; Badescu and Zamir 1999; Kadioglu and Sen 1999; Buyukalaca et al. 2001; Kadioglu et al. 2001; Matzarakis and Balafoutis 2004; Li et al. 2006; Yildiz and Sosaoglu 2007), no such investigation has been completed for Xinjiang. In this study, annual and seasonal variations of HDDs and CDDs in Xinjiang are estimated based on daily maximum and minimum temperature. Distribution patterns of annual HDDs and CDDs are analyzed and related to geographical elements (i.e., altitude, longitude, and latitude). Possible implications of these results are discussed for regional energy management. The findings of this study should be useful for energy management in the Xinjiang region under global warming trends.

2 Data and methods

2.1 Data

The daily maximum and minimum air temperature dataset for 55 stations in Xinjiang was provided by the National Climatic Centre of China, China Meteorological Administration, China. The quality of the dataset was firmly controlled before its release. Furthermore, homogeneity tests were also performed (Feng et al. 2004; Ding et al. 2007). Four stations having more than 1 year with missing temperature data were excluded from the analysis. The missing data were processed in the following ways: (1) If only 1 day had missing data, the missing data were replaced by the average value of its neighboring days; and (2) if consecutive two or more days had missing data, the missing data were estimated by simple linear correlation between its neighboring stations (R^2>0.95). As a result, 51 stations were selected for this study. The temperature series covers 1959–2004. Detailed information on the stations and dataset is presented in Table 1, while Fig. 1 shows the geographic locations of the 51 meteorological stations used in the study.

2.2 The degree-days

Degree-day is a measure of the energy requirement for heating and cooling of buildings. The degree-days of a time interval (monthly, seasonal, and annual) are defined as the summation of the temperature anomaly between the mean daily air temperature and the base temperature. A number of approaches have been used for computation of HDD and CDD (Thom 1952; EL-Shaarawi and AL-Masri 1996; Sen and Kadioglu 1998; Badescu and Zamir 1999; Kadioglu and Sen 1999; Buyukalaca et al. 2001; Matzarakis and Balafoutis 2004; Li et al. 2006; Yildiz and Sosaoglu 2007). Simple approaches use the difference between the mean daily air temperature and base temperature while more complicated approaches usually calculate HDD or CDD by comparing the daily pattern of air temperature and that of the base temperature (Kadioglu et al. 2001). In this study, the simple method was used to compute HDD and CDD. For a time interval of n days, accumulated HDD can be defined as:

$$HDD = \sum_{i=1}^{n} (T_{bh} - T_{meani})^{+} \quad (1)$$

which has the same unit as the temperature. In Eq.(1), the daily mean air temperature, T_{meani}, is defined as $T_{meani} = (T_{\max i} + T_{\min i})/2$, where T_{maxi} (T_{mini}) is the daily mean maximum (minimum) air temperature; T_{bh} is the base temperature and is usually defined as 10°C, 12°C, 14°C, 16°C, 18°C and 20°C (EL-Shaarawi and AL-Masri 1996; Sen and Kadioglu 1998; Kadioglu and Sen 1999; Buyukalaca et al. 2001; Matzarakis and Balafoutis 2004; Li et al. 2006; Yildiz and Sosaoglu 2007).

Similarly, CDD can be defined as:

$$CDD = \sum_{i=1}^{n} (T_{meani} - T_{bc})^{+} \quad (2)$$

Table 1 Information of stations and basic statistical features of annual mean HDDs and CDDs of 51 stations in Xinjiang

Station no.	Station name	Latitude (°N)	Longitude (°E)	Elevation (m)	Data period	Annual HDD Mean (Std)	Annual CDD Mean (Std)
1	Aheqi	40.93	78.45	1,984.9	1957.1.1–2004.12.31	4,115.5 (207.4)	0.0 (0.0)
2	Akesu	41.17	80.23	1,103.8	1953.6.1–2004.12.31	3,219.5 (191.9)	57.5 (22.9)
3	Alaer	40.55	81.27	1,012.2	1958.12.1–2004.12.31	3,208.1 (145.0)	33.1 (15.7)
4	Alashankou	45.18	82.57	336.1	1956.7.1–2004.12.31	4,230.7 (281.3)	181.8 (52.9)
5	Aletai	47.73	88.08	735.3	1954.1.1–2004.12.31	5,216.5 (365.4)	25.9 (18.8)
6	Bachu	39.8	78.57	1,116.5	1953.3.1–2004.12.31	2,937.3 (165.8)	81.8 (34.2)
7	Baicheng	41.78	81.9	1,229.2	1958.10.1–2004.12.31	3,850.4 (234.3)	1.5 (2.2)
8	Balikun	43.6	93.05	1,677.2	1956.12.1–2004.12.31	5,772.1 (355.8)	0.0 (0.0)
9	Baluntai	42.73	86.3	1,739	1957.11.1–2004.12.31	4,070.7 (231.5)	0.0 (0.0)
10	Bayinbuluke	43.03	84.15	2,458	1957.11.1–2004.12.31	7,973.4 (380.0)	0.0 (0.0)
11	Beitashan	45.37	90.53	1,653.7	1957–10.1–2004.12.31	5,572.5 (271.7)	1.8 (3.0)
12	Caijiahu	44.2	87.53	440.5	1958.10.1–2004.12.31	4,913.4 (275.0)	52.3 (24.2)
13	Dabancheng	43.35	88.32	1,103.5	1956.4.1–2004.12.31	4,300.1 (203.2)	0.6 (1.0)
14	Fuhai	47.12	87.47	500.9	1957.11.1–2004.12.31	5,375.4 (357.5)	7.2 (6.4)
15	Habahe	48.05	86.40	532.6	1957.11.1–2004.12.31	5,069.1 (412.6)	5.3 (6.1)
16	Hami	42.82	93.52	737.2	1951.1.1–2004.12.31	3,596.0 (186.5)	192.4 (49.3)
17	Hebukesaier	46.78	85.72	1,291.6	1953.7.1–2004.12.31	5,170.2 (292.0)	3.0(3.8)
18	Hetian	37.13	79.93	1,375	1953.2.1–2004.12.31	2,700.3 (196.2)	174.8 (46.8)
19	Hongliuhe	41.53	94.67	1,573.8	1952.7.1–2004.12.31	4,467.4 (227.3)	8.7 (10.5)
20	Jinghe	44.62	82.90	320.1	1953.1.1–2004.12.31	4,331.3 (277.4)	54.6 (28.2)
21	Kashi	39.47	75.98	1,289.4	1951.2.1–2004.12.31	2,914.7 (207.8)	111.5 (41.8)
22	Kelamayi	45.62	84.85	449.5	1956.12.1–2004.12.31	4,353.0 (317.1)	328.5 (69.1)
23	Kuche	41.72	82.97	1,081.9	1951.1.1–2004.12.31	3,093.9 (154.6)	145.6 (38.6)
24	Kuerle	41.75	86.13	931.5	1958.7.1–2004.12.31	3,119.3 (167.4)	207.3 (45.4)
25	Kumishi	42.23	88.22	922.4	1958.11.1–2004.12.31	3,938.7 (196.6)	68.3 (27.2)
26	Luntai	41.78	84.25	976.1	1958.10.1–2004.12.31	3,170.3 (200.8)	54.8 (34.5)
27	Mangai	38.25	90.85	2,944.8	1958.9.1–2004.12.31	5,638.8 (465.2)	0.0(0.0)
28	Minfeng	37.07	82.72	1,409.5	1956.12.1–2004.12.31	2,995.4 (196.4)	121.8 (46.6)
29	Pishan	37.62	78.28	1,375.4	1959.1.1–2004.12.31	2,845.6 (175.4)	57.3 (26.5)
30	Qiemo	38.15	85.55	1,247.2	1953.5.1–2004.12.31	3,290.7 (168.8)	24.1 (16.2)
31	Qinghe	46.67	90.38	1,218.2	1957.10.1–2004.12.31	6,303.7 (434.8)	0.4 (1.3)
32	Qitai	44.02	89.57	793.5	1951.4.1–2004.12.31	4,910.9 (258.7)	43.0 (23.0)
33	Ruoqiang	39.03	88.17	887.7	1953.3.1–2004.12.31	3,117.4 (154.7)	110.8 (30.3)
34	Shache	38.43	77.27	1,231.2	1953.7.1–2004.12.31	2,906.3 (171.9)	37.1 (16.8)
35	Shihezi	44.32	86.05	442.9	1952.9.1–2004.12.31	4,498.8 (277.3)	111.7 (39.0)
36	Shisanjianfang	43.22	91.73	721.4	1952.7.1–2004.12.31	3,805.1 (296.7)	120.9 (87.5)
37	Tacheng	46.73	83.00	534.9	1953.6.1–2004.12.31	4,302.0 (364.1)	47.2 (28.5)
38	Tasgkuergan	37.77	75.23	3,090.1	1957.1.1–2004.12.31	5,259.4 (317.4)	0.0(0.0)
39	Tieganlike	40.63	87.7	846	1957.1.1–2004.12.31	3,312.1 (160.2)	94.9 (35.8)
40	Tuergate	40.52	75.4	3,504.4	1958.10.1–2004.12.31	7,670.9 (231.1)	0.0 (0.0)
41	Tuoli	45.93	83.60	1,077.8	1956.10.1–2004.12.31	4,780.4 (394.0)	4.9 (4.7)
42	Turpan	42.93	89.2	34.5	1951.7.1–2004.12.31	2,884.7 (243.2)	792.1 (84.2)
43	Urumqi	43.78	87.65	935	1951.1.1–2004.12.31	4,429.8 (274.8)	124.5 (71.5)
44	Wenquan	44.97	81.02	1,357.8	1957.12.1–2004.12.31	5,096.1 (247.9)	0.0 (0.0)
45	Wuqia	39.72	75.25	2,175.7	1955.11.1–2004.12.31	3,979.6 (262.2)	5.3 (7.2)
46	Wusu	44.43	84.67	478.7	1953.3.1–2004.12.31	4,360.6 (298.8)	214.0 (56.0)
47	Yanqi	42.08	86.57	1,055.3	1951.5.1–2004.12.31	3,820.6 (194.2)	5.7 (5.2)
48	Yining	43.95	81.33	662.5	1951.8.1–2004.12.31	3,616.1 (292.1)	31.0 (18.0)
49	Yiwu	43.27	94.7	1,728.6	1958.11.1–2004.12.31	5,095.4 (230.8)	0.0 (0.0)
50	Yutian	36.85	81.65	1,422	1955.11.1–2004.12.31	2,866.2 (164.8)	25.0 (14.0)
51	Zhaosu	43.15	81.13	1,815	1954.3.1–2004.12.31	5,201.4 (251.7)	0.0 (0.0)

The base temperatures for HDDS and CDDs were 18 and 24°C, respectively

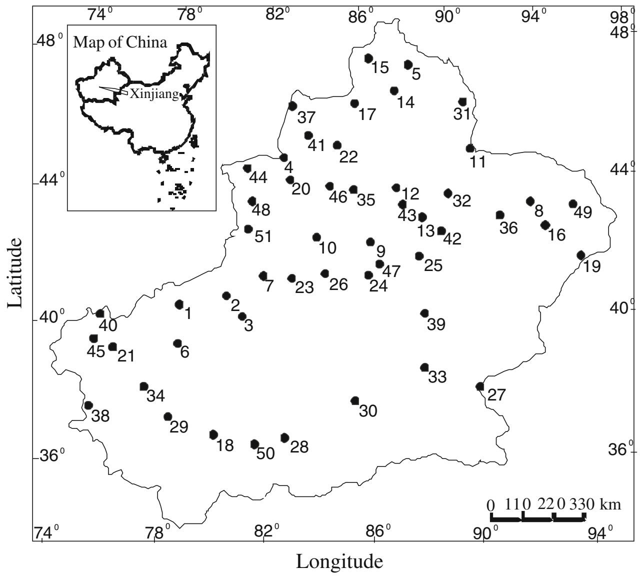

Fig. 1 Location of the selected meteorological stations

where, T_{bc} is the base temperatures and is usually defined as 18°C, 20°C, 22°C, 24°C, 26°C and 28°C (EL-Shaarawi and AL-Masri 1996; Sen and Kadioglu 1998; Kadioglu and Sen 1999; Buyukalaca et al. 2001; Matzarakis and Balafoutis 2004; Li et al. 2006; Yildiz and Sosaoglu 2007). The "+" signs in Eqs. (1) and (2) mean that only positive values were included in computation.

It should be noted here that definition of the base temperature differed from place to place. For instance, a base temperature of 15.5°C was used for HDD calculations in Jordan, while in Saudi Arabia, the base temperatures used for HDD calculations varied from 17.8 to 21.1°C. Many other countries, however, have chosen 18.3°C as the base temperature to define HDD (Kadioglu et al. 2001). In China, 18°C is usually accepted as the base temperature for HDDs and 24°C for CDDs (CIAS 1996). In this study as well, the base temperatures of 18 and 24°C were used for HDD and CDD calculations, respectively.

Inverse distance weighted (IDW) interpolation was used to illustrate the spatial patterns of annual mean HDDs and CDDs over the study region. The Pearson correlation coefficient (two-tailed) was applied to evaluate the relationships between mean HDDs and CDDs in terms of longitude, latitude, and altitude.

2.3 Methodology

A number of statistical methods can be used for trend detection. Every method has its own strengths and weaknesses. In our study, the linear regression technique and non-parametric Mann–Kendall (MK) test (Kendall 1938; Pei et al. 1999; Serrano et al. 1999; Partal and Kahya 2006; Yue et al. 2002) are used to detect trends. Linear regression analysis indicates the tendency rate (slope) by using least-squares method at the 0.05 significance level.

In the MK trend test, the null hypothesis, H_0, is that the data $\{X_i,\ i=1,\ 2,\ldots,\ n\}$ are independent and identically distributed (iid) random variables and the hypothesis, H_1, is that there is a trend in the series (Partal and Kahya 2006). Statistic S is defined as:

$$S=\sum_{k=1}^{n-1}\sum_{j=k+1}^{n} sgn\left(x_j-x_k\right) \tag{3}$$

where, n is the length of the series, and

$$\mathrm{sgn}\left(x_j-x_k\right)=\begin{cases}+1, \left(x_j-x_k\right)>0\\ 0, \left(x_j-x_k\right)\quad =0\\ -1, \left(x_j-x_k\right)<0\end{cases} \tag{4}$$

It has been proven that, when $n\geq 8$, statistic S approximately follows the normal distribution with 0 mean and the variance as:

$$Var(s)=\left[n(n-1)(2n+5)-\sum_t t(t-1)(2t+5)\right]\Big/18 \tag{5}$$

where, t is the extent of any given time. Standardized statistic Z can be calculated as:

$$Z=\left\{\begin{matrix}\frac{S-1}{\sqrt{Var(S)}}, S>0\\ 0,\qquad S=0\\ \frac{S+1}{\sqrt{Var(s)}}, S<0\end{matrix}\right\} \tag{6}$$

Z follows the standard normal distribution with 0 mean and unit variance. A positive S indicates an upward trend and vice versa.

3 Results

3.1 Heating degree-days (HDDs)

3.1.1 Basic statistical properties and spatial patterns of HDDs

Table 1 shows statistical features of annual HDDs (T_{bh}=18°C) at 51 stations in Xinjiang. It can be seen from Table 1 that annual mean HDDs ranged from 2,700 to 7,973°C. Maximum HDD was observed at Bayinbuluke station, while the minimum HDD was observed at Hetian station. HDDs were distinctly different from station to station showing great spatial variability, e.g., annual mean HDD at Aletai, a city located in northern Xinjiang, was 5,216°C, and that at Hetian, a city located in southern Xinjiang, was only 2,700°C. This indicates that energy required for heating the same building in Aletai is roughly two times more than that in Hetian. The standard deviations of annual HDDs ranged from 145 to 465°C. The largest standard deviations of annual HDD were found in Mangai and Qinghe, and the minimum was in Alaer (Table 1). This indicates that larger inter-annual variations of HDD usually corresponded to larger annual HDD.

Figure 2 maps the spatial patterns of annual mean HDD (a) and annual mean CDD (b) in Xinjiang. Figure 2a shows that the southwestern part of Xinjiang is characterized by lower annual mean HDDs, while higher HDDs can be observed in the northeastern part of Xinjiang. In the central Xinjiang, in the vicinity of the Tianshan Mountains, several regions were dominated by relatively higher HDDs, and lower HDD was observed in Tarim and Turpan Basins. Effects of terrain and geographic location on spatial patterns of annual mean HDDs were also evaluated by using a simple linear regression method (Fig. 3). Pearson correlation relations between annual mean HDDs and latitude and altitude indicated significant correlations at a significance level (two-tailed *t*-test) of 0.01 with correlation coefficients of 0.477 and 0.457, respectively. Furthermore,

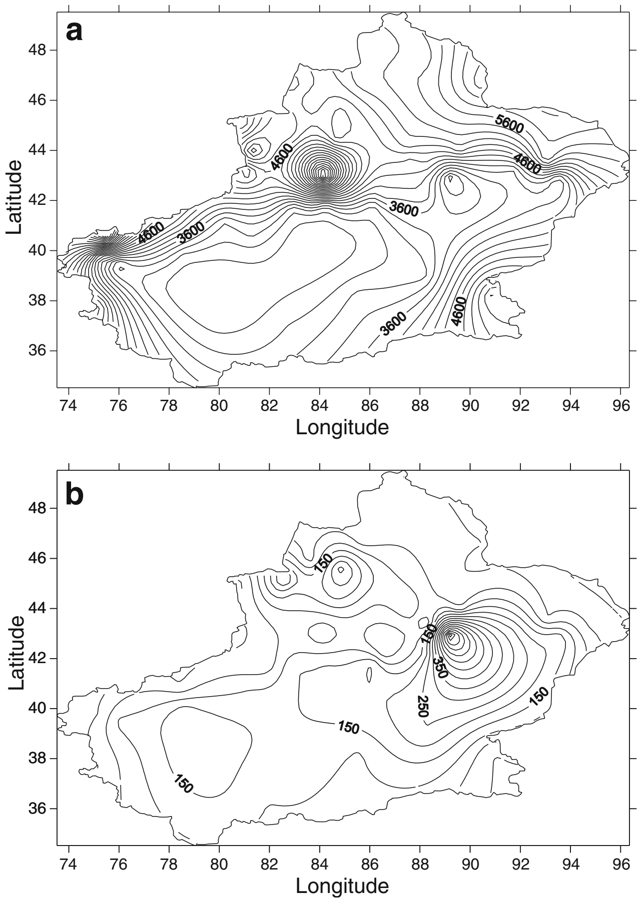

Fig. 2 Spatial distribution of annual mean heating (**a**) and cooling (**b**) degree-days in Xinjiang (the base temperatures were 18 and 24°C, respectively)

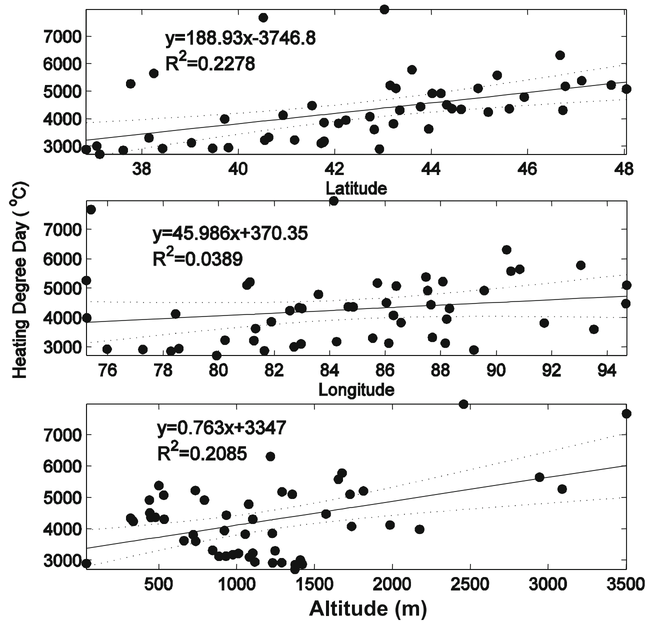

Fig. 3 Relationships between annual mean HDDs (T_{bh}=18°C) and latitude, longitude, and altitude in Xinjiang

similar relations were identified between annual mean HDDs and longitude with Pearson correlation coefficient of 0.197. However, this correlation was not significant at a significance level of 0.05 (Fig. 3). Based on the above-mentioned results, annual mean HDD can be obtained using the following equation:

$$Yh = -13717.1 + 330.37X_1 + 26.03X_2 + 1.461X_3 \quad (7)$$

Where Yh denotes annual mean HDD; X_1, X_2 and X_3 denotes latitude, longitude, and altitude, respectively. The correlation coefficient of this model (R^2=0.905) was significant at 0.001 significance level. Equation (7) can be used to assess annual mean HDD at any place where the temperature data were not available or accessible.

3.1.2 Trends analysis

Table 2 displays the results of MK and linear trends within annual and seasonal HDD (T_{bh}=18 °C) series in Xinjiang. It can be seen from Table 2 that decreasing trends of annual and seasonal HDDs were very evident during the past 46 years. In terms of annual HDDs, 96% of the total stations show significant decreasing trends at the 0.05 significance level. In spring, summer, autumn and winter, significant linear decreasing trends were observed at 13.7, 41.2, 78.4, and 84.3% of the total number of stations, respectively (Table 2).

The linear tendency rates of annual and seasonal HDDs for 51 stations in Xinjiang for the past 46 years were also analyzed by using the simple linear regression method. The slope of the linear equation is defined as the linear tendency

Table 2 Number of stations with significant trends at α=0.05 significance level

Period	MK trend		Linear trend	
	HDD	CDD	HDD	CDD
Annual	49	25	49	33
Spring	7	13	13	17
Summer	21	27	18	32
Autumn	40	8	40	7
Winter	43	0	46	0

rate. Results showed that during the past 46 years, linear tendency rates of annual HDDs of the 51 stations ranged from –25.1 to –312.1 °C/10a. Seasonally, linear tendency rates of HDDs in winter ranged from 2.4 to –103.7 °C/10a. Linear tendency rates of HDDs in spring, autumn, and summer ranged from 8.7 to –64.4 °C/10a, 0.5 to –85.4 °C /10a, and 1.0 to –68.2 °C/10a, respectively.

Significance test results (Table 2) indicate that 96.1% of the total stations showed significant decreasing trends in annual HDDs at the 0.05 significance level. In spring, summer, autumn, and winter, significant linear decreasing trends were observed at 25.5, 35.3, 78.4, and 90.2% of the total number of stations, respectively (Table 2).

3.1.3 Spatial distribution of trends

Figure 4 shows the spatial distribution of MK trends in annual and seasonal HDDs for the years 1959–2004. Figure 4 indicates that most places had significant decreasing trends in annual HDDs. Only two stations located in the central Xinjiang showed no trend in HDDs. Seasonally, spring HDDs had no trend in most regions. Seven stations located in the north, southwest, and southeast Xinjiang had significant decreasing trends. In summer, 21 stations indicated significant decreasing trends. The regions with significant decreasing HDDs were observed in the north Xinjiang, the western Tianshan Mountains, and the north Pamier Plateau. HDDs in autumn had significant decreasing trends in many regions of the north Xinjiang, the Yili River Basin, the Turpan Basin and the southwest Xinjiang. Except for the western Tianshan Mountains and the south Jungar Basin, most regions, particularly the north Xinjiang, the northwest edge of Tarim Basin, the south and north parts of middle Tianshan Mountains, as well as the Yili River Basin had significant decreasing trends in winter HDDs.

Figure 5 maps the distribution of linear tendency rates of annual and seasonal HDDs for the years 1959–2004. It can be observed from Fig. 5 that all stations showed negative linear tendency rates of annual HDDs. Most regions showed significant decreasing trends in annual HDDs. Only three stations located in the central Xinjiang showed no trends at 0.05 significance level. Higher negative linear tendency rates (lower than –160.1°C /10a) were observed mainly in the north and east of Xinjiang. In the spring, most stations exhibited negative linear tendency rates. Significant negative linear trends were identified mainly in the central and eastern Xinjiang. In the summer, except several stations with HDDs showing positive or no linear trends, many stations had decreasing trends. Significant negative linear trends and higher negative linear tendency rates were observed in north Xinjiang, the mountainous areas in central Xinjiang, as well as in eastern Xinjiang. In autumn, most stations exhibited significant negative linear trends. Higher negative linear tendency rates were observed mainly in northwestern, eastern, and southwestern Xinjiang. The spatial pattern of trends of winter HDDs was somewhat similar to that of annual HDDs. However, Bayinbuluke, located in the central Tianshan Mountains, was an exception with a negative winter trend in HDDs.

The findings indicated that the linear regression technique and MK method showed similar trends, that is, during the past 46 years, most stations at Xinjiang showed significant decreasing trends in annual, winter, and autumn HDDs. This may imply reduction of heating energy requirements in Xinjiang in the cold seasons. Spatially, Xinjiang was characterized by the presence of significant decreasing trends of annual, winter, and autumn HDDs, particularly this trend was more significant in northern Xinjiang. Ambiguous relations can be found between negative linear tendency rates of annual and seasonal HDDs and geographic locations of stations.

3.2 Cooling degree-days (CDD)

3.2.1 Basic statistical properties and spatial pattern of CDD

Table 1 displays statistical features of annual CDDs at the base temperature of 24°C. Table 1 indicates relatively low annual mean CDDs in Xinjiang. Annual mean CDDs ranged from 0.4 to 792°C. Minimum annual mean CDDs were found at Qinghe and maximum annual mean CDDs were observed at Turpan. The highest annual mean CDD of 792°C at Turpan was about 31 times higher than that observed at Aletai, and it was also about 4.5 times higher than what was observed at Hetian (175°C) (Table 1), a city located in southern Xinjiang. This may imply that the energy consumption for cooling the very same buildings in Turpan would be 31 times higher than that in Aletai, and about 4.5 times higher than that in Hetian. In terms of the standard deviation of annual mean CDDs, Shisanjianfang had the highest standard deviation, Turpan had the second largest, and Dababcheng had the smallest. This demonstrates that the

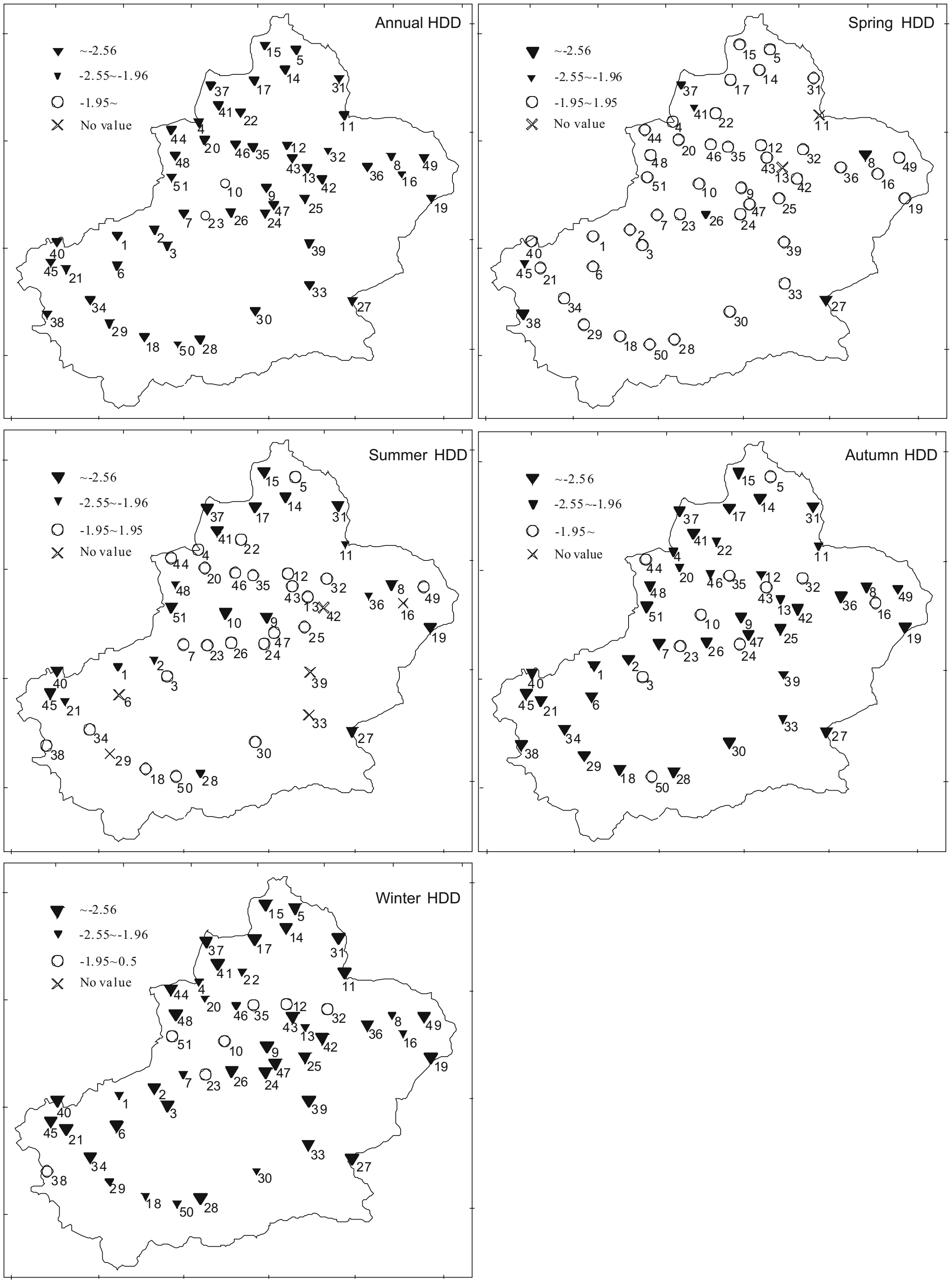

Fig. 4 MK trends of annual mean and seasonal HDDs (T_{bh}=18°C). *Black solid triangles* denote significant increasing and decreasing trend at 0.05 significance level

stations with higher annual mean CDDs usually exhibited larger inter-annual variations of CDDs (Table 1).

Figure 2b shows the spatial distribution of annual mean CDDs. It can be seen from Fig. 2b that the spatial distribution was obviously influenced by the terrain, which was reflected by three relatively higher values centered on the Turpan Basin, Tarim Basin and Jungar Basin. On the other hand, relatively lower annual mean CDDs were

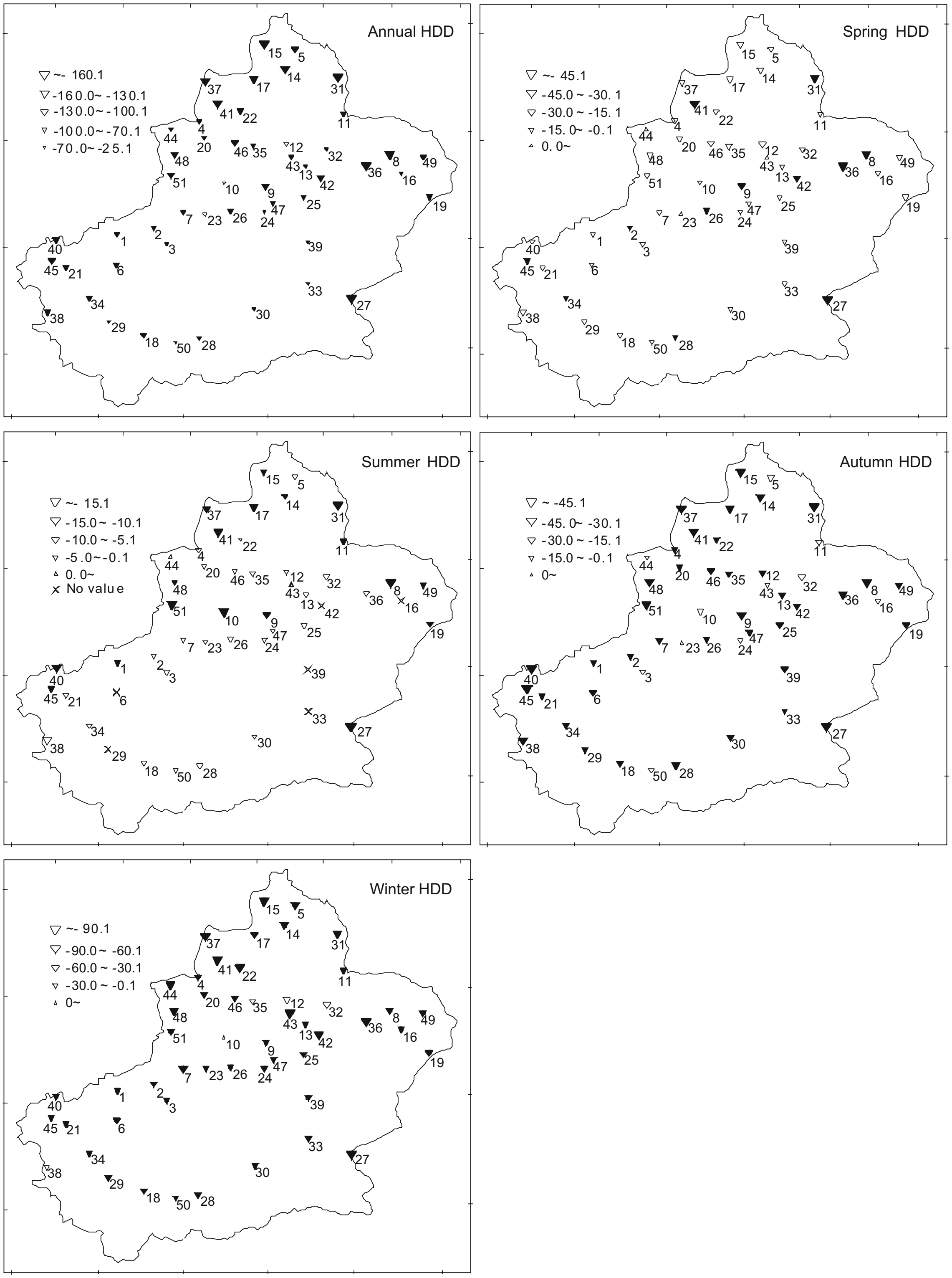

Fig. 5 Linear trends of annual mean and seasonal HDDs (T_{bh}=18°C). *Black solid triangles*denote significant increasing and decreasing trend at 0.05 significance level

observed in the mountainous regions. Correlation analyses were performed between annual mean CDDs and latitude, longitude, and altitude, with an aim to evaluate geographic influences. The results indicated no dependence of annual mean CDDs on latitude and longitude (Fig. 6). No significant correlations were detected between annual mean CDDs and latitude and longitude with correlation coefficients of -0.037 and 0.120, respectively. However, annual mean CDDs seemed to decrease when altitude increased. Significant correlation was detected between annual mean CDDs and altitude with a Pearson correlation coefficient of –0.481, which was significant at 0.01 significance level (Fig. 6). Based on the results mentioned above, annual mean CDD at any location can be obtained as:

$$Yc = 842.348 - 19.75X_1 + 3.52X_2 - 0.22X_3 \quad (8)$$

where Yc is the annual mean CDD, and X_1, X_2 and X_3 denote latitude, longitude, and altitude, respectively. The correlation coefficient (R^2=0.602) was significant at the 0.001 significance level. However, the magnitude of the regression error suggests that this model cannot be used to calculate annual mean CDDs at other locations where temperature data were not available.

3.2.2 Trend analysis

Table 2 displays MK trends of annual and seasonal CDDs (T_{bc}=24°C). Increasing trends of annual and summer CDDs were very evident over the past 46 years. With respect to annual CDDs, 25 out of 51 stations showed significant trends at the 0.05 significance level, accounting for 49.0% of the total stations. Three stations, Urumqi, Kuche, and Alaer, showed decreasing trends. More than half of the stations exhibit significant trends of summer CDDs. In spring, summer, and autumn, significant MK trends were observed at 25.5, 52.9, and 15.7% of the total number of stations, respectively (Table 2). No cooling energy was required at the base temperature of 24°C because no cooling degree-days were observed in winter.

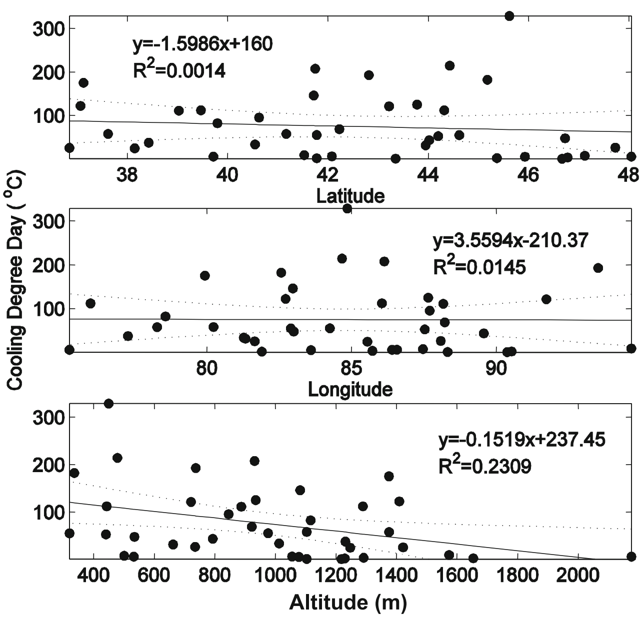

Fig. 6 Variations of annual mean CDDs (T_{bc}=24°C) with the latitude, longitude ,and altitude in Xinjiang

The linear tendency rates of annual and seasonal CDDs of 51 stations in Xinjiang were also analyzed by using the simple linear regression method. Results showed that in the past 46 years, linear tendency rates of annual mean CDDs in Xinjiang ranged from –21.5 to 38.4°C/10a. Seasonally, the linear tendency rates in summer mean CDDs ranged from –20.0 to 42.8°C/10a, and those in spring and autumn ranged from –0.6 to 10.1°C/10a, –1.0 to 10.1°C/10a, respectively.

Significance testing (Table 2) for the linear tendency rates showed that 33 out of 51 stations had significant trends in annual CDDs, accounting for 64.7% of the total stations. Four stations, Qitai, Urumqi, Kuche and Alaer, exhibited significant decreasing trends, while the other 29 stations showed significant increasing trends. In spring, summer and autumn, significant linear increasing trends were observed at 33.3, 62.7, and 13.7% of the total number of stations, respectively (Table 2). In autumn, only one station, Kuche, showed a significant decreasing trend.

The above-mentioned results indicate that more than half of stations considered in this study exhibited significant trends of annual and summer CDDs no matter which testing method was used.

3.2.3 Spatial pattern of trends

Figure 7 illustrates the spatial patterns of MK trends in terms of annual and seasonal CDDs of 51 stations. It can be seen from Fig. 7 that significant trends of annual CDDs were observed at about half of the stations considered in this study. Three stations located in the central Xinjiang showed decreasing trends of CDDs, while no remarkable positive trends were detected for the other stations. Significant increasing trends of CDDs were observed in northwest Xinjiang, the south and north edges of Tarim Basin as well as in the Turpan Basin. Most places of Xinjiang had no cooling requirements in the spring. Significant increasing trends were detected in the regions near the edges of the Tarim Basin. In the summer, more than half of the stations exhibited significant increasing or decreasing MK trends of CDDs, and, as mentioned in the previous sections, three stations located in the central Xinjiang showed significant negative trends. The spatial pattern of MK trends of summer CDDs was somewhat similar to that of annual CDDs. Significant increasing trends were observed in northwest Xinjiang, the edges of Tarim Basin and also in east Xinjiang. In the autumn, several stations exhibited significant increasing trends, while most stations showed no remarkable increasing trend. Increasing trends were evident in the Turpan Basin, the southwest, and north edges of Tarim Basin.

Figure 8 shows the distribution of linear tendency rates of annual and seasonal CDDs for the years 1959–2004. It can be seen from Fig. 8 that more than half of the stations

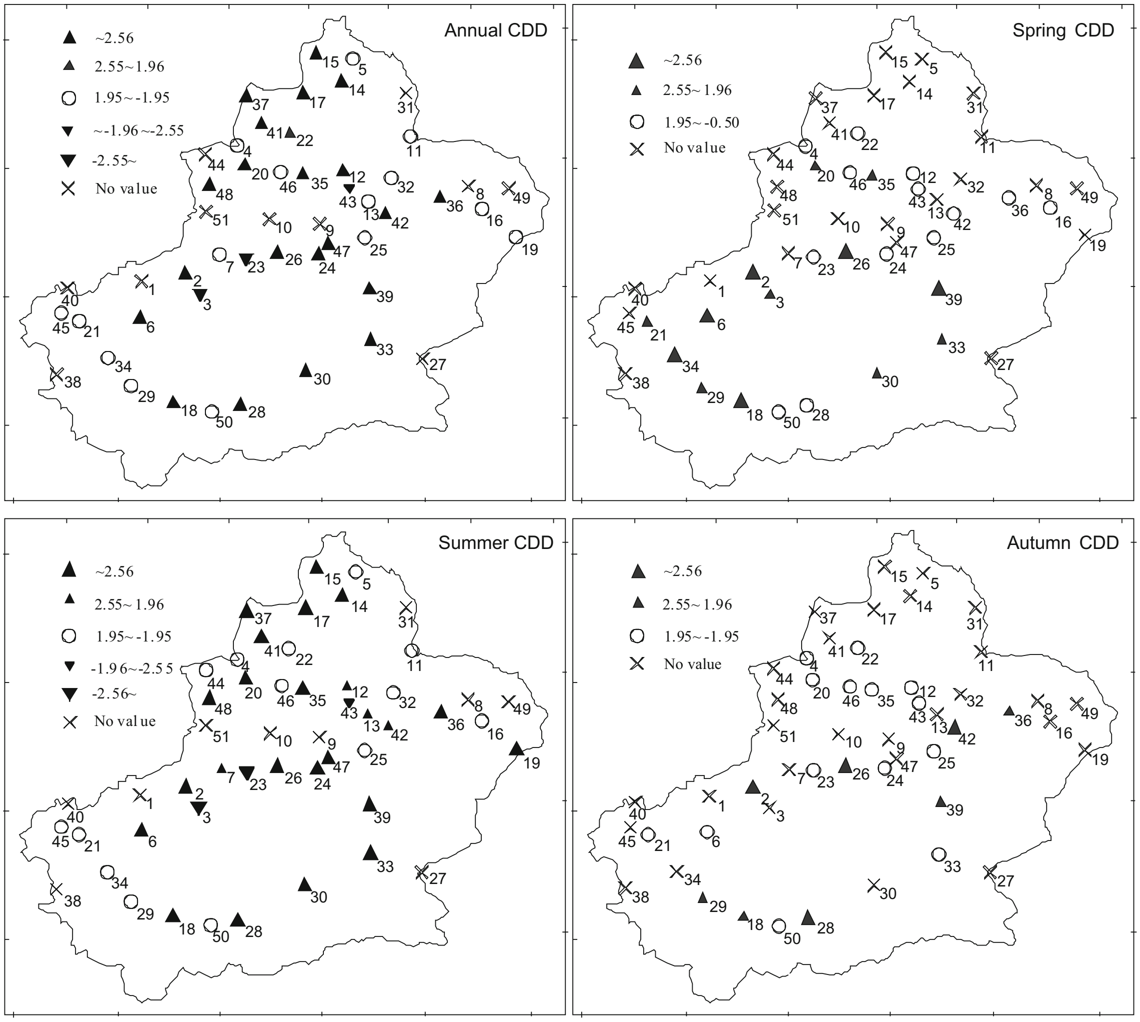

Fig. 7. MK trends of annual mean and seasonal CDDs (T_{bc}=24°C). *Black solid triangles*denote significant increasing and decreasing trend at 0.05 significance level

showed positive linear increase rates of annual CDDs; while only four stations showed remarkable negative trends of annual CDDs. Significant decreasing trends of annual CDDs were observed on the edges of Tarim Basin, north Xinjiang and the Turpan-Hami Basin. Stations with higher positive increase rates (>10.1°C/10a) were mainly located in the northern and the eastern parts of Xinjiang, as well as on the edges of Tarim Basin. In the spring, 17 stations had positive linear tendency rates, which were significant at 0.05 significance level. Significant positive linear trends were also observed in the southern Jungar Basin, the east parts of Xinjiang, and on the edge of Tarim Basin. In the summer, except for stations showing negative or no trends, more than half of the stations had increasing trends. Significant increasing trends and higher positive tendency rates were found mainly in the north parts of Xinjiang, the east Xinjiang, as well as on the edge of Tarim Basin. This spatial pattern implied no relations between CDDs and locations of the stations. In the autumn, several stations exhibited significant increasing trends of CDDs, while trends of CDDs of most stations indicated that cooling was not required. Several stations showed slight decreasing trends of CDDs. Higher positive tendency rates are observed mainly in the southern and northern edges of Tarim Basin and in the Turpan Basin.

The findings indicated that the linear regression method and MK trend test technique produced similar results for the last 46 years of data. The spatial patterns of trends of annual and summer CDDs were ambiguous. However, the western part of northern Xinjiang, the edge of Tarim Basin, and the Turpan-Hami Basin were identified as the areas with significant increasing trends of annual and summer CDDs. Ambiguous relations were found between negative linear tendency rates of annual and seasonal CDDs and geographic locations of stations.

Mean global temperature increased by about 0.6±0.2°C in the 20th century (IPCC 2001), and warming also occurred in Xinjiang with a temperature rising rate of

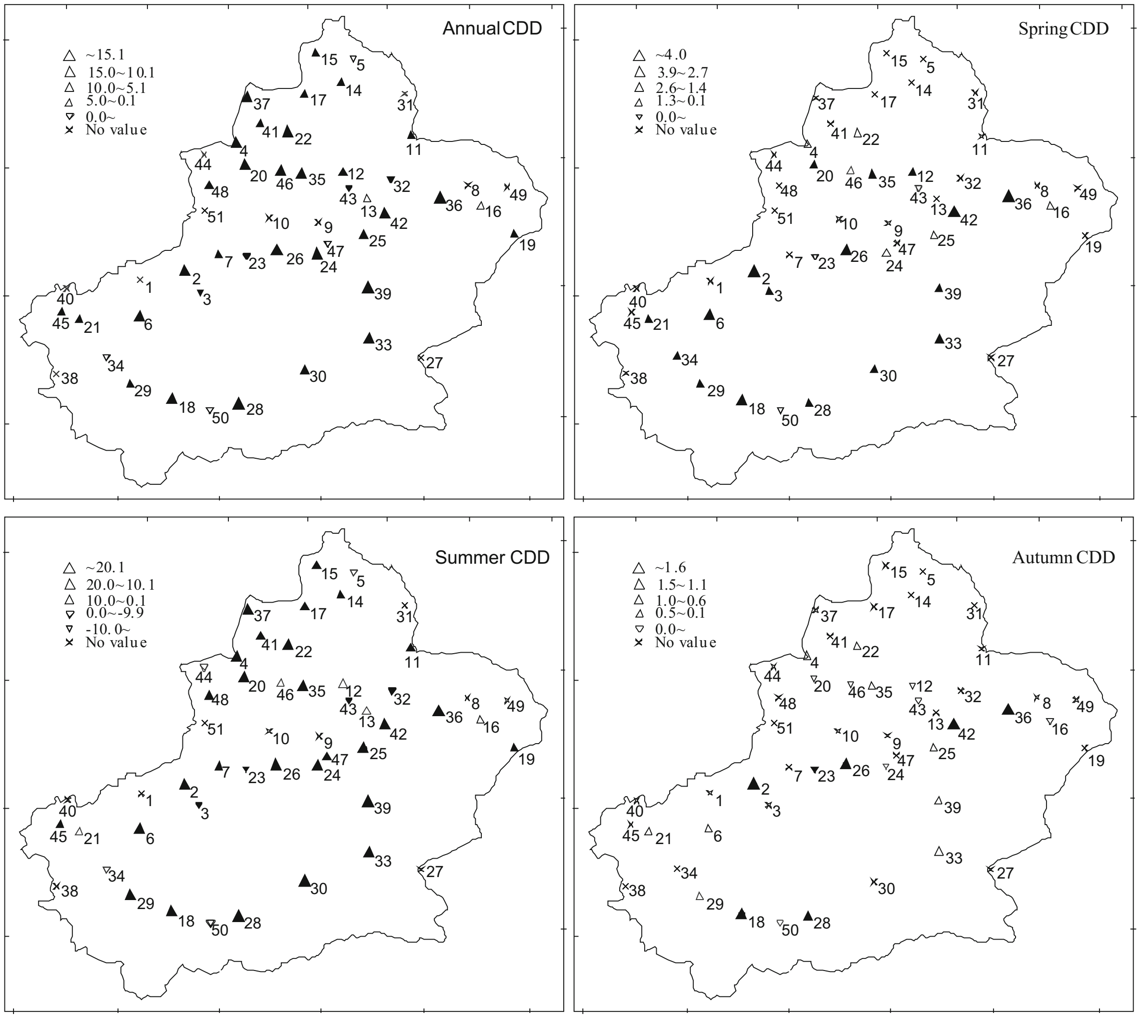

Fig. 8 Linear trends of annual mean and seasonal CDDs (T_{bc}=24°C). *Black solid triangles*denote significant increasing and decreasing trend at 0.05 significance level

0.2°C/decade during the past 50 years (Zhang et al. 2002). According to the IPCC, the global average temperature will rise between 1.4 and 5.8°C in the 21st century (IPCC 2001). By estimation, regional average annual air temperature in Xinjiang will rise between 1.9 and 3°C (Zhao et al. 2002). Higher maximum temperatures and more hot days over virtually all land areas will happen more often in the future (Easterling et al. 2000). Under this predicted global warming, decreasing winter and annual HDDs and increasing summer and annual CDDs tend to continue in the future, which will be undoubtedly helpful to reduce energy consumption for heating. Due to the fact that energy requirements in cold season for heating are much greater than that in the hot season for cooling, climatic warming may certainly improve heat comfort and reduce energy consumption during the cold season in Xinjiang. As a result, air pollution due to coal burning in the cities of Xinjiang may be alleviated and this will certainly be beneficial for local sustainable development.

4 Conclusions

Observed trends of annual and seasonal HDDs and CDDs and their spatial distribution in Xinjiang were thoroughly analyzed by using daily maximum and minimum temperatures for 51 stations. Some interesting conclusions can be drawn as follows:

(1) Taking 18°C as the base temperature, annual mean HDDs ranged from 2,700 to 7,973°C. CDDs were relatively low in Xinjiang. For the fixed base temperature of 24°C, annual mean CDDs ranged from 0.4 to 792°C.
(2) Annual mean and seasonal HDDs increased significantly with increasing latitude and altitude. This indicates that the potential of energy conservation in the northern parts of Xinjiang may be larger than that in the southern parts. Annual mean and seasonal CDDs decreased at the 0.01 significance level with increasing altitude.

(3) Significant decreasing MK trends of winter and annual HDDs were prevalent at most of the stations. The linear tendency rates of annual mean HDDs ranged from –25.1 to –312.1°C/10a. This indicates that most regions of Xinjiang have the potential to reduce their energy requirements for heating in the cold seasons. On the other hand, the linear tendency rates of annual mean CDDs ranged from –21.5 to 38.4°C/decade. Many stations had increasing trends and several stations exhibited significant increasing trends in annual and summer CDDs, while no remarkable positive trends could be observed at the remaining stations.
(4) Spatially, Xinjiang was characterized by significant decreasing trends of annual, winter, and autumn HDDs. This trend was more significant in northern Xinjiang. The spatial patterns of trends of annual and summer CDDs were somewhat ambiguous. However, the western part of north Xinjiang, the edges of Tarim Basin and the Turpan-Hami Basin were identified as the areas with significant increasing trends in annual and summer CDDs.

The results of this paper may provide valuable information for local energy management and planning.

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