Theor Appl Climatol (2013) 113:659–670
DOI 10.1007/s00704-012-0815-7

ORIGINAL PAPER

Quantitative relationships between precipitation and temperature over Northeast China, 1961–2010

Haibo Du · Zhengfang Wu · Yinghua Jin · Shengwei Zong · Xiangjun Meng

Received: 9 February 2012 / Accepted: 26 November 2012 / Published online: 11 December 2012

Abstract This paper investigates monthly and seasonal precipitation–temperature relationships (PTRs) over Northeast China using a method proposed in this study. The PTRs are influenced by clouds, latent and sensible heat conversion, precipitation type, etc. In summer, the influences of these factors on temperature decrease are different for various altitudes, latitudes, longitudes, and climate types. Stronger negative PTRs ranging from −0.049 to −0.075 °C/mm mostly occur in the semi-arid region, where the cold frontal-type precipitation dominates. In contrast, weaker negative PTRs ranging from −0.004 to −0.014 °C/mm mainly distribute in Liaoning Province, where rain is mainly orographic rain controlled by the warm and humid air of East Asian summer monsoon. In winter, surface temperature increases owing to the release of latent heat and sensible heat when precipitation occurs. The stronger positive PTRs ranging from 0.963 to 3.786 °C/mm mostly occur at high altitudes and latitudes due to more release of sensible heat. The enhanced atmospheric counter radiation by clouds is the major factor affecting increases of surface temperature in winter and decreases of surface temperature in summer when precipitation occurs.

1 Introduction

It has been known that the global surface temperature has increased about 0.74 °C in the last 100 years (1906–2005) with an increasing rate of about 0.13 °C/10 years in the past 50 years (Solomon et al. 2007). Generally speaking, the global land precipitation has increased about 2 % since the beginning of the twentieth century (Dai et al. 1997; Hulme et al. 1998). However, the observed trends in precipitation from 1900 to 2005 are significant increments in eastern parts of North and South America, northern Europe, and northern and central Asia, whereas there are decrements in the Sahel, Mediterranean region, southern Africa, and in many places of southern Asia (Toros 2012).

Intuitively, there is a relationship between precipitation and surface temperature that it is cooler when precipitation occurs in summer, while it is warmer when precipitation occurs in winter. Indeed, the precipitation–temperature relationships (PTRs) are important for understanding precipitation formation processes, weather forecasting, climate change predictions, and parameterizations of precipitation for modelings at large scales (Isaac and Stuart 1992). The early study of PTRs was summarized by Namias (1953) that there was a negative correlation between monthly temperature and precipitation during the summer, with the relationship being the strongest over the US Great Plains. Madden and Williams (1978) computed the correlations between seasonal mean temperature and precipitation at some 98 North American and European stations and confirmed that negative correlations were most frequent in summer, while negative and positive correlations appeared about equally in other seasons. There are some other similar works of studying the correlations between precipitation and temperature (Van den Dool 1988; Lyons 1990; Zhao and Khalil 1993). Furthermore, Isaac and Stuart (1992) defined a temperature–precipitation index (TPI) that the fraction of precipitation recorded on days when the average daily temperature is less than the median value and calculated TPI for 56 observing sites across Canada. It was shown that in some regions and seasons, larger precipitation amounts were observed when mean daily temperatures were much cooler than the median

H. Du · Z. Wu (✉) · Y. Jin · S. Zong · X. Meng
College of Urban and Environmental Sciences, Northeast Normal University, No. 5268, Renmin Street, Changchun 130024, China
e-mail: wuzf@nenu.edu.cn

X. Meng
Business Administration, Jilin University of Finance and Economics, 130024 Changchun, China

value, whereas in other locations and seasons, the opposite was found to be true. Stuart and Isaac (1994) used the TPI to compare the PTRs produced by the observed daily values with the PTRs estimated by the Canadian Climate Center second-generation climate model. They found that in winter, over broad areas, the model predictions and the observations agreed, both showing more precipitation when the average daily "screen-level" temperature was warmer than the median daily value. However, in summer, the observations that more precipitation occurred with colder temperatures over large regions were not simulated by the model. Rebetez (1996) confirmed that colder summer tended to be associated with more precipitation, mainly in terms of the frequency of precipitation occurrence, whereas in winter, higher temperatures were accompanied by rain at lower altitudes. Trenberth and Shea (2005) reported that over land, wet summer was cool, while at high latitudes in winter, air warm moist favored precipitation. Berg et al. (2009) verified that a general increase in precipitation intensity was indeed observed in winter, while in summer precipitation intensity decreased with increasing temperature. However, any survey of the recent literature suggests that no real quantitative PTRs have been reported. Duan and Yao (2003) confirmed that as mean temperature increases by 0.1 °C, the precipitation decreases 80 mm and vice versa in Northern Hemisphere. However, Adler et al. (2008) found that precipitation increased 2.3 % when temperature increased by 1 °C at global scale. How and how much do the temperatures change when precipitation occurs or does the precipitation vary when temperatures change deserves more investigation. The quantitative PTRs can be used for better understanding the physics of the relationships between atmospheric circulation, cloud effect, and climate change.

Indeed, the correlations between precipitation and temperature, TPI, and the quantitative PTRs are all important for understanding the relationships between precipitation and temperature and between the climate change processes and the climate change predictions. However, regional differences in the PTRs can be great. To improve our understanding of PTRs under global change, it is necessary to study the regional characteristics and causes. Northeast China, known as one of the Chinese Commodity Grain Bases, is the most important agricultural region in China (Wu et al. 2011). It is a complete physical geographical region. However, few results regarding PTRs in this region can be found. Studying of the characteristics of PTRs over Northeast China is thus important and significative. Therefore, the objectives of this work are to (1) analyze the correlations between precipitation and temperature in Northeast China, (2) investigate the percentage of precipitation observed on the days when the temperature is less than the median value, (3) represent the quantitative PTRs using a quantitative method firstly proposed in this study, and (4) interpret the different PTRs in various seasons and locations.

2 Data and method

Daily values of temperature and precipitation from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/index.jsp) are used, including daily mean temperature (T_{mean}), maximum temperature (T_{max}), minimum temperature (T_{min}), daily temperature range (T_{DTR}), and daily precipitation amount (referring to rainfall amount only in this study). We analyze year-round precipitation–temperature relationships. However, there are no snows in summer and autumn over Northeast China. We exclude the snow data in winter and spring to keep comparative analysis of monthly and seasonal PTRs. There are totally 131 weather stations in the region for the period 1951–2010. However, many of these stations have missing or inadequate data during the early operating period from 1951 to 1960. Therefore, we confine the period of 1961–2010. Meanwhile, quality control is performed to eliminate the stations with inhomogeneities, discontinuities, or obvious outliers in the raw data. Finally, the data for a set of 90 high-quality stations are used and illustrated in Fig. 1. Winter season includes December, January, and February, while summer season comprises June, July, and August, and so on. The study area is spread across the domain of 115° 52′–135°09′E and 38°72′–53°55′N, covering Provinces of Heilongjiang, Jilin, and Liaoning, as well as cities of Chifeng, Tongliao, Hulun Buir, and Hinggan League in Eastern Inner Mongolia (Fig. 1). It is a complete physical geographical region.

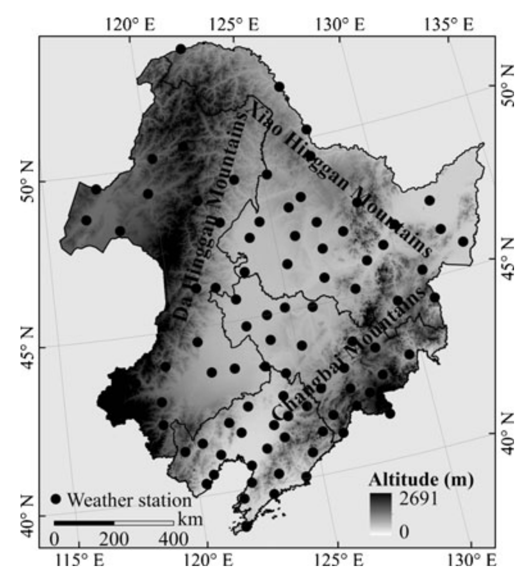

Fig. 1 Study area (115°52′–135°09′E, 38°72′–53°55′N) and the spatial distribution of the 90 weather stations used in this study

We calculate the correlations between precipitation and temperature using the Pearson correlation analysis (Dutilleul et al. 2000) for monthly means and seasonal means. We then calculate the fraction of precipitation recorded on days whose average daily temperatures are less than the median value (Isaac and Stuart 1992; Stuart and Isaac 1994). Meanwhile, we define a quantitative PTRs that the accompanied temperature variations when 1-mm precipitation amount occurs. Taking one station during the period 1961–2010 as example, our method consists of the following five steps:

1. Extracting the daily values of precipitation and temperature from 1 January to 31 December during the 50 years and then we can obtain 366 daily data sets, including precipitation amounts and accompanied temperature. Each data set is with the length of 50 (the length of the data series 29 February is 10).
2. Dividing the 366 data sets into two categories, including precipitation day series and non-precipitation day series.
3. Detecting the trend of the temperature of non-precipitation day series for each data set using the Mann–Kendall test (Mann 1945; Kendall 1975). Eliminate the trend if there is significant trend. Then calculate the average temperature of non-precipitation days, which represents the temperature on non-precipitation day.
4. For each data set, the temperature of each precipitation day subtracts the temperature on non-precipitation day. We can get the temperature difference between precipitation day and non-precipitation day for each precipitation day.
5. Calculating the regression coefficients between the obtained new temperature difference series and the precipitation amount series for each data set. The regression coefficients are quantitative PTRs, i.e., the accompanied temperature variation when 1-mm precipitation amount occurs. Then calculate the monthly and seasonal values. The quantitative PTRs values really represent the quantitative relationships between temperature and precipitation rather than the simple correlations between temperature and precipitation, which can quantitatively reveal different precipitation amounts accompanying temperature variation and vice versa.

3 Results and discussion

3.1 Correlations between temperature and precipitation

We calculate the correlations between daily precipitation and daily temperature within a given month to determine the relationships for that month. Table 1 shows the correlation coefficients for monthly relationships between precipitation and temperature (T_{mean}, T_{max}, T_{min}, and T_{DTR}). The correlations vary among different months. More than half the stations in 5 months (January, February, March, October, and November) have positive correlation between monthly T_{mean} and precipitation. Specially, the correlation of February of all the sites is positive ranging from 0.011 to 0.279. Meanwhile, the correlations of 72 sites are significant at the 0.05 confidence level. The largest positive correlation coefficient is 0.331 in January of Tulihe (121°41′E, 50°29′N), which is significant at the 0.05 confidence level. The other 7 months are mainly negative correlation between T_{mean} and precipitation. All the sites in May, June, and July have significantly negative correlation coefficients. The largest negative correlation coefficient is −0.352 in July of Linxi (118°4′E, 43°36′N), which is different from the findings by Adimula and Willoughby (2009) that the maximum negative correlation between temperature and precipitation is in March of sub-Sahel. It indicates that the correlations between precipitation and temperature are different in various regions. Negative correlation between T_{max} and precipitation dominates in 9 months (except January, February, and November). Meanwhile, all the sites in April to September have negative correlations, and the correlations of most sites are significant at the 0.05 confidence level. The strongest positive and negative correlations are 0.213 in January of Ergun Right Banner (120° 11′E, 50°15′N) and −0.424 in July of Ji'an (126°9′E, 41°6′N), respectively. By contrast with T_{max}, the overwhelming majority of months (except December) have positive correlations between T_{min} and precipitation. The largest positive and negative correlations are 0.367 in January of Tulihe (121°41′E, 50°29′N) and −0.146 in May of Dalian (121°38′E, 38°54′N), respectively. For all sites, the correlations between T_{DTR} and precipitation in January to November are significantly negative. The largest negative correlation is −0.506 in August of Ji'an (126°9′E, 41°6′N).

Figure 2 shows the correlations between precipitation and temperature (T_{mean} (a), T_{max} (b), T_{min} (c), and T_{DTR} (d)) for seasonal means. As seen in Fig. 2 I-a–IV-a, the correlations between T_{mean} and precipitation are positive in spring and autumn and negative in summer for all sites, whereas 92.2 % stations have positive correlations in winter. Moreover, the correlations of the overwhelming majority of sites are significant at the 0.05 confidence level. However, the spatial distributions for positive and negative correlations are different. In spring, autumn, and winter, the sites with large positive correlations mainly locate at the mountain areas (the Changbai Mountains, Xiao Hinggan Mountains, and Da Hinggan Mountains), where the places belong to humid high altitudes and high latitudes. In contrast, in summer the stations with big negative correlations mostly distribute in southeastern Northeast China, where the region belongs to semi-arid climate. The largest positive and negative correlations between T_{mean} and precipitation are 0.295 and −0.247 in winter and summer, respectively. Both

Table 1 Correlations between monthly precipitation and temperature

	P–T_{Mean}	P–T_{Max}	P–T_{Min}	P–T_{DTR}
January	0.001–0.331 (76, 64)	0.001–0.213 (61, 38)	0.016–0.367 (85, 73)	>0 (0, 0)
	−0.003 to −0.102 (14, 6)	−0.004 to −0.152 (29, 19)	−0.015 to −0.044 (5, 0)	−0.024 to −0.346 (90, 85)
February	0.011–0.279 (90, 72)	0.002–0.183 (67, 39)	0.062–0.331 (90, 90)	>0 (0, 0)
	<0 (0, 0)	−0.004 to −0.054 (23, 2)	<0 (0, 0)	−0.075 to −0.386 (90, 90)
March	0.000–0.194 (78, 47)	0.001–0.068 (27, 4)	0.011–0.290 (90, 88)	>0 (0, 0)
	−0.005 to −0.042 (12, 0)	−0.001 to −0.111 (63, 17)	<0 (0, 0)	−0.095 to −0.353 (90, 90)
April	0.002–0.074 (12, 1)	>0 (0, 0)	0.026–0.280 (88, 83)	<0 (0, 0)
	0.000 to −0.127 (78, 36)	−0.018 to −0.208 (90, 85)	−0.008 to −0.028 (2, 0)	−0.154 to −0.388 (90, 90)
May	>0 (0, 0)	>0 (0, 0)	0.001–0.269 (72, 49)	>0 (0, 0)
	−0.081 to −0.310 (90, 90)	−0.113 to −0.381 (90, 90)	−0.001 to −0.146 (18, 6)	−0.236 to −0.499 (90, 90)
June	>0 (0, 0)	>0 (0, 0)	0.000–0.339 (70, 44)	>0 (0, 0)
	−0.111 to −0.326 (90, 90)	−0.185 to −0.392 (90, 90)	0.000 to −0.124 (20, 6)	−0.196 to −0.467 (90, 90)
July	>0 (0, 0)	>0 (0, 0)	0.000–0.290 (67, 52)	>0 (0, 0)
	−0.099 to −0.352 (90, 90)	−0.200 to −0.424 (90, 90)	−0.003 to −0.140 (23, 8)	−0.175 to −0.469 (90, 90)
August	0.052 (1, 1)	>0 (0, 0)	0.029–0.331 (87, 83)	>0 (0, 0)
	−0.004 to −0.244 (89, 75)	−0.185 to −0.393 (90, 90)	−0.004 to −0.117 (3, 1)	−0.188 to −0.506 (90, 90)
September	0.005–0.147 (39, 21)	>0 (0, 0)	0.048–0.365 (89, 88)	>0 (0, 0)
	−0.001 to −0.156 (51, 21)	−0.056 to −0.256 (90, 90)	−0.028 (1, 0)	−0.132 to −0.474 (90, 90)
October	0.001–0.137 (76, 41)	0.007 (1, 0)	0.022–0.308 (89, 86)	>0 (0, 0)
	−0.002 to −0.048 (14, 0)	−0.005 to −0.142 (89, 53)	−0.030 (1, 0)	−0.040 to −0.384 (90, 89)
November	0.003–0.263 (85, 64)	0.005–0.113 (63, 30)	0.028–0.324 (89, 84)	>0 (0, 0)
	−0.014 to −0.079 (5, 2)	−0.001 to −0.107 (27, 8)	−0.019 (1, 0)	−0.011 to −0.390 (90, 88)
December	0.001–0.082 (32, 1)	0.002–0.089 (39, 2)	0.001–0.090 (28, 1)	0.001–0.092 (68, 13)
	−0.003 to −0.086 (58, 14)	0.000 to −0.067 (51, 5)	−0.001 to −0.091 (62, 18)	−0.002 to −0.040 (22, 0)

Here temperature includes mean temperature (T_{mean}), maximum temperature (T_{max}), minimum temperature (T_{min}), and daily temperature range (T_{DTR}). The values in the parenthesis are the numbers of all stations and stations with the correlations being significant at the 0.05 confidence level for corresponding correlation level, respectively

of them are significant at the 0.05 confidence level. Similarly, the correlations between T_{max} and precipitation in summer for all the sites are negative, but the correlations in the other three seasons for overwhelming majority of stations are positive (Fig. 2 I-b–IV-b). The sites with stronger positive correlations mainly locate at Xiao Hinggan Mountains in spring and autumn and at Changbai Mountains and Xiao Hinggan Mountains in winter. Generally, the absolute values of the negative correlations between T_{max} and precipitation in summer are larger than the positive correlations in the other three seasons. In summer, the strong negative correlations mostly are distributed in southwestern Northeast China and Changbai Mountains, which is different from the correlations between T_{mean} and precipitation. It indicates that latitudes and altitudes and the intercombination between them are one key factor influencing the correlations between T_{max} and precipitation. Almost all the sites have positive correlations between T_{min} and precipitation in all the seasons (except three sites in summer) (Fig. 2 I-c–IV-c). Meanwhile, the correlations of the overwhelming majority of stations are significant at the 0.05 confidence level. All the larger positive correlations for all seasons mainly distribute in Changbai Mountains, Xiao Hinggan Mountains, and Da Hinggan Mountains. As for the correlations between T_{DTR} and precipitation, all stations have negative values in all the seasons (Fig. 2 I-d–IV-d). The correlations of the overwhelming majority of stations are significant at the 0.05 confidence level. The larger negative correlations mainly occur in Changbai Mountains and Xiao Hinggan Mountains in spring, autumn, and winter, while the larger negative correlations mostly distribute in Changbai Mountains and northwestern Northeast China in summer. All of these results indicate that the relationships between temperature and precipitation are related to factors, such as seasons, altitudes, latitudes, and large-scale weather systems, or the interaction between them, which are similar to the findings by Stuart and Isaac (1994).

Adler et al. (2008) concluded that the correlations between precipitation and surface temperature are complicated with both positive and negative values of correlations and a strong seasonal variation in the correlations patterns in the Northern

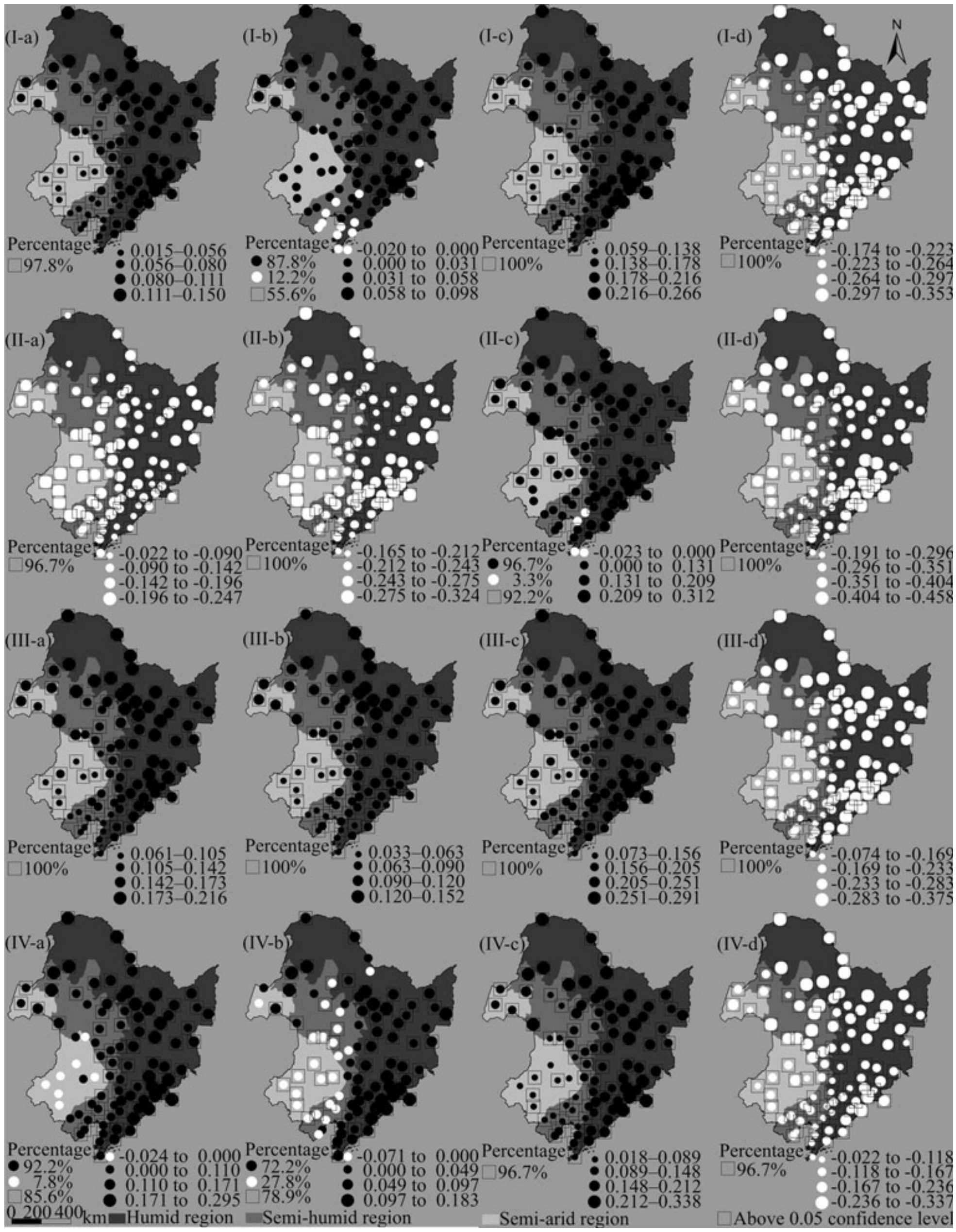

Fig. 2 Correlations between seasonal precipitation and temperature. Here temperature includes mean temperature (*a*), maximum temperature (*b*), minimum temperature (*c*), and daily temperature range (*d*). The symbols of *I*, *II*, *III*, and *IV* represent spring, summer, autumn, and winter, respectively. For example, the subfigure *II-b* represents the correlations between precipitation and maximum temperature in summer. *Dots* are scaled based on the amplitude of the correlations, with *white* signifying negative value and *black* signifying positive value. *Squares* indicate stations with correlations significant at the 0.05 confidence level. Percentage represents the percentage of each category of correlations

Hemisphere mid-high latitudes. Trenberth and Shea (2005) also deduced that negative correlations dominate in summer over land, while positive correlations dominate at high latitudes in winter when the moisture holding capacity of the atmosphere is low. Zhao and Khalil (1993) confirmed the strong negative correlations in summer over the USA during 1905–1984. The places with higher altitude and humid climate may have larger positive correlations between T_{mean} and precipitation in spring, autumn, and winter within a certain range, whereas larger negative correlations dominates in semi-arid or arid regions in summer. Nicholls et al. (2004) found a strong negative correlation between annual T_{max} and precipitation of −0.71 for New South Wales in Australia 1910–2002. In this study, however, strong positive correlations between T_{max} and precipitation dominate at high altitude humid regions and high altitude high latitude regions in spring, autumn, and winter, while large negative correlations in winter dominate in semi-arid lower latitude regions and high altitude and humid lower latitude regions over Northeast China. The big positive correlations between T_{min} and precipitation dominate at high altitude humid regions and high altitude high latitude regions for all seasons.

3.2 Percentage of precipitation frequency

After investigating the correlations between temperature and precipitation amounts, it is necessary to analyze the relationships between frequency of precipitation and temperature. Figure 3 shows the percentage of the frequency of precipitation on days when the temperature of that day is below the median temperature (T_{mean} (a), T_{max} (b), T_{min} (c), and T_{DTR} (d)) for monthly means and seasonal means. As is evident from Fig. 3 a, precipitation is mainly observed on relatively higher T_{mean} days in January to March, October and November, and spring, autumn, and winter, on lower T_{mean} days in April to August and summer and with little or no bias in September and December for all the 90 stations. The largest mean percentage of the 90 sites is in June for the monthly means and in summer for the seasonal means, which indicates that the lower T_{mean} is usually accompanied by precipitation events in June and summer. The largest and smallest percentages are 81.8 % in January and 11.0 % in February, respectively. The percentage of all the sites is larger than 50 % in May to July. The average percentages of precipitation occurring at T_{mean} below the median daily T_{mean} are 37.3, 61.3, 33.8, and 34.9 % in spring, summer, autumn, and winter for all the stations, respectively. Figure 3 b shows the relationships between the frequency of precipitation and T_{max}. It is clear that precipitation is mostly recorded on relatively lower T_{max} days in overwhelming majority of months (except February and December) and autumn, on higher T_{max} days in summer, and with little or no bias in February, December, spring, and winter. Similarly, the change range of the percentage in summer is the smallest, while that in winter is the largest. As for the relation between the percentage of precipitation and T_{min} in Fig. 3 c, precipitation is mainly observed on relatively higher T_{min} days in most months (except December) and all seasons and with little or no bias in December. Counter to T_{min}, precipitation is mostly occurred on relatively smaller T_{DTR} days in most months (except December) and all seasons and on larger T_{DTR} days in December. The variation range of the percentage of precipitation relatively on T_{DTR} is small in summer, but larger in winter. These results indicate that the relationships between precipitation and T_{mean} are different among various months and seasons. Isaac and Stuart (1992) concluded that more precipitation accompanies warm conditions in winter and cool conditions in summer for the east and west coasts and northern Canada. Rebetez (1996) confirmed that colder summer and lower altitude warmer winter tend to be associated with more precipitation. The onset of precipitation serves to decrease the monthly and seasonal T_{max} but increases the monthly and seasonal T_{min}, with an overall reduction in the T_{DTR}, which is similar to the results by Adimula and Willoughby (2009).

The variation range of the percentage for the 90 sites in winter is the largest, which indicates that there may be obvious spatial variation in the relationships between precipitation and temperature in winter. Figure 4 shows the spatial distributions of the percentage of the frequency of precipitation in winter represented in Fig. 3. As seen in Fig. 4a, b, the places with large percentage (above 50 %) mainly distribute in the semi-arid region, but the places with small percentage (below 50 %) mostly locate at the high altitudes and humid region (plateau and mountains) for both T_{mean} and T_{max}. Although all of the percentage for T_{min} is below 50 % and that for T_{DTR} is above 50 %, the places with larger values also mainly distribute in the semi-arid areas and the sites with smaller percentage mostly occur at the high altitudes and humid region (Fig. 4c, d). It demonstrates that there are obvious spatial variations in the percentage of the frequency of precipitation on days when the temperature of that day is below the median temperature in winter. The climate type, latitude, and altitude are the main factors. The

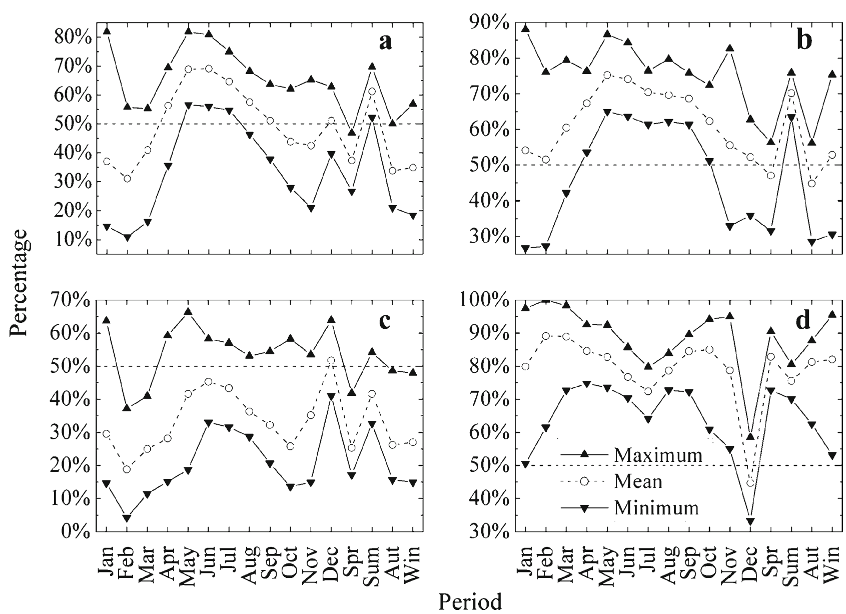

Fig. 3 Percentage of the precipitation on days when the temperature is below the median value for monthly means and seasonal means. Here temperature includes mean temperature (*a*), maximum temperature (*b*), minimum temperature (*c*), and daily temperature range (*d*)

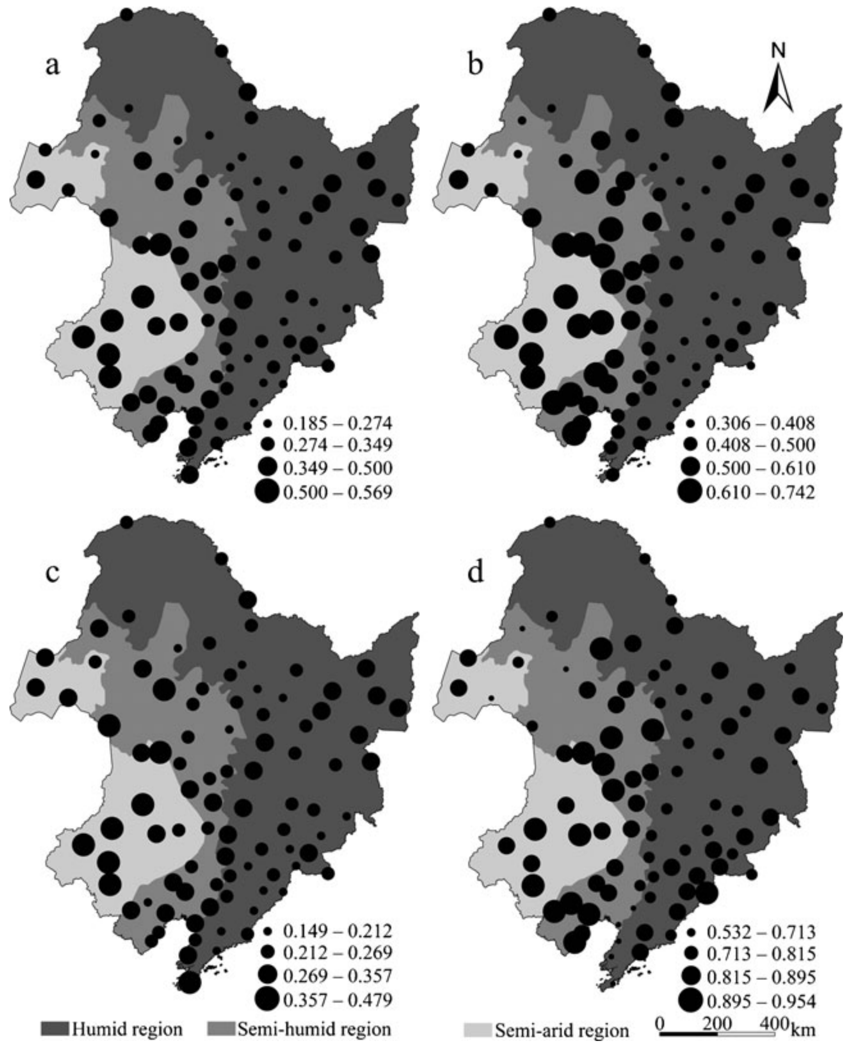

Fig. 4 Spatial distributions of the percentage of precipitation on days when temperature is less than the median value in winter. The symbols of **a**, **b**, **c**, and **d** represent mean temperature, maximum temperature, minimum temperature, and daily temperature range, respectively. *Dots* are scaled based on the amplitude of the percentage

more arid the region is, the larger is the percentage. The higher the altitude is, the smaller is the percentage. In contrast, the variation range in summer is the smallest. The spatial variations in the percentage mentioned above for spring, summer and autumn are not obvious.

3.3 Quantitative precipitation–temperature relationships

To quantitatively analyze the interaction between precipitation and temperature, the values of the PTRs are defined by the accompanied temperature (T_{mean}, T_{max}, T_{min}, and T_{DTR}) variation when 1-mm precipitation amount occurs. Table 2 shows the PTRs for monthly means. More precipitation occurs with higher T_{mean} during January to March and November to December, but more precipitation occurs with lower T_{mean} in April to August. The largest increment of T_{mean} is in January, which is represented by the precipitation–T_{mean} relationships (P–T_{mean} relationships) ranging from 0.023 to 4.516 °C/mm with an average value of 1.045 °C/mm. The largest decreased T_{mean} is in May ranging from −0.020 to −0.225 °C/mm with a mean value of −0.104 °C/mm. Specially, precipitation occurrence companies by lower T_{mean} with the range of −0.001 to −0.225 °C/mm during May to July for all the 90 sites, and the overwhelming majority of them have significant values at the 0.05 confidence level. The precipitation–T_{max} relationships (P–T_{max} relationships) are similar to those of P–T_{mean} relationships. The increment of T_{max} when precipitation occurs dominates in January to March and November to December, whereas the cooling influence of precipitation on T_{max} dominates in April to October. The largest increments of T_{max} when it rains are 0.024–3.864 °C/mm in January for 68 sites, in which the increments of 39 sites are significant at the 0.05 confidence level. The largest T_{max} reductions when it rains are −0.046 to −0.311 °C/mm in May for all the 90 sites, and all sites have significant values at the 0.05 confidence level. Precipitation occurs with higher T_{min} in most months (except July) for more than 50 % stations. The largest T_{min} increments are 0.016–5.171 °C/mm during January for 78 stations, and the increments

Table 2 Quantitative precipitation–temperature relationship for monthly means

	$P–T_{Mean}$	$P–T_{Max}$	$P–T_{Min}$	$P–T_{DTR}$
January	0.023–4.516 (76, 47)	0.024–3.864 (68, 39)	0.016–5.171 (78, 46)	0.018–0.446 (28, 5)
	−1.917 to −0.025 (14, 0)	−3.165 to −0.069 (22, 3)	−1.145 to −0.063 (12, 0)	−2.870 to −0.015 (62, 32)
February	0.000–3.778 (83, 58)	0.013–2.865 (81, 42)	0.003–4.060 (88, 60)	0.018–0.104 (7, 0)
	−0.205 to −0.046 (7, 0)	−0.739 to −0.013 (9, 0)	−0.080 to −0.023 (2, 0)	−2.790 to −0.001 (83, 38)
March	0.000–1.073 (64–21)	0.007–0.655 (48, 6)	0.004–2.037 (83, 40)	0.002–0.045 (7, 0)
	−0.251 to −0.003 (26, 1)	−0.566 to −0.004 (42, 3)	−0.063 to −0.001 (7, 0)	−1.577 to −0.007 (83, 55)
April	0.002–0.060 (7, 0)	0.069 (1, 1)	0.002–0.311 (69, 26)	>0 (0, 0)
	−0.227 to −0.002 (83, 41)	−0.295 to −0.021 (89, 61)	−0.079 to −0.002 (21, 0)	−0.366 to −0.041 (90, 86)
May	>0 (0, 0)	>0 (0, 0)	0.002–0.145 (52, 20)	>0 (0, 0)
	−0.225 to −0.020 (90, 90)	−0.311 to −0.046 (90, 90)	−0.125–0.000 (38, 5)	−0.414 to −0.050 (90, 90)
June	>0 (0, 0)	>0 (0, 0)	0.000–0.151 (54, 25)	>0 (0, 0)
	−0.127 to −0.014 (90, 89)	−0.224 to −0.033 (90, 90)	−0.048–0.000 (36, 12)	−0.320 to −0.009 (90, 88)
July	>0 (0, 0)	>0 (0, 0)	0.001–0.073 (38, 19)	>0 (0, 0)
	−0.072 to −0.001 (90, 84)	−0.101 to −0.009 (90, 88)	−0.029–0.000 (52, 16)	−0.171 to −0.005 (90, 88)
August	0.004–0.011 (5, 0)	>0 (0, 0)	0.001–0.108 (66, 32)	>0 (0, 0)
	−0.081 to −0.001 (85, 66)	−0.112 to −0.012 (90, 88)	−0.033–0.000 (24, 6)	−0.218 to −0.004 (90, 86)
September	0.000–0.053 (37, 4)	0.002–0.008 (5, 0)	0.000–0.190 (80, 53)	0.002–0.003 (2, 0)
	−0.123–0.000 (53, 18)	−0.181 to −0.003 (85, 66)	−0.041–0.000 (10, 0)	−0.371 to −0.001 (88, 81)
October	0.002–0.180 (41, 4)	0.001–0.118 (10, 0)	0.004–0.384 (79, 34)	0.005–0.019 (5, 0)
	−0.144 to −0.001 (49, 8)	−0.211–0.000 (80, 27)	−0.055 to −0.002 (11, 0)	−0.443 to −0.005 (85, 74)
November	0.001–1.561 (77, 33)	0.001–0.804 (78, 20)	0.011–2.149 (79, 38)	0.000–0.182 (22, 3)
	−0.536 to −0.004 (13, 0)	−0.501 to −0.001 (12, 0)	−0.315 to −0.002 (11, 0)	−1.484 to −0.003 (68, 27)
December	0.001–3.378 (83, 59)	0.050–2.801 (76, 52)	0.025–3.584 (83, 59)	0.012–0.602 (24, 6)
	−0.842 to −0.018 (7, 0)	−1.201–0.000 (14, 1)	−0.728 to −0.016 (7, 0)	−1.555 to −0.007 (66, 29)

Here temperature includes mean temperature (T_{mean}), maximum temperature (T_{max}), minimum temperature (T_{min}), and daily temperature range (T_{DTR}). The values in the parenthesis are the numbers of all stations and stations with the relationships being significant at the 0.05 confidence level for corresponding relationship level, respectively. The unit is degree Celsius per millimeter

of 46 sites are significant at the 0.05 confidence level. As for the T_{DTR}, the precipitation occurrence accompanies smaller T_{DTR} in all months for the majority of stations. The largest increment of T_{DTR} is −0.015 to −2.870 °C/mm during January for 62 sites, and 32 stations have significant increment at the 0.05 confidence level.

Duan and Yao (2003) confirmed that in a case of Northern Hemisphere mean temperature increases of 0.1 °C, the precipitation decreases 80 mm and vice versa. However, Adler et al. (2008) found that precipitation increased 2.3 % when temperature increased 1 °C at global scale. How and how much do the temperatures changes when precipitation occurs or does the precipitation vary when temperatures change? Figure 5 shows the spatial distribution of the PTRs for seasonal means. As is evident from Fig. 5 I-a–I-d, there exists negative PTRs in spring for all sites. The larger values of the $P–T_{mean}$ relationships ranging from −0.175 to −0.255 °C/mm distributes in the western Northeast China (semi-humid and semi-arid region), which decreases toward the southeast direction. It is because the precipitation is mostly the cold frontal-type precipitation in spring and the intensity of cold air mass caused by the Siberian high decreases along the NW–SE direction. Another important reason is that the latent heat of evaporation of rainwater when it rains results in the reduction of T_{mean}. The $P–T_{max}$ and $P–T_{min}$ relationships in spring are the range of −0.039 to −0.318 and −0.043 to 0.172 °C/mm, respectively. The larger values of the $P–T_{max}$ and $P–T_{min}$ relationships are mainly occur at the semi-humid and semi-arid region and the high altitude with humid regions. The negative values of the $P–T_{max}$ relationships are larger than those of the $P–T_{min}$ relationships, which results in the negative $P–T_{DTR}$ relationships with the range of −0.042 to −0.469 °C/mm.

The summer PTRs are presented in Fig. 5 II-a–II-d. The 1-mm precipitation amount mainly accompanies lower T_{mean}, lower T_{max}, higher T_{min}, and smaller T_{DTR} in summer, with the values of −0.004 to −0.075, −0.015 to −0.117, 0–0.099, and −0.005 to −0.189 °C/mm, respectively. The largest values of $P–T_{mean}$ relationships with the range of

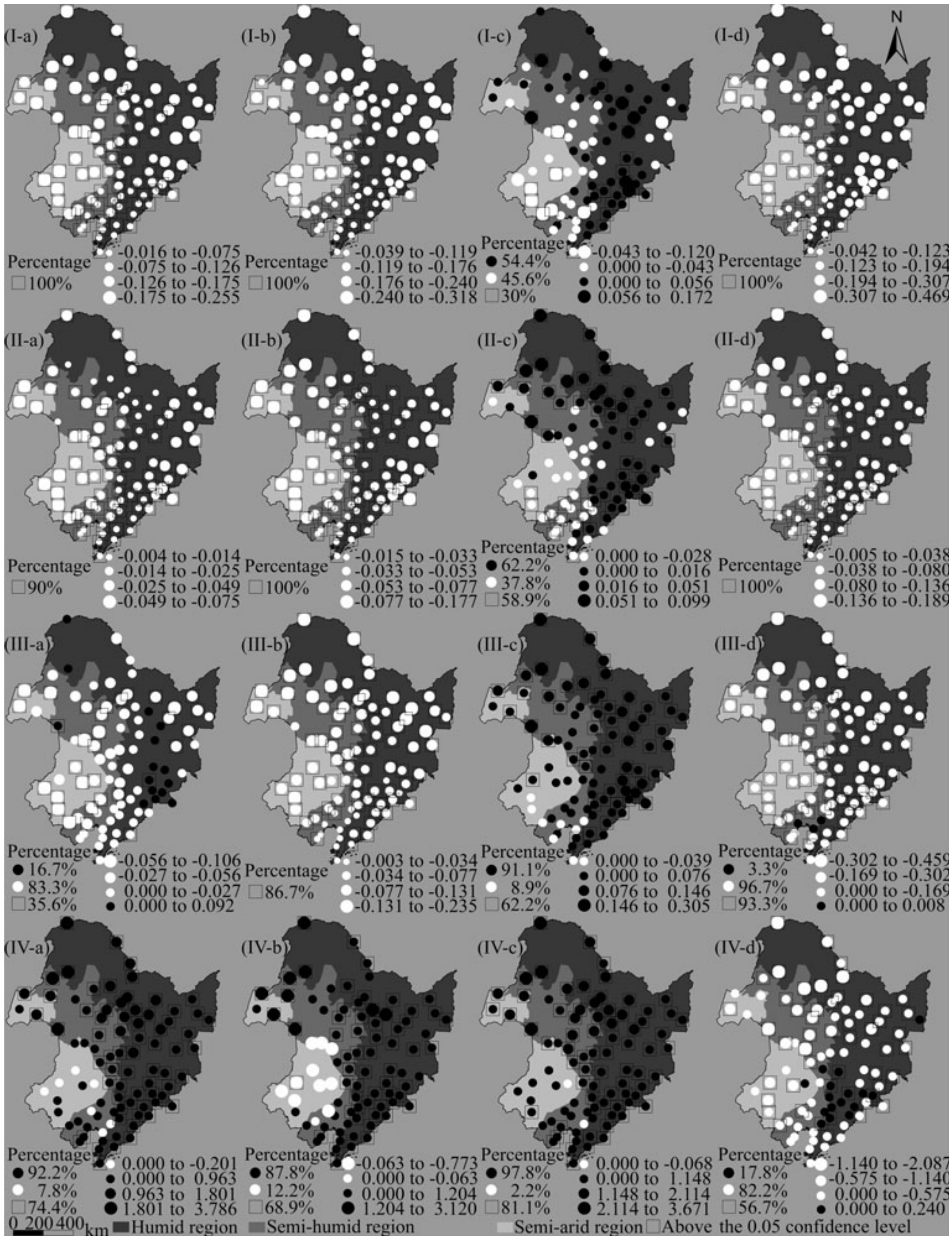

Fig. 5 Quantitative precipitation–temperature relationships for seasonal means. Here temperature includes mean temperature (*a*), maximum temperature (*b*), minimum temperature (*c*), and daily temperature range (*d*). The symbols of *I*, *II*, *III*, and *IV* represent spring, summer, autumn, and winter, respectively. For example, the subfigure *II-b* represents the quantitative precipitation–maximum temperature relationships in summer. *Dots* are scaled based on the amplitude of the correlations, with *white* signifying negative value and *black* signifying positive value. *Squares* indicate stations with correlations significant at the 0.05 confidence level. Percentage represents the percentage of each category of relationships. The unit is degree Celsius per millimeter

−0.049 to −0.075 °C/mm mostly occurs in the semi-arid region, where the cold air mass dominates the frontal system and the rain is mostly the frontal-type rain. In contrast, the smallest values of −0.004 to −0.014 °C/mm mainly distributes in Liaoning Province, where the rain is mainly the orographic rain controlled by the warm and humid air of East Asian summer monsoon. Meanwhile, when precipitation occurs, the temperature is diminished owing to more energy going into latent heat of evaporation rather than sensible heat (Milly and Dunne 2001; Walter et al. 2009). Moreover, the surface moisture is likely associated with clouds to block out the sun, providing less energy firstly, further reducing temperatures (Liepert 2002; Trenberth and Shea 2005). The distribution of the P–T_{max} relationships is similar to that of the P–T_{mean} relationships. In the high altitude and humid region, the 1-mm precipitation amount mainly accompanies increment of T_{min}.

The PTRs in autumn are presented in Fig. 5 III-a–III-d. The 1-mm precipitation amount mainly accompanies lower T_{mean}, lower T_{max}, higher T_{min}, and smaller T_{DTR}, with the values of 0 to −0.106, −0.003 to −0.235, 0–0.305, and 0 to −0.459 °C/mm, respectively. Autumn is the transition season that the atmospheric circulation in summer changes to winter. The rainfall types are similar to that in summer. The cold air mass dominates the frontal system in the semi-arid region, and the rain is mostly the frontal-type rain. In contrast, the orographic rain mainly distributes in piedmonts of the west slope and south slope of Changbai Mountains. The temperature variation when 1-mm precipitation occurs in autumn is larger than that in summer, since it has higher intensity of the cold air mass and smaller intensity of the frontal-type and orographic precipitation amounts in autumn. The high intensity of cold air mass in the semi-arid region in western and humid region in eastern Northeast China causes larger decreased T_{mean} when 1-mm precipitation occurs. The latent heat of evaporation reduces the surface temperature in these places. In some high altitude and latitude region in autumn, the 1-mm precipitation amount accompanies, contrarily, increased T_{mean}, with the range of 0–0.092 °C/mm (Fig. 5 III-a), owing to that the surface temperature has been below freezing point and that the release of latent heat of solidification increases the surface temperature. The larger values of the P–T_{max} relationships ranging from −0.131 to −0.235 °C/mm mainly occur in the higher altitude and latitude region and the northeastern Northeast China. The larger values of the P–T_{min} relationships with the range of 0.076–0.305 °C/mm mainly distribute in the high altitude region (the Chiangbai Mountains–Xiao Hinggan Mountains–Da Hinggan Mountains). The PTRs in winter are different from that in the other seasons. More stratocumulus cloud occurs when temperature are colder in summer but warmer in winter. Surface temperatures are warmer in summer with clear skies but warmer in winter with overcast skies (Isaac and Stuart 1996). Clouds literally provide a blanket for the Earth, both shielding it from radiation from the sun and trapping heat escaping from the surface. The presence of cloud in the summertime provides a cooling effect, while it makes the surface warmer in the wintertime (Isaac and Hallett 2006).

As is evident from Fig. 5 IV-a–IV-d, the 1-mm precipitation amount occurrence mainly accompanies higher T_{mean}, higher T_{max}, higher T_{min}, and smaller T_{DTR}, with the values of 0–3.786, 0–3.120, 0–0.367, and 0 to −2.087 °C/mm, respectively. For the overwhelming majority of stations, the rainwater temperature is lowered into environmental temperature and rainwater solidifies on the ground when it rains in early or late winter over Northeast China. The release of the latent heat of solidification and sensible heat increases the surface temperature. Meanwhile, the enhanced atmospheric counter radiation caused by cloud when it rains also increases the surface temperature. The lager values of the P–T_{mean} relationships ranging from 0.963 to 3.786 °C/mm mostly occurs at the high altitudes and latitudes (Xiao Hinggan Mountains and Da Hinggan Mountains), which indicates that the lower the surface temperature below freezing point is, the more the heat releases when precipitation occurs. In winter, however, there may be not any latent heat of solidification release when precipitation occurs in some region (e.g., the low latitudes and equatorial regions, such as Hainan). Table 3 shows the P–T_{mean} relationships in winter over Hainan during 1951–2001. It can be seen that the values of the P–T_{mean} relationships are positive, with the range of 0.006–0.027 °C/mm, while the values are smaller than those in Northeast China. In these areas, instead of latent heat of solidification release, latent heat of evaporation would have reduced the surface temperature when precipitation occurs in winter. However, precipitation is, indeed, accompanied by high temperature, which indicates that the enhanced atmospheric counter radiation by clouds is the major reason to increase surface temperature when precipitation occurs in winter. In cold winter, the moisture holding capacity of the atmosphere is low and, accordingly, the precipitation amount is small, which will increase the value of PTRs (degree Celsius per millimeter) if the temperature variation is about the same for seasonal means. This is one of the reasons why the values of the P–T_{mean} relationships in winter over Northeast China are larger than those in winter over Hainan and larger than those in other seasons over Northeast China. The larger values of the P–T_{max} and P–T_{min} relationships also mainly occur in Xiao Hinggan Mountains and Da Hinggan Mountains. The T_{DTR} of 82.2 % sites becomes smaller when 1-mm precipitation amount occurs, but the T_{DTR} of 17.8 % stations is larger in southeastern Northeast China.

Table 3 Quantitative relationships between precipitation and mean temperature over Hainan in winter during 1951–2001

Station	Latitude	Longitude	P–T_{mean} relationship	Significance
Dongfang	19°6′	108°37′	0.027	0.28
Danxian County	19°31′	109°35′	0.015	0.37
Qiongzhong	19°2′	109°50′	0.055	0.00
Qionghai	19°14′	110°28′	0.025	0.01
Sanya	18°14′	109°31′	0.009	0.51
Lingshui	18°30′	110°2′	0.006	0.50

Here P–T_{mean} relationships represent the relationships between precipitation and mean temperature. The unit is degree Celsius per millimeter

4 Conclusions

The purpose of our study is to investigate the relationships between precipitation and temperature (T_{mean}, T_{max}, T_{min}, and T_{DTR}) over Northeast China during the last five decades. We analyze the correlations between precipitation and temperature for monthly means and seasonal means, the percentage of the frequency of precipitation on days when the temperature of that day is below the median temperature for monthly means and seasonal means, and furthermore, the quantitative PTRs defined by the accompanied temperature variation when 1-mm precipitation amount occurs.

For monthly means, strong negative correlations between precipitation and T_{mean}, T_{max}, T_{min}, and T_{DTR} are in July, July, May, and August, respectively. Large positive correlations between precipitation and T_{mean}, T_{max}, and T_{min} are all in January. Higher altitudes with humid climate have stronger positive correlations between T_{mean} and precipitation in spring, autumn, and winter, whereas larger negative correlations dominate in semi-arid or arid regions in summer. Strong positive correlations between T_{max} and precipitation dominate at high altitude humid regions and high altitude high latitude regions in spring, autumn, and winter, while large negative correlations in winter dominate in semi-arid lower latitude regions and high altitude and humid lower latitude regions over Northeast China. Large positive correlations between T_{min} and precipitation dominate at high altitude humid regions and high altitude high latitude regions for all seasons. For monthly means, the precipitation is mainly observed on relatively higher T_{mean} days in January to March, October and November, on relatively higher T_{min} days in most months (except December), on larger T_{DTR} days in December, on lower T_{mean} days in April to August, on relatively lower T_{max} days in the overwhelming majority of months (except February and December), and on relatively smaller T_{DTR} days in major months (except December).

In spring, the 1-mm precipitation amount mainly accompanies lower T_{mean}, lower T_{max}, higher T_{min}, and smaller T_{DTR} ranging from −0.016 to −0.255, −0.039 to −0.318, 0–0.172, and −0.042 to −0.469 °C/mm, respectively. In summer, the 1-mm precipitation amount mainly accompanies lower T_{mean}, lower T_{max}, higher T_{min}, and smaller T_{DTR}, with the values of −0.004 to −0.075, −0.015 to −0.117, 0–0.099, and −0.005 to −0.189 °C/mm, respectively. The 1-mm precipitation amount mainly accompanies lower T_{mean}, lower T_{max}, higher T_{min}, and smaller T_{DTR} in autumn, with the values of 0 to −0.106, −0.003 to −0.235, 0–0.305, and 0 to −0.459 °C/mm, respectively. The 1-mm precipitation amount occurrence mainly accompanies higher T_{mean}, higher T_{max}, higher T_{min}, and smaller T_{DTR} in winter, with the values of 0–3.786, 0–3.120, 0–0.367, and 0 to −2.087 °C/mm, respectively.

The PTRs are influenced by different cloud fraction, latent and sensible heat conversion, rainfall type, etc. (Chapin et al. 2011; Frieler et al. 2011; Isaac and Hallett 2006; Walter et al. 2009). Moreover, these factors play different roles in different areas and period, such as various altitudes, latitudes, longitudes, climate types, months, seasons, and intercombination between them (Isaac and Stuart 1992; Screen and Simmonds 2010; Stuart and Isaac 1994). In summer, when precipitation occurs, the enhanced clouds block out the sun, providing less energy firstly and further reducing the surface temperature, the latent heat of vaporization lowers the surface temperature, and cold frontal-type precipitation reduces the surface temperature. In various altitudes, latitudes, longitudes, and climate types, the influence intensity of the factors mentioned above on temperature fall is different. The strongest negative P–T_{mean} relationships with the range of −0.049 to −0.075 °C/mm mostly occurs in the semi-arid region, where the cold air mass dominates the frontal system and the rain is mostly the cold frontal-type rainfall. In contrast, the smallest values of −0.004 to −0.014 °C/mm mainly distributes in Liaoning Province, where the rain is mainly the orographic rain controlled by the warm and humid air of East Asian summer monsoon. When precipitation occurs in winter, the clouds enhance the atmospheric counter radiation so that it increases the surface temperature. When rainwater temperature decrease, rainwater solidification, and ice temperature decrease occur on the ground, the releases of latent heat and sensible heat increase the surface temperature. The stronger positive P–T_{mean} relationships mostly occur at the high altitudes and latitudes (Xiao Hinggan Mountains and Da Hinggan Mountains), with the range of 0.963–3.786 °C/mm owing to releasing more heat, where the surface temperature below freezing point is lower than that of other regions. The enhanced atmospheric counter radiation by clouds is the major reason to increase surface temperature when precipitation occurs in winter (Section 3.3). Nevertheless, there have been many other factors influencing the P–T relationships, such as pressure, wind, atmospheric circulation, etc. It is a challenge to plenty interpret the P–T relationships considering all the factors, which will be, however, our future intent.

Acknowledgments This study was financially supported by the National Natural Science Foundation of China (grant no. 41171038) and the Natural Science Foundation of Jilin Province (grant no. 20101561).

References

Adimula IA, Willoughby AA (2009) Temperature and precipitation relation in the sub-Sahel. Niger J Phys 20(2):291–297

Adler RF, Gu G, Wang JJ, Huffman GJ, Curtis S, Bolvin D (2008) Relationships between global precipitation and surface temperature on interannual and longer timescales (1979–2006). J Geophys Res 113:D22104. doi:10.1029/2008JD010536

Berg P, Haerter JO, Thejll P, Piani C, Hagemann S, Christensen JH (2009) Seasonal characteristics of the relationship between daily precipitation intensity and surface temperature. J Geophys Res 114:D18102. doi:10.1029/2009JD012008

Chapin FS III, Matson PA, Vitousek PM, Chapin MC (2011) Principles of terrestrial ecosystem ecology, 2nd edn. Springer, New York, pp 23–62

Dai A, Fung IY, Del Genio AD (1997) Surface observed global land precipitation variations during 1900–88. J Climate 10(11):2943–2962. doi:10.1175/1520-0442(1997)010<2943:SOGLPV>2.0.CO;2

Duan KQ, Yao TD (2003) Precipitation variability in central Himalayas and its relation to Northern Hemisphere temperature. Chin Sci Bull 48(14):1480–1482. doi:10.1360/02wd0253

Dutilleul P, Stockwell JD, Frigon D, Legendre P (2000) The mantel test versus Pearson's correlation analysis: assessment of the differences for biological and environmental studies. J Agric Biol Environ Stat 5(2):131–150

Frieler K, Meinshausen M, Schneider von Deimling T, Andrews T, Forster P (2011) Changes in global-mean precipitation in response to warming, greenhouse gas forcing and black carbon. Geophys Res Lett 38:L04702. doi:10.1029/2010GL045953

Hulme M, Osborn TJ, Johns TC (1998) Precipitation sensitivity to global warming: comparison of observations with Hadcm2 simulations. Geophys Res Lett 25(17):3379–3382. doi:10.1016/S0092-8674(00)81604-9

Isaac GA, Hallett J (2006) Clouds and precipitation. Encyclopedia of Hydrological Sciences, published online, 15 April, 2006: 48–72, doi:10.1002/0470848944.hsa031.

Isaac GA, Stuart RA (1992) Temperature–precipitation relationships for Canadian stations. J Climate 5(8):822–830. doi:10.1175/1520-0442(1992)005<0822:TRFCS>2.0.CO;2

Isaac GA, Stuart RA (1996) Relationships between cloud type and amount, precipitation, and surface temperature in the Mackenzie river valley—Beaufort Sea area. J Climate 9(8):1921–1941. doi:10.1175/1520-0442(1996)009<1921:RBCTAA>2.0.CO;2

Kendall MG (1975) Rank correlation measures. Charles Griffin, London

Liepert BG (2002) Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990. Geophys Res Lett 29(10):1421–1424. doi:10.1029/2002GL014910

Lyons SW (1990) Spatial and temporal variability of monthly precipitation in Texas. Mon Weather Rev 118(12):2634–2648. doi:10.1175/1520-0493(1990)118<2634:SATVOM>2.0.CO;2

Madden RA, Williams J (1978) The correlation between temperature and precipitation in the United States and Europe. Mon Weather Rev 106(142–147). doi:10.2307/1907187

Mann HB (1945) Nonparametric tests against trend. J Econom Soc 13(3):245–259

Milly PCD, Dunne KA (2001) Trends in evaporation and surface cooling in the Mississippi River basin. Geophys Res Lett 28(7):1219–1222. doi:10.1029/2000GL012321

Namias J (1953) Thirty-day forecasting: a review of a ten-year experiment. American Meteorological Society, Boston

Nicholls N, Della-Marta P, Collins D (2004) 20th Century changes in temperature and rainfall in New South Wales. Aust Meteorol Mag 53(4):263–268

Rebetez M (1996) Seasonal relationship between temperature, precipitation and snow cover in a mountainous region. Theor Appl Climatol 54(3):99–106. doi:10.1007/BF00865152

Screen JA, Simmonds I (2010) The central role of diminishing sea ice in recent Arctic temperature amplification. Nature 464:1334–1337. doi:10.1038/nature09051

Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (2007) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Stuart RA, Isaac GA (1994) A comparison of temperature–precipitation relationships from observations and as modeled by the general circulation model of the Canadian climate centre. J Climate 7(2):277–282. doi:10.1175/1520-0442(1994)007<0277:ACOTRF>2.0.CO;2

Toros H (2012) Spatio-temporal precipitation change assessments over Turkey. Int J Climatol 32(9):1310–1325. doi:10.1002/joc.2353

Trenberth KE, Shea DJ (2005) Relationships between precipitation and surface temperature. Geophys Res Lett 32:L14703. doi:10.1016/j.bmc.2009.02.010

Van den Dool HM (1988) A utilitarian atlas of monthly and seasonal precipitation temperature relations, the United States, 1931–1987. University of Maryland SR-88-17

Walter MT, Wilks DS, Parlange JY, Schneider RL (2009) Increasing evapotranspiration from the conterminous United States. J Hydrometeorol 5(3):405–408. doi:10.1175/1525-7541(2004)005<0405:IEFTCU>2.0.CO;2

Wu ZF, Du HB, Zhao DS, Li M, Meng XJ, Zong SW (2011) Estimating daily global solar radiation during the growing season in Northeast China using the Ångström—Prescott model. Theor Appl Climatol 108(3–4):495–503. doi:10.1007/s00704-011-0545-2

Zhao W, Khalil MAK (1993) The relationship between precipitation and temperature over the contiguous United States. J Climate 6(6):1232–1240. doi:10.1175/1520-0442(1993)006<1232:TRBPAT>2.0.CO;2