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Impact of Urbanization on Low-Temperature Precipitation in Beijing during 1960–2008

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ABSTRACT

Daily precipitation and temperature records at 13 stations for the period 1960–2008 were analyzed to identify climatic change and possible effects of urbanization on low-temperature precipitation [LTP, precipitation of $\geqslant 0.1$ mm d^{-1} occurring under a daily minimum temperature (Tmin) of $\leqslant 0°$C] in the greater Beijing region (BJR), where a rapid process of urbanization has taken place over the last few decades. The paper provides a climatological overview of LTP in BJR. LTP contributes 61.7% to the total amount of precipitation in BJR in the cold season (November–March). There is a slight increasing trend [1.22 mm (10 yr)$^{-1}$] in the amount of total precipitation for the cold season during 1960–2008. In contrast, the amount of LTP decreases by 0.6 mm (10 yr)$^{-1}$. The warming rate of Tmin in BJR is 0.66°C (10 yr)$^{-1}$. Correspondingly, the frequency of LTP decreases with increasing Tmin by -0.67 times per °C. The seasonal frequency and amount of LTP in southeast BJR (mostly urban sites) are 17%–20% less than those in the northwestern (rural and montane sites). The intensity of LTP for the urban sites and northeastern BJR exhibited significant enhancing trends [0.18 and 0.15 mm d^{-1} (10 yr)$^{-1}$, respectively]. The frequency of slight LTP (<0.2 mm d^{-1}) significantly decreased throughout BJR [by about -15.74% (10 yr)$^{-1}$ in the urban area and northeast BJR], while the contribution of the two heaviest LTP events to total LTP amount significantly increased by 3.2% (10 yr)$^{-1}$.

Key words: urbanization, low-temperature precipitation, empirical orthogonal function, climate change

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1. Introduction

Low temperature precipitation (LTP) is a type of disastrous weather for urban areas, capable of causing traffic accidents, power outages and personal injury (Zhao et al., 2002; Sun et al., 2003). LTP can be defined as daily precipitation of $\geqslant 0.1$ mm d^{-1} occurring under a daily minimum temperature (Tmin) of $\leqslant 0°$C, and—in the greater Beijing region (BJR)—it usually occurs during the cold season (November–March). There have not been many studies on climate change in LTP, nor about the possible effects of urbanization on LTP. However, it is certainly of interest to study how LTP has changed in BJR during the past few decades, when and where a rapid process of urbanization was happening.

Many researchers have studied the possible effects of urbanization on temperature and precipitation in Beijing and surrounding areas (Sun and Shu, 2007; Zheng and Liu, 2008; Wang et al., 2009; Zhang et al., 2009). It is well recognized that urbanization enhances local warming and that the observed decrease in the diurnal temperature range (DTR) results from a larger increase in the daily minimum temperature than in the daily maximum temperature (Gallo et al., 1999; Zhou et al., 2004; Tokairin et al., 2010). In the case of Beijing Observatory, a site near the city center, Yan et al. (2010) suggested an urbanization-related warming trend of about 0.3°C (10 yr)$^{-1}$ in the daily mean temperature, in addition to a regional mean warming of about 0.5°C (10 yr)$^{-1}$ during 1977–2006.

In general, an enhanced Urban Heat Island (UHI) effect should result in a decrease of LTP in urban areas and an increase downstream of the UHI (Baik et al., 2000; Changnon, 2003). However, various different types of weather systems are responsible for inducing LTP, and therefore the relationship between urbanization and changes in precipitation have yielded a variety of conclusions (Shepherd et al., 2002; Diem and Mote, 2005; Wang et al., 2007; Mitra et al., 2011). Changnon et al. (1971) argued that the size of the urban area plays an important role in downwind precipitation anomalies. Mölders and Olson (2004) pointed out that loca-

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tions of maximum increase in precipitation vary depending on the particular urban case under study because of different mechanisms involved. Furthermore, according to Landsberg (1981) and Changnon (2003), snowfall events in urban areas could decrease by 10%–35% simply due to the UHI effect. It therefore appears highly likely that some LTP occurrences would be altered by the UHI effect. Nevertheless, precipitation is influenced not only by the UHI effect in a direct manner, but also by complex interactions between the UHI and atmospheric circulation (Shepherd, 2005; Zhai et al., 2005). Kishtawal et al. (2010) suggested that urbanization and changes in the urban–rural boundary could play a significant role in the formation of precipitation. Undoubtedly, more climatological analyses will be beneficial for improving understanding of the effects of urbanization on LTP.

The work reported in the present paper was aimed at quantifying any secular trend in LTP in BJR in recent decades and identifying possible impacts of urbanization on the trend in LTP. The investigation was carried out on the basis of a homogenized daily observation dataset for the period 1960–2008. Using Tmin $\leqslant 0$ as a threshold is a rather rough measure for identifying the occurrence of freezing rain. However, as mentioned above, the focus of the present study was the climate trend in LTP, rather than a weather-based study that would have required a more strictly defined target. Thus, as is critical for climate change assessments, the definition provided—given the availability of data—a reasonably comparable measure for different sites across the study area. The data and methods are explained in section 2. The results are illustrated and discussed in section 3, followed by a summary in section 4.

2. Data and methods

We defined LTP, which includes snowfall and freezing rain, as daily precipitation of $\geqslant 0.1$ mm d^{-1} occurring under a Tmin of $\leqslant 0$°C. According to the observations used in the present study, we found that 95% of snowfall and freezing rain events happened when Tmin $\leqslant 0$°C at the BJR local sites, and that snowfall accounts for 85% of total LTP. It is worthwhile noting that the present definition of LTP is not a strict description of the weather phenomena, but an index for investigating the climate trend in association with a type of disastrous weather in an urban area.

Daily observations of precipitation and Tmin at 13 meteorological stations in BJR were obtained from the Information Center of the Beijing Meteorological Bureau. Figure 1 shows the topography of Beijing and the geographic distribution of the 13 stations.

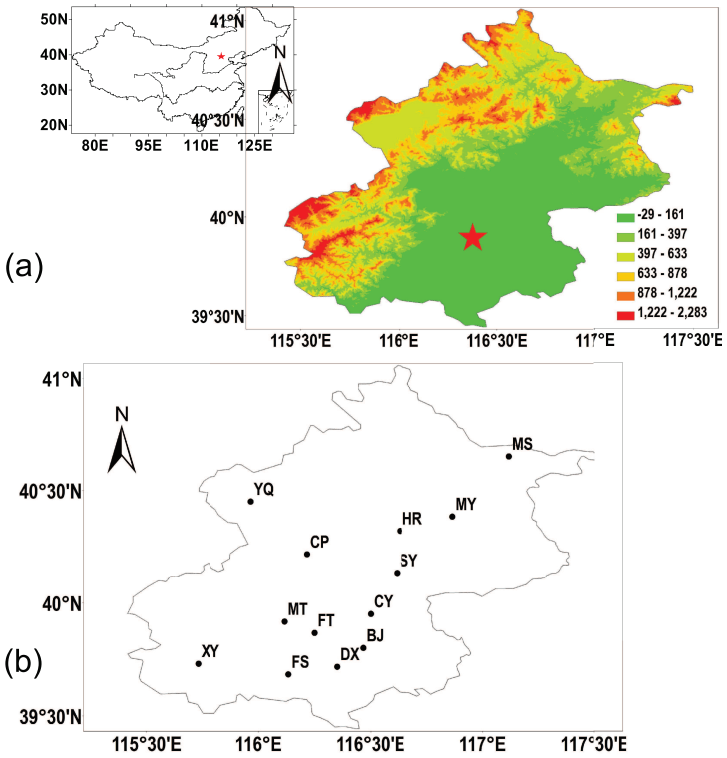

Fig. 1. (a) Location and topography (m) of Beijing and (b) the distribution of the 13 chosen stations: MS (Miyun-Shangdianzi); MY (Miyun); HR (Huairou); SY (Shunyi); YQ (Yanqing); CP (Changping); CY (Chaoyang); BJ (the Beijing Observatory); FT (Fengtai); MT (Mengtougou); XY (Xiayunling); FS (Fangshan); and DX (Daxing). The pentagram represents Tian'anmen Square in the city centre.

The inhomogeneities in climate observations in China due to frequent changes of observing locations and equipment have been highlighted by a number of studies in recent years (Li and Dong, 2009; Li and Yan, 2009; 2010; Li et al., 2011b). To adjust for biases in the observational temperature and precipitation time series, the Multiple Analyses of Series for Homogenization (MASH) method developed by Szentimrey (1999) was applied. Homogenization of a climate series involves adjusting biases in the series due to site relocations, changes of observing rules, or updates to instruments etc. by comparing neighboring site records. The intention is not to make individual site observations similar to the regional mean, but the resultant data in general exclude non-climate signals in the original data. In MASH, the additive (e.g., for temperature) or multiplicative (e.g., for precipitation) models are applied depending on the different distributions (normal for temperature and quasi-lognormal for precipitation) of examined climate elements.

It is essential that climate change analyses are based on homogenized time series, but this has not been the case for many previous studies of climate change in China. The present study is among the first to examine climate change with consideration of urbanization in BJR based on a homogenized dataset, which has been available only recently. The 13-station-averaged seasonal (November–March) mean Tmin and precipitation series based on the homogenized data are compared with those based on original data in Fig. 2. The adjusted Tmin series exhibits a larger warming trend during the study period than the original series [0.66°C (10 yr)$^{-1}$ vs. 0.51°C (10 yr)$^{-1}$; Fig. 2a]. There is no significant difference in the seasonal precipitation between the adjusted and original data, except for different amounts of LTP for some years (e.g., 1989). There is almost no difference in the trends of the regional mean LTP amount and frequency between the adjusted and original data.

The annual mean intensity of LTP is defined as:

$$I = \frac{P}{N} , \tag{1}$$

where P is the total amount of LTP and N is the total number of LTP events (times or days) during the cold season at a station.

To classify urban and rural sites regarding variability of LTP, an Empirical Orthogonal Function (EOF) analysis (Deng et al., 1989) was carried out on the normalized series of the seasonal amount of LTP at the 13 stations. The ordinary least squares regression method was adopted to estimate a linear trend in the studied time series, and a t-test was applied to assess its significance.

3. Results and discussion

3.1. *Climatology of LTP in Beijing*

The regional mean seasonal amount of LTP (15.4 mm) accounts for 61.7% of the total precipitation (25.4 mm) in the cold season. Although Tmin was used to define LTP, there does not appear to be a straightforward relationship between

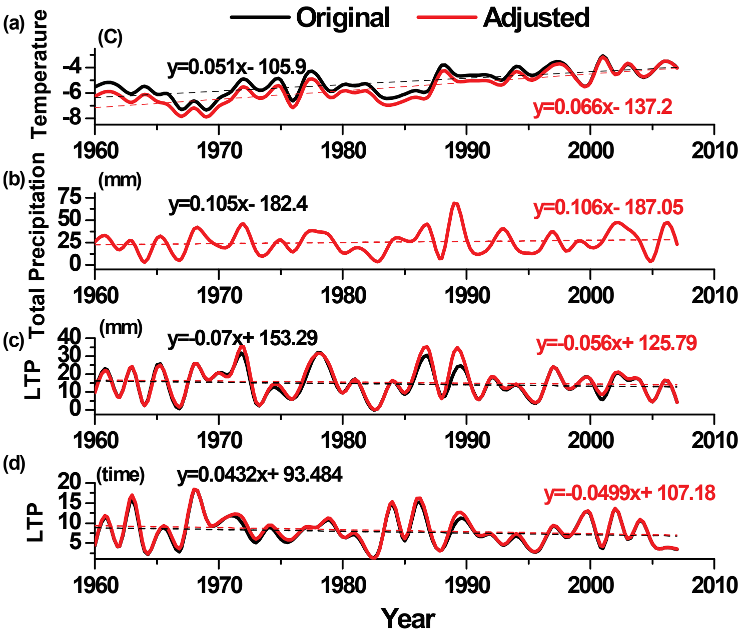

Fig. 2. (a) Regional mean time series of seasonal mean Tmin, (b) amount of total precipitation, (c) amount of LTP, and (d) frequency of LTP in the cold season (November–March) during 1960–2008 based on the original and homogenized data at the 13 stations in BJR. Dashed lines indicate linear trends for the corresponding time series.

the two variables. There is an insignificant negative correlation ($R = -0.11$) between the regional mean Tmin and the amount of LTP for the cold season. However, there is a moderate correlation ($R = -0.30$; significant at $\alpha = 0.1$) between Tmin and the frequency of LTP. The regional mean frequency of LTP decreases with increasing Tmin by $-0.67°\mathrm{C}^{-1}$. It is therefore apparent that urbanization is favorable for increasing temperature and decreasing the frequency of LTP.

The climatological mean pattern of the seasonal mean Tmin in BJR during 1960–2008 is shown in Fig. 3a, indicating a northwest–southeast gradient. As can be seen, a UHI tends to be centered in the southeast of BJR, where the seasonal mean Tmin is 1.8°C–4.2°C higher than that in the northwest (rural or mountainous locations). Topography plays a role in forming the geographical pattern of Tmin in BJR (Sun and Yang, 2008).

Figures 3b–e show the geographical patterns of LTP, total precipitation and their frequencies for the cold season in BJR. The frequency of precipitation exhibits little difference among the different sites—about 12 times per year almost everywhere (Fig. 3e), implying that the region mainly receives large-scale precipitation in the cold season under westerly circulation such that a precipitation event is observed somehow simultaneously at most of the sites. However, the amount of total precipitation exhibits larger values to the northeast of the central urban area (Fig. 3c). Note that precipitation in BJR in the cold season usually happens when a westerly trough approaches, and LTP is usually attributed to the water vapor transportation through the southwesterly jet in the middle and lower troposphere and/or results from the easterly wind (return flow) at the bottom of the troposphere (Sun and Zhao, 2003; Li et al., 2011a). The larger amount of precipitation to the northeast can likely be attributed to a downstream effect of the UHI, as depicted in Fig. 4, caused by the southerly flow prevailing in BJR during times of LTP. Although the gradient of LTP amount is also closely linked to the special topography in Beijing (Sun et al., 2007; Li et al., 2011a), the effect of the UHI favors the occurrence of LTP in downstream parts.

In comparison, as Figs. 3b and d show, the LTP amount and frequency appear larger in the northwestern montane

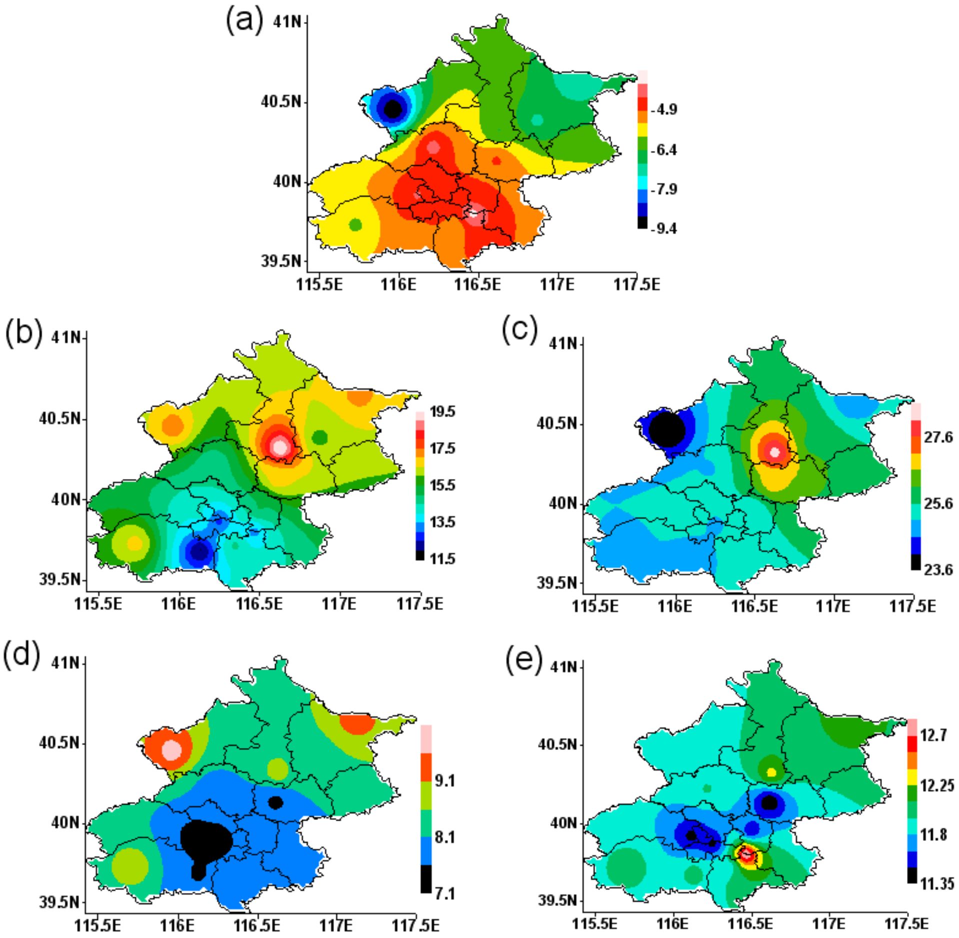

Fig. 3. (a) Geographical distribution of seasonal mean Tmin (units: °C), (b) amount of LTP (units: mm), (c) amount of total precipitation (units: mm), (d) frequency of LTP (units: days per season), and (e) frequency of total precipitation (units: days per season) in the cold season (November–March) during 1960–2008 in BJR.

sites (about 18 mm and nine days per year, respectively) than in the southeastern urban sites (down to 12 mm and seven days per year, respectively). This is because warmer temperatures in the southeast or urban area is unfavorable for LTP. Nevertheless, the southwest–northeast gradient of the LTP amount across Beijing City might somehow reflect the downstream effect of the UHI on LTP (Fig. 3b).

3.2. *Climate change in LTP in Beijing*

There was a significant warming trend [0.66°C (10 yr)$^{-1}$; Fig. 2a] in the regional mean Tmin during the period of study. In comparison, Sun and Shu (2007) found an average warming trend of about 0.6°C (10 yr)$^{-1}$ in BJR for winter during 1975–2004. A large warming trend of 0.71°C (10 yr)$^{-1}$ occurred at BJ—the station nearest to the city center—compared with the average warming trend of 0.59°C (10 yr)$^{-1}$ at the rural sites XY, MS, MY and HR (YQ was excluded as it is near to the town center, though the town as a whole is in a mountainous area). This warming background helps in understanding relevant changes in LTP.

As Fig. 5 shows, the regional mean amount of total precipitation and that of LTP exhibit different long-term trends, in spite of a significant correlation (with a coefficient as large as 0.8, $\alpha = 0.1$) of interannual variations. On average over BJR, LTP contributes 61.7% to the total amount of precipitation in the cold season, as shown in Fig. 5, and 95% of snowfall and freezing rain events happened when Tmin was $\leqslant$ 0°C at the local sites (not shown). There was a slight increasing trend [1.22 mm (10 yr)$^{-1}$] in the amount of total precipitation for the cold season during 1960–2008. Wang and Yan (2009) reported an increasing trend in winter precipitation over most of northern China during the same period. The present result is in agreement with this previous analysis. In contrast, the amount of LTP was decreasing by 0.6 mm (10 yr)$^{-1}$ during the period of study. Consequently, the ratio of the amount of LTP to that of total precipitation was decreasing by 3% (10 yr)$^{-1}$. It is inferred that the decrease of LTP mainly resulted from a large-scale warming environment in the region, especially for the cold season during the last half century, as discussed in Yan et al. (2011).

3.3. *Effects of urbanization*

An EOF analysis was applied to normalized time series of the seasonal LTP amount for November–March during 1960–2008 to help identify whether there are different regional regimes of climate variability in LTP in association with urban/rural divisions in BJR. Figure 6 shows the first two EOF patterns.

The first EOF mode explains 72.6% of the total variance, showing a coherent phase (positive coefficients) over the whole region, indicating that interannual variations of LTP are very similar to each other across the different sites in BJR. However, the larger coefficients in southeast BJR [an area more urbanized than the northwest (shaded red in Fig. 6a) and including the four stations Shunyi (SY), the Beijing Observatory (BJ), Chaoyang (CY) and Daxing (DX)] suggest a possible urban-related regime with slightly enhanced interannual variations of LTP. Figure 5 also suggests an overall decreasing trend of LTP amount during 1960–2008 across the whole region, which is slightly more pronounced in the more urbanized southeast, as implied in the geographic pattern. A reason is simply that urbanization leads to enhanced warming in the southeast urban area, as depicted in Fig. 3a.

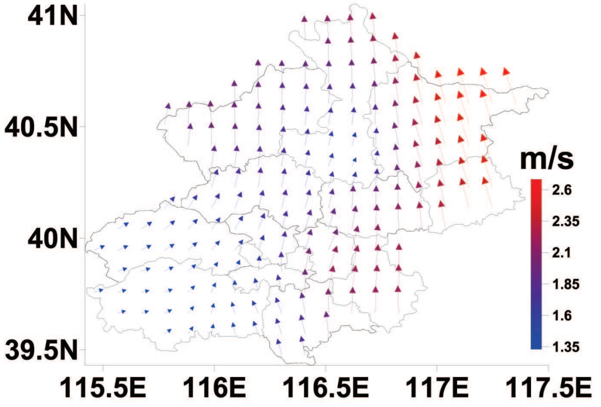

Fig. 4. Average pattern of surface winds for all the LTP events in Beijing during 1960–2008.

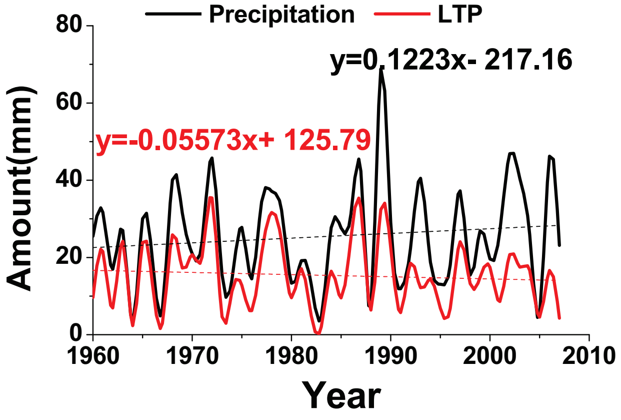

Fig. 5. Trends in the amount of precipitation and LTP in BJR in the cold season during 1960–2008. Dashed lines indicate linear trends for the corresponding time series.

The second EOF mode explains 10.2% of the total variance. This pattern clearly demonstrates the southwest–northeast gradient of LTP across the urban center (Fig. 3b). If this pattern represents the downstream effect of the UHI on LTP, as discussed above, the slight linear increasing trend in the time coefficient series should represent an enhancing UHI effect on LTP to the northeast of the city under a rapid process of urbanization in Beijing during 1960–2008. However, the linear trend outlined in Fig. 6b is not significant due to strong interdecadal variations of LTP in this mode. It is suggested that although an urbanization effect on the long-term trend of LTP in BJR for the past few decades appeared likely, it could be overwhelmed in large-scale climate variations.

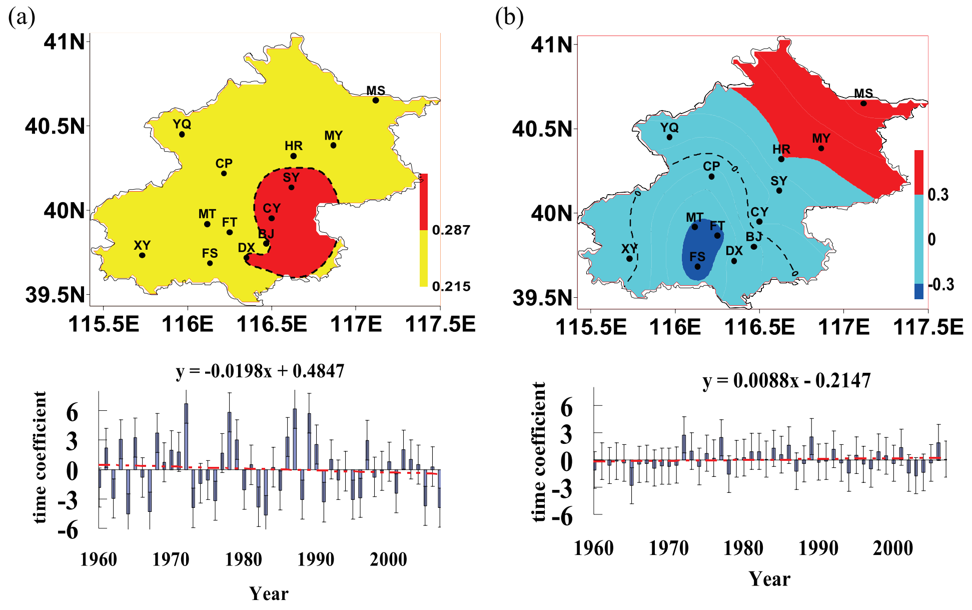

Fig. 6. The first two EOFs of the normalized seasonal amount of LTP in BJR during 1960–2008: (a) first EOF mode and time coefficient series; (b) second EOF mode and time coefficient series.

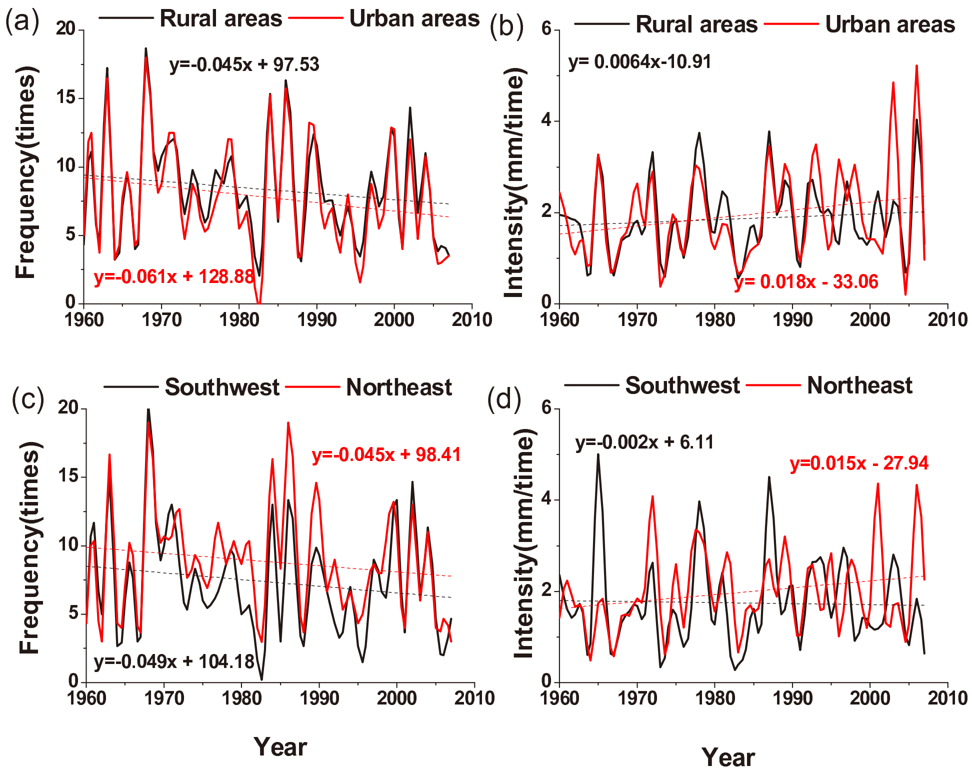

Fig. 7. Frequency (a) and intensity (b) of LTP in the cold season in urban and rural regions in BJR as outlined by the first EOF mode in Fig. 6a, and the frequency (c) and intensity (d) of LTP in northeastern (red) and southwestern (blue) BJR as outlined by the second EOF mode in Fig. 6b. Dashed lines indicate linear trends for the corresponding time series during 1960–2008.

To further investigate differences between the urban and rural regimes of LTP variations, we calculated the mean time series of the frequency and intensity of LTP for the four urban sites, as classified by the first EOF pattern, and those calculated for the other (rural) sites. Figures 7a and b compare the trends of the frequency and intensity of LTP for urban and rural areas during 1960–2008. The frequency of LTP exhibits a decreasing trend for the period of study—more considerable for urban than rural sites (0.61 vs. 0.45 times per decade; Fig. 7a). The intensity of LTP for the urban sites exhibits a significant enhancing trend [0.18 mm per time (10 yr)$^{-1}$; $\alpha = 0.1$], while that for the rural sites is a negligible trend [0.06 mm per time (10 yr)$^{-1}$; Fig. 7b]. It is inferred that an enhancing UHI due to the rapid urbanization in Beijing over the last few decades should be favorable for intensifying convection over the urban area.

Considering the second EOF pattern, we inferred that the intensity of LTP should be enhancing in the northeast with an enhancing UHI, due to its downstream effect on precipitation. Figures 7c and d compare the LTP frequency and intensity in the downstream region and that in the upstream southwestern region as outlined in Fig. 6b. The frequency of LTP exhibits a decreasing trend in both southwest and northeast BJR. However, there is a significant intensifying trend [0.15 mm per time (10 yr)$^{-1}$, $\alpha = 0.1$] in the LTP intensity for the period of study in northeastern BJR, but not on the southwestern side. This reinforces the assumption of an effect of urbanization on LTP in BJR, i.e., intensifying LTP on the downstream (northeast) side of the urban center.

To identify changes in LTP events of different intensities, we calculated the linear trends in the amount and frequency of the different LTP events and compared the changes between rural and urban sites, and those between northeastern and southwestern BJR, as listed in Table 1.

For convenience of discussion, we define a slight LTP event if the daily precipitation is $\leqslant 0.2$ mm (corresponding to a percentile of $\leqslant$ 20th of all the LTP events in the region during the period of study). Extreme LTP events are defined as surpassing the threshold of intensity of 5.0 mm (corresponding to the 90th percentile). Moderate events are defined as those between the 20th and 90th percentiles. In general, there are no significant trends in the extreme and moderate LTP events over BJR for the period of study. However, slight LTP events have significantly decreased in frequency and amount by about 16% (10 yr)$^{-1}$ ($\alpha = 0.1$) for the urban sites and northeastern BJR during 1960–2008.

To identify possible impacts of urbanization on the most extreme LTP events, we calculated the trends in the intensity of the two heaviest LTP events in a year during 1960–2008. The two extreme events contribute more than 65% of the total LTP amount on average for the region.

Figure 8a shows that the intensity of the heaviest events bears a slight increasing trend in both urban and rural areas [0.14 mm d^{-1} (10 yr)$^{-1}$ vs. 0.25 mm d^{-1} (10 yr)$^{-1}$]. In contrast, the contribution of extreme events to total LTP amount in the urban area exhibits a significant increasing trend [3.22 % (10 yr)$^{-1}$, $\alpha = 0.1$], with an average percentage of 66.4% (Fig. 8b). This should be due to the significant reduction of light LTP events in the urban area.

Figure 8c indicates that northeastern BJR is likely to have experienced enhancing LTP extremes with a considerable intensifying trend compared with a slight decreasing trend in southwestern BJR [0.47 mm d^{-1} (10 yr)$^{-1}$ vs. -0.19 mm d^{-1} (10 yr)$^{-1}$]. This suggests a possible indication of the downstream effect of urbanization on extreme LTP, although neither of the linear trends in the regional series of LTP extremes is significant due to strong interannual variability of the LTP extremes.

4. Summary

This paper has provided an overview of LTP climatology and demonstrated relevant long-term climatic trends in BJR for the period 1960–2008. Based on a homogenized dataset of daily climate observations, the focus was on the possible effects of urbanization on LTP. The major conclusions can be summarized as follows.

(1) Rapid urbanization might have induced a considerable additional warming signal in Tmin for urban sites by more than 0.1°C (10 yr)$^{-1}$ during the period of study. The estimate

Table 1. Trends in LTP of different intensities for the cold season in BJR during 1960–2008 (significance levels: $^{*}\alpha = 0.1$;** $\alpha = 0.05$).

Percentile	Urban/Rural/ Northeast/Southwest	Frequency trend [% (10 yr)$^{-1}$]	Amount trend [% (10 yr)$^{-1}$]	Contribution to total LTP amount [% (10 yr)$^{-1}$]
⩾ 90th	U	−5.5	+1.95	+8.68
	R	−7.82	−3.73	−1.13
	NE	−2.39	−1.96	+2.28
	SW	−16.8	−9.99	−5.45
[20th–90th]	U	−6.35	−7.76	−4.60
	R	−4.75	−3.7	−0.52
	NE	−3.71	−2.39	−1.13
	SW	−6.61	−5.71	+2.05
⩽ 20th	U	$\mathbf{-15.74}^{**}$	$\mathbf{-17.68}^{**}$	$\mathbf{-20.87}^{*}$
	R	−7.00	−8.61	−7.64
	NE	$\mathbf{-15.28}^{**}$	$\mathbf{-15.49}^{**}$	$\mathbf{-22.99}^{*}$
	SW	−0.54	−2.65	−0.32

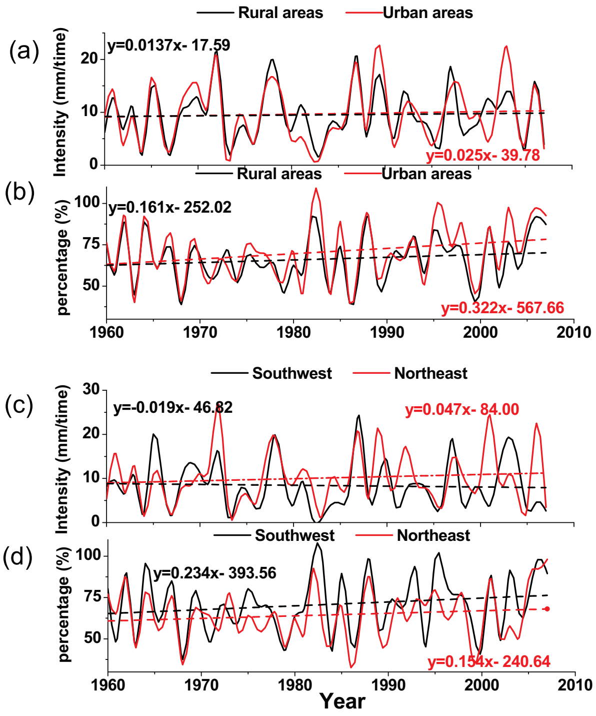

Fig. 8. Mean intensity of the two heaviest LTP events and their contributions to total LTP amount (%) in urban/northeast (red solid lines) and rural/southwest (black solid lines) regions in the cold season during 1960–2008 in BJR. Dashed lines indicate linear trends for the corresponding time series.

of the urbanization-related warming signal in the present study was less pronounced than in some previous reported results (e.g., Zheng and Liu, 2008; Yan et al., 2010), partly because the time periods of study were not the same and partly because previous studies did not apply a homogenized dataset. The geographical pattern of temperature, as well as that of warming, provided a background for the climatology and changes of LTP in the region.

(2) The seasonal frequency and amount of LTP in southeastern BJR are 17%–20% less than those in the mountainous northwestern region, indicating a UHI effect around the urban area. A southwest–northeast gradient of the LTP amount across the urban center reflects the downstream effect of the UHI on LTP, as southerly winds prevail in BJR during times of LTP. The frequency of LTP has significantly decreased with increasing Tmin, while the amount of LTP did not change much, implying an average intensifying trend of LTP over the region. The intensity of LTP exhibited a significant increasing trend (0.15–0.18 mm per time per decade, $\alpha = 0.1$) during 1960–2008 in the urban and northeastern parts of BJR, but not on the southwestern side.

(3) The frequency of occurrences of slight LTP ($\leqslant 0.2$ mm) in BJR reduced significantly; specifically, by -15.74% and 15.28% (10 yr)$^{-1}$ at urban sites and in northeastern BJR, respectively. Consequently, the contribution of extreme events to total LTP amount in the urban area exhibited a significant increasing trend [3.2% (10 yr)$^{-1}$, $\alpha = 0.1$], with an average of 66.4%. There was a considerable intensifying trend of LTP extremes in northeastern BJR compared with a slight decreasing trend in southwestern BJR [0.47 mm d^{-1} (10 yr)$^{-1}$ vs. -0.19 mm d^{-1} (10 yr)$^{-1}$]. Li et al. (2011b) found that urbanization considerably reduced regional mean wind speed, but appeared to hardly influence extreme wind speeds over BJR. One reason might be due to large interannual variability in climate extremes, which obscured urbanization-related signals, if any. Nevertheless, the present results are enlightening for further studies of relevant mechanisms in order to quantify the effect of urbanization on regional climate.

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