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Characteristics and Changes of Cold Surge Events over China during 1960–2007

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Abstract This paper demonstrates regional characteristics, a long-term decreasing trend, and decadal variations in the frequency of cold surge events based on daily mean temperature and daily minimum temperature data in mainland China from 1960 to 2008. During these 48 years, four high frequency centers of cold surge events were located in Xinjiang, central North China, northeast China, and southeast China. A main frequency peak of cold surge events occurs in autumn for the four regions and another peak is detected in spring over northeast China and southeast China. The regional pattern of cold surge frequencies is in accordance with the perturbation kinetic energy distribution in October–December, January, and February–April. The long-term decreasing trend (–0.2 times/decade) of cold surge frequencies in northeast China and decadal variations in China are related to the variations of the temperature difference between southern and northern China in the winter monsoon season; these variations are due to the significant rising of winter temperatures in high latitudes.

Keywords: cold surge, extreme event, temperature, climate change, trend

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1 Introduction

East Asia's climate is largely controlled by summer and winter monsoons. During the boreal winter, the planetary-scale circulation in the Northern Hemisphere (NH) is dominated by strong baroclinic westerly waves in the mid-high latitudes (Ryoo et al., 2005). When a cold high following a warm low passes, a station will record a very large drop in temperature over a couple of days. Over Eurasia continent, the Siberian High is particularly intensified with surface pressures at the center often reaching over 1040 hPa and up to 1053 hPa (Zhang et al., 1997). In the winter half-year, cold air frequently moves southeastward from Siberia through Mongolia to China and other regions in East Asia (Wu and Chan, 1995; Ryoo et al., 2005; Hayasaki et al., 2006). Intense cold air activity in East Asia is referred to as a cold surge (Chan and Li, 2004). A cold surge causes sharp temperature drops and increasing surface pressure with strong northerly winds in 1–2 days. Cold surges carry a large amount of energy, not only dominating the weather over China and East Asia, but also affecting the convection over the maritime continent (Chang and Lau, 1980), the Southern Hemisphere (SH) monsoon (Davidson et al., 1983), the genesis of tropical cyclones in the SH (Love, 1985) and the development of ENSO events (Li, 1990; Zhang et al., 1997; Xu and Chan, 2001). Cold surges also form types of climate extremes (unusually strong weather fluctuations). Therefore, changes in cold surges in East Asia are of global significance.

In recent years, many studies have shown rising trends in regional mean and extreme air temperatures in China for the last half century (Zhai and Ren, 1997; Zhai and Pan, 2003; Qian and Lin, 2004; Qian and Qin, 2005) and its relationship with winter planetary-scale circulation variations (Jeong and Ho, 2005; Chen et al., 2005; Li and Bates, 2007). Change in the frequency of extreme weather, such as cold surges, is an important aspect of climate change because it affects society and ecosystems more directly than mean climate change does. As for China, the national and localized cold surges have decreased in the last few decades (Wang and Ding, 2006; Qian and Zhang, 2007). However, more regional features of cold surges in different seasons with homogenized data need to be investigated. In this paper, we analyze regional and seasonal features and variations of the cold surges in China with updated and higher-resolution data, in order to obtain additional insight into previous results and link changes in cold surges with large-scale temperature changes in the region.

2 Data and method

In this study, we used the homogenized daily mean/maximum/minimum temperature series at 549 national standard stations for China during 1960–2008 to determine cold surge events (Li and Yan, 2009). The dataset was developed using the Multiple Analysis of Series for Homogenization (MASH) (Szentimrey, 1999). This method of homogenization usually performs better than others. All major breakpoints caused by non-natural changes are detected by MASH (Lizuma et al., 2008; Domonkos, 2008). Cold surges tend to occur with conditions of intense baroclinic wave activity (Lau and Li, 1984; Boyle, 1986). Baroclinic waves are associated with the

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meridional temperature differences in the mid-high latitudes. The air temperature difference between southern and northern China was calculated using the 549-station daily mean temperature series to examine changes in the potential of baroclinic wave development. A sudden outburst of cold air is called a "cold surge" (Lau and Li, 1984). The definition of a cold surge event may vary depending on the region of interest, e.g., countrywide cold surges, regional cold surges, spot cold surges, and sometimes defined by identifying surface anticyclones (Ding, 1994; Zhang et al., 1997; Qian and Zhang, 2007). In the present analysis, a daily minimum temperature drop exceeding 10°C for one station during a certain time interval was defined as a cold surge event, based on consideration of the previous studies and criteria set by the China National Meteorological Center (CNMC) for operational weather forecasting (temperature drop exceeding 10°C in two days). Cold surge events were separated based on temperature drops in one day (0–24 h) or two days (0–48 h), as temperature drops for shorter time periods may have a more serious effect on socio-economical human activities. To avoid the effects of solar radiation on the daily temperature variations, the daily minimum temperature was used instead of the maximum temperature. NCEP/NCAR (the National Center for Environmental Prediction/the National Center for Atmospheric Research) reanalysis data for 1960–2008 (Kistler et al., 2001) were used to analyze the Perturbation Kinetic Energy (PKE) associated with the seasonal characteristics of cold surges. A linear trend was calculated for each time series, and the *t*-test was used to judge the trend's significance.

3 Results

The frequency of cold surge events varies for areas and seasons in China (Qian and Zhang, 2007). Cold surges occurred most frequently in northern China and southern parts of the middle to lower reaches of the Yangtze River (Figs. 1a and 1b). Figure 1 also shows the seasonal frequency of one-day and two-day cold surge events in four special areas, Xinjiang, central North China, northeast China, and southeast China, to help identify more localized features of cold surge activity. In Xinjiang and central North China, cold surges mainly occur from October to February, with one peak in November (Figs. 1c and 1d). In northeast China, cold surges mainly occur from October to March, with the first peak in November and the second peak in February (Fig. 1e). One peak of cold surge frequency is found in southeast China for autumn and another in spring (Fig. 1f). Notably, the peak of cold air activity in northwest China (Xinjiang) and central North China is in late autumn, while the peaks in northeast China and southeast China are not only during autumn, but also through the end of winter to early spring. Subsequently, we define October–April as the East Asian winter monsoon season with three periods, October–December, January, and February–April, with regard to different cold surge activity.

Cold surges are associated with baroclinic waves, which are closely connected to atmospheric PKE in mid-latitudes (Dong and Yang, 1991) and released potential energy in highly unstable conditions (Zhang et al., 1997). Figures 2a–c show the 850 hPa PKE average for October–December, January, and February–April over 48 years. In mainland China, high PKEs are observed in October–December and February–April, while the PKE in January is relatively low. In October–December and February–April, cold and warm air masses are frequently alternated over mainland China. During the two periods, higher PKE leads to more cyclonic activity, which favors cold surge events. In January, mainland China is dominated by a cold air mass with relatively low PKE. Hence, there are fewer cold surge events. These seasonal variations are especially clear in northeast China and southeast China. It is interesting to compare the intensity of the Siberian High (Fig. 2d) and the seasonal cycles of cold surge event frequency. It can be noted that the high frequency of cold surges does not appear concurrently with the intensity of the Siberian High. To some extent, the frequency of cold surge events was usually affected by the intensity variation of the Siberian High, not the intensity itself.

There are long-term trends of the various regional cold surge activities. Significant decreasing trends in the cold surge event frequency over two days, including those in the 0–24 h and 0–48 h intervals, are found for October–December over northern China and part of the lower reaches of the Yangtze River (Fig. 3a). Significant decreasing trends in the cold surge frequency are observed in North China and northeast China for January (Fig. 3b). Additionally, significant decreasing trends in the cold surge frequency in the north of China for February–April are also seen, while slight increasing trends exist at some stations in the middle of China (Fig. 3c).

Decadal variations in the frequency of cold surge events, with temperature drops greater than 10°C in two days (including those in 0–24 h and 0–48 h intervals), averaged over all of China for October–December, January, and February–April were analyzed. For October–December, the frequency of cold surge events was high in the 1960s, low in the 1970s–early 1980s, high in the late-1980s–1990s, and low again after the mid-1990s (Fig. 4a). For January, the frequency of cold surges was low since the 1980s (Fig. 4b). For February–April, the frequency was relatively high in the 1960s, low in the 1970s–1990s, and has remained high since the late-1990s (Fig. 4c). A significant decreasing long-term trend of cold surge events was found for the October–December period with a reduction of approximately −0.04 times/decade, while no significant trend was detected for the other two averaging time periods.

Long-term variations and trends of the temperature difference were estimated between southern China (15–38°N, 75–140°E) and northern China (38–55°N, 75–140°E) during 1960–2007 for the three periods (Fig. 4). The temperature differences averaged from the 1960s to 1970s were about 13.7°C, 18.7°C, and 11.8°C, while they were about 13.0°C, 17.6°C, and 10.9°C for the dura-

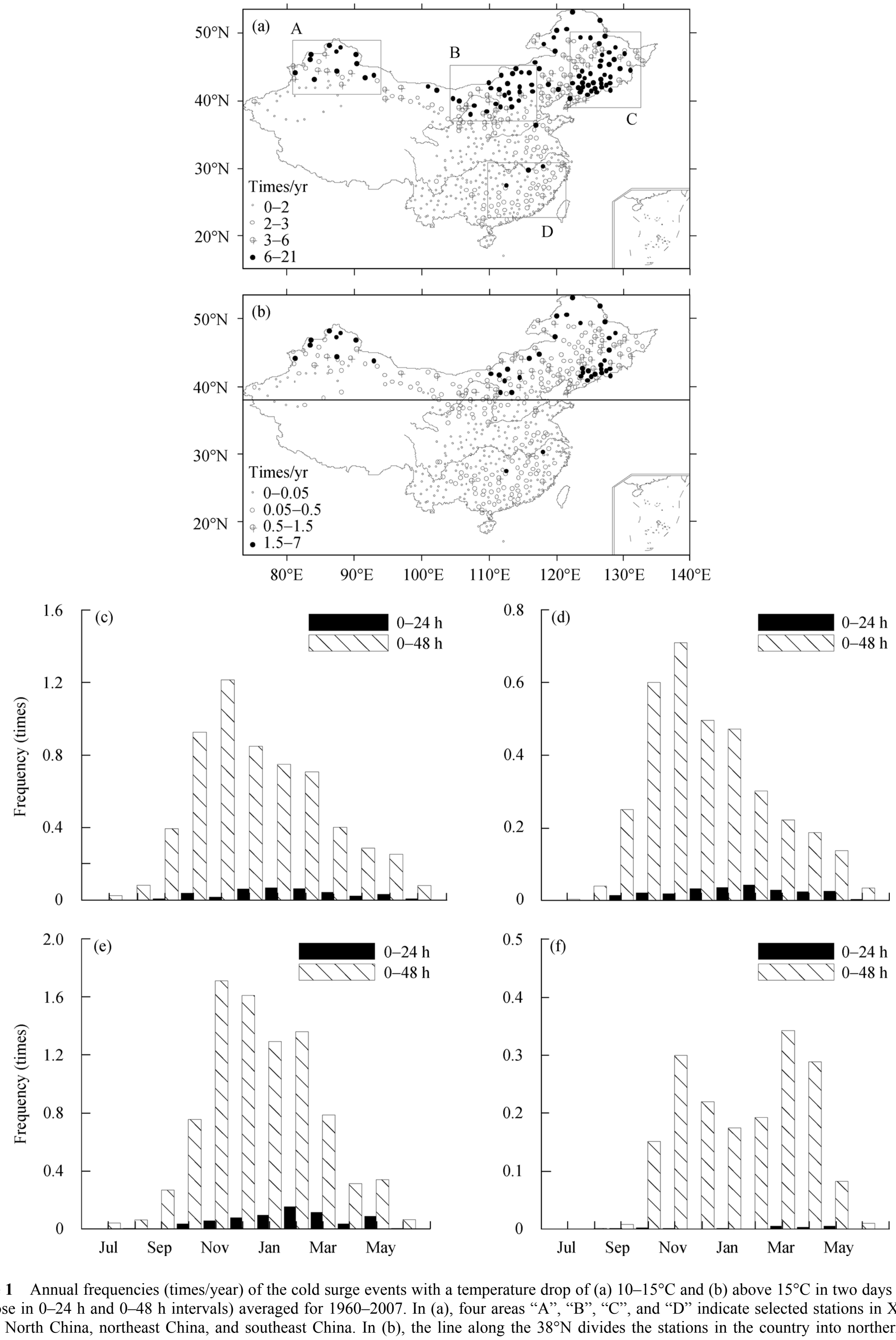

Figure 1 Annual frequencies (times/year) of the cold surge events with a temperature drop of (a) 10–15°C and (b) above 15°C in two days (including those in 0–24 h and 0–48 h intervals) averaged for 1960–2007. In (a), four areas "A", "B", "C", and "D" indicate selected stations in Xinjiang, central North China, northeast China, and southeast China. In (b), the line along the 38°N divides the stations in the country into northern China (38–55°N, 75–140°E) and southern China (15–38°N, 75–140°E). Seasonal cycles of frequencies (times) of the cold surge events (temperature drop>10°C in 0–24 h or 0–48 h interval) in the four areas (averaged over all sites in the area): (c) Xinjiang, (d) central North China, (e) northeast China, and (f) southeast China for 1960–2007.

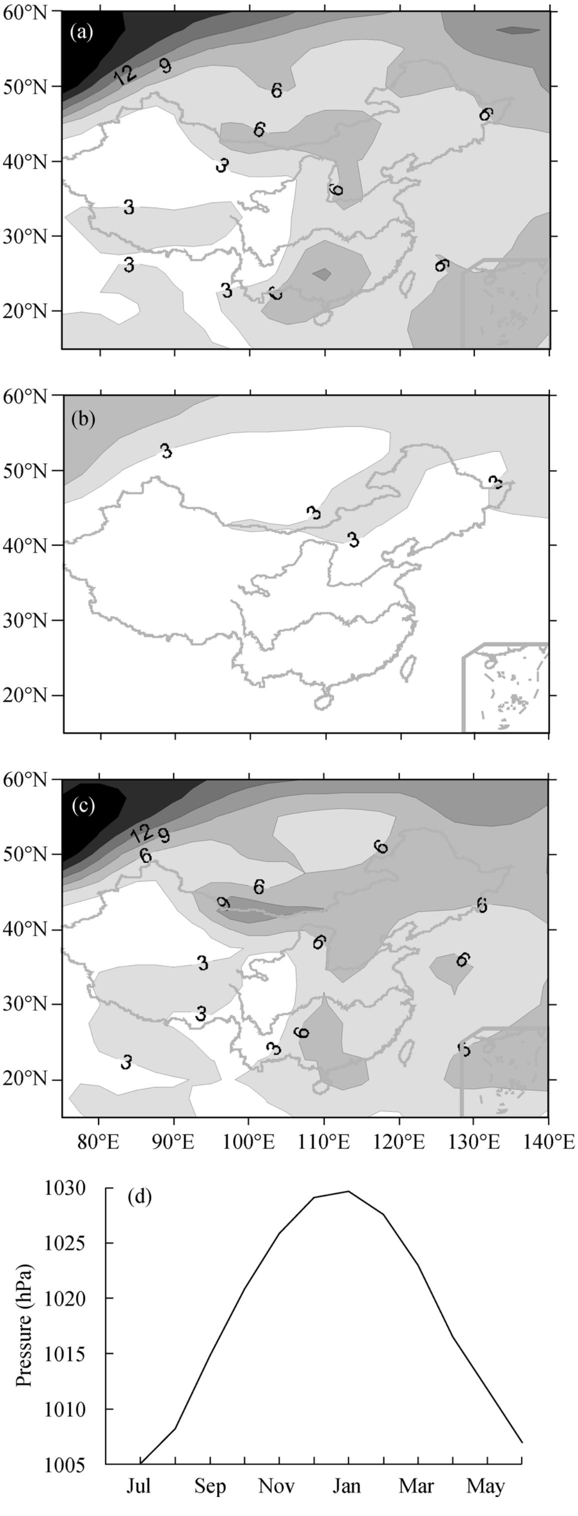

Figure 2 Climatology of the 850 hPa Perturbation Kinetic Energy ($m^2 s^{-2}$) in (a) October–December, (b) January, (c) February–April, and (d) seasonal cycles of intensity (hPa) of the Siberian High, calculated for 1960–2007.

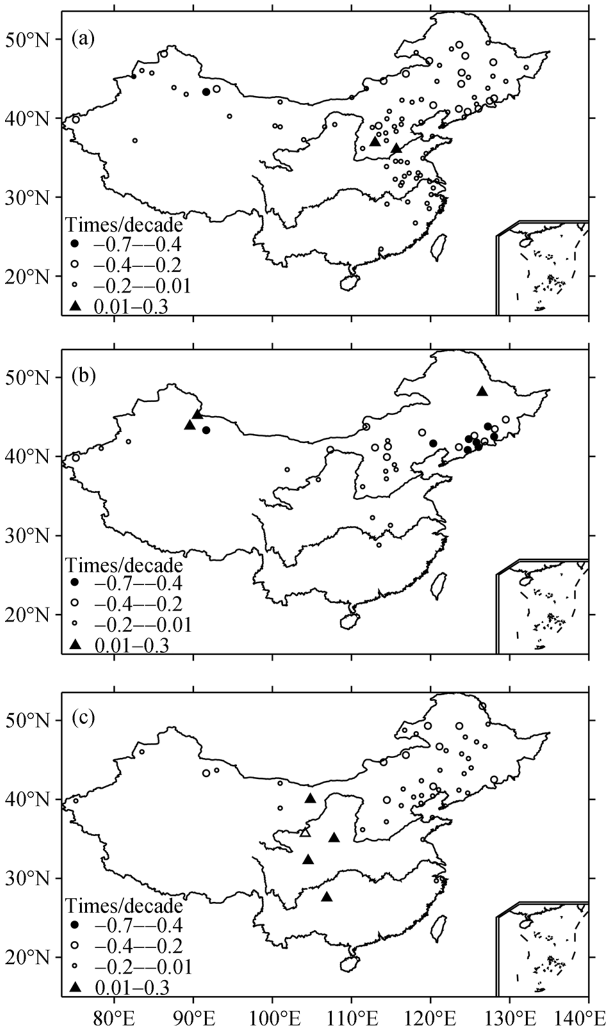

Figure 3 Stations with significant (at the 0.05 level) linear trends (times/decade) of the cold surge events with temperature drops >10°C in two days (including those in 0–24 h and 0–48 h intervals) during 1960–2007 for (a) October–December, (b) January, and (c) February–April.

tion since 1990 to 2007, for the three periods. The decreases in trends of the temperature differences for the last 48 years were −0.15°C/decade, −0.25°C/decade, −0.26°C/decade, for October–December, January, and February–April, respectively. This reduction in meridional temperature difference is not favorable for baroclinic wave development. Furthermore, weaker baroclinic wave activity leads to weaker or fewer strong cyclones and thus fewer cold surges. Based on a 61-station network, Yan and Yang (2000) found significant increases (5 −10°C/50 years) in the annual minimum temperatures in northern China and less warming in the south, indicating a decrease in the temperature difference between southern and northern China and implying a decrease in cold surges events. Table 1 shows that significant positive correlations exist between the meridional temperature differences and cold surges averaged in China, which suggests that interannual variations in the meridional temperature difference can considerably explain the winter cold surge events in China.

Sharp drops in the minimum temperature in two days, including those in the 0–24 h and 0–48 h intervals, are concerning. Table 2 lists the decadal total times of very strong cold surge events in northern China with temperature drops of 20–25°C and above 25°C in two days. There were 274 and 35 events with temperature drops of 20–

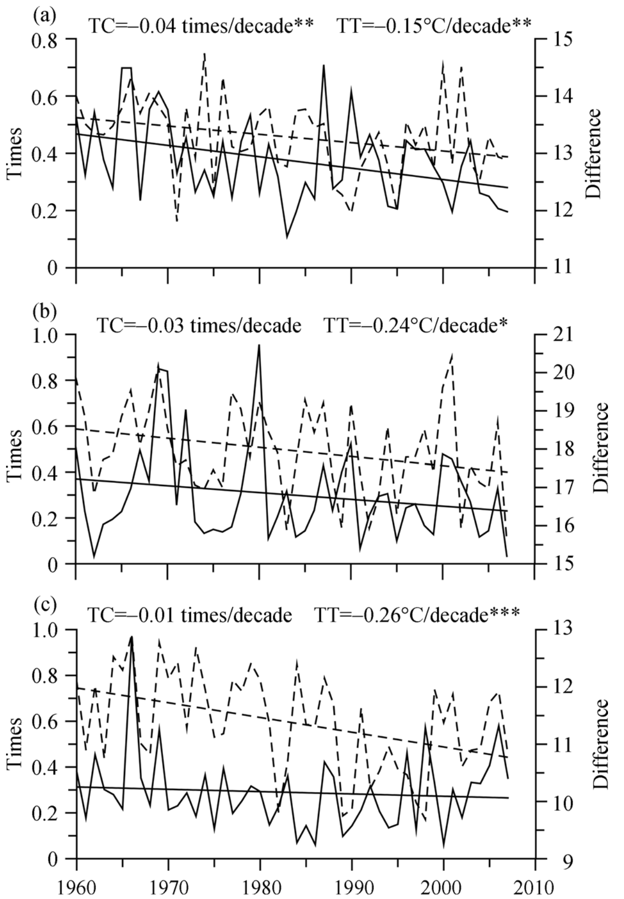

Figure 4 Annual frequencies (times/year) of the cold surge events in China with temperature drop >10°C (solid line) and the mean air temperature differences (°C), estimated as southern China (15–38°N, 75–140°E) minus northern (38–55°N, 75–140°E) China (dashed line), averaged for (a) October–December, (b) January, and (c) February–April during 1960–2007. The heavy solid line and heavy dashed line highlight the linear trends of cold surge events (TC) and temperature differences (TT) in the series. Symbols '*', '**', and '***' indicate linear trends reaching 0.05, 0.01, and 0.001 significance levels, respectively.

25°C and >25°C, respectively, in two days in northern China (205 sites) in the 1960s. For the 1980s, there were 111 and 8 events, respectively, and 103 and 8 events in 2000–07. The maximum temperature drop in two days was −33.4°C in the 1960s and −28.9°C during 2000–07. Decreasing trends in both the frequency and intensity of the cold surge events from the 1960s to the 1980s–2000s is shown in Table 2.

4 Discussion and conclusions

This paper shows an overall decreasing trend in the frequency of cold surge events in China for different periods of the winter monsoon season. Climatologically, high frequencies of regional cold surge events were observed in Xinjiang, central North China, northeast China, and southeast China with peak periods in October–December. In the early spring, cold surges can also frequently be observed in northeast China and southeast China. These surges can be related to the large PKE in mainland China in October–December and February–April, while relatively low PKE exists in the other time periods; however, the Siberian High remains the strongest in January.

The frequencies of cold surge events have decreased significantly in northern China, with a reducing trend of −0.02 times/decade for the October–December period for the five recent decades. Previous studies indicate that this long-term trend of cold surges is associated with variations of the Siberian High (Wang and Ding, 2006), the Arctic Oscillation (Qian and Zhang, 2007), and weather timescale fluctuations (Yan et al., 2001) for mid-high latitudes in winter due to global warming. A long-term reduction in the meridional temperature difference (−0.15°C/decade, −0.24°C/decade, −0.26°C/decade, respectively, for October–December, January, and February–April) between southern China and northern China was also notable. This reduction should result in a decrease of the baroclinic wave system in the region during the same period. Consequently, decreasing cyclone frequency in China (Qian et al., 2002) and increasing winter temperatures in high-latitudes around Lake Baikal (Zhu et al., 2008) for the recent five decades may have internal connections. All of these changes are consistent with the weakening and decreasing of cold surges in the winter monsoon season and reflect the systematic impact of recent global climate changes on the region. Notably, the

Table 1 Correlation between the annual frequencies of the cold surge events in China with temperature drops >10°C in two days (including those in 0–24 h and 0–48 h intervals) and the mean air temperature difference between southern and northern China during 1960–2007.

Period/Correlation	October–December	January	February–April
Correlation coefficient	0.31**	0.46***	0.28**
Correlation coefficient (de-trend)	0.27*	0.43***	0.27*

Symbols '*', '**', and '***' indicate correlation significance at the 0.05, 0.01, and 0.001 levels by the *t*-test, respectively.

Table 2 Decadal total times of very strong cold surge events in northern China (totaling 205 stations to the north of 38°N) with temperature drop of 20–25°C and above 25°C in 2 days（including those in 0–24 h and 0–48 h intervals）.

times	1960–69	1970–79	1980–89	1990–99	2000–07
[20, 25]°C	274	235	111	149	103
⩾25°C	35	34	8	21	8
Max (°C)	–33.4	–31.1	–32.2	–29.7	–28.9

cold surges occurred more frequently in northern China than in southern China and most frequently in October–December. Hence, the temperature difference impact could be considerable more for the October–December cold surge trend. On the other hand, the frequency peak of cold surges in February–April was relatively low in northern China but was relatively high in southern China, where other factors might be considerable. This fact remains a challenge for further study of the cold surge climatology.

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