Changes in surface icing duration over north China during 1961–2015

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Climate extremes are changing at mid–high latitudes due to the effects of climate change. We defined the duration of surface icing (ice formation on open water) in north China from 1961 to 2015, along with its annual start and end date, based on daily measurements by observers at 346 weather stations. A comprehensive analysis of the temporal and spatial variations in these data showed that the regional mean of annual surface icing duration has a high correlation coefficient of 0.97 with the number of frost days (calculated from the daily minimum temperature below 0 °C), with some discrepancies. As the start date trended later and the end date trended earlier in this region, the surface icing duration decreased by 2.6 days/decade from 1961 to 2015 and the slope became steeper by −4.8 days/decade during the most recent 25 years. These results contribute to a better understanding of changes in climatic extremes related to global climate change.

KEYWORDS
climate change, climate extremes, north China, surface icing duration

1 INTRODUCTION

The global mean surface temperature has undoubtedly increased since the late 19th century (Hartmann et al., 2013). In this context, changes in the intensity and frequency of extreme climatic events are likely to have greater impacts on the vulnerability of communities and ecosystems than changes in mean climate (Manton et al., 2001; Frich et al., 2002; Lynch and Brunner, 2007; Peterson et al., 2008; Alexander et al., 2009). A suite of climate change indices have been derived by the Expert Team on Climate Change Detection and Indices (ETCCDI) from daily temperature and precipitation data to enable the presentation of a seamless and comprehensive global picture of trends in extreme events (Alexander et al., 2006; Donat et al., 2013a).

The 27 indices recommended by ETCCDI and other relevant indices have been used in many studies focusing on climate variability, frequency, and trends in global or regional areas such as China, Canada, central and western Europe, and even the polar regions (Bonsal et al., 2001; Zhai and Pan, 2003; Moberg and Jones, 2005; Alexander et al., 2006; Fan et al., 2012; Donat et al., 2013b; Wei et al., 2016). For example, during the past few decades, the United States and Canada have experienced decreasing trends of extreme low-temperature events and frost days (FD; Easterling et al., 2000; Bonsal et al., 2001). Similarly, mean minimum temperature has increased significantly over China during the past 40 years, especially in the winter in northern China (Zhai et al., 1999). In a recent study, the variability and trends in the frost-free period over the conterminous United States from 1920 to 2012 were examined using daily minimum temperature data, indicating a longer-period length for most locations in that region (McCabe et al., 2015). Similar work has been performed in China, but focused only on the northeast part of the country (Wang et al., 2017).

Climate change has accelerated in recent decades as manifested by changes in a number of climate variables (Heim, 2015). In previous research, analyses of global or
regional FD and ice days were all based on daily air temperature measurements. However, in this study, we utilized daily surface icing measurements recorded by meteorological observers at Chinese weather stations, defined as the presence of ice in evaporation pans, lakes, or rivers in the open air. Such surface icing, which is independent from temperature observations, can be regarded as a new and different indicator for changes in extreme climate events. First, we developed a set of surface icing series over north China (NC) with high quality, good integrity, and long periods. We then defined the surface icing duration (SID) with start date (SSID) and end date (ESID) and analyzed their variations. As the mean minimum temperature in China has shown an increasing trend during recent decades (Zhai et al., 1999) and surface icing is closely related to temperature, this work illustrates the impacts of climate change from a distinct perspective.

2 | DATA

First, using manual weather observations obtained from national weather stations in China, we created a sequence of the daily surface icing values indicating the occurrence or lack of such conditions on a given day by using “1” or “0,” respectively. Rough statistics of the annual mean for surface icing days at each station showed that the number of icing days in the northern part of northeast China and most of the Qinghai–Tibetan region exceeded 200 days. However, the number of icing days in the region south of Yangtze River was below 50 days. In areas located south of latitude 25°N and in the Sichuan Basin, the number of annual icing days was less than 10 days with the observations being more dispersed. Therefore, as it was difficult to find an icing period sufficiently long for statistical analysis in the southern region of China, in this study we focused on analyzing icing conditions from the region north of latitude 35°N, hereafter referred as NC.

Through station surveys and statistical analysis of data, we discovered that before 1981, the recording of icing weather conditions was not mandatory at some stations in China due to simplification of the observation work, and in other stations the required recording was not carried out due to negligence. For the above reasons, the annual number of icing days during some periods was unusually low, even zero.

We calculated the mean value $\text{Mean}$ and the standard deviation $\sigma$ of the annual number of surface icing days at each station from 1981 to 2010. If the number of icing days during the period 1961–1980 for any station in any given year was $<\text{Mean} – 5 \times \sigma$, the icing data for that year were deemed invalid, and no further analysis of the data from that station was carried out. The results showed that 476 stations in NC experienced unusually low annual icing days (a total of 2,061 times); the maximum at a single station was 19.

After screening out the data from stations with unusually low numbers of annual icing days, we selected the icing observations from a total of 346 stations which had no discontinuities from 1961 to 2015 (Figure 1). It can be clearly seen that these stations are mainly concentrated in the eastern region while being relatively sparse in the western region. After the NC area was gridded using $2.5 \times 2.5°$ boxes, 75 grids contained at least one station, essentially covering the entire NC with the exception of the western part of the northeast region and the central and southern parts of the northwest region.

Before 1980, the data integrity for daily minimum ground temperature was relatively low as it was not a required observation category in China, so these data were not of sufficient quality to use in our study. Because of the close relationship between surface ice and air temperature, we used the minimum temperature $T_{\text{min}}$ to check the internal consistency of the icing conditions. These data, obtained from the “China National Stations’ Fundamental Elements Datasets (V3.0)” published by the National Meteorological Information Center, had already been subjected to systematic quality inspection and control. We calculated the maximum value of $T_{\text{min}}$ for every station where surface ice was manually observed; all results were below 2 °C. Thus, we concluded that there were no inappropriate ice records under warm weather conditions. Further statistics showed that 90% of the maximum values were not greater than 0 °C and 95% were within 0.2 °C. Therefore, we set the threshold of $T_{\text{min}}$ to $-1$ °C to check for missing records of surface ice. If five or more days occurred continuously when $T_{\text{min}} < -1$ °C, while the icing condition value for the same period was “0”, the latter value was changed to “1” for the entire period. The daily icing data were revised for a total of 35 stations over 39 years, with a cumulative number of 674 days.

3 | METHODS

The instability of weather conditions needed to be taken into consideration; for example, a one-time rapid drop in temperature may cause a short-duration icing at the observation station. In order to analyze climate changes for a continuous period of icing, we defined a method for selecting the start and end dates of the icing duration. Starting on July 1 of each year, the first day of the first icing condition that lasted for five or more consecutive days was defined as the start date of surface icing duration (SSID). The last day of the last icing condition that lasted for five or more consecutive days and occurred before June 30 of the next year was defined as the end date of surface icing duration (ESID). The threshold of 5 days was chosen to screen out non-consecutive icing conditions and to obtain a SID with sufficient statistical significance. These start and end dates were then used to obtain the number of icing days for the year. Moreover, in order for the period between the start and the end date to be defined...
as the SID, frost-free conditions should not occur for five or more consecutive days during that period.

We also analyzed the annual number of FD, a temperature-related extreme index proposed by ETCCDI. FD is one indicator showing the duration of temperature-related events and can be calculated by counting the days when daily minimum temperatures were lower than 0 °C.

Using 2.5 × 2.5° as the latitudinal and longitudinal grid distance, we carried out grid analysis of the observed data and used the arithmetical mean of the station values in each grid as the grid’s value. We used the latitude cosine value of the center point of the grid as its weight (Jones and Hulme, 1996) and obtained the weighted average of the grid data to acquire the average value for the NC region. We then used a linear model \( y = a + bx \) to calculate the trend of the considered variables by minimizing the chi-square error statistic. The nonparametric Mann–Kendall approach was utilized to test significance.

4 | RESULTS

Figure 2 shows the duration of annual surface icing in the NC region during 55 consecutive years. The maximum value of 170.6 days occurred in 1964 and the minimum of 144.9 days occurred in 2015. In the context of global warming, the SID showed a declining trend with an average decrease of 2.6 days/decade, which is essentially the same as the Easterling (2002) analysis results (−2.1 to −2.6 days/decade) for the annual FD variation trend in the western United States between 1948 and 1999. In addition, Figure 2 shows the 30-year SID trends (the last period being 25 years). From 1961 to 1990 and 1971 to 2000, the downward trends are relatively small and are not statistically significant, while the largest downward trend occurs during the most recent 25 years, with an average decrease of −4.8 days/decade. Moreover, the SID variance increases gradually with time during the four different periods by 13.1, 14.8, 28.5, and 33.5 days, respectively, showing an increase in the year-to-year amplitude.

The SID values of the 75 non-null grids shown in Figure 3a demonstrate downward trends. After sorting the values, the median value was −2.2 days/decade, while the 10th and 90th percentile values were −0.7 and −3.7 days/decade, respectively. Considering the spatial distribution, with the exception of Shandong Province, almost all of the trend values in the region east of 112.5°E exceeded −2.5 days/decade. Most of the region west of 112.5°E had values of less than −2.5 days/decade, indicating that the SID in northwest China was decreasing faster. The SSID distribution in Figure 3b shows an increasing trend in most of the region, with a median value of 1.0 days/decade. In some parts of Xinjiang, Qinghai, and Jilin Provinces the increasing trend exceeded 1.5 days/decade. Figure 3c shows a decreasing trend in the ESID distribution, with a median value of −1.1 days/decade. This trend was relatively slow in northeast China, not exceeding −1.2 days/decade. In summary, the delay of the icing start date and the advancement of the icing end date produced a downward trend in the SID in NC.

As the trends of SID, SSID, and ESID varied spatially, we analyzed their relationship with other parameters such as the grid altitude (the mean elevation of the stations within every box) and the gridded mean minimum temperature. The results showed that the trends of both SID and SSID had
significant correlations with altitude. The trends of SID changed negatively with higher altitude (correlation coefficient, cc, of $-0.44$), while SSID changed positively with higher altitude (cc of $0.53$). However, the correlation between the trends of ESID and altitude was not significant. In addition, the trends of ESID correlate with the mean minimum temperature of March and April (cc of $-0.24$), during which the surface icing no longer occurred.

Considering the significance of these trends, the 69 grids showed a significantly decreasing trend in the SID, in which the surface icing start and end dates altered significantly in 54 and 64 grids, respectively.

Based on the FD index recommended by the ETCCDI, we statistically analyzed the consecutive yearly FD values in NC from 1961 to 2015. Figure 4 shows anomaly variations after subtracting the mean value of the 55-year period from the FD values. It is evident that almost all FD anomalies are positive before 1988, and have an overall downward trend with an average of $-4.0$ days/decade ($p \leq .01$). This is consistent with the results in Wang.
et al. (2017), who used the minimum air temperature and showed through statistical analysis that the frost-free season in northeast China increased every decade by 3.6 days from 1961 to 2013. Compared with the SID variation trends (−2.5 days/decade), the FD decreased more rapidly.

Figure 5 displays the scatterplot of the 2.5 × 2.5° gridded annual values of SID and FD. All data points were distributed along the diagonal 1:1 line and showed a high correlation (cc = 0.97), indicating that the two variables are comparable. The largest difference between gridded SID and FD was 51.5 days, while the mean value of absolute differences was 9.2 days. As shown in Figure 4, the annual FD of NC was always larger than SID, but their differences are gradually declining.

5 | DISCUSSION AND SUMMARY

There is a discrepancy between the SID and FD data. One reason for this is the difference in the statistical data sources. The SID data come from station-based observations of surface icing, while the FD data are obtained through the statistics for minimum daily temperatures below 0 °C during any given year. Although surface icing is mainly affected by the temperature, other meteorological factors (such as wind speed and humidity) also play a role. Thus, we obtained and analyzed the highest $T_{\text{min}}$ values during the initial 5 days (IFD − $T_{\text{min}}$) and the final 5 days (FFD − $T_{\text{min}}$) of the SID period for each year from 346 stations in NC and ordered these from low to high. The median values for IFD − $T_{\text{min}}$ and FFD − $T_{\text{min}}$ were −1 and −0.8 °C, respectively, and the 75th percentile values were 0 and 0.2 °C, respectively. It is evident that the SID included some periods with $T_{\text{min}}$ values above 0 °C. The second reason for the discrepancy is that, based on the SID definition used in this study, only continuous icing periods were selected, while in the FD analysis, the total number of days that satisfied the requirements was used and so a continuous sequence was not required. Despite these discrepancies, both sets of values show a decreasing trend that confirms the warming impact in NC.

In this study, the influence of climate change in NC was demonstrated from the unique perspective of changes in surface icing. We analyzed these changes from 1961 to 2015 based on ground daily observation of icing weather phenomena from 346 national level stations above of latitude 35°N. Because the start date of icing is postponed and the end date is brought forward, the duration of surface icing in NC over the 55 years studied shows a remarkable negative trend of −2.6 days/decade, while the greatest descending slope with −4.8 days/decade occurred in the recent 25 years from 1991 to 2015. The SID also has a high correlation coefficient with the FD index proposed by ETCCDI in analyzing climate extreme events, as both show significant downward trends, while the FD declined with −4.0 days/decade.

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