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Authors: Wang, Kang, Zhang, Tingjun, Guo, Hong, and Wang, Huijuan

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Climatology of the timing and duration of the near-surface soil freeze-thaw status across China

Kang Wang[1,2], Tingjun Zhang[1,*], Hong Guo[1], and Huijuan Wang[1]

[1]Key Laboratory of Western China's Environmental Systems (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China
[2]Institute of Arctic and Alpine Research, University of Colorado at Boulder, 450 UCB, Boulder, Colorado 80309-0450, U.S.A.
[*]Corresponding author's email: tjzhang@lzu.edu.cn

ABSTRACT

The near-surface soil is an important interface in ground-atmosphere interactions. The near-surface soil freeze-thaw status is critical for energy, moisture, and carbon exchange between the ground and the atmosphere, plant growth, and the ecosystem as a whole. The main objective of this study is to investigate climatology of the timing and duration of the near-surface soil freeze-thaw status using data from 636 meteorological stations across China for the baseline period from July 1971 through June 2001. The long-term average first date of the near-surface soil freeze is 14 September (30 July–30 October), the last date is 15 May (8 April–21 June), the duration is 245 ± 85 days, and the actual number of the near-surface soil freeze days is 202 ± 90 days over China as a whole. On the Qinghai-Tibetan Plateau, the near-surface soil freeze can occur essentially in any month of a year. The spatial variations of the near-surface soil freeze-thaw status are strongly controlled by latitude in east China, and by elevation in west China. The long-term average 220-day and 260-day contours of the near-surface soil freeze coincide approximately with the southern boundary of high-latitude permafrost regions in northeastern China and the lower boundary of high-altitude permafrost regions in west China, respectively. The number of days and duration of the near-surface soil freeze decreased with increasing long-term mean annual air temperature (MAAT). Variation of the actual number of the near-surface soil freeze days presents nonlinear linkage to the length of the near-surface soil freeze duration and also to the MAAT climatology. The timing and duration of the near-surface soil freeze-thaw status are strongly nonlinearly related to air freezing index, but are nearly linearly related to air thawing index.

INTRODUCTION

Investigation of climatology of the near-surface soil freeze-thaw status is important for climate change studies and practical applications. The values of long-term (30-yr) means are critical reference points for detecting changes in the near-surface soil freeze-thaw timing, duration, and length of freeze-thaw period (Zhang and Armstrong, 2001; Zhang et al., 2003). The local- and regional-scale climatology of the near-surface soil freeze-thaw is critical for studies on energy and water exchange between the ground surface and the atmosphere (Zhang and Armstrong, 2001; Zhang et al., 2003; Guo et al., 2011); for agriculture (Fowler, 2008; Henry, 2013; Parkin et al., 2013), the ecosystem, and the carbon cycle (McDonald et al., 2004; Henry, 2008; Saito et al., 2013; Mu et al., 2014a, 2014b); surface hydrological processes (Knox, 2001; Niu and Yang, 2006; Rempel, 2012); and engineering applications (Zhang et al., 2008). Study of the climatology of the near-surface soil freeze-thaw status is also helpful for climate modeling (Betts et al., 1996; Viterbo et al., 1999; Rawlins et al., 2013) and satellite remote algorithm validation and calibration (Zhang et al., 2003, 2004; Jin et al., 2009; Zhang et al., 2009; Li et al., 2012).

Remote sensing technology has been applied in monitoring and exploring the near-surface soil freeze-thaw processes across large spatial regions. Zhang and Armstrong (2001) developed and validated a frozen soil algorithm using satellite passive microwave data and soil temperatures for the 1997/1998 winter across the contiguous United States. The algorithm was applied to detect the near-surface soil freeze-thaw status, and it found the maximum frozen soil area extent over snow-free surfaces was ~3.75×10^6 km^2. Zhang et al. (2003) used a combined frozen soil algorithm to detect the timing, duration, and number of days of freezing in the near-surface soil in the contiguous United States and found that the average length of the freeze period was ~200–220 days during the 2-yr period from July 1997 through June 1999. Likewise, Smith et al. (2004) used scanning multichannel microwave radiometry (SMMR) and special sensor microwave imagery (SSM/I) data to identify the trends in the near-surface soil freeze-thaw cycles from 1988 to 2002. Their results indicated an earlier thaw date of frozen soil in Eurasia, and a later freeze date in North America. The National Aeronautics and Space Administration (NASA) scatterometer (NSCAT) data were applied to identify the daily frozen and thawed areas in Alaska, U.S.A., from January to June 1997 and obtained a favorable comparison with the regional meteorological stations (Kimball et al., 2001). Also, the growth season in early spring advanced by 8 days from 1988 through 2001 in Alaska from the NSCAT record (McDonald et al., 2004). At a global scale, Kim et al. (2011) used satellites' passive microwave remote sensing to establish a daily landscape freeze-thaw status database, which provided a continuous and long-term record for daily freeze-thaw dynamics.

In China, the near-surface soil freeze-thaw status, particularly on the Qinghai-Tibetan Plateau, was investigated using data from remote sensing and meteorological stations in past decades. Jin et al. (2009) developed a decision tree algorithm based on SSM/I brightness temperature data and applied it to identify the near-surface soil freeze-thaw status across China with an accuracy of 91.7%. Zhao et al. (2011) developed a soil freeze-thaw discriminant algorithm using advanced microwave scanning radiometer–Earth observing system (AMSR-E) data. Their overall accuracy was about 86% and their results agreed well with the Map of Geocryological Regionalization and Classifications in China (Zhou et al., 2000). Jin et al. (2009) and Zhao et al. (2011) showed a good agreement with the Map of Geocryological Regionalization and Classifications in China (Zhou et al., 2000). On the Qinghai-Tibetan Plateau, Li et al. (2012) investigated changes in the near-surface soil freeze-thaw cycle using SSM/I data from 1988 to 2007. They found an earlier onset date of soil thaw in spring, and determined that the number of frozen days decreased by ~16. Yang et al. (2007) investigated the freeze-thaw processes in central Qinghai-Tibetan Plateau based on one-station high-frequency observation from 2003 through 2004. They found that the number of days at the station with a daily minimum temperature below 0 °C was ~230, and the freeze-thaw cycles were of high frequency at the ground surface.

Although remote sensing provides data with good spatial continuity and coverage, it needs more validation at large spatial scales and also for a long-term observation period to improve its accuracy because no single sensor can capture the ground "truth" measurements of the near-surface soil freeze-thaw status (Zhang et al., 2004). Two major approaches have been planned to improve the understanding of the soil freeze-thaw status. On the one hand, by enhancing the remote sensing techniques and sensor, NASA has launched the Hydrosphere State Mission as part of the Earth System Science Pathfinder Program (ESSP) to monitor global land freeze-thaw and soil moisture status (Entekhabi et al., 2004). On the other hand, some researchers and organizations are expanding and improving the ground observation networks. It should be noted that a multiscale soil freeze-thaw monitoring network has been established on the central Qinghai-Tibetan Plateau, and 56 stations were installed in a cold and high-elevation region to observe soil temperatures and moisture (Su et al., 2011; Yang et al., 2013).

The objective of this study was to investigate the spatial characteristics of the long-term means of the timing and duration of the near-surface soil freeze for the 30-yr period from July 1971 through June 2001, based on daily ground surface temperatures obtained from 636 meteorological stations across China (Fig. 1). Specifically, we investigated the climatology of the first date, last date, duration, and number of days of the near-surface soil freeze across China over the study period (collectively referred to hereafter as "the soil freeze indicator"). We further investigated the factors controlling the spatial characteristics of the near-surface soil freeze conditions across China.

DATA AND METHODS

Definitions

In this study, we define the soil "freeze day" as a day with a minimum temperature at or below 0 °C at the ground surface (0 cm). We use this definition for the following reasons: First, almost all previous studies used daily minimum temperature to define the near-surface soil freeze because it can seriously affect plants and growing crops (Kunkel et al., 2004; McCabe et al., 2015; Wang et al., 2015). Second, daily minimum temperature is sensitive to climate change. Especially, soils in southerly latitudes may be closer to freezing points, and the freeze-thaw dynamics of these sites may be more sensitive to climate change (Henry, 2008). Daily minimum temperature always occurs before dawn, avoiding most influence of direct solar radiation. Third, there are still several thresholds, ranging from −2.2 to 0 °C, to define a freeze day (Baker and Ruschy, 1995). McCabe et al. (2015) looked at the results using a −2.2 °C threshold (Robeson, 2002; Peterson and Abatzoglou, 2014) and found similar results to those obtained using a threshold of 0 °C. Finally, some studies used continuousness of freeze to define the freeze timing, but disagreed concerning the thresholds. For example, some studies defined the soil freeze status based on the soil surface remaining frozen continuously for at least 5 days (Jin et al., 2009) or continuously for at least 3 days (Li et al., 2012). Selection of the threshold may result in a gap of ~20 days in the number of freeze days (330 and 350 days on the Qinghai-Tibetan Plateau, respectively). Taking all these studies into consideration, we decided to take the above definition of the soil "freeze day" using the minimum temperature at the ground surface.

The annual values for each variable were estimated from observed daily time series. The first

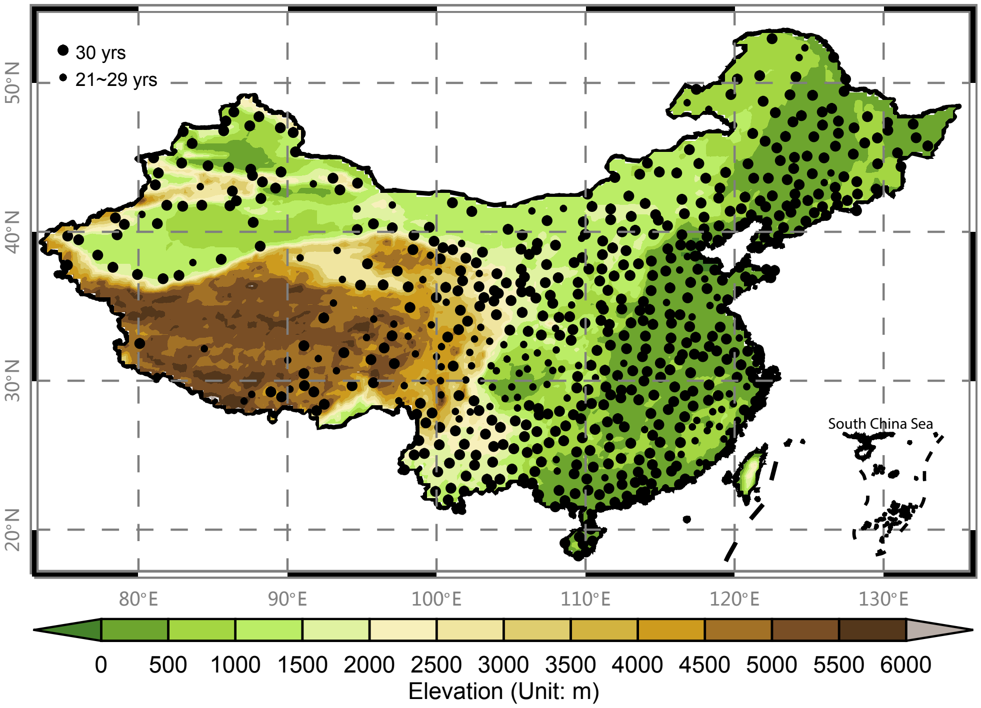

FIGURE 1. Map of meteorological stations across China used in this study. Background reflects elevation, and sizes of circles reflect data availability during the period from July 1971 to June 2001.

date of the near-surface soil freeze was defined as the first date after 1 July of the year when the daily minimum ground surface temperature is at or below 0 °C. The last date of the near-surface soil freeze was defined as the last date after 1 July of the next year when the daily minimum ground surface temperature is at or below 0 °C. The near-surface soil freeze duration was defined as the time span between the first date of freeze and the last date of freeze. Because of extreme weather events, the near-surface soil may not be frozen continuously from the first date through the last date. Thus, we further defined the actual number of freeze days to depict the exact days of near-surface soil freeze, calculated by counting the number of days with a daily minimum ground surface soil temperature at or below 0 °C.

Data Sources

Data used for this study include daily minimum ground surface temperatures obtained from China Meteorological Administration (CMA, 2007a). Ground surface temperatures were measured using a thermometer. The thermometer sensor has a mercury bulb on one end with diameter of 5 mm. The measurement standard requires that half of the thermometer sensor be buried in ground and the other half exposed to the air, and we used this standard in our study. The ground surface temperatures at 0 cm were recorded four times per day using Beijing Standard Time of 2:00, 8:00, 14:00, and 20:00. Mean daily ground surface temperature is an average of these four measurements (CMA, 2007b). The minimum (maximum) temperature thermometer records the daily minimum (maximum) temperature once a day, although it cannot record the time when it occurs. MAAT data were also used for further analysis (CMA, 2007a). We used the Map of Geocryological Regionalization and Classification in China (Zhou et al., 2000). The digital elevation model was mosaicked from original Shuttle Radar Topography Mission (SRTM) 90-m data sets (Jarvis et al., 2008).

Climatological Statistics

The variables investigated in this study are the first date, last date, duration, and actual number of days of near-surface soil freeze. All annual summary statistics of these variables were calculated for each year beginning on 1 July and ending on 30 June of the next year, in order to cover the entire period with potential freezing events. We used the 30-yr "normal" period of the World Meteorological Organization, starting 1 July 1971 and ending 30 June 2001, for the baseline of climatology in this paper (IPCC-TGICA, 2007).

We used the thin plate smoothing splines method to interpolate station results to a 0.5° × 0.5° grid over the study area. This interpolation process considered latitude, longitude, and altitude and was implemented by the ANUSPLIN package (Hutchinson, 2004). We randomly extracted 30 stations (three of them are on Qinghai-Tibetan Plateau) to verify the accuracy of interpolation using the other 600 stations. Results indicated that the root-mean-square error (RMSE) of the first date, last date, duration, and number of freeze days were about 9, 8, 21, and 15 days, respectively. Correlation coefficients were 0.93 to ~0.99. Thus, we believe that the interpolation can basically reflect spatial variability. Not all of the meteorological stations in this study have continuous data for the 30-yr period. Generally, there must be ≤8 missing years allowed (~26% of the 30-yr period, which is slightly greater than 25% suggested by Jones and Hulme [1996], to ensure adequate spatial coverage) in the calculation of the time-mean. In this study, the outliers were identified as values greater than three standard deviations from their long-term mean—that is, any point outside the control limits (mean ± 3 standard deviations) will be considered as an outlier (Devore, 2011).

RESULTS

First Date of the Near-Surface Soil Freeze

The 30-yr average of the earliest date of the near-surface soil freeze occurs as early as in July of the current year and as late as in January of the next year (Fig. 2, part a). The first date of the near-surface soil freeze in east China, east of 110°E, shows obvious latitudinal zonal characteristics. In the northernmost part of China, the earliest date of the near-surface soil freeze occurred in August, due to the region's relatively high latitude. In the regions south of ~28°N, the near-surface soil did not freeze until December. The first date of the near-surface soil freeze in regions south of ~24°N was not included in this study because these regions were classified as essentially unfrozen regions according to the Map of Geocryological Regionalization and Classification in China (Zhou et al., 2000). In the following area statistics, we excluded the unfrozen regions (total area is about 8.7 million km^2).

In west China, we identified three specific regions. The earliest freeze date of the near-surface soil is approximately in July on the Qinghai-Tibetan Plateau. That means the near-surface soil freeze can occur in any month of the year on the plateau, due primarily to its high elevation. In the Tarim basin, by contrast, located at 75°–94°E and 36°–44°N, the near-surface soil freeze begins later than in other regions at the same latitude due to elevation and a desert environment. In Sichuan basin, located at 103°–111°E and 28°–32°N, the specific climatic conditions caused by the surrounding mountains can result in the near-surface soil freeze not occurring until December. Additionally, there is a region (~84°E, 43°N) on the middle Tianshan Mountain with a first freeze date of July due to its high elevation and the long-term averaged MAAT of –4.5 °C.

Overall, the average starting date of the near-surface soil freeze occurred around 14 September with one standard deviation of 47 days (30 July–30 October) from its long-term mean over China as a whole. The main reason for the large standard deviation is due to the large span in latitude ranging from around 24°N to 53°N and in elevation ranging from sea level in the east to higher than 4500 m a.s.l. on the Qinghai-Tibetan Plateau. The near-surface soils in China mainly start to freeze in September and Octo-

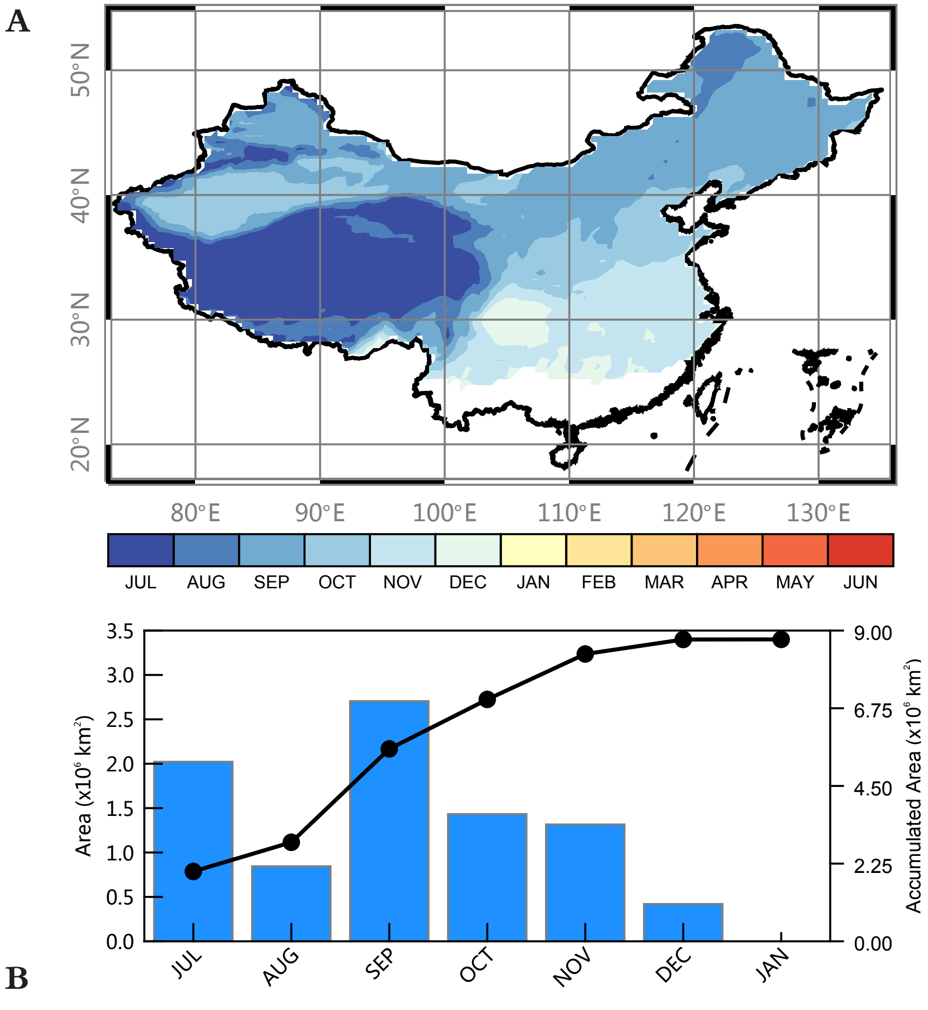

FIGURE 2. (A) Climatology of the first date of the near-surface soil freeze over China, July 1971 to June 2001. The blank regions are essentially not frozen under a normal climate. (B) Area and accumulated area of the first date of the near-surface soil freeze by month.

ber (Fig. 2, part b). Areas with these freeze dates consist of 2.7 × 10^6 km^2 (September), and 1.4 × 10^6 km^2 (October), or 31% and 16% of the total study area, respectively. In particular, 23% of the total area (2.0 × 10^6 km^2) starts to freeze in July, primarily occurring on the Qinghai-Tibetan Plateau. More than 80% of the total study area starts to freeze in or before October (Fig. 2, part b). Areas with freeze dates in January of the next year total only 0.003 × 10^6 km^2; likewise, the regions where the freeze begins in other months, including August, November, and December, make up ~2.6 × 10^6 km^2 or 29% of the study area.

Last Date of the Near-Surface Soil Freeze

The 30-yr average of the last date of the near-surface soil freeze occurs as early as in February of the next year and as late as in June of the next year (Fig. 3, part a). The last date of the near-surface soil freeze in east China shows a strong latitudinal characteristic. In the northernmost part of China, the latest date of the near-surface soil freeze occurred in June of the next year due to the area's relatively high latitude. In the regions south of ~28°N, the near-surface soils generally began thawing by February of the next year.

In west China, we identify three specific regions (similar to those in the first section of Results). The latest end-freeze date in the near-surface soils on the Qinghai-Tibetan Plateau occurs in June, due primarily to the high elevation. In the Tarim basin, the near-surface soil thaws earlier than surrounding regions due to its elevation and the desert environment. In addition, the near-surface soil in the Sichuan basin thaws by February of the next year due to the effects of the surrounding mountains. The latest freeze event of the near-surface soil can be in

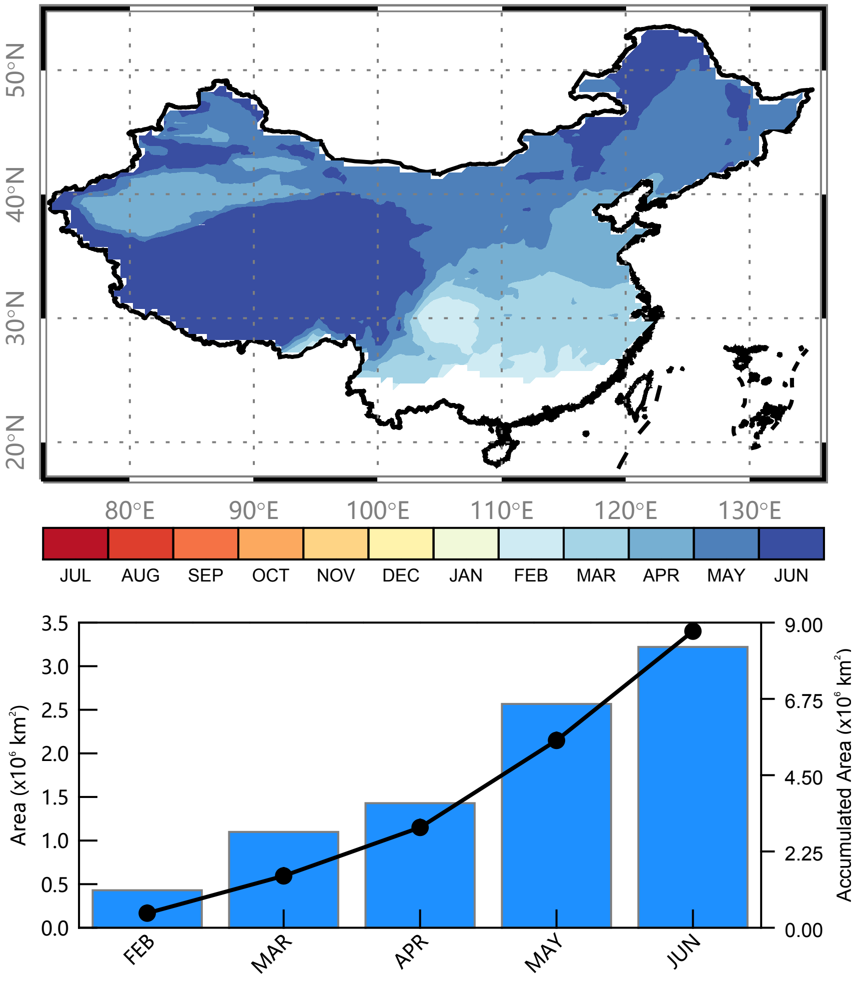

FIGURE 3. (A) Climatology of the last date of the near-surface soil freeze over China, July 1971 to June 2001. The blank regions are essentially not frozen under a normal climate. (B) Area and accumulated area of the last date of the near-surface soil freeze by month.

June of the next year in the region on the middle of the Tianshan Mountains.

Overall, the average last date of the near-surface soil freeze occurs around 15 May with one standard deviation of 38 days (8 April–21 June) from its long-term mean over China as a whole (Fig. 3, part b). Regions with the latest freeze date in May and June comprise 2.6 × 10^6 km^2 and 3.2 × 10^6 km^2, or about 29% and 36% of the total study area, respectively. More than 63% of the total study area has started to thaw by May (Fig. 3, part b). In contrast, the area of those regions that start to thaw in February of the next year is small, ~0.43 × 10^6 km^2 or 5% of this study area. The total area of the regions that start to thaw in February, March, and April is roughly 3.0 × 10^6 km^2 or 34% of the study area.

Duration of the Near-Surface Soil Freeze

The duration of the near-surface soil freeze in China ranges from less than two weeks in south China to almost the entire year on the Qinghai-Tibetan Plateau (Fig. 4, part a). Because the duration of the near-surface soil freeze is the time period between the first date and the last date of freezing, the spatial features of the duration of the near-surface soil freeze partially reflect the first and last freeze dates. The duration of the near-surface soil freeze in east China varies from less than 15 days in southern regions to ~300 days in the northernmost regions. The duration shows latitudinal zoning from south to north, because elevation variation in the region is not significant. In west China, the duration of the near-surface soil freeze can exceed 345 days on the Qinghai-Tibetan Plateau and in the middle Tianshan Mountains due to its high altitude. In the Tarim and Sichuan basins, the duration of the near-surface soil freeze is shorter than in other regions at the same latitude. The freeze duration in the Tarim basins range from ~160 to 200 days, while in the interior of Sichuan basin, the duration is only up to 15 days, since their latitudes vary by only ~10°.

The long-term average duration of the near-surface soil freeze is 245 ± 85 days over China as a whole. The regions with a freeze duration >345 days are approximately 1.8 × 10^6 km^2, or 21% of the study area, and are mainly located on the Qinghai-Tibetan Plateau. The regions with a freeze duration ranging from 225 to 255 occupy approximately 1.5 × 10^6 km^2 or 17% of the total area. Approximately 3.3 × 10^6 km^2 or 38% of the total study area have a near-surface soil freeze duration ranging from 195 days to 285 days (Fig. 4, part b). The near-surface soil freeze duration lasts up to 285 days in two-thirds of the total study area.

Number of the Near-Surface Soil Freeze Days

It is important to note that the near-surface soil may not be frozen continuously during the entire time period from the first date to the last date of the near-surface soil freeze. The actual number of days of the near-surface soil freeze is the number of days with ground surface minimum temperatures at or below 0 °C. The number of the near-surface soil freeze days ranges from <15 to >345 across China (Fig. 5, part a). It is 202 ± 90 days (mean ± 1 standard deviation) over China as a whole. On the Qinghai-Tibetan Plateau, the number of the near-surface soil freeze days can exceed 300. In the northwestern part of the plateau, the number of the near-surface soil freeze days is >345 due to its high altitude. In the Tarim and Sichuan basins, the number of the near-surface soil freeze days is less than that in surrounding regions. Particularly, the number of the near-surface soil freeze days in the Sichuan basin is <15. The number of the near-surface soil freeze days in east China varied from <15 in southern regions to >285 in the northernmost regions. Overall, the number of the near-surface soil freeze days represents an obviously latitudinal characteristic in east China. Approximately 61% of the total study area has <225 days of the near-surface soil freeze (Fig. 5, part b). The rest of the regions with a high frequency of near-surface soil freeze occupies approximately 3.3 × 10^6 km^2 or 38% of the study area.

DISCUSSION

This study found that the near-surface soil freeze-thaw can occur in any month of a year on the Qinghai-Tibetan Plateau because of its high elevations (average elevation is above 4000 m a.s.l.); thus the earliest freeze onset date and lat-

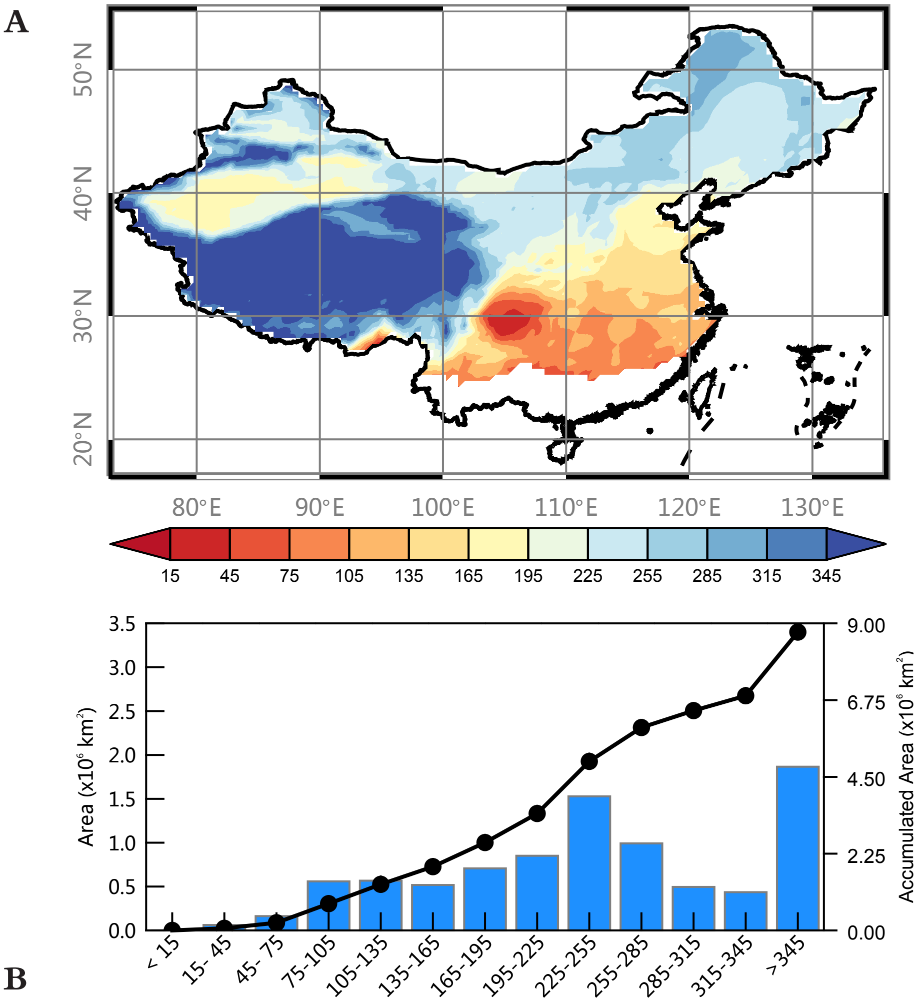

FIGURE 4. (A) Climatology of the duration of the near-surface soil freeze over China, July 1971 to June 2001. The blank regions are essentially not frozen under a normal climate. (B) Area and accumulated area of the duration of the near-surface soil freeze.

est end date both happen on the Qinghai-Tibetan Plateau. These results are different from previous studies on the Qinghai-Tibetan Plateau. Jin et al. (2009) reported that based on SSM/I brightness temperature data from 1 October 2002 through 31 September 2003, the earliest onset date on the Qinghai-Tibetan Plateau is between August and September. It is significantly later than results from this study of between July and August. Jin et al. (2009) indicated also a last freeze date on the Qinghai-Tibetan Plateau in April or May, which is earlier than the results from this study in May or June. There may be two major reasons to explain the difference. First, results from Jin et al. (2009) were based on satellite remote sensing, which can have a large coverage over the plateau. However, their near-surface soil freeze-thaw algorithm may produce large uncertainties and need in situ data validation. Second, results from Jin et al. (2009) only covered a 1-yr (October 2002–September 2003) period, which may introduce biases, while results from this study cover a 30-year period average. Also, since it is potentially possible that the near-surface soil freeze can occur almost every month on the Qinghai-Tibetan Plateau, it is less meaningful to define the first and last dates of the near-surface soil freeze in this region.

Results from this study demonstrate that the longest duration and maximum number of the near-surface freeze days occurred on the Qinghai-Tibetan Plateau. Previous studies in a large region mainly used satellite remote sensing data. Jin et al. (2009) and Li et al. (2012) used SSM/I light brightness temperatures in the early morning to detect the freeze status of the near-surface soil over China for the winter 2002/2003 and the Qinghai-Tibetan Plateau from 1988 through 2007, respectively; Zhao et al. (2011) used AMSE-R passive microwave

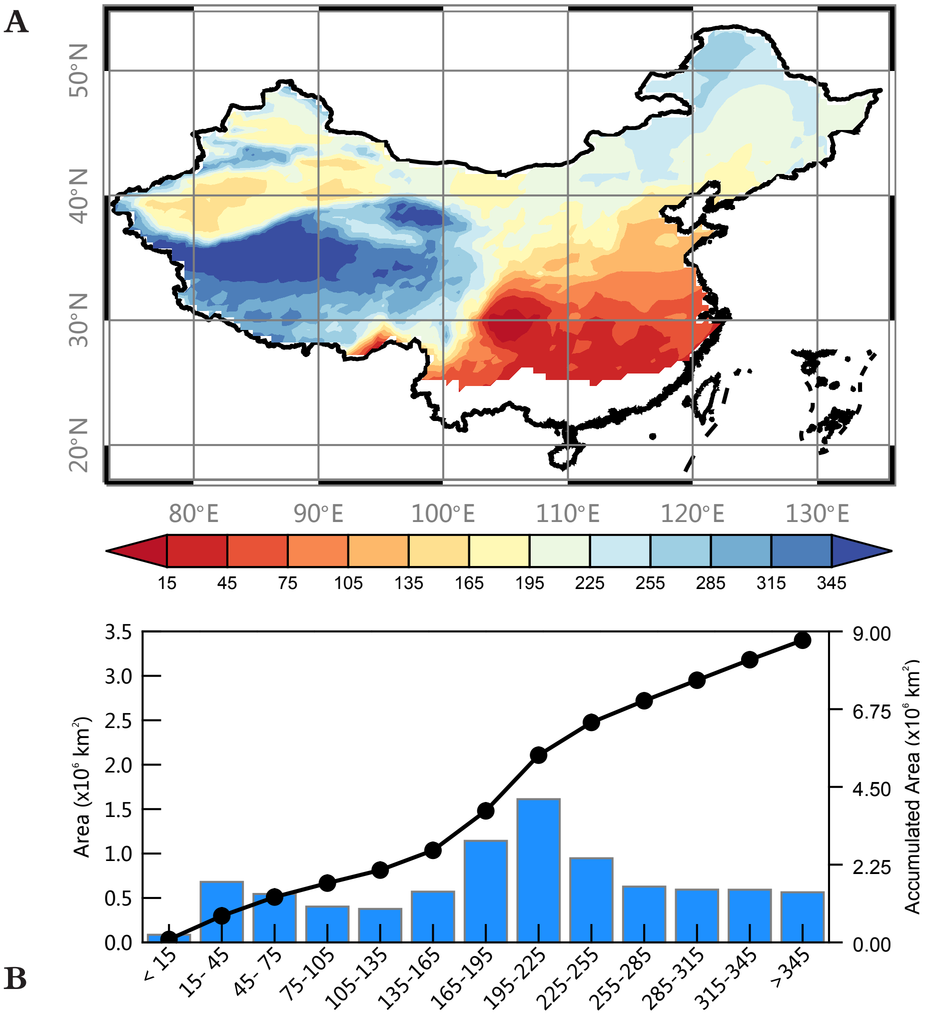

FIGURE 5. **(A) Climatology of the actual number of the near-surface soil freeze days over China, July 1971 to June 2001. The blank regions are essentially not frozen under a normal climate. (B) Area and accumulated area of the number of the near-surface soil freeze days.**

data to detect the near-surface soil freeze-thaw status over China from 2004 through 2008. Based on satellite remote sensing data, it was found that the maximum number of near-surface soil freeze days over the Qinghai-Tibetan Plateau varied from 330 (Jin et al., 2009) and 360 (Zhao et al., 2011), to >350 (Li et al., 2012), respectively. Although the relative error of these results is within 10%, they are not comparable mainly because their study periods varied from 1 yr (Jin et al., 2009) to almost 20 yr (Li et al., 2012). Thus, these results could be misleading for ecological studies and engineering design. In this study, we used data available from ground-based observations from 636 stations and averaged over a 30-yr period (1971–2001). The definition of the near-surface soil freeze was also different in the previous studies. Jin et al. (2009) used five continuous days as the threshold to define the near-surface soil freeze-thaw period, while Li et al. (2012) used three continuous days as the threshold. The difference between Jin et al. (2009) and Li et al. (2012) has a gap of about 20 days. Despite not being able to split the contributions of data periods and detection methods, five continuous days should be more strict and underestimated than three continuous days because the stricter condition (five continuous days) ignores more freeze-thaw events in late spring and early fall. Methods used by Zhao et al. (2011) may also present an underestimation of soil freeze days. The definition of a freeze event used in this study was selected through thorough comparisons between different methods (see Definitions section under Data and Methods). Meanwhile, from the validations based on randomly selected stations (including some stations on the Qinghai-Tibetan Plateau), we confirmed the interpolation could reflect well the spatial distribution of the duration and number of the near-surface freeze days.

Thus, through the comparisons of major results in previous studies and this study, we indicated that those remote sensing data (SSM/I and AMSE-R) could underestimate the freeze events of the near-surface soil when compared with in situ observations. Furthermore, detailed experiments are needed to verify the contributions of different ways to detect freeze-thaw states.

Relationship between Actual Number of Days and Duration of the Near-Surface Soil Freeze

Obviously, regions with a longer duration have more actual freeze days (a comparison of Fig. 4, part a, to Fig. 5, part a; Fig. 6). In order to present an eventual freeze probability during a potential freeze period (i.e., duration of the near-suface soil freeze), we compared the climatology of the duration and number of days of the near-surface soil freeze. A nonlinear characteristic is demonstrated in the relationship between the duration and actual number of days of the near-surface soil freeze (Fig. 6). Through multiple comparisons including quadratic, cubic, s-curve, and logistic functions, we determined the logistic function should be used as the fitness function. It indicates a good fitness—that is, RMSE is ~6.7 days. However, the range above ~280 days shows some obvious biases. These stations are located mostly on the Qinghai-Tibetan Plateau.

Actual number of days increases slightly by ~12 with an increase of ~50 in duration of the near-surface soil freeze (Phase 1)—that is, the trend is ~0.24 when duration of the near-surface soil freeze is less than 50 days. Subsequently, actual number of days increases sharply by ~163 with an increase of ~160 in the duration of the near-surface soil freeze (Phase 2) starting from 51 through 210 days, that is, the trend is more than 1.00. When the duration of the near-surface soil freeze is more than 210 days, variations of the actual number of days are smaller than that of the duration of the near-surface soil freeze (Phase 3). The overall variation in the actual number of days is 130, with a variation of 154 days in the duration of the near-surface soil freeze. The maximum rate is found at the duration of the near-surface soil freeze around ~130 days. If we consider Phase 1 as a warm zone, Phase 2 as a transition zone, and Phase 3 as a cold zone, Figure 6 may imply a significant signal: the transition zone is more important under a changing climate. This is because an equal scale of variation may result in a greater variety in the near-surface soil freeze than warm or cold zones and partly proves the viewpoint of Henry (2008).

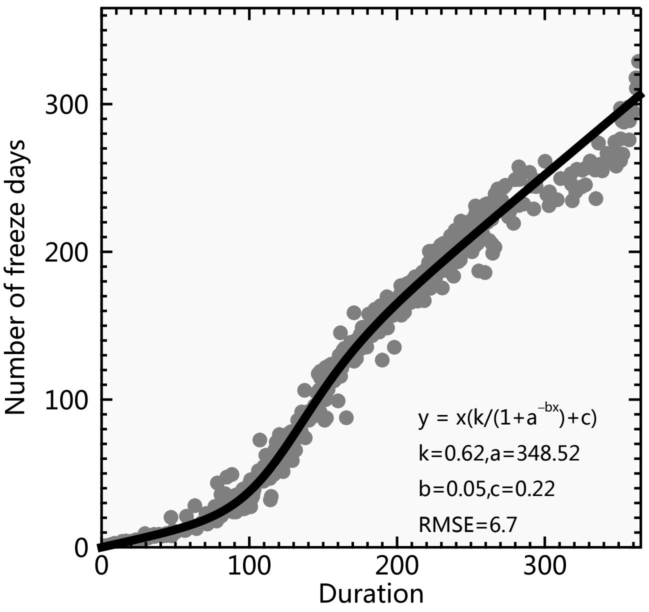

FIGURE 6. Relationship between the actual number of the near-surface soil freeze days and the duration of the near-surface soil freeze. The circles are data points and the line is the non-linear fitted line. The overall fitness is good (RMSE is 6.7 days).

Relationship between the Freeze Indicators of the Near-Surface Soil and Air Temperature

Air temperature is an important climatic factor influencing the near-surface soil thermal states (Zhang et al., 2001; Henry, 2008). We compared the climatology of the first date, the last date, duration, and the actual number of the near-surface soil freeze to the climatology of MAAT by stations. All these relationships seem to be cubic function.

All coefficients of the cubic term are near to zero, and the coefficients of the quadratic term also are smaller than the coefficients of the linear term. The first date of the near-surface soil freeze occurs later while the ending date of the near-surface soil freeze occurs earlier with the increasing air temperature (Fig. 7, parts a and b). The actual number of days and duration of the near-surface soil freeze reduce with an increasing MAAT (Fig. 7, parts c–f).

Comparing results from the west (<110°E) with east (≥110°E) of China, we find that the variations in west China are larger than the variations in the east (Fig. 7). This may be caused by significant differences in dry/wet conditions between west and east China. Water in soils always plays an important role in freeze-thaw processes because of latent heat effect (Williams and Smith, 1989). Unfortunately, we don't have soil moisture to thoroughly examine the effects of aridity on the timing and duration of the near-surface soil freeze. In addition, the actual number of days and duration of the near-surface soil freeze in cold regions, where MAAT is less than 0 °C, in west China are larger than that in east China. It was caused by the differences of climate conditions between the Qinghai-Tibetan Plateau and northeast China, which are dominated by altitudes and latitudes, respectively.

The nonlinear relationship can be found both in west and east China (Fig. 7). In order to explain the nonlinear corrections, we examined subsequently the relationships between these indicators and air freezing and thawing indexes. A dramatic difference is shown: there is a linear relationship between the soil freeze indicators and the air thawing index (Fig. 8), but a strongly nonlinear relationship with the air freezing index (Fig. 9). These results demonstrate that the nonlinear relationships between the soil freeze indicators and the climatology of MAAT may be affected strongly by the air freezing index. The possible reason is latent heat variations during the freeze-thaw process. In this study, despite some stations located in per-

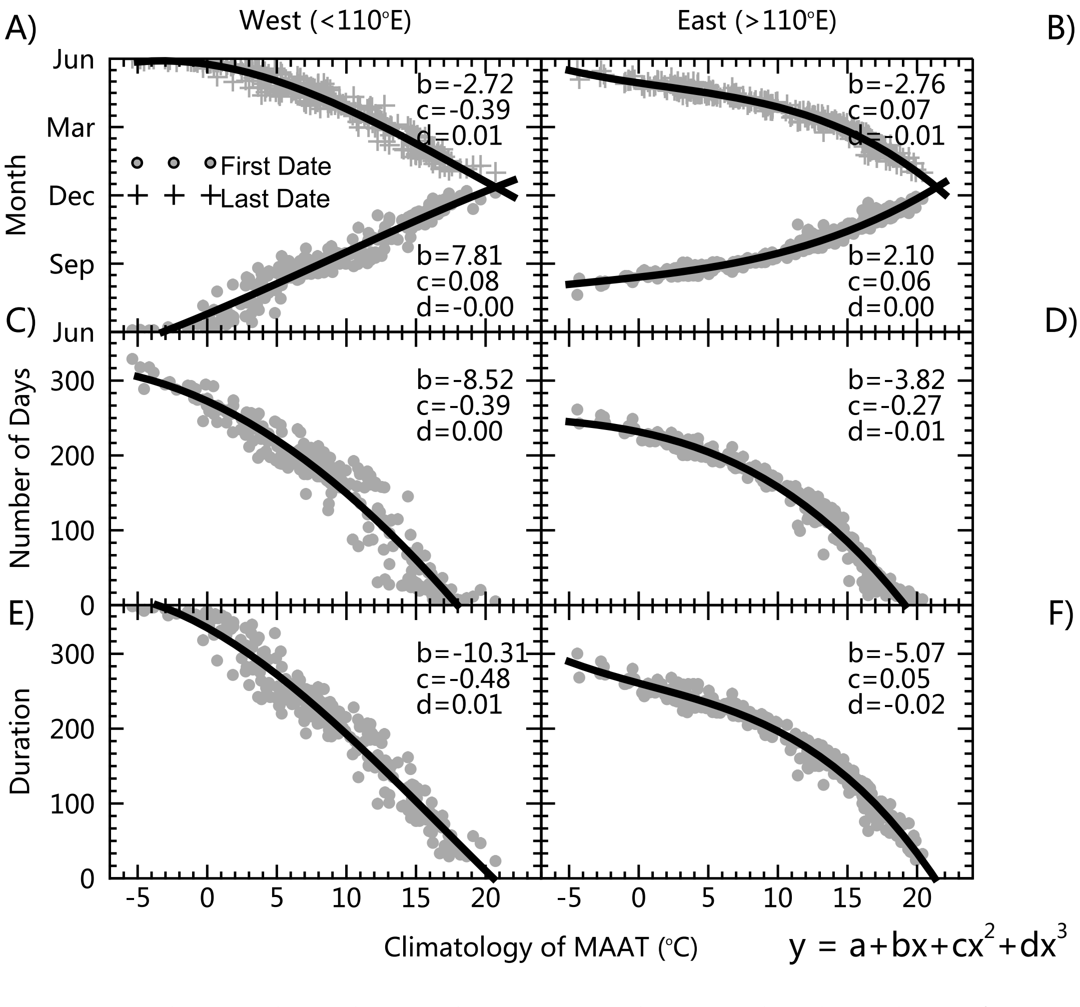

FIGURE 7. **(A) Non-linear relationships (cubic equation) between the climatology of mean annual air temperature (MAAT) and the first date and last date, (C) the actual number of the near-surface freeze days, and (E) duration in west China; (B), (D), and (F) are same as (A), (C), and (E) but for east China.**

mafrost regions, there is not enough evidence to prove the existence of permafrost. In other words, at least most of these stations represent the characteristics of seasonally frozen ground. In contrast, a previous study found the strongly nonlinear relationship is caused by air thawing index in permafrost sites (Zhang et al., 1996).

Comparison between the Number of the Near-Surface Soil Freeze Days and the Permafrost Distribution in China

The near-surface soil freeze-thaw status influences the thermal states of frozen soil, including permafrost and seasonally frozen ground. We used the Map of Geocryological Regionalization and Classification in China to compare the number of the near-surface soil freeze days across China in order to explore whether our results can be used to infer and classify frozen ground in China.

Different thresholds are detected for high-latitude and high-altitude permafrost regions. Obviously, ~220-day contours are consistent with the southern boundary of the high-latitude permafrost region, located in northeastern China (Fig. 10). In west China, most of the permafrost region is altitude dominated. Results from this study indicated that ~260-day contours agree well with the existing lower boundary of the high-altitude permafrost region (Fig. 10). The reason is the intensity of freezing is not strong. Although the number of freezing days on the Qinghai-Tibetan Plateau is more than northeastern China, averaged air freez-

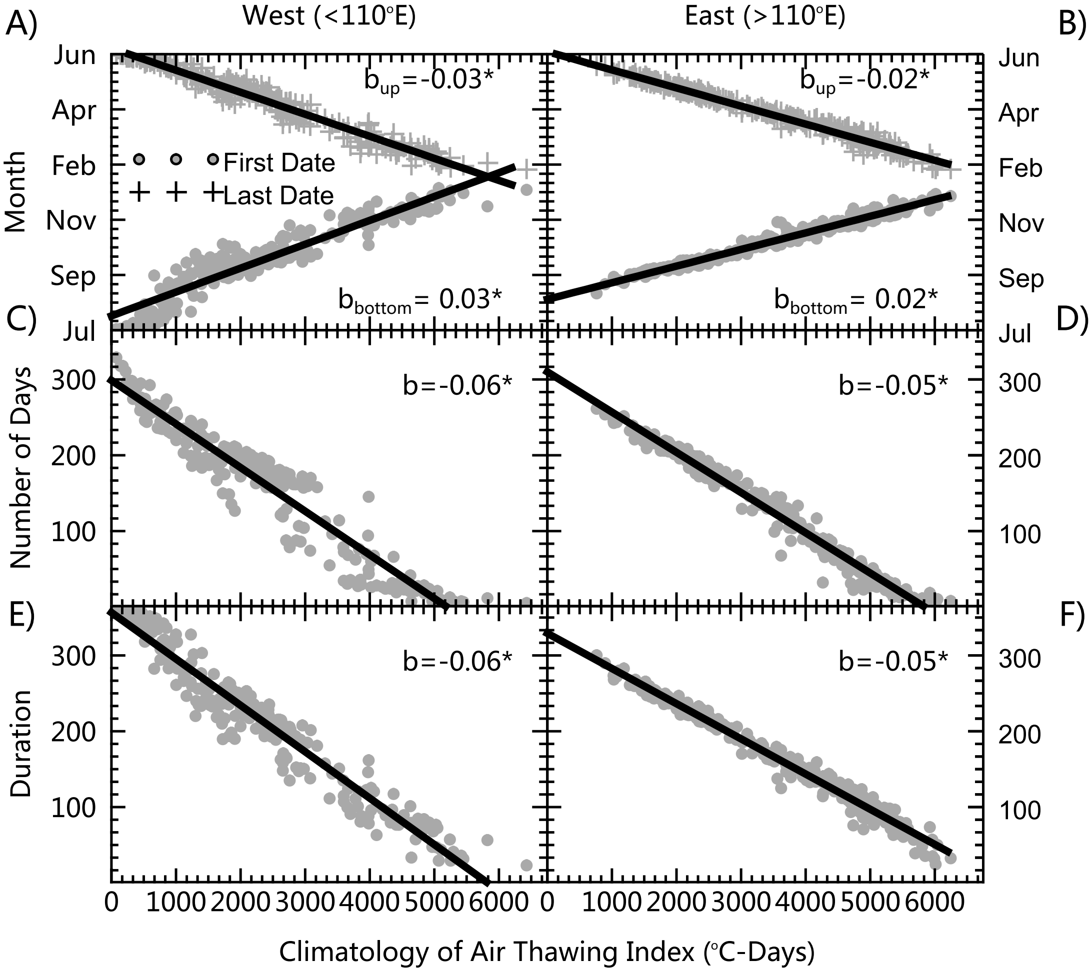

FIGURE 8. (A) Relationship between the climatology of air thawing index and the first date and last date, (C) actual number of the near-surface soil freeze days, and (E) duration in west China; (B), (D), and (F) are same as (A), (C), and (E) but for east China.

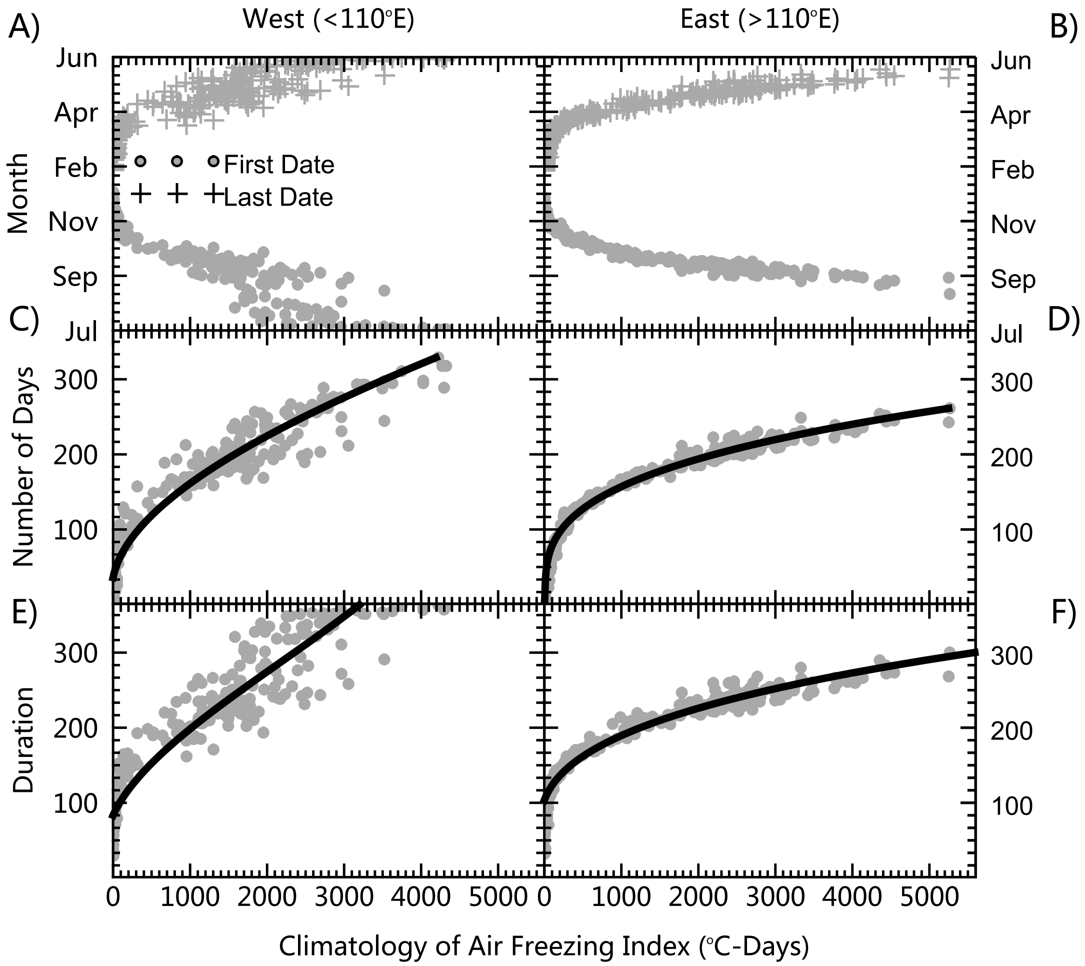

FIGURE 9. (A) Relationship between the climatology of air freezing index and the first date and last date, (C) actual number of the near-surface soil freeze days, and (E) duration in west China; (B), (D), and (F) are same as (A), (C), and (E) but for east China.

ing index is ~2200 °C-days (Frauenfeld et al., 2007) and is less than that in northeastern China (~2700 °C-days) (Luo et al., 2014). We used 220 and 260 days as the thresholds to calculate areas of permafrost regions in northeastern China and the Qinghai-Tibetan Plateau. The results indicate that the area of permafrost regions in northeastern China is ~0.8 × 10^6 km^2, which overestimates ~0.4 × 10^6 km^2 in the southern part. Similarly, an area of permafrost regions on the Qinghai-Tibetan Plateau is ~2.1 × 10^6 km^2, which overestimates ~0.5 × 10^6 km^2 in the southeastern part. All above results have an overestimation of ~0.8 × 10^6 km^2 to the statistics (2.2 × 10^6 km^2) using the Map of Geocryological Regionalization and Classification in China. Interpolation bias may be an important error source.

SUMMARY

We used meteorological data across China to investigate the climatology of the timing and duration of the near-surface soil freeze-thaw status over the 30-yr period from July 1971 to June 2001. The primary results are summarized as follows:

- Overall, the long-term average first date of the near-surface soil freeze is 14 September (30 July–30 October), the average last date is 15 May (8 April–21 June), the duration is of 245 ± 85 days, and the actual number of soil freeze days is 202 ± 90 days over China as a whole.
- The duration of the near-surface soil freeze is almost a whole year on the Qinghai- Tibetan

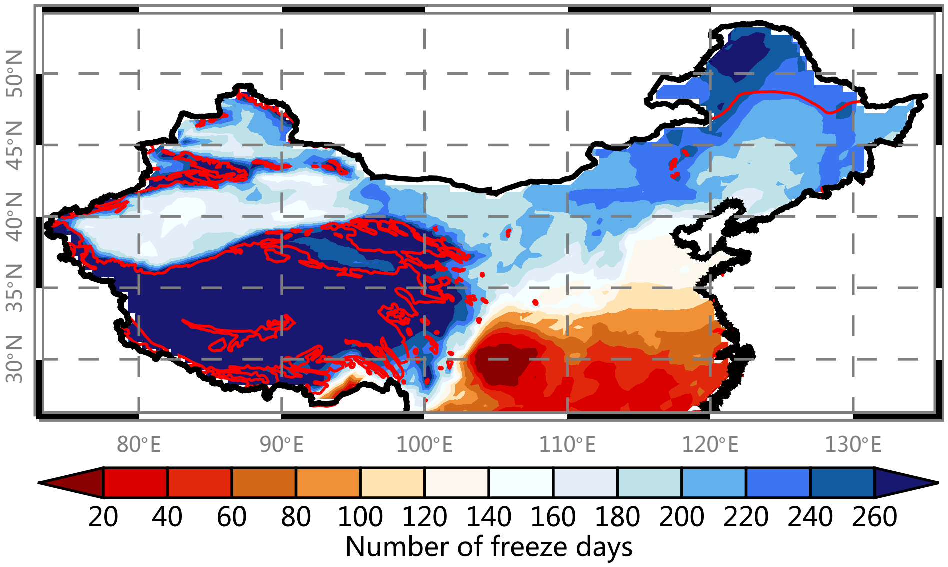

FIGURE 10. Comparison between the climatology of the actual number of the near-surface soil freeze days and the Map of Geocryological Regionalization and Classification in China (Zhou et al., 2000).

Plateau and in the middle Tianshan Mountains. Essentially, the near-surface soil freeze-thaw status can occur in any month of a year on the Qinghai-Tibetan Plateau. In other words, definitions of the onset and end date of the near-surface soil freeze are less meaningful for the Qinghai-Tibetan Plateau. It is generally <15 days in south China (south of 25°N) and the Sichuan basins.

- The near-surface soil freeze is mainly controlled by latitude in east China, while in west China it is primarily dominated by changes in elevation.
- The actual number of the near-surface soil freeze days ranges from <15 in south China to almost a whole year on the Qinghai-Tibetan Plateau. Its 220-day and 260-day contours approximately coincide with the southern boundary of high-latitude permafrost regions and the lower boundary of high-altitude permafrost regions, respectively, based on data and information from the Map of Geocryological Regionalization and Classification in China.
- The actual number of days and duration of the near-surface soil freeze decrease with increasing MAAT, and the rates are higher in west China than those in east China. The soil freeze indicators are nonlinearly related to MAAT and the air freezing index, but nearly linearly linked to the air thawing index.
- The near-surface soil freeze-thaw status in transition regions between cold and warm regions are the most sensitive to climatic change.

This study shows the spatial patterns of the near-surface soil freeze-thaw status across China. Our results differ with previous studies. The source of those differences is mainly the discrepancy in the methods used to define the freeze event. But there may also be some misestimates due to the lack of observation points. Any uncertainties should be attenuated by a higher density of future observation networks, as well as extensive field work integrated with other technologies that allow for better spatial coverage.

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