Dear Dr. Gruber,

Thank you very much for your comments on this manuscript. Based on your recommendation and reviewers' comments, we have made careful revision. Please find enclosed term by term response to all related issues. If you have any questions or concerns, please let us know.

Thanks again for your great help and support for possible publication of this manuscript in The Cryosphere.

Sincerely,

Kang Wang and Tingjun Zhang

Response to reviewers' comments and suggestions

Thank you very much for your substantial and thorough revisions to this manuscript. After renewed review, one referee recommends acceptance as is and one asks for minor revisions. I concur with the request for minor revisions and have included below a list of items to be addressed, also those raised by the reviewer. EC1 and EC2 border major revisions as they may change the results of your analysis somewhat.

EC1: How do you justify removing outliers (cf. RC3, below)? The hot summer of 2003 in Europe was 5 sigma out from the mean and a very real and relevant event. Consider not removing outliers or finding a cleaning procedure that will check if neighboring station also have outliers.

Response:

We discussed this issue in great detail according to your suggestion. We careful checked data outliers and made related changes. All figures and texts have been revised. We revised the data procedure described in the last paragraph of data and methods section (start from Line 131), as well as relevant results and figures (Figures 6-9 and 11) as follows:

"First, we detect the outliers with three standard deviations (3σ) from its long-term mean as described by Polyakov et al. (2003) and Park et al. (2014). To ensure a specific outlier which may be questionable, we check the outlier with neighboring stations within 200 km. If data from the neighboring stations are normal, we consider this data point as an outlier and remove it from the time series. Otherwise, if there are at least two and/or more neighboring stations that have data points with three standard deviations (3σ) or higher, we consider these data points represent true values and keep them in the analysis."

References added:

Park, H., Sherstiukov, A. B., Fedorov, A. N., Polyakov, I. V., and Walsh, J. E.: An

observation-based assessment of the influences of air temperature and snow depth on soil temperature in Russia, Environ. Res. Lett., 9, 064026, 2014.

Polyakov, I. V., Bekryaev, R. V., Alekseev, G. V., Bhatt, U. S., Colony, R. L., Johnson, M. A., Maskshtas, A. P., and Walsh, D.: Variability and Trends of Air Temperature and Pressure in the Maritime Arctic, 1875–2000, J. Clim., 16, 2067-2077, 2003.

Revised results: These results are slightly revised because of changes in outliers removal as described above.

Line 18: “0.09 ±0.03 day/yr” -> “0.10 ±0.03 day/yr”
Line 19: “0.14 ±0.02 day/yr” -> “0.15 ±0.02 day/yr”
Line 21 : “-0.24 ± 0.04 day/yr” -> “0.25 ± 0.04 day/yr”
Line 22 : “-0.19 ± 0.03 day/yr” -> “0.20 ± 0.03 day/yr”
Line 158: “0.09 ±0.03 day/yr” -> “0.10 ±0.03 day/yr”
Line 161: “R^2=0.21” -> “R^2=0.25”
Line 164: “0.21 day/yr” -> “0.22 day/yr”
Line 165: “0.71 ±0.17 day/yr” -> “0.72 ±0.17 day/yr”
Line 182: “-0.14 ± 0.02 day/yr” -> “0.15 ± 0.02 day/yr”
Line 184: “44%” -> “46%”
Line 188: “-0.56 ± 0.14 day/yr” -> “0.60 ± 0.14 day/yr”
Line 199: “-0.24 ± 0.04 day/yr” -> “0.25 ± 0.14 day/yr”
Line 201: “-0.43 day/yr” -> “0.45 day/yr”
Line 202: “-0.24 day/yr” -> “0.25 day/yr”
Line 203: “-0.14 day/yr” -> “0.15 day/yr”
Line 216: “-0.19 ± 0.03 day/yr” -> “0.20 ± 0.03 day/yr”
Line 221: “-0.34 day/yr” -> “0.35 day/yr”, “-0.84 day/yr” -> “0.89 day/yr”
Line 260: “3.73 ±0.53 day/yr” -> “3.86 ±0.52 day/yr”
Line 263: “-2.68 ± 0.68 day/yr” -> “2.82 ± 0.72 day/yr”
Lines 269 - 270: “-7.61 ± 1.24 day/℃” -> “7.75 ± 1.31 day/℃”, “-6.40 ± 1.06 day/℃”-> “6.61 ± 1.06 day/℃”
Lines 283 – 284: “25%” -> “21% and 26%”
Line 296: “0.09 day/yr” -> “0.10 day/yr”
Line 300: “0.71 day/yr” -> “0.72 day/yr”
Line 305: “0.14 day/yr” -> “0.15 day/yr”
Line 308: “0.56 day/yr” -> “0.60 day/yr”
Line 359: “-0.26 day/yr” -> “-0.27 day/yr”; “37%”->”42%”; “44%”->”50%”
Line 369: “-0.84 day/yr” -> “0.85 day/yr”
Line 438: “0.09 ±0.03 day/yr” -> “0.10 ±0.03 day/yr”
Line 439: “0.14 ±0.02 day/yr” -> “0.15 ±0.02 day/yr”
Line 442: “-0.19 ± 0.03 day/yr” -> “0.20 ± 0.03 day/yr”
Line 445: “3.73 ±0.53 day/yr” -> “3.86 ±0.52 day/yr”
Line 446: “-2.68 ± 0.68 day/yr” -> “2.82 ± 0.72 day/yr”
Line 451: “-7.61 ± 1.24 day/℃” -> “7.75 ± 1.31 day/℃”
Line 452: “-6.40 ± 1.06 day/℃” -> “6.61 ± 1.06 day/℃”

EC2: Why do you only keep stations with significant change for your analysis (L122)? I assume this is the reason why numbers a lot smaller than 636 are reported in Sections 3.2–5 and in Figures 3–6. Your results and abstract state that you used 636 stations and that certain changes in ground freezing occur. Are those numbers really informative if you exclude the time series with non-significant trends? In the extreme, you could have only one significant station and then conclude on an overall trend. Please consider revising this methodology (and adding non-significant stations as e.g., black dos to Figures 3–6) or explain again if I misunderstood you.

Response:

We may have an unclear description. In this study, each station has been investigated by trend analysis while only statistically significant stations represented in Figures 3-6. However, in the combined time series, we used data from all stations to represent regional composite changes (Figure 3-6 A). The time series may not show significant trend in a single station, however, they may become significant when they are combined together. This is a common practice for climate change, including air temperature and precipitation (IPCC, 2007; 2013; Mallakpour et al., 2015; Dai et al., 2013; Piao et al., 2010).

References：

Solomon, Susan, et al. "The physical science basis." Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change (2007): 235-337.

Stocker, T. F., et al. "IPCC, 2013: climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change." (2013).

Mallakpour, I. and Villarini, G.: The changing nature of flooding across the central United States, Nature Clim. Change, 5, 250-254, 2015.

Dai, A.: Increasing drought under global warming in observations and models, Nature Clim. Change, 3, 52-58, 2013.

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, K., Yu, Y., Zhang, T., and Fang, J.: The impacts of climate change on water resources and agriculture in China, Nature, 467, 43-51, 2010.

Changes:

We have added a sentence to clarify this procedure in the last paragraph (Line 128) of data and methods section. “The combined time series of anomalies was generated by using data from all available stations with at least 22 years of records.”

EC3: In your conclusion, you present the result of auxiliary analyses performed only in your discussion (L433: “…, the North …. few decades.”). This should not be presented as your major investigation or result as it did not receive the same level of analysis as the freezing regimes. Do you really need the NAO and AO analysis to discuss your results?

Response:

This part was added in the previous version because of the suggestion from the referee. All of the discussions were performed to explain the cause of the changes in surface soil freeze. Considering not statistical significant correlations, relevant paragraphs or sentences in abstract and conclusion have been deleted.

Changes:

Lines 27-30 (Abstract): deleted.

Lines 446-447 (the first paragraph in summary section): deleted 'the North Atlantic Oscillation and Arctic Oscillation indexes'.

Lines 477-481 (the last paragraph in summary section): deleted.

EC4: Please address these small items: L177 "…, primarily due to…" Delete rest of sentence or move to discussion. L76: "… at THE ground surface…" L77: "ground-surface temperature and mean…" (no comma) L79: "Temperature monitoring was conducted…" L82: " Although the measurement standard states…" (the, delete s)

Changes:

Line 76: add 'the' before "ground surface"

Line 77: delete the comma ',' after 'ground-surface temperature'

Line 79: 'were' -> "was"

Line 82: "states" -> 'state'

Line 177: delete rest of sentence starting from "primarily due to".

RC1. The kriging procedure, Fig. 2: The soil freezing critically depends on a number of factors, such as altitude, as investigated in detail by the authors. The map, however, is simply an interpolation between the individual stations, without considering e.g. the real topography, and changes in other factors. If all stations were for instance located in valley systems in an otherwise mountainous region, the "average" soil freezing of the region would not be adequately represented. I agree that Fig. 2 is a nice illustration, but the authors should critically evaluate (and discuss in the manuscript) the possibility of false representations and interpolation artifacts in certain regions. For instance, is it reasonable to believe that the three dark blue spots in Fig. 2C are really localized areas with more pronounced ground freezing, or is it simply the effect of the particular setting of the station in the center of each region?

Response:

Simple kriging interpolation method doesn't consider any additional information out of latitude and longitude.

Changes:

To avoid the uncertainties of representations by interpolation, we use color-point to instead Kriging interpolation. It does not change our analysis.

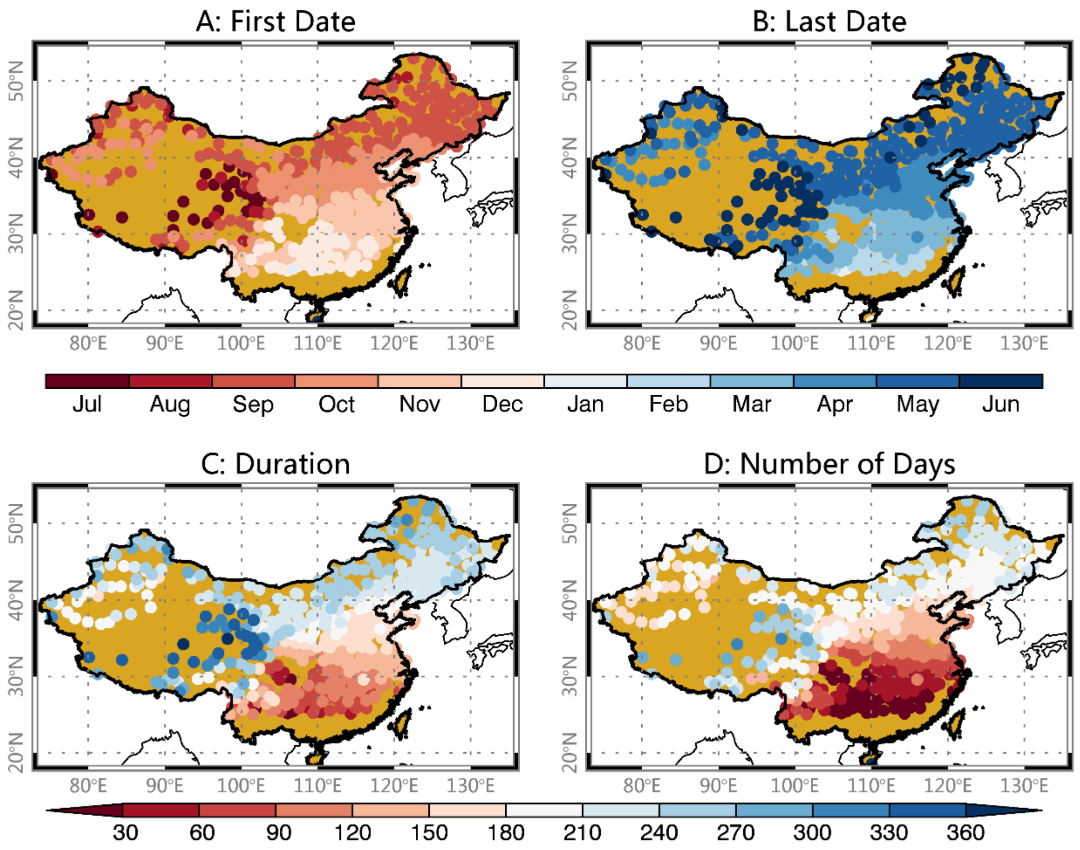

Fig.2. Climatology of the first date (A), the last date (B), the duration (C) and the number of days (D) of the near-surface soil freeze/thaw status across China. The 30-year reference period was from July 1961 through June 1991.

RC 2. For the last date, the rate has a plus-sign in the abstract, and a minus-sign later (l.182). In the abstract (and l. 182 again), it says that “the last date was advanced…”, which at least I misunderstood in the beginning. Just state that the last date occurred earlier, or something similar, then the direction of the change is clear.

Changes:

We thank the reviewer and correct everywhere. There is a list of them (magnitudes of trend may change because of the revised data processing).

Line 21 : “-0.24 ± 0.04 day/yr” -> “0.25 ± 0.04 day/yr”
Line 22 : “-0.19 ± 0.03 day/yr” -> “0.20 ± 0.03 day/yr”
Line 182: “-0.14 ± 0.02 day/yr” -> “0.15 ± 0.02 day/yr”
Line 188: “-0.56 ± 0.14 day/yr” -> “0.60 ± 0.14 day/yr”
Line 192: “-0.30 day/yr” -> “0.30 day/yr”
Line 199: “-0.24 ± 0.04 day/yr” -> “0.25 ± 0.14 day/yr”
Line 201: “-0.43 day/yr” -> “0.45 day/yr”
Line 202: “-0.24 day/yr” -> “0.25 day/yr”
Line 203: “-0.14 day/yr” -> “0.15 day/yr”
Line 206: “-0.50 day/yr” -> “0.50 day/yr”

Line 216: “-0.19 ± 0.03 day/yr” -> “0.20 ± 0.03 day/yr”
Line 219: “-0.27 day/yr” -> “0.27 day/yr”
Line 221: “-0.34 day/yr” -> “0.35 day/yr”, “-0.84 day/yr” -> “0.89 day/yr”
Line 227: “-0.50 to -0.20 day/yr” -> “0.50 to 0.20 day/yr”
Line 263: “-2.68 ± 0.68 day/yr” -> “2.82 ± 0.72 day/yr”
Lines 269 - 270: “-7.61 ± 1.24 day/℃” -> “7.75 ± 1.31 day/℃”, “-6.40 ± 1.06 day/℃” -> “6.61 ± 1.06 day/℃”
Line 369: “-0.84 day/yr” -> “0.85 day/yr”
Line 442: “-0.19 ± 0.03 day/yr” -> “0.20 ± 0.03 day/yr”
Line 446: “-2.68 ± 0.68 day/yr” -> “2.82 ± 0.72 day/yr”
Line 451: “-7.61 ± 1.24 day/℃” -> “7.75 ± 1.31 day/℃”
Line 452: “-6.40 ± 1.06 day/℃” -> “6.61 ± 1.06 day/℃”

RC3. L.131 ff: What’s the reason for rejecting “outlier” years? Is it reasonable to assume that such an outlier is due to bad data quality? Or could it not just as well be natural variability which should be included when calculating trends? In the worst case, excluding outlier years could even make a trend statistically significant, which otherwise would not could not be statistically secured.

Response:

We discussed this issue in great detail according to your suggestion. We careful checked data outliers and made related changes. All figures and texts have been revised. We revised the data procedure described in the last paragraph of data and methods section (start from Line 131), as well as relevant results and figures (Figures 6-9 and 11) as follows:

“We detect the outliers with three standard deviations (3σ) from its long-term mean as described by Polyakov et al. (2003) and Park et al. (2014). To ensure a specific outlier which may be questionable, we check the outlier with neighboring stations within 200 km. If data from the neighboring stations are normal, we consider this data point as an outlier and remove it from the time series. Otherwise, if there are at least two and/or more neighboring stations that have data points with three standard deviations (3σ) or higher, we consider these data points represent true values and keep them in the analysis.”

References added:

Park, H., Sherstiukov, A. B., Fedorov, A. N., Polyakov, I. V., and Walsh, J. E.: An observation-based assessment of the influences of air temperature and snow depth on soil temperature in Russia, Environ. Res. Lett., 9, 064026, 2014.

Polyakov, I. V., Bekryaev, R. V., Alekseev, G. V., Bhatt, U. S., Colony, R. L., Johnson, M. A., Maskshtas, A. P., and Walsh, D.: Variability and Trends of Air Temperature and Pressure in the Maritime Arctic, 1875–2000, J. Clim., 16, 2067-2077, 2003.

RC4. Sect. 4.2: It is excellent that the authors investigate a potential influence of urbanization. However, it does not become immediately clear why the authors chose to do this somehow involved analysis and not simply excluded stations which are in urban areas at present. The

text seems to suggest that there is a digitized product of urban areas, so it should be straight-forward to filter out the stations that are now in urban areas, and simply calculate the trends with these stations removed. The authors should clearly state why they chose to do the analysis this way, and why "detailed investigation of this issue is far beyond this study".

Response:

We thank the reviewer for such an excellent question. The issue itself is a project to study. In the current paper, we intend mainly to study changes in the near-surface soil freeze-thaw across China over the past several decades. In the discussion section, we try to explain the cause of the changes in surface soil freeze, such as changes in air temperature, freezing index of air temperature, urbanization, AO/NAO, and possible snow cover. We may deal with the urbanization issue deeper in a separate paper later.

Changes in the Timing and Duration of the Near-Surface Soil Freeze/Thaw Status from 1956 to 2006 across China

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Abstract

The near-surface soil freeze/thaw status is an important indicator of climate change. Using data from 636 meteorological stations across China, we investigated the changes in the first date, the last date, the duration, and the number of days of the near-surface soil freeze over the period 1956—2006. The results reveal that the first date of the near-surface soil freeze was delayed by about 5 days, or at a rate of 0.~~09~~10 ±0.03 day/yr, and the last date was advanced by about 7 days, or at a rate of 0.~~14~~ 15 ± 0.02 day/yr. The duration of the near-surface soil freeze decreased by about 12 days or at a rate of ~~-~~0.~~24~~ 25 ±0.04 day/yr, while the actual number of the near-surface soil freeze days was decreased by about 10 days or at a rate of ~~-~~0.~~19~~20 ±0.03 day/yr. The rates of changes in the near-surface soil freeze/thaw status increased dramatically from the early 1990s through the end of the study period. Regionally, the changes in western China were greater than those in eastern China. Changes in the near-surface soil freeze/thaw status were primarily controlled by changes in air temperature, but urbanization may also play an important role. ~~Although the effect of seasonal snow cover on the near-surface soil freeze/thaw status may be limited, changes in the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) indexes are closely related to changes in the near-surface soil freeze/thaw status.~~

1. Introduction

The near-surface soil freeze/thaw state is related to the timing and duration of cold/warm seasons, and is an important indicator of climate change (Zhang et al., 2001). During the past few decades, many studies have focused on the dynamics of the near-surface soil freeze/thaw status and the interactions between the ground surface and the atmosphere. These studies have shown that changes in the near-surface soil freeze/thaw status are interrelated, and soil freeze/thaw affects hydrological processes (Cherkauer and Lettenmaier, 1999; Niu and Yang, 2006; Rempel, 2012), ecological processes (Schimel et al., 1996; Tagesson et al., 2012), and soil microbial processes (Lloyd and Taylor, 1994; Gilichinsky and Wagener, 1995; Edwards and Jefferies, 2013).

Variations in the timing and duration of the near-surface soil freeze/thaw state have been widely investigated using a range of approaches, including remote sensing and in-situ observations, across spatial-temporal scales ranging from regional to global. Menzel et al. (2003) used data from 41 meteorological stations across Germany (from 1951 through 2000) to investigate soil frost dynamics. Their results showed that the freeze-free period was extended with increasing air temperature. Henry (2008) used observations from 31 stations across Canada to examine soil freeze dynamics and found that number of days of the near-surface soil freeze declined from 1966 through 2004. Using long-term data from three stations in Indiana, USA, Sinha et al. (2008) found that the number of soil freeze days had significantly decreased at the central and southern study sites, but the near-surface soil temperature at the northernmost site showed a significant decrease in the cold season due to a decrease in snow depth. Anandhi et al. (2013) carried out a more-detailed analysis of frost indices at 23 stations across Kansas, USA, and found that the first date and the last date of freezing occurred later and earlier, respectively, over their study period.

Numerous studies have reported significant improvements in monitoring soil the freeze/thaw status. NASA is launching the Hydrosphere State Mission as part of the Earth System Science Pathfinder Program (ESSP) to improve satellite monitoring of global land freeze/thaw status and soil moisture (Entekhabi et al., 2004). In China, a multi-scale monitoring network has been established on the Qinghai-Tibetan Plateau (Yang et al., 2013). Fifty-six (56) stations have been installed in cold and high-elevation regions to enhance monitoring of soil temperature and moisture and hence to support remote sensing data and large-scale climate modeling (Su et al., 2011; Yang et al., 2013).

In this study, we use ground-based station data to investigate the long-term spatiotemporal variation in the timing and duration of the near-surface soil freeze/thaw across China over the period 1956–2006. Using data from 636 stations, we examine the first date, last date, duration, and actual number of days of the near-surface soil freeze, as well as the spatial characteristics of these variables across China. Finally, we further investigate the response of the near-surface soil freeze/thaw status to climate changes over the past few decades.

2. Data and Methods

We define the soil “freeze day”, as a day with a minimum temperature at or below 0℃ at the ground surface (Henry, 2008). Data used for this study include daily minimum ground-surface temperature~~,~~ and mean annual air temperature (MAAT) obtained from the China Meteorological Administration (CMA, 2007).

Temperature monitoring was~~were~~ conducted each day by trained professional technicians at all meteorological stations across China. Ground surface temperatures were measured with a mercury ball thermometer (ball diameter of about 3 mm). Although measurement standards state~~s~~ that half of the thermometer sensor should be buried in the ground and the other half exposed to the air, in practice, the sensors were usually buried more than halfway and were often colored white to reduce solar heating. When the ground was covered by snow, the sensor was moved to the snow surface. Thus snow surface temperature was measured rather than the ground surface temperature. In this case, it is assumed that soils near the ground surface are in a frozen state (Zhang, 2005). Daily minimum temperatures were measured using a minimum temperature thermometer, which recorded the daily minimum temperature once a day although it could not record the time when it occurred. Daily minimum temperature was reported at 20:00 Beijing Standard Time. Ground surface temperatures were measured four times per day (02:00, 08:00, 14:00, and 20:00 Beijing Standard Time) and averaged as a daily mean. The thermometers at the study stations have an accuracy of ±0.1℃ and should be calibrated at least once a year (CMA 2007). None of the thermometers were replaced during the study period. The large majority of the meteorological stations remained geographically stable over the study period (Ma et al., 2009); however, information is not available for those stations with a history of location changes. We believe that effect of station movement on our results is minimal.

Our daily surface temperature dataset was created with thorough data quality control. ~~First, o~~On daily time scale, we checked the consistency of the temperature time series by cross-referencing temperature values with the day before and the day after the checking day. ~~On annual time scale, we plotted and screened each individual time series to identify questionable data points, and removed the statistical outliers of those points out of the three standard deviations range from the long-term mean.~~

Annual values of the first and last date, duration, and actual number of days of the near-surface soil freeze 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. The anomalies of each variable were calculated over the entire study period after removing the long-term average (1 July 1961 through 30 June 1991) across China. We used linear regression to investigate the trend of changes for each variable. Stations with statistically significant changes ($P < 0.05$) were kept in the analysis. We also compared the linear trends of the freeze/thaw variables with latitude and elevation to investigate the geographic characteristics of the freeze/thaw changes. In addition, we used the Quantile-Quantile method to ensure that the linear hypothesis was statistically appropriate (John, 2006; David, 2009).

The first date (FD) and last date (LD) of the near-surface soil freeze are defined as the first and last date after 1 July on which the daily minimum ground surface temperature is at or below 0℃. The duration (DR) of the near-surface soil freeze is defined as the time span between the first and last date of the near-surface soil freeze. It is common for the near-surface soil not be continuously frozen during the period between the first date and the last date of freeze. Thus, we further define the actual number of the near-surface soil freeze days (NF) by counting the number of days with a daily minimum ground surface soil temperature at or below 0℃.

Not all of the meteorological stations in this study have continuous data over a 30-yr period (1 July 1961 through 30 June 1991). Generally, 8 or less missing years (<25% of the 30-yr period) are permitted in a calculation of the long-term mean (Jones and Hulme, 1996). The combined time series of anomalies was generated by using data from all available stations with at least 22 years of records. In this study, we applied a thorough data quality control approach to ensure the reliability and consistency of results by station and year. Firstly, study years with 365 daily records were utilized in the annual indices. Secondly, we detect the outliers with three standard deviations (3σ) from its long-term mean as described by Polyakov et al. (2003) and Park et al. (2014). To ensure a specific outlier which may be questionable, we check the outlier with neighboring stations within 200 km. If data from the neighboring stations are normal, we consider this data point as an outlier and remove it from the time series. Otherwise, if there are at least two and/or more neighboring stations that have data points with three standard deviations or higher, we consider these data points represent true values and keep them in the analysis.~~we rejected the outliers of years with values at or higher than three standard deviations (3σ) from the long-term mean for a station.~~ ~~On annual time scale~~Finally, we plotted and screened

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each individual time series to identify questionable data points~~, and removed the statistical outliers of those points out of the three standard deviations range from the long-term mean~~. This resulted in 636 meteorological stations being included in this study (Fig. 1).

3. Results

3.1 Climatology of the timing and duration of the near-surface soil freeze

~~We used the Kriging method to interpolate our climate~~Long-term mean of the timing and duration of the near-surface soil freeze was performed over a 30-yr period (1 July 1961 through 30 June 1991) to reveal the ~~data points to create spatial~~spatial patterns of climatology (Fig. 2). Regions south of 24° N were considered as freeze-free regions because freeze events were generally scarce in those areas.

The timing and duration of the near-surface soil freeze varied greatly across China. FD occurred from July of the current year through January of the next year across China. LD occurred from January of the next year through June of the next year. DR ranged from two weeks or less in southern China through almost the entire year on the Qinghai-Tibetan Plateau. The maximum of NF was up to 315 days, which was significantly less than the maximum of DR because of the discontinuous freeze events during the freeze period.

The earliest and latest dates of the near-surface soil freeze occurred in July of the current year and in June of the next year on the Qinghai-Tibetan Plateau. NF was up to ten months on the plateau.

Our results showed an understandable latitudinal zonal pattern in eastern China, and a significant elevation correlation in western China. Maximum elevations in eastern China are about 1500 m in eastern China and 5000 m in western China due to the location of the Qinghai-Tibetan Plateau. Overall, NF increased about 10 days per degree of latitude in eastern China and about 5 days per 100 m of elevation in western China. The DR increased about 9 days per degree of latitude in eastern China and 6 days per 100 m of elevation in western China.

3.2 Changes in the First Date of the Near-Surface Soil Freeze

Overall, FD departures from its long-term mean showed a significant increase across China by nearly 5 days, or a trend of 0.~~09~~10 ± 0.03 day/yr, for the period 1956–2006 (Fig. 3a). We found that the near-surface soil started to freeze later due to a general warming in the fall season across China during the study period. The coefficient of determination, R^2=0.~~21~~25, means that one-fifth of the total variability in the FD can be explained by the regression equation.Variations can be mainly broken into two periods: before and after the early 1970s. FD anomalies during ~~1965~~the middle 1960s through the middle ~~–~~1970s~~75~~ are the lowest in the study period. A delay in FD (0.~~21~~ 22 day/yr) started in the early 1970s when a short cold period ended. Meanwhile, a large delay in FD (0.7~~1~~2 ± 0.17 day/yr) occurred after the early 1990s (Fig. 3a); FD has occurred approximately 10 days later since the early 1990s with R^2 = 0.~~61~~60, implying that about 60% of the total variability in the FD can be explained by the linear trend.

Over the study period, the ~~130~~ 126 study stations showed a significant trend in FD delay in autumn (Fig. 3b). Most stations showed long-term FD delays, except for a few stations where FD was advanced. Among about ~~90~~ 84 of the ~~130~~ 126 stations, the FD delay was <0.25 day/yr (Fig. 3b). When comparing stations in western China and eastern China (east and west of 110^{o} E), we found that the FD delay was greater in the west than in the east. A dry environment in western China may be an important element enhancing the changes in FD because latent heat is less when moisture is low. FD at stations surrounding or on the Qinghai-Tibetan Plateau was delayed by >0.5 day/yr (Fig. 3b)~~, primarily due to the higher average elevation, more complex terrain, stronger monsoon circulation, and more solar radiation on the Qinghai-Tibetan Plateau (Sun, 1996)~~.

3.3 Changes in the Last Date of the Near-Surface Soil Freeze

The LD was advanced in spring significantly over the period of 1956–2006, by about 7 days, or a trend of -0.~~14~~ 15 ± 0.02 day/yr (Fig. 4a). This indicates that warming spring seasons result in an earlier end of the near-surface soil freeze. Approximately ~~44~~46% of the total variability in the LD can be explained by the linear trend. Variations in LD are divided into two periods: before and after the early 1990s. LD occurred slightly earlier from 1956 through 1991. The highest deviated from the long-term mean occurred during 1965–1980. A rapid advancement of LD appeared after the early 1990s, with a linear trend of –0.60~~56~~ ± 0.14 day/yr; i.e., LD has occurred earlier by about 9 days since 1992.

LD changed significantly at 30% (~~190~~ 202 stations) of all stations (Fig. 4b). This percentage is larger than that of the stations with a significant delay in FD. Among ~~162~~ 160 stations, LD was advanced by about –0.30 day/yr (Fig. 4b). LD changes in western China were larger than those in eastern China. Overall, FD and LD were significantly delayed and advanced, respectively, at 85 stations. These stations show a delayed onset of autumn soil freeze and an earlier ending of the spring soil freeze over the study period.

3.4 Changes in the Duration of the Near-Surface Soil Freeze

Over the period from 1956 through 2006, DR was shortened by almost 12 days, or –0.2~~4~~5 ± 0.04 day/yr (Fig. 5a). Anomalies during 1966–1980 were higher than the rest of the study period. The most significant decrease in DR appeared mainly after the 1970s (–0.4~~3~~5 day/yr). Since the early 1990s, DR has decreased sharply (–1.1~~2~~8 ±0.20 day/yr) (Fig. 5a), by almost 16 days. The overall variation in DR (–0.~~24~~ 25 day/yr) is a combination of changes in FD (0.~~09~~ 10 day/yr) and LD (–0.~~14~~ 15 day/yr). For example, the increase in DR (12 days) corresponds to the delay of FD by 5 days and the advance of LD by 7 days.

~~227~~ 235 study stations showed a significant decrease in DR of < –0.50 day/yr (Fig. 5b). Most stations showed a long-term decrease in DR, except for three stations where DR showed a slight increase. DR decreased more in western China than in eastern China. This general decrease in DR indicates a shortening frost period in the near-surface soil across China over our study period.

3.5 Changes in the Number of Days of the Near-Surface Soil Freeze

It is important to realize that near-surface soil may not be continuously frozen during the period from the first date to the last date of the near-surface freeze, especially in mid- or low-latitude sites. We determine NF by counting the actual number of days with minimum soil temperature ≤0℃.

NF decreased by almost 10 days (–0.~~19~~ 20 ± 0.03 day/yr) for the period 1956–2006 (Fig. 6a). The trend in NF is similar to but smaller than that in DR (compare to Fig. 4a). A statistically significant increase in NF has occurred since the early 1970s. During the period from 1971 through the early 1990s, NF decreased slightly (–0.27 day/yr). The NF decrease for the period from 1971 through the end of our study period is –0.~~34~~ 35 day/yr, with a decrease of –0.~~84~~ 89 day/yr since early 1990s (Fig. 6a). The actual number of freeze days in near-surface soil decreased by 12 or more days over our study period.

At ~~368~~ 344 stations (about ~~60~~54% of all study stations), NF varied significantly over the study period (Fig. 6b). Although a few stations in western China showed an increasing trend in NF, the remaining stations showed a significant decreasing trend, with decreasing trends ranging from –0.50 to –0.20 day/yr (Fig. 6b). This general decrease in NF indicates a shortening cold season across China.

3.6 Variations in the Near-Surface Soil Freeze with Latitude and Elevation

Changes in the near-surface soil freeze are primarily controlled by elevation in western China and by latitude in eastern China. In western China, the rate of change in FD increases as elevation increases (Fig. 7A), which implies that changes in FD in higher-elevation regions are greater than those over lower elevation areas. The rate of change in NF decreases (becoming more negative) as the elevation increases (Fig. 7B). In other words, the absolute magnitude of the rate of NF change increases with increasing elevation. This implies that NF decreases faster in the higher-elevation areas than in the lower-elevation regions, which is consistent with the FD changes. However, changes in LD and DR with elevation are not statistically significant in western China (not shown).

Over eastern China, the rates of change in LD, DR, and NF are significantly correlated with latitude. The rates of change in LD (Fig. 7C), DR (Fig. 7D), and NF (Fig. 7E) increase as latitude increases, which demonstrates that the magnitude of changes in LD, DR, and NF is greater in lower-latitude regions than in higher-latitude regions. Lower-latitude regions are more sensitive to freeze/thaw timing and duration because soils at more southerly latitudes are closer to the freezing point in cold seasons. Under warming climate conditions, changes in soil temperature in southern regions have a greater impact on the timing and duration of the near-surface soil freeze. The FD is not significantly correlated with changes in latitudes in eastern China (not shown). However, the rate of NF change increases (becoming less negative) with elevation in eastern China (Fig. 7F). In other words, the magnitude of NF changes decreases with elevation in eastern China. This is contradictory to the rate of NF changes in western China. We believe that there are two possible explanations: (i) changes in soil freeze in eastern China are primarily controlled by latitudes; (ii) elevation changes in eastern China are relatively small compared with those in western China. Elevation difference in western China is up to 5000 m (Fig. 7B), while in eastern China, the difference is about 1500 m (Fig. 7F).

3.7 Effects of Air Temperature on the Near-Surface Soil Freeze

Air temperature is an important factor that affects the near-surface soil freeze/thaw dynamics. The FD increased as mean autumn (September, October and November) air temperature increased at a rate of about 3.~~73~~86 ±0.~~53~~ 52 day/℃ (Fig.8A), implying that the FD was delayed in autumn. This positive correlation between FD and mean autumn air temperature implies that overall delay in FD indeed reflects autumn warming in recent decades across China. The LD decreased at a rate of -2.~~68~~ 82 ±0.~~68~~ 72 day/℃ as mean spring (March, April, and May) air temperature increased (Fig. 8B), indicating that the LD advanced in spring as mean spring air temperature increased over the past several decades across China. As a result, the DR and NF are inversely correlated with MAAT (Figs. 8C and 8D), i.e., the DR was shortened and the NF was decreased with increased MAAT, as expected. However, the DR was shortened as a rate of -7.~~61~~ 75 ±1.~~24~~ 31 day/℃, while the NF decreased at a rate of -6.~~40~~ 61 ±1.06 day/℃; the rate of NF change is about ~~16~~15% less than that of the DR change. Changes in DR are mainly controlled by changes in FD and LD. In other words, changes in DR are mainly controlled by changes in autumn and spring air temperatures, while changes in NF are controlled not only by changes in autumn and spring air temperatures, but also by changes in air temperature during the entire cold season.

The freeze index of air temperature (AFI) is a measure of the combined magnitude of temperatures below 0℃ from 1 July in the current year through 30 June in the next year, in order to cover the entire freeze period (Zhang et al., 2001). Overall, DR and NF are positively correlated with freeze index, as expected (Fig. 9). During the entire period, DR was lengthened and NF was increased with increasing freeze index across China. Similar to the correlations with mean annual air temperature, the rate of the DR extension is larger than the rate of NF increase with the freeze index. In addition, the variations of NF and DR can be explained about 21% and ~~25~~26% by the freeze index of air temperature ~~(R^2=0.25)~~, which are significantly less than that by MAAT (Figs. 8C and 8D). This is because the freeze index reflects not only the freeze period but also the magnitude of freeze temperatures in air; in other words, a higher freeze index can not be singly correlated to a longer freeze period because the freeze index value may be caused by a greater magnitude of the cold temperatures.

4. Discussion

4.1 Comparisons with previous results

The timing and duration of the near-surface soil freeze were investigated using ground-based measurements from 636 stations across China from 1956 through 2006. Primary results indicate that the FD occurred later, while the LD became earlier, resulting in a decrease in both the duration and number of days of the near-surface soil freeze in China.

FD was delayed by about 5 days (0.~~09~~ 10 day/yr) over the entire study period, as a result of warming climate. Similar results have been found on the Qinghai-Tibetan Plateau (Li et al., 2012), in Indiana, USA (Sinha and Cherkauer, 2008), and in Kansas, USA (Anandhi et al., 2013). However, results from this study indicate that the rate of FD change from the early 1990s to 2006 across China was about 0.72~~1~~ day/yr, while Li et al. (2012) found that the rate of FD change was about 0.50 day/yr over the

Qinghai-Tibetan Plateau from 1988 through 2007. Their results were obtained from passive microwave satellite remote sensing data, which may have a large uncertainty and may underestimate the autumn warming on the Qinghai-Tibetan Plateau.

Similarly, LD occurred approximately 7 days earlier (0.~~14~~ 15 day/yr) over our study period. Li et al. (2012) showed a later date of soil freeze by about 14 days (or 0.70 day/yr) from 1988 to 2007. We found more change in the ~~FD~~LD in China since the early 1990s (0.~~56~~ 60 day/yr). The last freeze date in Kansas, USA, occurred earlier by 0.01–0.19 day/yr from 1919 through 2009 (Anandhi et al., 2013), and this is similar to our results for our study period.

Our results indicate that DR and NF decreased 12 and 10 days, respectively, from 1956 to 2006 and have decreased sharply since the early 1990s. We also found significant regional diversity. On the Qinghai-Tibetan Plateau, the number of freeze days decreased by 1.68 day/yr during the period 1988–2007 (Li et al., 2012). This corresponds to our results (Fig. 6a). The number of freezing days in Kansas, USA, varied from 0.01 to 0.24 day/yr from 1919 through 2009 (Anandhi et al., 2013), which is similar to our results for our study period.

Increasing air temperature significantly influences the timing and duration of near-surface soil freeze. Warming ground can play a significant role in carbon cycles in land-atmosphere processes (Koven et al., 2011; Schuur et al., 2009; DeConto et al., 2012; Tagesson et al., 2012), but the mechanism of this role is complex and not clear, even though studies have found correlations between growing season carbon fluxes and increased soil temperature, particularly in the high Arctic (Tagesson et al., 2012;

Mastepanov et al., 2008; Heimann and Reichstein, 2008). Other studies have shown that increasing temperature results in the lengthening of the growing season and improved productivity (Kimball et al., 2006; Barichivich et al., 2013).These effects may partly counteract the negative effects of climate warming (Cornelissen et al., 2007). Additionally, Kumar et al. (2013) suggested that the impact of climate change on soil microbes in Arctic regions may be impossible to predict. Thus more and deeper research is necessary in order to determine the role of soil freeze/thaw in land-atmosphere feedbacks.

4.2 Potential influences of urbanization

Data used in this study were obtained from China Meteorological Stations. The majority of these stations were established in the 1950s and 1960s (Ma et al., 2009), and intentionally sited outside of cities in order to reduce the impact of human activities on meteorological observations, and thus weather forecasts. However, since the late 1970s, urban areas have expanded dramatically. Studies indicate that cities in China have expanded by two to five times in area during the past 30 years (Wang et al., 2012). Because of this, some of Chinese meteorological stations are now located within urban areas. Hence, the immediate question is how much of the changes in the near-surface soil freeze detected during this study are due to natural variations in climate change versus the impact of human activities such as urban expansion. Detailed investigation of this issue is far beyond this study; however, we provide here some preliminary analysis using limited data.

To explore the impact of urbanization on the near-surface soil freeze, we used data and information of urban expansion in China from 1990 through 2010 (Wang et al., 2012). The urban areas were manually identified using Landsat TM/ETM+ in the 1990s, 2000s and 2010s. The identification was mainly performed by three experienced operators and revised by high-resolution images in Google Earth^{TM}. The interpreted urban areas were finally integrated using statistical data of urban areas in local official yearbooks (Wang et al., 2012).

Over the period from 1990 through 2010, three regions can be divided based upon different degree of urbanization rates, i.e., low rate (<200%), medium rate (200% – 500%), and high rate (>500%) of urban expansion (Fig. 10). We calculated the regional anomalies of the number of soil freeze days (Fig. 11). For all three regions, there were significant decreasing trends in the near-surface soil freeze days since 1956 (Fig. 11). For the low- and medium- rate regions, the trends in NF were approximately -0.~~18~~ 19 to -0.~~19~~ 18 day/yr; while for the high-rate regions, the trend was about -0.~~26~~ 27 days/yr, approximately ~~37~~42% to ~~44~~50% higher than the other two regions. It showed a similar phenomenon to that shown in Figure 6b. Meanwhile, interannual variations were also significantly large in high-rate regions (Fig. 11). Here we chose 1990 as the breakpoint because (1) urban expansion data begins in 1990 (Wang et al., 2012), and (2) 1990 was close to the breakpoint that shown in Figure 6a.

We found that NF changed in a statistically non-significant manner in all three regions before 1990, and significantly decreased after 1990 (Fig. 11). The NF decreased sharply and continuously even though air temperature has a warming hiatus since approximately 1998 worldwide (Easterling et al., 2009). Further analysis indicated that after 1990, NF in the regions with the lower rate of urban expansion decreased at a rate of about –0.~~84~~ 85 day/yr, while NF in regions with a high rate of urban expansion showed a statistically non-significant change over the same period (Fig. 10).

Based on these results, regions with high expansion rates had a significant long-term (1956–2006) decreasing trend in NF, while regions with low and medium expansion rates show a significant decrease in NF but their magnitudes were reduced almost by one-third (Fig. 11). This is because the regions with the high urban expansion rates are large cities along the east coast of China. These regions have been relatively more developed since the mid 1950s, resulting in a greater long-term impact of urban expansion over the past five decades on the near-surface soil freeze, superimposed on long-term climate warming. Over the period from 1990 through 2006, the trend in NF was not statistically significant ($P > 0.05$), probably due to climate warming hiatus, while the urban effect may be minimal because the urban expansion mainly occurred around the edges of the large cities and meteorological stations were not moved. For regions with low and medium expansion rates, the long-term decrease trends in NF may mainly reflect the impact of climate warming, with a relatively limited urban expansion effect because these regions are located far inland and are less developed. Meteorological stations in these regions were installed in the 1950s and generally located several kilometers away from small and medium cities by to avoid an urban effect on meteorological observations. However, over the period from 1990 through 2006, the magnitude of the decreasing trends in NF increased sharply (Fig. 11). This may be due to the boundary of urban was close to and probably far beyond the meteorological stations, resulting in substantial heat island impacts on the near-surface soil freeze.

4.3 Relationship with snow cover, North Atlantic Oscillation and Arctic Oscillation

Snow cover may be an important contributors to the near-surface soil freeze/thaw states in Arctic or pan-Arctic regions. The data used in this study reflected snow surface temperature when the ground surface was fully snow covered. In this case, it was simply assumed that the near-surface soil under the snow is in a frozen state. This assumption is valid because the minimum requirement for the existence of snow on ground is that the ground surface temperature be at or below the freezing point (Zhang et al., 2003). It is possible that soil may not freeze in places where snow cover starts early in autumn, and is relatively thick due to the snow insulation effect (Zhang 2005). Meanwhile, because of the effect of a monsoon climate over the Eurasian continent, winter precipitation (snowfall) accounts for a very small fraction of the annual precipitation in China; thus, the influence of snow cover on the near-surface soil freeze-thaw status is very limited.

We examined the relationship between the long-term winter (December through February) North Atlantic Oscillations (NAO) and the freeze/thaw parameters in this study. Preliminary results indicated that there is a statistically significant negative relationship between the winter NAO and the duration of the near-surface soil freeze ($P < 0.05$) over the study period. We found that a higher winter NAO index corresponds to a shorter duration of the near-surface soil freeze over China. The first date of the near-surface soil freeze in autumn is positively correlated with the coming January NAO index ($P < 0.05$), indicating that the late near-surface soil freeze corresponds to a higher January NAO index. The number of days of the near-surface soil freeze is also negatively correlated with the February Arctic Oscilation (AO) index ($P < 0.05$), showing that the NF decrease corresponds to a higher February AO index. These results are consistent with shorter DR, less NF, and late FD corresponding to higher winter NAO and/or AO indexes.

We further conducted a correlation analysis between the monthly NAO/AO and the annual freezing index of air temperature, and between the monthly NAO/AO and the MAAT (July–June). The preliminary results show that NAO/AO indexes are positively correlated with the MAAT and negatively correlated with the freezing index of air temperature during winter months. These results further demonstrate that higher NAO/AO indexes correspond to warmer winters over China. These results are also consistent with changes in the shorter DR, less NF, and late FD found in our study.

5. Summary

Changes in the timing and duration (the first date, last date, duration, and number of days) of the near-surface soil freeze across China were investigated using ground-based observations at 636 meteorological stations from 1956 through 2006. We also investigated the response of changes in the timing and duration of the near-surface soil freeze to the mean monthly, seasonal, and annual air temperature~~, the North~~

~~Atlantic Oscillation and Arctic Oscillation indexes~~, freeze index of air temperature and urban expansions across China during the past few decades.

The timing and duration of the near-surface soil freeze changed significantly from 1956 through 2006 across China. The first date of the near-surface soil freeze was delayed by about 5 days (0.10~~09~~ ±0.03 day/yr). The last date of the near-surface soil freeze has occurred by about 7 days earlier (0.~~14~~15 ±0.02 day/yr) over the same period. As a result, the duration of the near-surface soil freeze decreased by about 12 days, and the number of the near-surface soil freeze days decreased by about 10 days (–0.~~19~~20 ±0.03 day/yr) for the period 1956–2006.

The changes in the timing and duration of the near-surface soil freeze were accompanied by changes in air temperature. The first freeze date was delayed by about 3.~~73~~86 ± 0.~~53~~52 day/℃ with increasing mean autumn (September through November) air temperature, and the last date of freeze advanced by about -2.~~68~~82 ± 0.~~68~~72 day/℃ with mean spring (March through May) air temperature. As a result, the duration and number of days of the near-surface soil freeze were negatively correlated with mean annual air temperature while positively correlated with freeze index of air temperature. The duration of the near-surface soil freeze was shortened at a rate of -7.~~61~~75 ± 1.~~24~~31 day/℃, while the number of days of the near-surface soil freeze decreased at a rate of -6.~~40~~61 ± 1.06 day/℃, which is about ~~16~~15% less than that of the duration trend.

Urban expansion during the past few decades may also play a role in the changes of the timing and duration of the near-surface soil freeze. The rates of change since the early 1990s were approximately four times larger than the average rates from 1956 through 2006. Since the early 1990s, cities in China have expanded, by approximately two to five times in urban area. The heat island effect may play a significant role in the timing and duration of the near-surface soil freeze. We found that changes in the timing and duration of the near-surface soil freeze in areas with low rates of urban expansion were about one-third larger than those in areas with high rates of urban expansion, indicating that the heat island effect in small cities was greater than that in larger cities.

~~Changes in the timing and duration of the near-surface soil freeze are also closely correlated with the AO and the NAO. The changes in the timing and duration of the near-surface soil freeze were inversely correlated with changes in AO and NAO indexes, indicating that cold winters in high Arctic regions may respond to relatively warmer winters across China.~~

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Figure Captions

Fig. 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. Boundary line of Qinghai-Tibetan Plateau is from Zhang, Y., et al. (2014).

Fig.2. Climatology of the first date (A), the last date (B), the duration (C) and the number of days (D) of the near-surface soil freeze/thaw status across China. The 30-year reference period was from July 1961 through June 1991.

Fig. 3. (A) Composite of anomalies for the first date (FD) from 1956 through 2006 across China. The composite of anomalies for FD was simply an average of anomaly across all available stations for each year. The solid circles represent the composite anomaly for a year. The shaded area represents one standard deviation from the mean for each year. The thick line represents a smoothed curve by a cut-off frequency of 0.091. The thick straight lines are linear regression trends. Asterisk indicates a statistically significant trend with a 95% or higher confidential level. (B) Rate of linear trends in FD from 1956 through 2006 for stations with 95% or higher confidential level across China; center-top panel is the histogram the rate of changes in FD.

Fig. 4. Same as Fig.3 except for the last date of the near-surface soil freeze.

Fig. 5. Same as Fig.3 except for the duration of the near-surface soil freeze.

Fig. 6. Same as Fig.3 except for the number of days of the near-surface soil freeze.

Fig. 7. Trends of the first date (FD), the last date (LD), duration (DR), and number of freeze days (NF) at stations in western China (in first row, longitude $\leqslant 110^{o}$ E) and in eastern China (in second and third rows, longitude $>110^{o}$ E) against latitude (^{o} N) and elevation (x10^{3} m a.s.l). Each point represents one station, with a statistically confidential level of 95% or higher. Solid cycles are data points, and lines are linear fitted lines. Asterisk indicates a significant trend at the 95% confidential level or higher.

Fig. 8. Relationship between (A) anomalies of mean autumn air temperature (September through November) and the firs date (FD), (B) anomalies of mean spring air temperature (March through May) and the last date (LD), (C) anomalies of mean annual air temperature (July through June) and duration (DR), and (D) number of days (NF) from 1956 through 2006 across China. All regression lines have a statistically significant trend with at least a 95% confidential level.

Fig. 9. Relationship between anomalies of the freeze index of air temperature (AFI) and (A) duration (DR), and (B) number of days (NF) from 1956 through 2006 across China. All regression lines have a statistically significant trend with at least a 95% confidential level.

Fig. 10. Rates of urban expansion from 1990s through 2010s in China (modified from Wang et al., 2012).

Fig. 11. Regional changes of number of days (NF) in regions with different urbanization rates (lefts, i.e., A, C, and E). Black lines and red lines depict the linear regression for the period after 1990 and the period since 1956, respectively. Asterisk indicates a statistically significant trend at a 95% confidential level or higher. Rights (B, D, and F) are number of stations used to create each time-series.