Cover Letter

Dear Dr. Stephan Gruber,

Thank you for the decision letter. We would like to thank both the reviewers and you for a thorough study of the manuscript:

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

Authors: T. ZHANG et al.

MS No.: tc-2014-90

We have re-organized the manuscript by rewriting thoroughly the Abstract, Introduction, Methods, Results, Discussion and Summary sections, as well as some figures, based on the comments made by the reviewers. Meanwhile, we have also corrected the language. Accordingly, we have uploaded a copy of the original manuscript marked with all the changes made during the full revision process.

Appended to this letter is our point-by-point reply to all the comments raised by the reviewers. We agreed with all the comments and would like to thank the reviewers for their suggestions and critics.

Please do not hesitate if you have any questions or concerns about the revised manuscript.

Sincerely,
Tingjun Zhang

Responses to all the comments:

We appreciate the reviewers and editor for these insightful comments. We have thoroughly revised the manuscript according to reviewers' suggestions. Some of the major changes made to address reviewers' suggestions are explained as following:

Major Comments:

(1) Quality control: The argumentation in lines 202-206 is not clear with respect to how this test was performed. If up to 65 days are missing, how are the start/end dates computed to within 2 days? Depending on the timing of the gap that cannot be done. If the averaged result over all stations only changes by 2 days, than the spatial coverage may still be polluted by heavily flawed values. This argument needs to make sure that for each station included, the values derived do not change by more than a certain threshold.

Answer: We have updated all results throughout the manuscript according to the reviewer's suggestion, in other words, a year with 365 daily records can be utilized in the annual indices. Spatial characteristics show not significantly alteration that it does not influence previous results. But the magnitudes, such as number of stations with significant, estimated long-term linear trends, altered slightly. In fact, majority of stations with more than 300 daily records always have very limited missing value. The section have revised as following:

"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). 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 rejected the outliers of years with values at or higher than three standard deviations (3σ) from the long-term mean for a station. This resulted in 636 meteorological stations being included in this study (Fig. 1)."

(2) Urbanization: Similar to the quality control with respect to missing days, the effect of urbanization should be controlled for at the level of individual stations. Aggregation to areas such as the one shown in the new Figure 8 does not necessarily inform what happens at the stations. Given the size of the aggregation domain, there could be unchanged rural stations, even in the polygons labeled "high". On line 405 and following, "This is because…" you invoke a causality that I do not see justified from the evidence presented.

Answer: Detailed investigation of this issue is far beyond this study. We intended only to conduct some preliminary analysis using some limited but available data. But we are planning to obtain long-term satellite-based urban boundaries to explore deeply this question while it is unspecified period we can finish. The changes under a changing climate are significantly differing between sites. It is so hard to explain all the changes at individual stations level. The major reasons are (i) the spheres of urbanization influences may be irregular and difficult to determine; (ii) intensity within the sphere of influence is also uncertain and non-uniform; (iii) even if the affected area can be determined, but there are also other stations within the affected area, including rural stations.

We reorganized the discussion:

"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 EarthTM. 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 to -0.19 day/yr; while for the high-rate regions, the trend was about -0.26 days/yr, approximately 37% to 44% 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 haste 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 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."

(3) As Reviewer 2 pointed out, actual values are needed in order to provide context for interpreting anomalies. The relevance of a 5-day change is different for a freezing duration of 2 weeks as compared with one of 4 months. Include maps of the actual values and a plot showing the trends as a function of e.g. freezing duration. The paper in review you mention in your response has not been mentioned in your reference list or in the cover letter – it would be very unfortunate to have the values and their changes surgically separated into differing publication.

Answer: We added a new section (section 3.1 in revised manuscript) to depict the climatology of the timing and duration of the near-surface soil freeze/thaw status. We thrashed out the following text:

"We used the Kriging method to interpolate our climate data points to create 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."

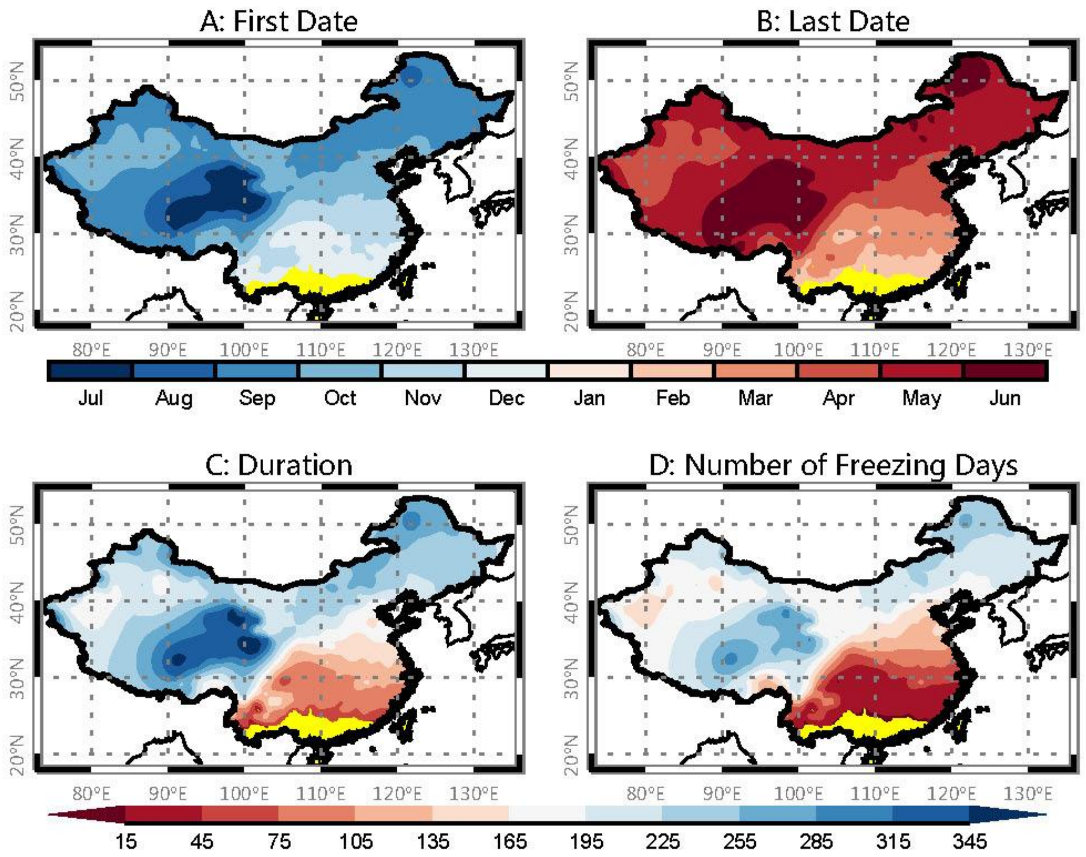

Fig.2. Climatology of the first date (A), the last date (B), the duration (C) and the number of days (D) of the near-surface soil freeze/thaw status across China. The 30-year reference period was from July 1961 through June 1991.

(4) A better conceptual framework (and sketch?) is required for discussing what GST is and what drives it. If you relate GST changes to climate, urbanization, etc and you state that changes in snow cover are negligible, it would be useful to first describe the system under investigation and what drivers control it.

Answer: We reorganized the Discussions as following: in 4.1, we compared our main results with other previous works to discuss some regional diversity; in 4.2, we discussed the potential influences of urbanization on the near-surface soil freeze status; in last section, 4.3, we discussed the relationships with snow cover, NAO and AO.

However, influence of snow cover on the near-surface soil freeze-thaw status is very limited. It can be explained by two ways: First, the minimum requirement for the existence of snow on ground is that the ground surface temperature at or below the freezing point (Zhang et al. 2003); Second, winter precipitation (snowfall) accounts for a very small fraction of the annual precipitation in China.

The results further demonstrate that higher NAO/AO indexes correspond to warmer winters over China. We further conducted correlation analysis between the monthly NAO/AO and the annual freezing index of air temperature and between the monthly NAO/AO and the mean annual air temperature (July-June). These results are also consistent with changes in shorter DR, less NF, and late FD from this study.

Reference added:

Zhang, T., Armstrong, R. L. and Smith, J.: Investigation of the near-surface soil freeze-thaw cycle in the contiguous United States: Algorithm development and validation, J. Geophys. Res., 108(D22), 8860, doi:10.1029/2003JD003530, 2003.

Finally, after rewriting entirely the Discussion, the recent contents are as following:

"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 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 0.71 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 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 in China since the early 1990s (0.56 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 to -0.19 day/yr; while for the high-rate regions, the trend was about -0.26 days/yr, approximately 37% to 44% 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 haste 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 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.”

Other comments:

Throughout: (a) replace “altitude” with “elevation”; (b) consider “unfrozen” instead of

"freeze-free" (e.g., L83); (c) consider replacing "soil freeze" with "soil freezing" (e.g., L85); (d) better indicate the unit for Figures 2 etc. are the numbers days, or anomalies w.r.t. a certain time period; (e) the English needs substantial editing; (f) insignificant means that something is negligible, non-significant however means that something does not show a statistical relation with a p-value you accept as satisfactory. This is a big difference, please correct in your text.

Answer:

a) We have replaced all throughout the revised paper.

b) We have replaced all throughout the revised paper.

c) We deem that this paper emphasized the states or events of soil freeze, thus the term "freeze" may be more suitable.

d) We revised y-titles of Figures 3-6.

e) It has been substantial edited throughout the article.

f) We have corrected.

Measurement method: If the thermometer is buried half and exposed half (L153) how can it be read-out daily in regions with a snow cover without causing a significant disturbance? It is not sufficient to believe that (L163-L166) that station relocation was not significant. Please indicate the number of stations without relocation (also on the map) and test if the subset without relocation produced a different result.

Answer:

- We have added the following sentences to explain these questions. "When the ground is covered by snow, the sensor is moved on the snow surface, thus snow surface temperature is measured rather than the ground surface temperature. In this case, it is assumed that soils near the ground surface are in frozen state (Zhang, 2005)."
- The large majority of the stations have no location change over period of the records (Ma et al., 2009). However, information is not available for those stations with location change history.

Not only that, but this section also have been rewritten and reorganized in order to describe the measurement method as following:

"Temperature monitoring 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 states 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."

References added:

Ma, L., T. Zhang, O. W. Frauenfeld, B. Ye, D. Yang, and D. Qin: Evaluation of precipitation from the ERA-40, NCEP-1, and NCEP-2 Reanalyses and CMAP-1, CMAP-2, and GPCP-2 with ground-based measurements in China, J. Geophys. Res., 114, D09105, doi:10.1029/2008JD011178, 2009.

Zhang, T.: Influence of the seasonal snow cover on the ground thermal regime: An overview, Rev. Geophys., 43, RG4002, doi:10.1029/2004RG000157, 2005.

L215 and Reviewer 2 Q10: It still seems to me that what you describe is called the "coefficient of determination". Your answer to the Reviewer does not actually explain that. Please explain in the methods section, how you use this and what insight is derived from it.

Answer: The term, "coefficient of determination", is a number to indicate how well observations were fitted by a statistical model, donated R^2.

L34: "coupled" is a very vague term. Do you mean "related to" or "caused by"? Be more specific.

Answer: Correct. Change made.

L148: Only acknowledge the SRTM in the figure legend, this is not a method influencing your results.

Answer: We have removed it to acknowledge.

Figure 6: Rescale the horizontal axis of the bottom right part from 0-2km.

Answer: We have revised, meanwhile, noted that different x-axes scales in the figure caption.

Figure 8 and 9: Do you mean "median" or "medium"?

Answer: Correct. Change made.

The first bullet of the summary seems contradictory (5 days or 10 days?) and may miss a word after "soil" on L441.

Answer: We showed two data to denote different rate of changes in different periods, i.e., a number of five days was for the entire period while another number (ten days) was for the period since 1990s only.

Finally, some major changes made are listed as following:

- We have completely re-organized the manuscript including the methods, results and discussion sections meanwhile included some references and new figures in the manuscript.
- We revised the figures according to reviewer’s comments.
- We have revised the style and the language, according to reviewer’s comments.

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~~, with a 0 ℃ threshold~~, we investigated the changes~~ the long-term spatiotemporal variations of~~ in the first date~~, of the near-surface soil freeze,~~ the last date~~ of the freeze~~, the duration~~ of the freeze~~, and the number of ~~freezing ~~days of the near-surface soil freeze ~~ across China ~~over the period 1956—~~-~~2006~~ (with a baseline period of July 1971 through June 2001)~~. The results reveal that the~~ responses of the near-surface soil freeze to warming climate. The~~ first date of the near-surface soil freeze was delayed by about 5 days, or at a rate of ~~(~~0.~~10~~09 ±0.03 day/yr, and~~) and~~ the last date was advanced by about 7 days, ~~(~~or at a rate of 0.14~~5~~ ±0.02 day/yr~~) over this period~~. The duration of the near-surface soil freeze decreased by about 1~~3~~2 days or at a rate of -0.24 ±0.04 day/yr~~ from 1956 through 2006~~, while~~and~~ the actual number of the near-surface soil freeze days was decreased~~fell~~ by ~~~~~about 10 days or at a rate of -0.19±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 Altantic Oscillation (NAO) and the Arctic Oscillation (AO) indexes are closely related to changes in the near-surface soil freeze/thaw status.~~ All of these climate~~

~~indicators have varied sharply since the early 1990s. Climate indicators in west China generally vary more than those measured in east China. Altitude plays an important role in soil freeze/thaw dynamics in west China, and latitude is critical in the eastern portion of the country. Air temperature significantly affects near-surface soil freeze, especially the duration of freeze and number of freeze days.~~

1. Introduction

The near-surface soil freeze/thaw state is ~~coupled~~related to the timing and duration of cold/warm seasons, and is an important indicator of climate change (Zhang et al., 2001). ~~The latest assessment report from the International Panel on Climate Change (IPCC) indicated that the globally averaged combined land and ocean surface temperature rose 0.89 ℃ over the period 1901–2012 (IPCC, 2013).~~ During the past few decades, many studies have focused on the dynamics of the near-surface soil freeze/thaw status and the interactions~~the feedback~~ between the ground surface and the atmosphere. Th~~ey~~ese 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). ~~A possible significant consequence of global warming may be permafrost degradation (Koven et al., 2011; DeConto et al., 2012; Schuur et al., 2009).~~

~~Near-surface soil freeze/thaw is an essential factor in hydrological processes, especially in cold climates, because it influences energy balances and water movement (Zhang and Armstrong, 2001; Williams and Smith, 1989). Generally, the frost layer in near-surface soil can reduce hydraulic conductivity, which then affects runoff. This can result in increased flooding in winter and spring, as seen in the upper Mississippi River basin of the United States during the late 20th century (Knox, 2001). A study in a typical permafrost watershed on the Qinghai-Tibet Plateau indicated that~~

~~thawing of the active layer in the upper 60 cm of soil contributed to an increase in runoff (Wang et al., 2009). Soil water freezing delays the near-surface soil freezing in winter (Poutou et al., 2004). This is important for modeling the climate in cold regions and for climate forecasting. Mintz and Serafini (1992) used a simple water budget model to estimate global evapotranspiration and soil moisture distribution, but their modeled results do not agree with other studies in high-latitude regions. However, the introduction of soil freeze to climate models reduces bias in winter (Viterbo et al., 1999).~~

~~Soil freeze is an important factor in soil microbial activity and carbon cycles. microbial activity in Arctic tundra soils showed a step-function decrease with decreasing temperature from +2 ℃ to +0.5 ℃(Schimel and Mikan, 2005). Soil freeze may disturb soil nitrogen, phosphate, and carbon chemistries, thereby accelerating nitrogen and phosphate loss (DeLuca et al., 1992; Fitzhugh et al., 2001). Thus soil freeze/thaw plays an important role in soil carbon cycles, especially in permafrost regions (DeConto et al., 2012; Koven et al., 2011; Schuur et al., 2008; Walker, 2007; Gilichinsky and Wagener, 1995; Knorr et al., 2005). Knorr et al. (2005) found that non-labile soil organic carbon (SOC) is more sensitive to changes in temperature than labile SOC, and they inferred long-term positive feedback effects of soil carbon decomposition may be stronger than projected by models. McDonald et al. (2004) suggested that the timing of the seasonal thaw can be a useful indicator for predicting the seasonal amplitude of atmospheric CO_2 in the next year.~~

Variations in the timing and duration of the near-surface soil freeze/thaw

~~stat~~state~~us~~ 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.

~~Data from meteorological stations are important for examining the long-term dynamics of soil freeze and its response to climate change.~~ Menzel et al. (2003) used data from 41 meteorological stations across Germany (from 1951 through 2000) to investigate soil frost dynamics.~~, and they~~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~~ across Canada,~~ and ~~he~~ found that ~~annual~~number of days of the near-surface soil ~~freezing day~~freeze~~s~~ declined from 1966 through 2004. Using ~~Long~~long-term data from three stations in Indiana, USA, Sinha et al. (2008) found~~ were utilizedto analyze soil frost dynamics (Sinha and Cherkauer, 2008). The results showed~~ 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~~to a~~ the~~ 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.

~~Remote sensing data, such as Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave Imager (SSM/I) data, have also been used to investigate large-scale dynamics of near-surface soil freeze/thaw status (Zhang et al.,~~

~~2004; McDonald and Kimball, 2005). Smith et al. (2004) used Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave Imager (SSM/I) data in order to identify trends in near-surface soil freeze/thaw cycles from 1988 to 2002. The results indicate an earlier thaw date of soil freeze in Eurasia and a later freeze date in North America. McDonald et al. (2004) also found that the pan-Arctic region in Alaska experienced an earlier thaw onset date between 1988 and 2001. Li et al. (2012) used SSM/I data and found an earlier thaw date on the Qinghai-Tibetan Plateau, and a decrease in the number of frost days by ~16 days, from 1988 to 2007. At global scale, Kim et al. (2011) used passive microwave remote sensing (SMM/I) data to establish a 20-year daily landscape freeze/thaw database. Based on the classification method of Kim et al. (2011), Kim et al. (2012) constructed a 30-year (1979–2008) daily landscape freeze/thaw database through merging the SMMR and SMM/I records. Kim et al. (2011) provided continuous and long-term records for daily freeze/thaw dynamics at global or hemispherical scales.~~

~~Generally, remote sensing can provide records with good spatial continuity. However, these data sources need more validation on large spatial scales and require longer-term observation periods, because no single sensor can obtain the true soil freeze/thaw status (Zhang et al., 2004).~~ 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).

~~Many studies on near-surface soil freeze/thaw dynamics are based on in-situ observations; however, there is still no agreement on the basic definition of soil freeze status. Generally, there are two methods to detect soil freeze/thaw. One uses daily minimum soil temperature, but thresholds to obtain the freeze/thaw status range from −2.2 ℃ to 0 ℃ (Baker and Ruschy, 1995). The other method defines the freeze/thaw status based on surface soil remaining frozen or thawed for several continuous days, (e.g., atleast 3 continuous days (Li et al., 2012)). It should be pointed out that soil in southern latitudes may be closer to the freezing point, and the freeze/thaw dynamics at these sites may be more vulnerable to changing climate (Henry, 2008). Thus, the freeze/thaw state might be misidentified in warm regions when using the lower threshold (e.g., −2.2 ℃) to determine the freeze state.~~

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~~ of near-surface soil freeze~~, last date, duration, and actual number of days of the near-surface soil freeze~~ across China~~, as well as the~~and also the~~ spatial characteristics of these variables across China.~~across stations, based on a 0 ℃ threshold.~~ Finally, ~~W~~we ~~then~~further investigate the response of the near-surface soil freeze/thaw status to climate changes over the past few decades~~ investigate the relationship between these parameters and air temperature~~.

2. Data and Methods

We define the soil “freeze day”~~ following Henry (2008)~~, as a day with a minimum temperature at or below 0~~–~~℃ at ground surface (Henry, 2008~~0 cm~~). Data used for this study include daily minimum ground-surface temperature~~s~~, and mean annual air temperature (MAAT) ~~data were~~ obtained from the China Meteorological Administration~~–~~ (CMA, 2007).~~ The digital elevation model is mosaicked from original Shuttle Radar Topography Mission (SRTM) 90 m datasets (Jarvis et al., 2008).~~

Temperature monitoring 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 states 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, 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~~statistics~~ of the first ~~date~~ 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. ~~We use the 30-yr "normal" period of the World Meteorological Organization, starting 1 July 1971 and ending 30 June 2001, for the baseline of climatology (IPCC-TGICA, 2007) and to calculate~~The anomalies of ~~these~~each variable~~s~~ were calculated over ~~our~~the entire study period after removing the long-term average (1 July 1961 through 30 June 1991) across China. We used ~~A~~ linear regression ~~method is used~~ to ~~calculate~~investigate the trend~~s~~ of changes for each variable. Stations with statistically significant changes ($P < 0.05$) were kept in the analysis. ~~indicator and to test their statistical significance.~~ 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~~We also calculated the linear regression of trends of latitude, altitude, and mean annual air temperature to investigate geographical relationships~~. 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 ~~(FD) is~~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 last date of soil freeze (LD) is defined as the last date after 1 July on which the daily ground surface temperature is at or below 0 ℃.~~ The ~~near-surface soil freeze~~ duration (DR) of the near-surface soil freeze is defined as the time span between the first ~~date of freeze~~ and last date of the near-surface soil freeze. It is common for~~Because of extreme weather events,~~ the near-surface soil ~~may~~ not be continuously frozen ~~continuously~~during the period between ~~from~~ the first date ~~to~~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 ~~our~~this study have continuous data over a~~ data for the~~ ~~30 ~~30-yr ~~study ~~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 ~~time ~~mean (Jones and Hulme, 1996). In this study, we applied a thorough data~~ some~~ quality control approach~~es~~ to ensure the reliability and consistency of results by station and year. ~~First~~Firstly, ~~a~~study ~~year~~years with ~~at least ~~3~~00~~65 daily records~~ (more than 75% of a year)~~ ~~could be~~were utilized in the annual indices. Secondly, ~~W~~we rejected the outliers of years with values at or higher than three standard deviations (3 σ) from the long-term mean for a station.~~, based on statistical 3σ error, by station. Finally, we selected those stations with >21 points of annual statistical data. ~~ This resulted in ~~Locations of the ~~636 meteorological stations being included in this study ~~ are shown in ~~(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 data points to create 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.

~~3.~~ 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.

~~3.1~~3.2 Changes in the First ~~Da~~Date~~y~~ of the Near-Surface Soil Freeze

~~3.2~~ Overall, ~~–~~FD departures from its long-term mean showed ~~increased~~a ~~significantly~~significant increase across China by nearly 5 days, or a trend of 0.~~10~~09 ± 0.03 day/yr, for the period 1956–2006 (Fig. ~~2a~~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 ~~of multiple~~ determination, R^2=0.~~23~~21, means that ~~somewhat less than~~ one-~~fourth~~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 ~~decreased, but insignificantly, before the 1970s (-0.20 day/yr, p = 0.14) and changes~~ during 1965–

1975 are the lowest in the~~our~~ study period. A~~ major~~ ~~increase~~delay in FD (0.21 day/yr) started in ~~in FD appeared after~~ the early 1970s when a short cold period ended ~~(0.21 day/yr)~~. ~~However~~Meanwhile, ~~the greatest~~a large ~~increase~~delay in FD (0.~~72~~71 ± 0.17 day/yr) occurred after the early 1990s (Fig. ~~2~~3a); FD has occurred ~~∼~~approximately 10 days later since the early 1990s with~~.~~ $R^2 = 0.$~~59~~ 61, ~~means~~implying that about 60% ~~that somewhat more than one-half~~ of the total variability in the FD can be explained by the linear trend~~regression equation~~. ~~For the period before the early 1990s, FD had no significant change (0.03 day/yr, p = 0.45).~~

~~3.3 For our~~Over the study period, the~~ stations~~ ~~140~~ 130 study stations showed a significant trend in FD delay in autumn (Fig. ~~2b~~3b). Most stations showed long-term FD ~~delay~~delays,~~s of FD,~~ except for ~~at~~ ~~four~~few stations where FD was advanced. ~~At~~Among about ~~∼100~~ 90 of the ~~140~~ 130 stations, the FD ~~delay~~delay ~~in FD is~~was <0.25 day/yr (~~histogram in~~ Fig. ~~2b~~3b). When comparing stations in ~~west~~western China and ~~east~~eastern China (east and west of 110~~°~~° E), we found that the FD ~~greater delays~~delay ~~in FD~~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~~s~~/yr (Fig. ~~2b~~3b), primarily due to the higher average ~~altitude~~elevation, more complex terrain, stronger monsoon circulation, and more solar radiation ~~in those regions.~~on the Qinghai-Tibetan Plateau (Sun, 1996).

~~3.4~~3.3 Changes in the Last ~~day~~Date of the Near-Surface Soil Freeze

~~In China,~~The LD ~~declined~~was advanced in spring significantly over the period of 1956–2006, by ~~>~~about 7 days, or a trend of -0.~~15~~ 14 ± ~~–~~0.02 day/yr (Fig. ~~3a~~4a). This indicates that warming spring seasons result in an earlier ~~end~~end of ~~to~~ the near-surface soil freeze. Approximately~~Somewhat~~ ~~less than 50~~44% of the total variability in the LD can be explained by the linear trend~~our regression~~. Variations in LD are ~~distributed~~divided into ~~over~~ two periods: before and after the early 1990s. ~~Prior to the early 1990s,~~ LD occurred slightly earlier from 1956 through 1991. The highest deviated from the long-term mean ~~Anomalies~~occurred during 1965–1980 ~~are the highest over our study period~~. ~~The~~A rapid ~~advancement~~advancement of LD appeared after the early 1990s, with a linear trend of –0.5~~8~~6 ~~–~~± ~~–~~0.14 day/yr; i.e., LD has occurred earlier ~~(~~by ~~~~~ about 9 days~~)~~ since ~~the early 1990s~~1992.~~–~~

LD changed significantly at ~~36~~30% (~~229~~ 190 stations) of ~~the~~all ~~study~~ stations (Fig. ~~3b~~4b). This percentage is ~~greater~~larger than that of the stations with a significant~~ly~~ delay in~~ed~~ FD. ~~Most stations show a long-term advancement in LD. At ~140~~ Among 162 stations, LD was advanced by ~~~~~about –0.30 day/yr (~~see the histogram in~~ Fig. ~~3b~~4b). ~~We found that~~LD changes in ~~west~~western China were ~~generally~~ larger than those in ~~east~~eastern China. Overall, ~~we found that~~ FD and LD ~~was~~were ~~dramatically~~significantly delayed and advanced, respectively, at 85 stations. These stations show a delayed onset of ~~fall~~autumn soil freeze ~~frost~~ and an earlier ending of the ~~last~~ spring ~~frost~~ soil freeze over ~~our~~the study period.

~~3.5~~3.4 Changes in the Duration of the Near-Surface Soil Freeze

Over the period from 1956 through 2006, DR was shortened by almost ~~13~~ 12 days, or –0.~~25~~ 24 ± –0.04 day/yr (Fig. ~~4a~~5a). ~~DR increased, but statistically insignificantly, from 1956 through 1970 (–0.27 day/yr, P = 0.18).~~ Anomalies during 1966–1980 were higher than the rest of ~~over~~ the ~~entire~~ study period~~,~~. The most significant decrease in DR appeared mainly after the 1970s (–0.43 day/yr). Since the early 1990s, DR has decreased sharply (–1.~~13~~ 12±0.~~21~~ 20 day/yr) (Fig. ~~4a~~5a), by almost 16 days. The overall variation in DR (–0.~~25~~ 24 day/yr) is ~~similar~~a combination of changes ~~to the variation~~ in FD (0.~~10~~ 09 day/yr) and LD (–0.~~15~~ 14 day/yr). For example, the increase in DR (~~13~~ 12 days) corresponds to the ~~change~~delay of~~in~~ FD by ~~(~~5 days~~)~~ and~~plus~~ the ~~change~~advance ~~in~~of LD ~~(~~by 7 days~~)~~. ~~An earlier last freeze in spring might contribute to more than half of the shortening of the DR.~~

~~255~~ 227 study stations showed a significant decrease~~linear trend~~ in DR of <–0.50 day/yr (Fig. ~~4b~~5b). Most stations showed a long-term decrease in DR, except for three stations where DR showed a slight increase. ~~We found that~~ DR decreased more in ~~west~~western China than in ~~east~~eastern China. This general decrease in DR indicates a shortening frost period in the near-surface soil across China over our study period.

~~3.6~~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 ~~continuously~~ 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.~~20~~ 19 ± –0.03 day/yr) for the period

1956–2006 (Fig. ~~5a~~6a). The trend in NF is similar to but smaller than that in DR (compare to Fig. 4a). A statistically ~~in~~significant increase in NF has occurred since ~~from 1956 to 1970 (0.30 day/yr, P = 0.10), but NF decreased after~~ the early 1970s. During the period from 1971 through the early 1990s, NF decreased slightly (–0.27 day/yr~~, P = 0.02~~). The NF decrease for the period from 1971 through the end of our study period is –0.34 day/yr, with a decrease of –0.~~87~~ 84 day/yr since early 1990s (Fig. ~~5a~~6a). The actual number of freeze days in near-surface soil decreased by ~~>~~12 or more days over our study period.

At ~~381~~ 368 stations (about ~~∼~~60% of ~~the~~all study stations), NF varied significantly over ~~during~~ the~~our~~ study period (Fig. ~~5b~~6b). Although a few stations in western China showed an ~~increas~~increasing trend~~ed variability~~ in NF, the remaining ~~almost all~~ stations showed a significant decreasing trend~~e~~, ~~ranging~~with decreasing trends ranging from –0.50 to –0.20 day/yr (~~histogram in~~ Fig. ~~5b~~6b). This general decrease in NF indicates a shortening cold season ~~in near-surface soil~~ across China.

~~There are two regions in China with large-scale variability: Qinghai-Tibet Plateau in the west, and the lower reaches of the Yangtze River in east China. Previous studies have indicated that more warming has more pronounced effects in high-altitude regions, such as the Qinghai-Tibet Plateau (Cheng and Wu, 2007; Li et al., 2012; Wu and Zhang, 2008). However, it should be noted that the warming observede in the lower reaches of the Yangtze River is probably a result of urbanization.~~

~~3.7~~3.6 Variations in the Near-Surface Soil Freeze with Latitude and

~~Altitude~~Elevation

Changes in the near-surface soil freeze are primarily controlled by elevation in western China and by latitude in eastern China. ~~In order to explore the spatial features of near-surface soil freeze, we classified the Chinese meteorological stations as either eastern or western.~~ In ~~west~~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.~~altitude is statistically correlated to FD and NF (slope of 0.10; Fig. 6a), so that the first date of soil freeze~~ 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).~~is later in higher-altitude regions. Similarly, trends in NF relate significantly to altitude. Higher-altitude regions have lower NF values.~~

~~In~~Over ~~east~~eastern China, the rates of change in ~~latitude correlates with~~ 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.~~, but altitude correlates to NF (Fig. 6b).~~ ~~Low~~Lower-latitude ~~stations~~regions are more sensitive to freeze/thaw timing and duration because soils at more southerly latitudes ~~remains~~are closer to the freezing point in cold seasons. Under warming ~~climat~~climate~~ic~~ conditions, changes in soil temperature in southern regions~~ of China~~ 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). ~~Thus, we believe that soil freeze/thaw dynamics at southerly sites may be more vulnerable and sensitive to changing climate, and therefore should be studied closely.~~

~~3.8~~3.7 Effects of Air Temperature on the Near-Surface Soil Freeze

Air temperature is an important factor that affects ~~in~~the near-surface soil freeze/thaw dynamics. ~~We calculated changes in air temperature at Chinese meteorological stations and correlated this with FD, LD, DR, and NF.~~The FD increased as mean autumn (September, October and November) air temperature increased at a rate of about 3.73±0.53 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 ±0.68 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 ± 1.24 day/℃, while the NF decreased at a rate of -6.40 ±1.06 day/℃; the rate of NF change is about 16% 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 25% by the freeze index (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.

~~The statistical relationships between air temperature and our four frost indicators were all significant (Fig. 7). FD, LD, DR, and NF varied with air temperature by 3.89 ±0.76, −3.93 ±0.82, −7.65 ±1.25, and −6.55 ±0.99, respectively, demonstrating thatthe timing and duration of near-surface soil freeze correlates with increasing air temperature. Correlations with FD and LD are smaller than those of DR and NF. In addition, we found that R^2 of soil freeze timing (FD and LD) is less than R^2 of soil freeze duration (DR and NF). This implies that air temperature is a more effectively indicator of freeze duration (i.e., DR and NF). The probable reason for this is that the timing statistics used in this study may be influenced by extreme weather events in some years. For example, an incidental cold event in the fall could delay or advance the first soil freezeby several days. Similar differences in R^2 exist between DR and NF.~~

4. Discussion

4.1 Comparisons with previous results

~~We calculated four indicators~~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 ~~across China~~. Primary~~Our~~ results indicate that the ~~first date~~FD occurred later, while the ~~and last date~~LD ~~of near-surface soil freeze occurred later and~~became earlier, ~~respectively, than normal, thereby~~ 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.~~10~~09 day/yr) over the entire study period, as a result of~~.~~ ~~This shows that~~ warming climate ~~resulted in a later first day of freeze in near-surface soil~~. 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, ~~the changes in soil freeze vary across different regions and different time periods, probably due to natural and climatic conditions as well as to different data sources and data collection methods. For example, our~~ results from this study indicate that ~~a later~~the rate of FD change from the early 1990s to 2006 across~~over~~ China ~~(trend is~~was about 0.7~~2~~1 day/yr~~)~~, ~~than~~while Li et al. (2012) ~~results from~~found that the rate of FD change was about 0.50 day/yr over the Qinghai-Tibetan Plateau ~~(10 days, \~0.50 day/yr)~~ from 1988 through~~to~~ 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. ~~(Generally, the Qinghai-Tibetan Plateau appears to be more susceptible to climate change.) The differences between our results and Li et al. (2012)'s results on the Qinghai-Tibetan Plateau may be due to different methods of determining the soil freeze state, as well as differences of remote sensing data and ground-based observations.~~

Similarly, LD occurred ~~\~~~approximately 7 days earlier (0.1~~5~~4 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 in China since the early 1990s (0.5~~8~~6 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 ~~th~~our~~e entire~~ study period.

Our results indicate that DR and NF decreased 1~~3~~2 and 10 days, respectively, from 1956 to 2006 and have decreased sharply since the early 1990s. ~~There~~We ~~is~~ 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. ~~5a~~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~~ the~~ 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 ~~a~~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 ~~feedback~~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$^{\text{TM}}$. 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 to -0.19 day/yr; while for the high-rate regions, the trend was about -0.26 days/yr, approximately 37% to 44% 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 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 Oscillation (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.

~~5. ~~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.

~~6.~~5.Summary

Changes in the timing and duration~~We investigated variations in four indicators~~ (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~~, across China~~. ~~We~~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~~ examined the spatial characteristics and statistical relationship between these indicators and~~ air temperature, the North Atlantic Oscillation and Arctic Oscillation indexes, and urban expansions across China during the past few decades. ~~Our results are summarized as follows:~~

- ~~The~~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)~~ over the entire study period~~. ~~The first date of near-surface soil has occurred ∼10 days later since the early 1990s.~~

- The last date of the near-surface soil freeze has occurred by about ~~\~~~7 days earlier (0.1~~5~~4 – ± –0.02 day/yr) over the same period~~ over our study period~~. As a result, ~~Near-surface soil freeze occurred earlier by of –0.58 ±0.14 day/yr since the early 1990s.~~

- ~~The~~the duration of the near-surface soil freeze decreased by about ~~13~~ 12 days~~ from 1956 through 2006. It has decreased by ∼15 days since the early 1990s~~, and~~.~~

- ~~The~~the number of the near-surface soil freeze days decreased by about ~~\~~~10 days (–0.~~20~~ 19 ± –0.03 day/yr) for the period 1956–2006.~~ The decrease in the number of freeze days has been –0.87 ±0.15 day/yr since the early 1990s. There are two regions in China with the most changes in NF: the Qinghai-Tibet Plateau and the lower reaches of the Yangtze Basin.~~

~~Air~~The changes in the timing and duration of the near-surface soil freeze were accompanied by changes in air temperature~~ significantly influences all four soil freeze indicators, and correlates best with indicators of duration, such as duration or number of days~~. The first freeze date was delayed by about 3.73 ± 0.53 day/℃ with increasing mean autumn (September through November) air temperature, and the last date of freeze advanced by about -2.68 ± 0.68 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 ± 1.24 day/℃, while the number of days of the near-surface soil freeze decreased at a rate of -6.40 ± 1.06 day/℃, which is about 16% 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.

~~Near~~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 ~~provides abundant information about climate variations. Indicators of soil freeze timing and duration can serve as indicators of climatic~~

~~change, particularly air temperature. However, the relationship between soil freeze status and other climatic factors (soil water, snow depth, etc.) should be explored over large spatial scales in the future. Then, soil freeze status might be used for climate projections and might be a constructive contribution to climate change science~~.

Acknowledgements. We wish to thank two anonymous reviewers for their insightful and constructive critiques and suggestions which helped to improve this paper. This study was funded by the National Key Scientific Research Program of China (grant No. 2013CBA01802) and the National Natural Science Foundation of China (grant No. 91325202). The SRTM DEM data used in Figure 1 was obtained from website: http://srtm.csi.cgiar.org/.

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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. ~~2~~3. (A) Composite of anomalies for the first date (~~variations of~~ 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 ~~red line with~~ solid circles ~~is~~represent the composite anomaly for a ~~data~~year ~~line~~. The shaded area represents one standard deviation from the mean for each year. The thick ~~Blue~~ line~~s are~~ represents a smoothed curve by ~~linear trends, and black line represents a low-pass filter with~~ a cut-off frequency of 0.091. The thick straight lines are linear regression trends. Asterisk~~Symbol *~~ indicates a statistically significant trend ~~at~~with a 95% or higher confidential level. (B) Rate of ~~Changes~~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. ~~3~~4. ~~(A) Composite variations of LD from 1956 through 2006 across China. The red line with solid circles is data line. Blue lines are linear trends, and black line represents a low-pass filter with a cut-off frequency of 0.09. Symbol * indicates a significant trend at 95% confidential level. (B) Changes in LD from 1956 through 2006 across China; center-top is histogram of changes in LD.~~Same as Fig.3 except for the last date of the near-surface soil freeze.

Fig. ~~4~~5. ~~(A) Composite variations of DR from 1956 through 2006 across China. The red line with solid circles is data line. Blue lines are linear trends, and black line represents a low-pass filter with a cut-off frequency of 0.09. Symbol * indicates a significant trend at 95% confidential level. (B) Changes in DR from 1956 through 2006 across China (its legend is different to Fig. 2, 3 and 5 in order to show widely variability) ; center-top is histogram of changes in DR.~~ Same as Fig.3 except for the duration of the near-surface soil freeze.

Fig. ~~5~~6. ~~(A) Composite variations of NF from 1956 through 2006 across China. The red line with solid circles is data line. Blue lines are linear trends, and black line represents a low-pass filter with a cut-off frequency of 0.09. (B) Changes in NF from 1956 through 2006 across China; center-top is histogram of changes in NF.~~Same as Fig.3 except for the number of days of the near-surface soil freeze.

Fig. ~~6~~7. Trends of the first date (FD), the last date (LD), duration (DR), and number of freeze days (NF) at ~~(A) west~~ stations in western China (in first row, longitude ⩽110° ~~°~~E) and ~~(B) east stations~~in eastern China (in second and third rows, longitude >110° ~~°~~E) against latitude (° ~~°~~N) and ~~altitude~~elevation (x10^3 ~~k~~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. ~~Symbol *~~Asterisk indicates a significant trend at the 95% confidential level or higher.

Fig. ~~7~~8. Relationship between ~~of~~ (A) anomalies of mean autumn air temperature (September through November) and ~~(a) FD~~the firs date (FD), (B~~b~~) anomalies of mean spring air temperature (March through May) and the last date (LD), (C~~c~~) anomalies of mean annual air temperature (July through June) and duration (DR), and (D~~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.

~~**The solid circles are individual data points, and the lines are linear regression. Symbol * indicates a significant trend at 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.