Reply on comments from Anonymous Referee #1

This paper provides an interesting overview of station-based soil freeze/thaw processes in China over recent 51 years. As such, it provides useful information, especially because this information is difficulty to obtain observationally. Overall it is a good paper, and below I provide some suggestions which may improve and strengthen the paper.

Response: We appreciate the referee's insightful and constructive comments on the manuscript. All comments are very helpful for improving the manuscript. We have studied all comments thoroughly and made necessary changes and corrections.

It isn't stated anywhere what type of data actually form the basis for this entire analysis. The paper only says "station data" of "near-surface freeze/thaw," and also refers to "ground-surface temperature" (GST). The "CMA, 2007" data citation is not in the reference list. If they are GST, measured in the uppermost layer (centimeters) of the ground, what types of sensors did they come from? What is the quality of these data? Were there sensor changes over 1956-2006? Were the data homogenized to remove certain (potential) artifacts such as station moves, location biases, etc.? Please comment on these issues.

Response: We added two paragraphs in text to clarify these issues (insert into ***section 2, p3790, line 16***):

"Ground surface temperatures were measured by using a thermometer. The thermometer sensor has mercury ball on one end with diameter of 5 mm. It is required by the measurement standard that half of the thermometer sensor be buried in ground and the other half expose to the air. In practice, the sensor is usually buried more than half in the ground and it is colored in white to reduce solar heating. Daily minimum (maximum) temperatures were measured using a special minimum (maximum) temperature thermometer. The minimum (maximum) temperature thermometer records the daily minimum (maximum) temperature once a day although it cannot record the time when it occurs. Ground surface temperatures were also measured four times a day (02:00, 08:00, 14:00, and 20:00 Beijing Standard Time) and averaged as a daily mean. Daily minimum (maximum) temperature was reported at 20:00 Beijing Standard Time. The thermometer has an accuracy of ±0.1 ℃ and by requirements, these thermometers should be calibrated once a year. The thermometer sensors were used for the entire study period. The large majority of the stations have no location change over period of the records. However, information is not available for those stations with location change history. We believe that effect of station movement on overall outcome is very minimum. All of these measurements were conducted routinely each day by trained professional technicians at all meteorological station across China.

The daily surface temperature dataset was performed basic quality control that identified and excluded questionable data points. In details, we checked with the following two procedures. First, at daily time scale, we checked the consistency of temperature time series by cross-referencing temperature values with the day before and after the checking day. At annual time scale, we plotted and screened each individual time series to identify questionable data points and delete the statistical outliers of points out of the three standard deviations range from the long-term mean."

The Data and Methods section describes SRTM data, but it then isn't mentioned what this is used for. I'm sure the metadata for the station observations include elevation–so I am unclear where SRTM elevations are employed.

Response: We used only SRTM data to show the topographic features across China in Figure 1 (**p3803**).

This section 2 also mentions calculation of regression "trends" for latitude and altitude. Given that latitude and altitude probably don't change over time, how are you calculating trends for these variables?

Response: What we mean is that the relationships between the trends of the mentioned variables with latitude and altitude. We have made the changes as follows (**p3790, line 24-26**):

"We also compared the linear trends of the mentioned variables with latitude and altitude in stations to investigate the geographic characteristics of the changes."

Any mentions in the paper of "insignificant" trends and changes should be removed; a non-significant trend means there is no trend at all (it cannot be distinguished from "0"); this also includes most of the panels in figure 6. Similarly, it is also not necessary to state the p-values for all of the findings. Usually a significance threshold (like 95%) is chosen a priori, and then the results are reported as either significant, or not. But the magnitude of the p-value itself is not useful.

Response: We have deleted all figures with insignificant trends, and state only the significant level instead of p-values. Also, we have deleted all text mentioned "insignificant" in revised manuscript.

P3791, 25-27: "FD decreased, but insignificantly, before the 1970s (−0.20 day yr^{-1}, p = 0.14) and changes during 1965–1975 are the lowest in our study period." -> "Anomalies of FD during 1965–1975 are the lowest in our study period."

P3792, 5-6: deleted "For the period before the early 1990s, FD had no significant change (0.03 day/yr, p = 0.45)."

P3793, 5-6: deleted “DR increased, but statistically insignificantly, from 1956 through 1970 (−0.27 day yr−1, P = 0.18).”

P3793, line 26- P3794, line 1: “A statistically insignificant increase in NF occurred from 1956 to 1970 (0.30 day yr–1, P = 0.10), but NF decreased after the early 1970s.” -> “A statistically significant increase in NF occurred since the early 1970s.”

P3794, line 2: “(−0.27 day yr−1, P = 0.02).”-> “(−0.27 day yr–1)”.

P3808, Figure 6: modified the figure and caption:

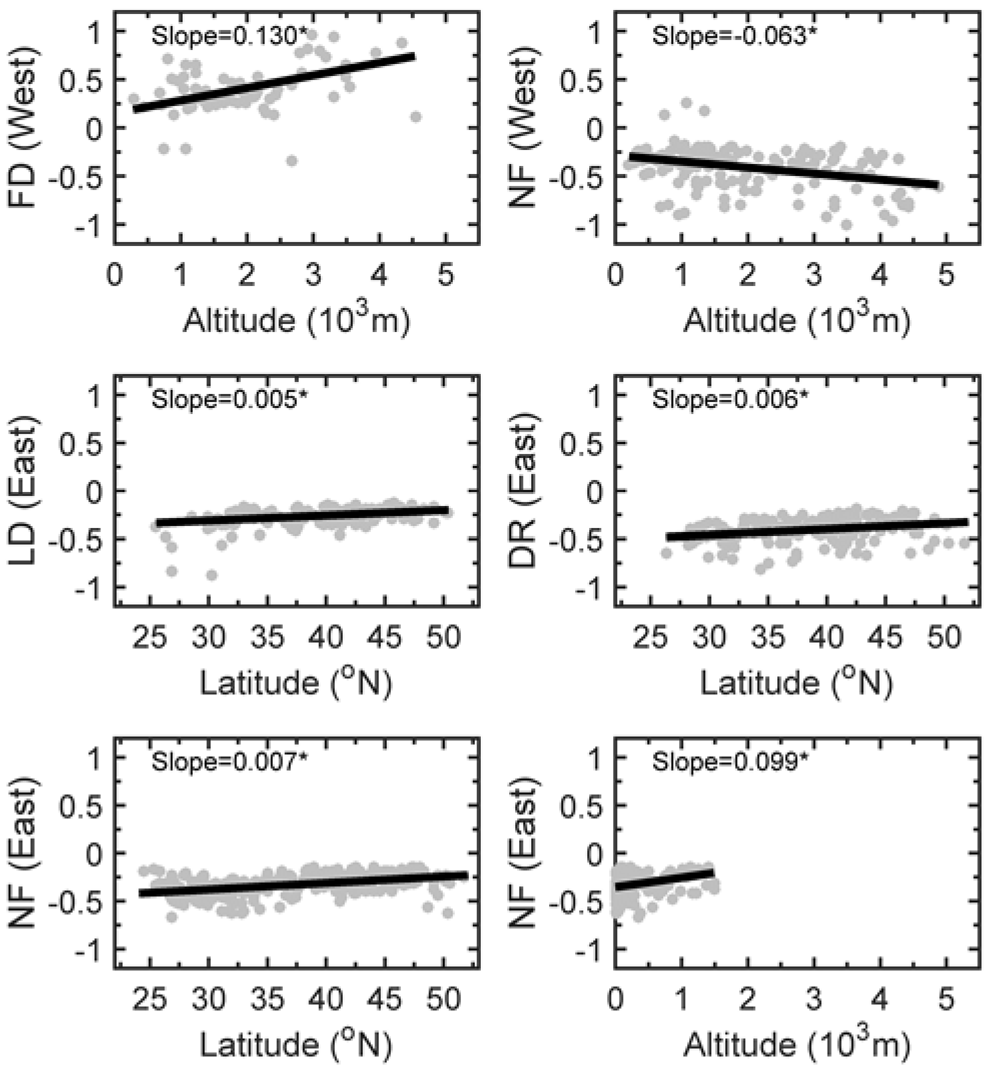

Figure 6. Trends of FD, LD, DR, and NF at west stations (the first row, longitude ≤110 °E) and east stations (the second and third rows, longitude >110 °E) against latitude (°N) and altitude (103m a.s.l). We show only graphs passed significant test at least 95% confidential level. Solid cycles are data points, and lines are linear fitted lines. Symbol * indicates a significant trend at 95% confidential level.

How were the various "breakpoints" in the time series determined? For example, in addition to providing trends pre- and post-1970 in the text, figures 2, 3, 4, and 5 all show separate trend lines from "the early 1990s" (it looks like 1992, but this is not actually stated anywhere in the paper) onwards–how was this break-point chosen? The lead author has a previous publication where an objective change-point analysis was applied to determine breakpoints (Frauenfeld, Zhang, & McCreight, 2007, IJoC). Could this be employed here? In many cases (figures 2-5), it looks like 1995 might also (if not more so) be an appropriate break point, so using an objective method may be advisable.

Response: Following the objective method used in Frauenfeld et al. (2003), we determined the break point in the time series of DR. Year 1991 is the first break point, and the year 1998 is the second break point. Here we select year 1991 as the most appropriate mutation point. In addition, we used the same break point to all variables to facilitate comparisons.

Reference: Frauenfeld, O. W. and R. E. Davis, 2003: Northern Hemisphere Circumpolar Vortex Trends and Climate Change Implications. J. Geophys. Res., 108(D14), 4423, doi:10.1029/2002JD002958.

A more fundamental question pertains to which aspect of "climate change" the authors are attributing the observed freeze/thaw changes. The rapid and incredible urban expansion of Chinese cities is well-known. To what degree does, e.g., urbanization (and other land cover changes) factor into the findings? These surface changes are, of course, part of "climate change," so it would be useful if the authors could more precisely attribute the freeze/thaw status changes to certain aspects of climate change. E.g., you could categorize stations as rural, urban, or having transitioned from rural to urban, and then check to see if this accounts for some of the changes. Alternatively, you could explicitly state that it is not possible to distinguish between, e.g., greenhouse gas warming and land use change, and that both effects are thought to contribute.

Response: Both referees gave comments about potential effect of urbanization on the changes in soil freeze/thaw cycles in this study. We agree with the reviewers' comments and have done a thorough search in literature and data. We add the following materials, including one paragraph and one figure, in the revised version of the manuscript:

“Our results indicated that urbanization may play an important role in decrease of the near-surface soil freeze days in China over the past three decades. To further explore the impact of urbanization on soil freeze, we used data and information of urban expansion in China from 1990 through 2010 (Wang et al., 2012). The urban built-up areas were manually interpreted using Landsat TM/ETM+ in the 1990s, 2000s and 2010s, which have a spatial resolution of 30 m. The interpretation processes were mainly performed by three experienced operators and revised by the high-resolution images in Google Earth. The interpreted urban areas were finally integrated by 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%), median rate (200% - 500%), and high rate (>500%) of urban expansion regions (Fig. 8). We then calculated the regional anomalies of the number of soil freeze days (Fig. 9). For all three regions, there were significant decreasing trends in the near-surface soil freeze days since 1956 (Fig. 9). For the low and median rate regions, the trends in NF were approximately -0.19 day/yr; while for the high rate regions, the trend was about -0.27 days/yr, approximately 42% larger than the other two regions. It showed a similar phenomenon to Fig.5B (spatial trend patterns of NF from 1956 through 2006 across China). Meanwhile, interannual variations were also significantly large in high rate regions (Fig. 9). However, an important issue occurred roughly before and after 1990. Here we chose 1990 as the breakpoint because (1) 1990 was the starting year of urban expansion data and information available (Wang et al., 2012), and (2) 1990 was close to the breakpoint as shown in Fig.5A.

We found NF changed insignificantly in all three regions before 1990 and significantly decreased after 1990 (Fig. 9). The NF was decreased sharply and continuously even though air temperature had a warming hiatus from approximately 1998 (Easterling et al., 2009). It showed that natural forcing (air temperature) may not be the major factor to affect NF. Further analysis indicated that after 1990, NF in the regions with the lower rate of urban expansion decreased at a rate of about –0.86 day/yr, while NF in regions with high rate of urban expansion showed a statistically insignificant change over the same period (Fig. 9).

Based on results from the above analysis, regions with large expansion rate had a significant long-term (1956-2006) decreasing trend in NF, while regions with low and median expansion rates, the decrease in NF was also significant but their magnitudes were reduced almost by one-third (Fig. 9). This is because the regions with the high urban expansion rates are large cities along the east coast of China. These regions were relatively more developed since the mid-1950s, resulting in the greater long-term impact of urban expansion over the past five decades on the near-surface soil freeze, superimposed on the 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 the climate warming hiatus effect, while urban effect may be minimal because the urban expansion was mainly occurred around the edges of the large cities and meteorological stations were not moved. For regions with low and median expansion rates, the long-term decrease trends in NF may mainly reflect the impact of climate warming with relatively limited urban expansion effect because these regions are located far inland and less developed. Meteorological stations in these regions were installed in the 1950s and generally located away from small and median cities by several kilometers to avoid the urban effect on meteorological observations. However, over the period from 1990 through 2006, the magnitude of the decreasing trends in NF increased sharply (Fig. 9) this may be due to the urban expansion was close to and probably far beyond the meteorological stations, resulting in substantial heat island impact on the near-surface soil freeze."

Reference:

Wang, L., Li, C., Ying, Q., Cheng, X., Wang, X., Li, X., Hu, L., Liang, L., Yu, L., Huang, H., and Gong, P.: China's urban expansion from 1990 to 2010 determined with satellite remote sensing. Chin. Sci. Bull., 57, 2802-2812, doi: 10.1007/s1434-012-5235-7, 2012

Easterling, D., and Wehner, M.: Is the climate warming or cooling? Geophys. Res. Lett., 36, L08706, doi:10.1029/2009GL037810, 2009.

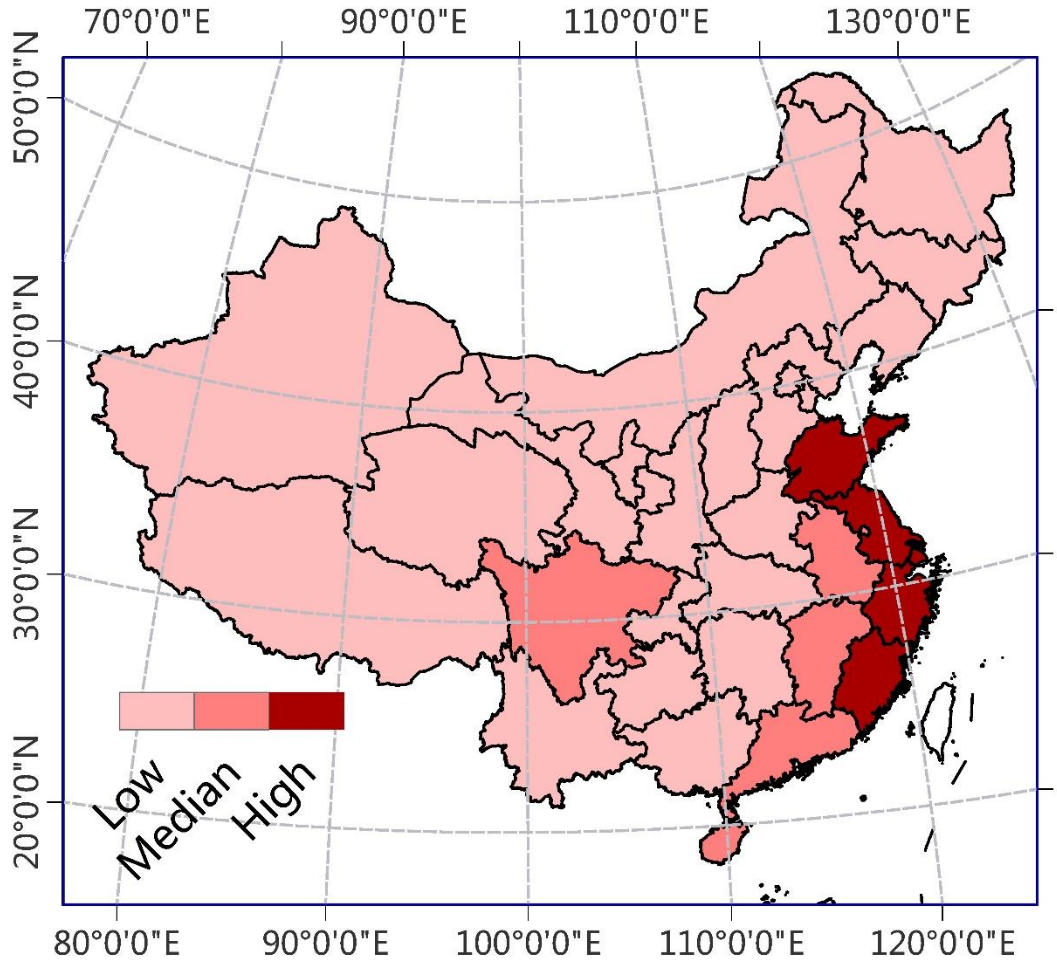

Figure 8. Rates of urban expansion from 1990s through 2010s. (Reclassified from Wang et al. (2012))

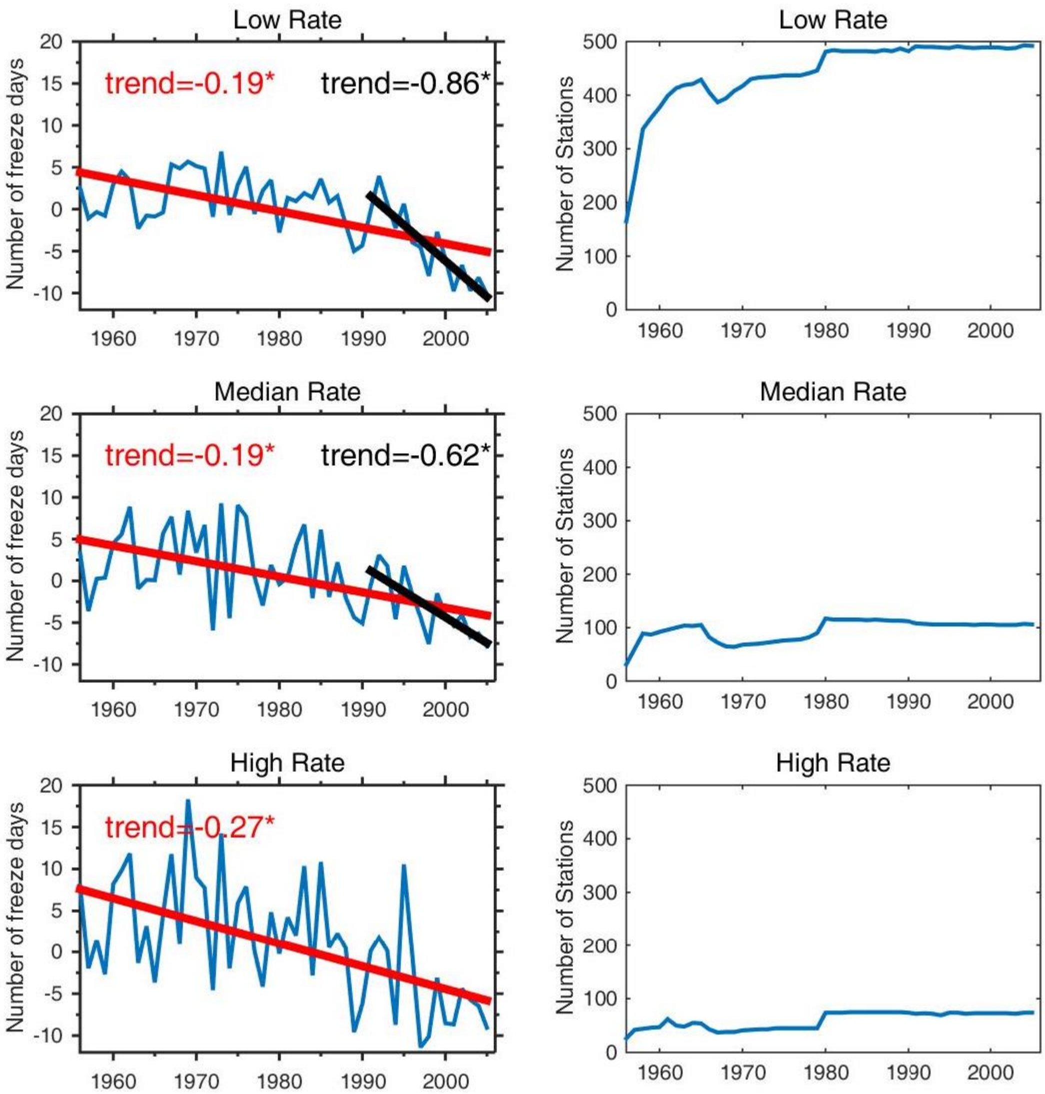

Figure 9. Regional changes of NF in regions with different urbanization rates (left). Black lines and red lines depict respectively the linear regression for the period after 1990 and the period since 1956. Symbol '*' indicates a statistically significant at 95% confidential level. Rights are number of stations used to create each time-series.

What is the explanation for some of the interdecadal variations, e.g., in regard to the "major increase in FD...after the 1970s?" In other recent work (Frauenfeld and Zhang, 2011, ERL), you suggested a strong role of the NAO in affecting soil freezing (or lack thereof) in Russia over this exact same time period–is there a similar explanation here? This is one important aspect that is currently missing from the paper: attribution of the soil freeze/thaw changes to 'something' beyond air temperature. Land surface and soil properties, vegetation, latent/sensible heat sources, snow cover (in the cold season), etc. could all be playing a role in GST variability, yet only air temperature is used. It seems a little simplistic to essentially conclude that when it is cold, the ground freezes, and when it is warm, the ground thaws.

Response: We have also examined the relationship between NAO (seasonal mean from December to February) and our indicators (not shown in the manuscript). Our results indicated barely significant in first date, last date and number of days, and only a statistically significant relationship between winter NAO and duration. It shows that effects of NAO on our indicators exist but may be limited at least in a way of statistical results.

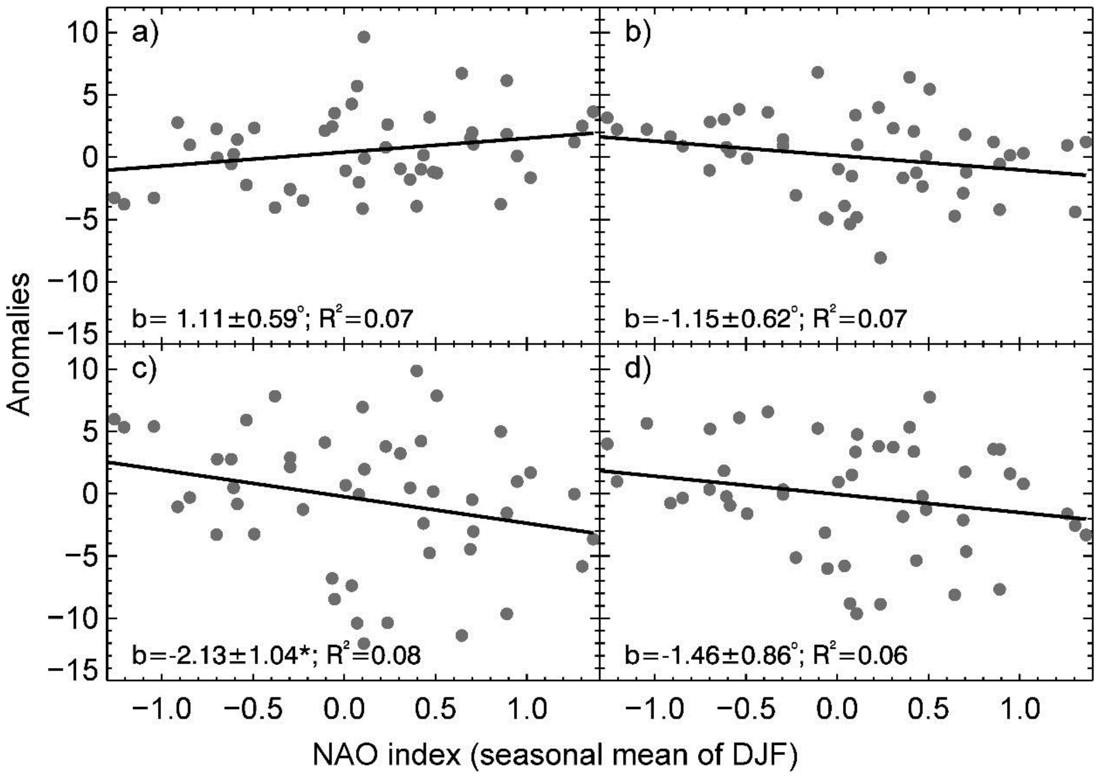

Figure 1. Relationship between of NAO in winter and (a) FD, (b) LD, (c) DR, and (d) NF from 1956 through 2006 across China. The solid circles are individual data points, and the lines are linear regression. Symbol * indicates statistically significant trend or 95% confidential level; and symbol 'o' indicates a barely significant or 90% confidential level.

In addition, soil profiles, snow cover, and other factors suggested by the Referee all might be the important issues to near-surface soil freeze/thaw states. Unfortunately, we don’t have enough and valid materials of soil parameters in all stations especially the dynamics of these soil parameters. Despite we have some observations of snow depth in meteorological stations; the duration of snow cover on the ground is always short. Thus its effects on the near-surface soil freeze/thaw status also are limited.

A couple of minor, final points: why are the results of this study compared to Kansas, USA (are there some expected similarities)?

Response: We compared with previous study in Kansas, USA to indicate a common long-term trend also to show some interregional differences.

Also, please carefully check the paper for grammatical errors. There may be some PDF conversion issue, but in many places, two words are merged together (e.g., "datewas" in line 9 of the abstract, also "utilizedto" on p. 3788 line 14, "atleast" p. 3790 line 25, p. 3792 lines 20-21, and many others). P. 3792 line7 contains a mistake ("the stations 140 stations"), "observede" on p. 3794 line 15, "effectively" on p. 3796 line 13 (should be effective), and line 26 on p. 3796 is missing a word after "land-atmosphere."

Response: We have checked and corrected in revised manuscript.

P3786, line 9: “datewas”->”date was”

P3788, line 14:”utilizedto”->”utilized to”

P3789, line 25: ‘atleast’ -> ‘at least’

P3792, line 7: “the stations 140 stations”->”the 140 stations”

P3792, line 20: ‘earlier.Anomalies’, add a space after ‘.’. (i.e., ‘earlier. Anomalies’).

P3792, line 21: ‘appearedafter’->”appeared after”; ‘alinear’-> ‘a linear’;

P3795, line 15: ‘observede’->’observed’

P3792, line 27: ‘FD and LD was’ -> ‘FD and LD were’

P3794, line 14: ‘Qinghai-Tibet Plateau’ -> ‘Qinghai-Tibetan Plateau’

P3795, line 13: ‘effectively’ -> ‘effective’

P3796, line 26: added a word “processes” after ‘land-atmosphere’.

P3797, line 5: ‘arctic’ -> ‘Arctic’

P3797, line 24: ‘Qinghai-Tibet Plateau’ -> ‘Qinghai-Tibetan Plateau’

Reply on comments from Anonymous Referee #2

This paper examines the soil temperature data collected at numerous stations in China for the long-term trend of the first day and last day of soil frost, and the duration and number of soil frost days. A number of previous studies have reported the decreasing trend of soil frost in various parts of the world. This study is a useful exercise that adds another piece of evidence to the growing body of literature substantiating the common notion that the rising air temperature results in fewer days of soil frost. However, I feel that the paper in its present form does not contribute significant new knowledge to the scientific understanding of interaction between environmental changes and soil freeze-thaw status. That is partly because the paper is somewhat vague in the technical definition of frozen/unfrozen status of soil, as well as the statistical treatment of data set. The paper can be strengthened significantly by more creative and rigorous analysis of data and their discussions. Please see my comments below for specific suggestions.

> **Response**: We appreciate the referee's insightful and constructive comments on the manuscript. All comments are very helpful for improving the manuscript. Specifically, many questions about the fundamentals of statistical method are very important to enhance reliablibility of our statistical results. We have studied all comments thoroughly and made necessary changes and corrections.

SPECIFIC COMMENTS:

1) **P3788-3790. This section contains a large volume of texts reviewing previous literature on similar studies. I feel that the literature review is too long, and also much of the material on remote sensing is not directly relevant to this paper. On the other hand, it is fairly thin on the current understanding of the physical processes that control how the environmental changes (e.g. air temperature, precipitation, land use, urbanization etc.) affect soil freezing and thawing. I suggest that the introduction be re-written to sharpen the focus of the paper. I also suggest that the scientific question, hypothesis, or objective of the study be clearly stated in the introduction.**

   Response: We have rewritten the introduction through deleting few sentences not-so-close to major aim of this paper and shortening the literature reviews about advancement of study of soil freeze/thaw. The revised section is as following.

“The near-surface soil freeze/thaw state is coupled 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 C 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 feedback between the ground and atmosphere. They 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 status have been widely investigated using a range of approaches, including satellite 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 and showed that the freeze-free period was extended with increasing air temperature. Henry (2008) used observations from 31 stations to examine soil freeze dynamics across Canada and found that annual soil freezing days declined from 1966 through 2004. Using long-term data from three stations in Indiana, USA, Sinha and Cherkauer (2008) analyzes found that the number of soil freeze days 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 the decrease in snow depth. Anandhi et al. (2013) carried out a more-detailed analysis of frost indices using data from 23 stations across Kansas, USA, and found that the first date and the last date of freezing occurred later and earlier, respectively.

Numerous studies have reported significantly improvements of monitoring soil 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 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 meteorological station data to investigate the long-term spatiotemporal variation in the timing and duration of near-surface soil freeze/thaw across China over the period 1956–2006. Using data from 636 stations, we examine the first date, the last date, duration and actual number of the near-surface soil freeze, as well as their spatial characteristics over China. Finally, we briefly investigated the response of the near-surface soil freeze/thaw status to changes in climate conditions in the past few decades. ”

2) **P3790, L5. How were these stations selected? Did all of these stations register soil temperature below freezing point? Is it meaningful to include the stations from warm regions (e.g. southeastern China) in the analysis?**

   Response: Essentially, all stations with recorded soil surface temperatures are selected in this study. However, the near-surface soil temperature at some southern stations may never be below the freezing point, data from these stations were not used in the analysis.

3) **P3790, L6. How is "near-surface" defined? Please present a precise definition.**

   Response: The reviewer raised an excellent question. We often say ground surface but in real world, it is hard to define. By “near-surface” in our previous publications, we mean the top 2 to 5 cm of soils from the surface. It is hard to define the true ground surface since the surface is not a perfect flat plate, any micro-scale horizontal changes within a few centimeters may have a few millimeters or even centimeter changes in roughness. A true 0 cm surface is essentially meaningless. However, in this study, by “near-surface”, we mean the top a few millimeters of soils from the “surface” since the thermometer tip has a diameter of 5 mm, it is slightly more than half buried in soils, slightly less half exposed in the air as we defined in the text.

4) **P3790, L11. Did all stations have continuous hourly temperature data? If not, how was the daily minimum temperature determined? This needs to be explained carefully. Note that Henry (2008) used the data sets that had only two measurements per day.**

   Response: The reviewer #1 raised the same question. We have added more information on this issue as follows:

“Ground surface temperatures were measured by using a thermometer. The thermometer sensor has mercury ball on one end with diameter of 5 mm. It is required by the measurement standard that half of the thermometer sensor be buried in ground and the other half expose to the air. In practice, the sensor is usually buried more than half in the ground and it is colored in white to reduce solar heating. Daily minimum (maximum) temperatures were measured using a special designed minimum (maximum) temperature thermometer. The principle is that when the mercury ball at the tip of the thermometer cools (warms) due to the change in the near-surface soil temperature, its volume will shrink (expand). The volume change will be recorded on the graduated glass tube. For minimum (maximum) temperature thermometer, the mercury volume will not return to the normal after the temperature reaches the minimum (maximum) without the extra force. In this case, the daily minimum (maximum) temperature will be recorded and the mercury scale on the glass tube will be reset by the technician. The minimum (maximum) temperature thermometer records the daily minimum (maximum) temperature once a day but it cannot record the time when it occurs. Ground surface temperatures were also measured four times a day (02:00, 08:00, 14:00, and 20:00 Beijing Standard Time) and averaged as a daily mean. Daily minimum (maximum) temperature was recorded 20:00 Beijing Standard Time. The thermometer has an accuracy of ±0.1 ℃ and by requirements, these thermometers should be calibrated once a year. The thermometer sensors were used for the entire study period across China. The large majority of the stations have no location change over period of the records. However, information is not available for those stations with location change history. We believe that effect of station movement on overall outcome is very minimum. All of these measurements were conducted routinely each day by trained professional technicians at all meteorological station across China.”

Here is a reference.

China Meteorological Administration. 2007b. Specifications for surface meteorological observation, Part 13: Measurement of soil temperature, China Meteorological Press: Beijing, China.

5) **P3790, L12. How was the temperature of ground surface (0 cm) measured? It is not trivial to measure the surface temperature. Accurate measurements would require an infrared thermometer. Was the same method used to measure soil temperature at all stations? What is the accuracy of measurements? This is a very important point, and should be discussed thoroughly in the paper.**

Response: We have answered this question in the previous question. The good thing is that the same method was used for all stations across China.

6) **P3790, L23. The temporal trend analysis concerning environmental changes, such as this paper, requires rigorous statistical treatment of the data, if it is to be published in a peer-reviewed journal. The authors need to explain the statistical methods carefully and justify the assumptions used in the analysis. Why is a linear regression method used? Does the statistical distribution of data set justify the use of linear regression?**

Response: We agree with the reviewer's comments and have made thorough checks. Generally, if mean of residual approach to zero, estimated coefficient can be assured as unbiased estimator. In this case, we use a table to summary the estimated parameters of probabilistic distributions of the residual, which included mean, standard deviation, skewness and kurtosis. Then we show Q-Q plot, a quantile-quantile plot of the sample quantiles of residual versus theoretical quantiles from a normal distribution. If the distribution of residual is normal, the plot will be close to linear.

Table 1 shows the means of residual are all close to zero, thus our estimated coefficients are close to unbiased. Considering skewness and kurtosis, they stray slightly from zero. More directly, Figure 1 indicates the subplots all are close to linear. Thus, we can find the hypothesis of normal distribution for our linear fitness should be appropriate. To keep the paper short, we did not include the Table 1 and the Figure in the text. However, we added text and reference.

References:

Rice, John. Mathematical statistics and data analysis. Cengage Learning, 2006.

Freedman, David. Statistical models: theory and practice. Cambridge University Press, 2009.

Table 1. Descriptive Statistics of residual

	Minimum	**Maximum**	**Mean**	**Std. Deviation**	**Skewness**		**Kurtosis**	
	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
First date	-5.60	6.70	0.00	2.70	0.02	0.34	-0.14	0.66

Last date	-5.11	5.10	0.00	2.41	0.25	0.34	-0.66	0.66
Number	-6.10	6.39	0.00	3.43	0.04	0.34	-1.12	0.66
Duration	-8.70	8.12	0.00	4.08	0.16	0.34	-0.63	0.66

* All results were calculated with IBM SPSS Statistics v20.

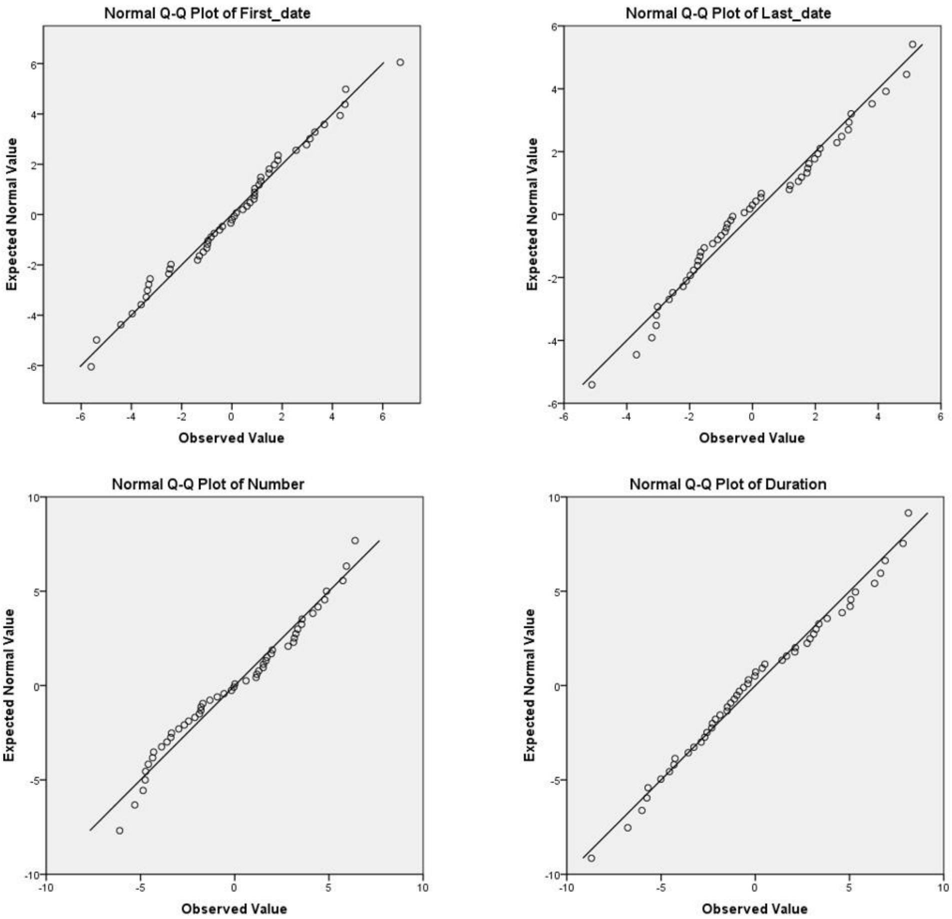

Figure 1. Q-Q plots of residual for each variables.

* All subplots were created with IBM SPSS Statistics v20.

7) **P3791, L14. How was this number (300 days) selected? If the missing days occur more frequently during winter than in summer, it will bias the statistics. How was this issue addressed?**

Response: Before we selected the threshold, we also used years with 365 daily records to calculate the indicators. Through comparison, the results used 300 days as threshold have errors of +/- 2 days. In this case, we believe that the 300-day threshold and will have very limited effects on results. However, it will give us more stations to cover more spatial areas.

8) **P3791, L20-21. It took me a while to understand what is shown in Fig. 2a. Please remind the reader that you are showing the anomalies in this graph, both in the figure caption and in the texts.**

Response: We have made changes that they are anomalies, and modified this sentence as following.

"Overall, departure of FD showed a significantly increase across China by nearly 5 days, or a trend of 0.10 ± 0.03 day yr^{-1}, for the period 1956–2006 (Fig. 2a)."

9) **P3791, L21. How is the range (+/- 0.03) defined?**

Response: It was estimated by a width of 1-standard variation in linear regression. In other words, any estimated coefficient is also a random variable and has a given statistical distribution. So we gave a range of estimated coefficient.

10) **P3791, L23. How is the coefficient of multiple determination defined?**

Response: We described the long-term change through two aspects. One of them was estimated linear trend, and another was total change over the period. For example, here, the estimated linear trend is -0.58 day/yr, since the early 1990s; the ending of study period is 2006, so the total change is estimated as 0.58*15~=9 days.

11) **P3791, L26. How is the p value defined? Do the data meet the assumptions for the calculation of p value (e.g. normal distribution)?**

Response: P value is for F statistic of the hypotheses test that the corresponding coefficient is equal to zero or not. For example, the p-value of the F-statistic for 'slope' is less than 0.05, so this term is statistically significant at the 5% significance level.

To examine the normalization, we have shown in **Response 6)**. Here is only a Q-Q plot. If the distribution of residual is normal, the plot will be close to linear. This figure shows the precondition should be met.

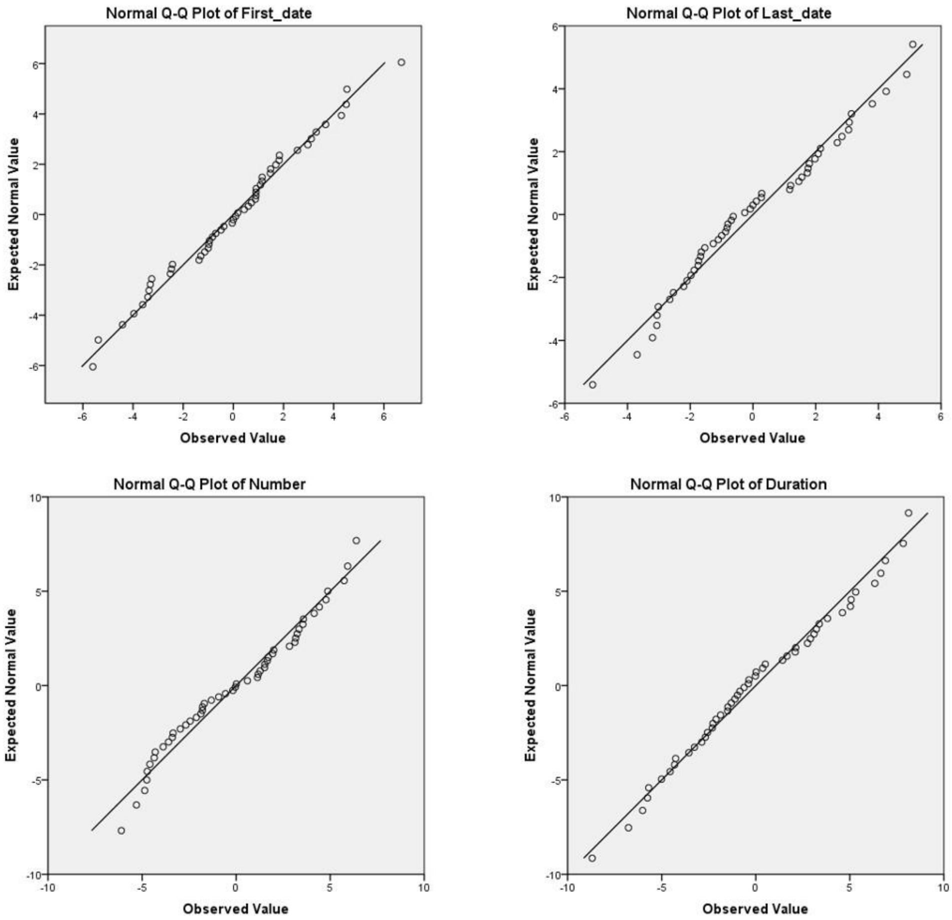

Figure 1. Q-Q plots of residual for each variables.

* All subplots were created with IBM SPSS Statistics v20.

12) P3792, L1-2. A "major" increase in the early 1970's is not visible in Fig. 2a. The data seem to be more or less steady until after 1990.

Response: Before the early 1970s (or exactly 1969-1970), there was a short cold period. From Figures 2-5, we can find this characteristic. Hence, we deem that an increase occurred since the early 1970s. The original adjective 'major' may mislead readers. We have corrected it as following.

"An increase started from the early 1970s when a short cold period was ended."

13) P3792, L6. This sentence contradicts with the statement in L1-2 (see above).

Response: We have corrected it as following.

"An increase started from the early 1970s when a short cold period was ended."

14) P3792, L19-20. Is this statistically significant?

Response: It was insignificant thus we did not show any estimated trend. We have modified this sentence to make it clear:

"Prior to the early 1990s, LD occurred slightly and insignificantly earlier."

15) P3792, L26. How is "west China" defined?

Response: West and east China is defined according to 110E, i.e., west of 110E in China is defined as "west China". It also was referred in this article (P3792, Line 10) as well as in caption Figure 6 (P3808).

16) P3792, L28. What does "dramatically" exactly mean?

Response: We mean "significantly".

17) P3794, L6. "NF varied significantly". This needs to be explained a bit more carefully, as there was a period with very little change, followed by a period of visible change. What is the statistical significance of NF during the two periods?

Response: Here we showed stations with $p<0.05$. We believe they varied significantly. Of cause, some of stations may also have one or more break points. Using 1991 as unified break point, we also created a map to show stations with significant trends (~130 stations, not shown in the manuscript).

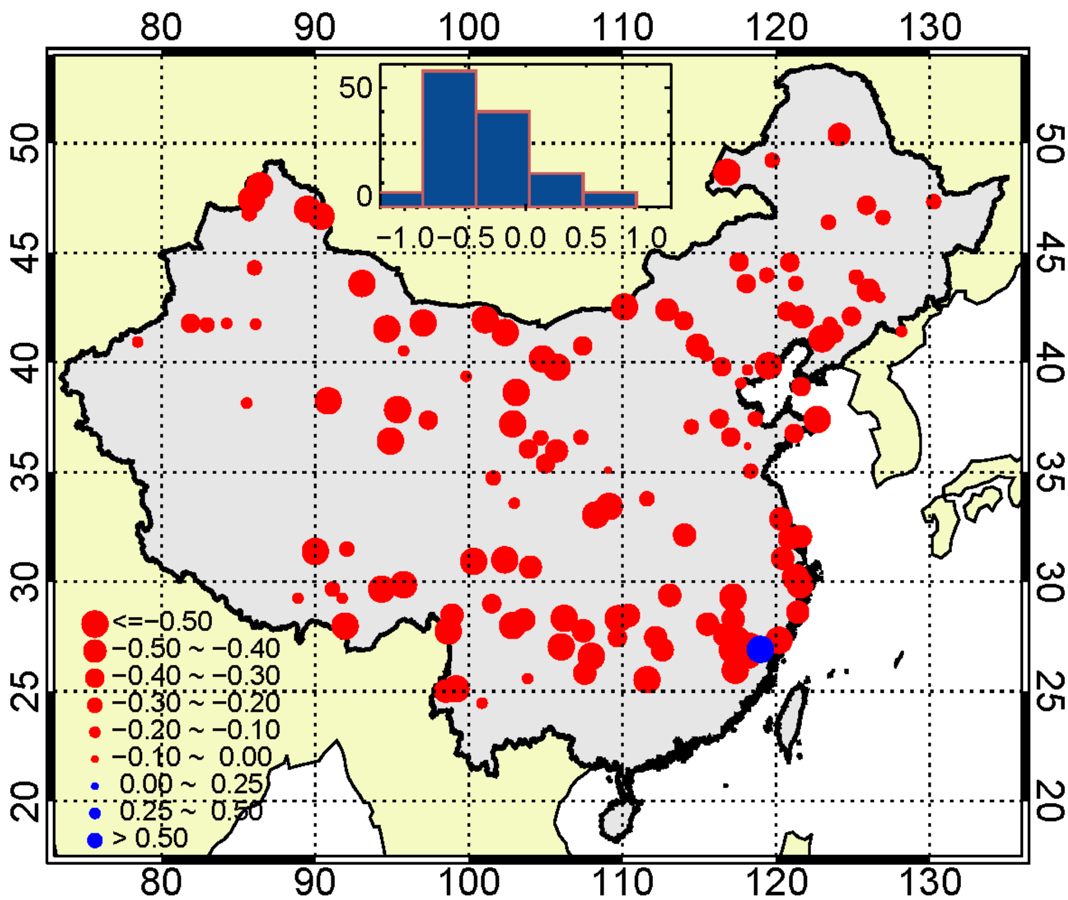

Figure 1. Changes in NF from 1956 through 2006 across China; center-top is histogram of changes in NF.

18) P3794, L11-12. Please indicate Qinghai-Tibet Plateau and Yangtze River on a map.

Response: We have added the boundary of Qinghai-Tibetan Plateau and also Yangtze River on Figure 1.

19) P3794, L15-16. The issue of urbanization needs to be investigated much more carefully. Is the urbanization restricted to the lower reaches of the Yangtze? I imagine urbanization has been occurring in other parts of China. How many of the monitoring stations are located in rural areas? Should the analysis be conducted separately for urban and rural stations?

Response: Both referees gave comments about potential effect of urbanization on the changes in soil freeze/thaw cycles in this study. We agree with the reviewers' comments and have done a thorough search in literature and data. We add the following materials, including one paragraph and one figure, in the revised version of the manuscript:

“Our results indicated that urbanization may play an important role in decrease of the near-surface soil freeze days in China over the past three decades. To further explore the impact of urbanization on soil freeze, we used data and information of urban expansion in China from 1990 through 2010 (Wang et al., 2012). The urban built-up areas were manually interpreted using Landsat TM/ETM+ in the 1990s, 2000s and 2010s, which have a spatial resolution of 30 m. The interpretation processes were mainly performed by three experienced operators and revised by the high-resolution images in Google Earth. The interpreted urban areas were finally integrated by 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%), median rate (200% - 500%), and high rate (>500%) of urban expansion regions (Fig. 8). We then calculated the regional anomalies of the number of soil freeze days (Fig. 9). For all three regions, there were significant decreasing trends in the near-surface soil freeze days since 1956 (Fig. 9). For the low and median rate regions, the trends in NF were approximately -0.19 day/yr; while for the high rate regions, the trend was about -0.27 days/yr, approximately 42% larger than the other two regions. It showed a similar phenomenon to Fig.5B (spatial trend patterns of NF from 1956 through 2006 across China). Meanwhile, interannual variations were also significantly large in high rate regions (Fig. 9). However, an important issue occurred roughly before and after 1990. Here we chose 1990 as the breakpoint because (1) 1990 was the starting year of urban expansion data and information available (Wang et al., 2012), and (2) 1990 was close to the breakpoint as shown in Fig.5A.

We found NF changed insignificantly in all three regions before 1990 and significantly decreased after 1990 (Fig. 9). The NF was decreased sharply and continuously even though air temperature had a warming hiatus from approximately 1998 (Easterling et al., 2009). It showed that natural forcing (air temperature) may not be the major factor to affect NF. Further analysis indicated that after 1990, NF in the regions with the lower rate of urban expansion decreased at a rate of about –0.86 day/yr, while NF in regions with high rate of urban expansion showed a statistically insignificant change over the same period (Fig. 9).

Based on results from the above analysis, regions with large expansion rate had a significant long-term (1956-2006) decreasing trend in NF, while regions with low and median expansion rates, the decrease in NF was also significant but their magnitudes were reduced almost by one-third (Fig. 9). This is because the regions with the high urban expansion rates are large cities along the east coast of China. These regions were relatively more developed since the mid-1950s, resulting in the greater long-term impact of urban expansion over the past five decades on the near-surface soil freeze, superimposed on the 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 the climate warming hiatus effect, while urban effect may be minimal because the urban expansion was mainly occurred around the edges of the large cities and meteorological stations were not moved. For regions with low and median expansion rates, the long-term decrease trends in NF may mainly reflect the impact of climate warming with relatively limited urban expansion effect because these regions are located far inland and less developed. Meteorological stations in these regions were installed in the 1950s and generally located away from small and median cities by several kilometers to avoid the urban effect on meteorological observations. However, over the period from 1990 through 2006, the magnitude of the decreasing trends in NF increased sharply (Fig. 9) this may be due to the urban expansion was close to and probably far beyond the meteorological stations, resulting in substantial heat island impact on the near-surface soil freeze."

Reference:

Wang, L., Li, C., Ying, Q., Cheng, X., Wang, X., Li, X., Hu, L., Liang, L., Yu, L., Huang, H., and Gong, P.: China's urban expansion from 1990 to 2010 determined with satellite remote sensing. Chin. Sci. Bull., 57, 2802-2812, doi: 10.1007/s1434-012-5235-7, 2012

Easterling, D., and Wehner, M.: Is the climate warming or cooling? Geophys. Res. Lett., 36, L08706, doi:10.1029/2009GL037810, 2009.

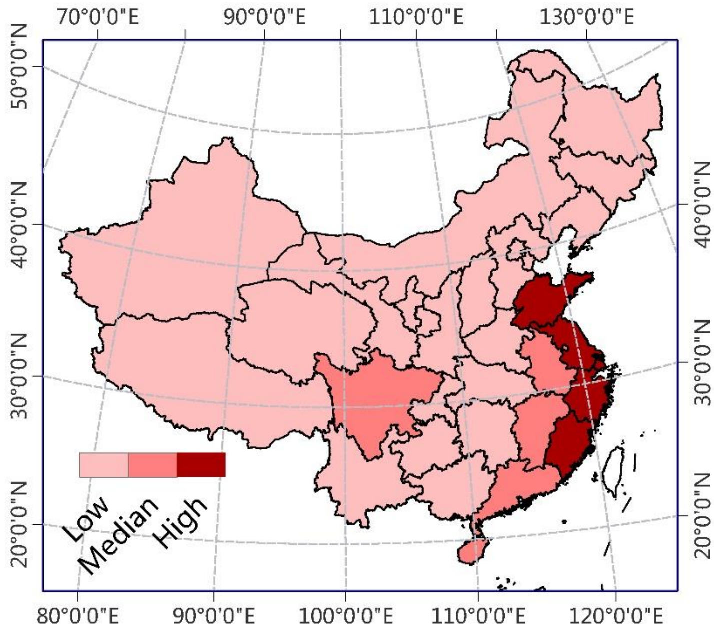

Figure 8. Rates of urban expansion from 1990s through 2010s. (Reclassified from Wang et al. (2012))

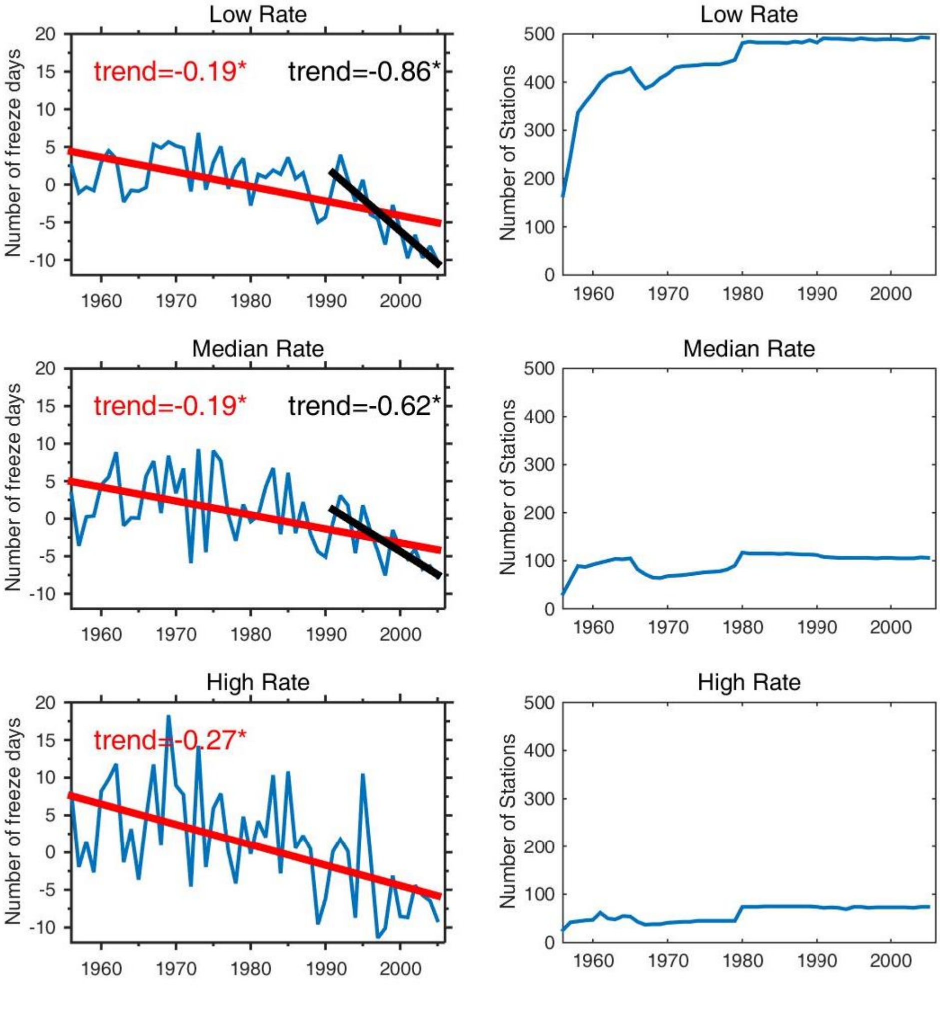

Figure 9. Regional changes of NF in regions with different urbanization rates (left). Black lines and red lines depict respectively the linear regression for the period after 1990 and the period since 1956. Symbol '*' indicates a statistically significant at 95% confidential level. Rights are number of stations used to create each time-series.

20) **P3794, L16. Another related issue is the relocation of stations and changes in measurement methods and depth. If any station has been affected by relocation or other changes, it should be excluded from the data analysis. Also, did all stations have continuous data from 1956 to 2006 (P3790, L5)? If new stations have been added over time, how does it affect the statistical analysis? Can there be a bias in the regional distribution of new stations? These are very important issues, which should be discussed thoroughly.**

Response: Most stations were built in the early 1950s. A known large scale of stations adjustment (about three provinces) was taken in 2007. Some new stations was built since 21st century, however, we defined the baseline period as July, 1971-June, 2001. In this way, we excluded many newer stations with less than 30 years of records. We have also done thorough data quality control to make sure consistency at annual scale through plotted and screened each individual time series.

21) **Figure 1. This map appears to show the stations that are not likely affected by soil frost at all. For the purpose of this paper, it will be better to include only those stations that are subjected to soil freeze-thaw. Also, this map shows Taiwan and southern islands that are not relevant to this paper at all. They should be removed.**

Response: We agree with the reviewer's comments. In order to keep the completeness of meteorological station distribution, we have them all stations in the map. However, we added information for stations that have no frost.

22) **Figure 2. In the caption for (a), what are "composite variation" and "low-pass filter"? Please explain these in the texts. What are the units of the values shown in these figures? Please indicate. This map appears to have a smaller number of data points than in Figure 1. Why?**

Response: The composite variation is combined by all valid station's time series. Low-pass filter is a method generally used in a long-term climatic series analysis; it can smooth high-frequency noises according to a cut-off frequency. Its mathematical foundation is fast Fourier transform (FFT). More detail numerical algorithm can be found in many references (for example, Brault, J. W. and White, O. R., 1971, The analysis and restoration of astronomical data via the fast Fourier transform, Astron. & Astrophys., 13, pp. 169-189.)

Figure 2 showed only the stations with significant trends at 95% confidence level. Due to the first date may be influenced by some extreme weather; its long-term trend was not strongly significant. Thus not all stations changes significantly over our study period, and that is why a small number of stations was shown in Figure 2.

23) The paper presents the data in the form of anomalies, but the reader is given no information on the actual number of frost days, etc. It will be useful to include a map or histograms showing the distribution of duration of frost, or number of frost days.

Response: The climatology, mainly focused on spatial characteristics, of these indicators was analyzed in another paper, which is under reviewing for publishing.

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, with a 0 ℃ threshold, we investigated the long-term spatiotemporal variations of 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 across China over the period 1956-2006 (with a baseline period of July 1971 through June 2001). The results reveal the responses of the near-surface soil freeze to warming climate. The first date of soil freeze was delayed 5 days (0.10 ± 0.03 day/yr) and the last date was advanced 7 days (0.15 ± 0.02 day/yr) over this period. The duration of the near-surface soil freeze decreased 13 days from 1956 through 2006, and the number of near-surface soil freeze days fell by ~10 days. 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 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 near-surface soil freeze/thaw status and the feedback between the ground and atmosphere. They 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 status 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 showed that the freeze-free period was extended with increasing air temperature. Henry (2008) used observations from 31 stations to examine soil freeze dynamics across Canada, and he found that annual soil freezing days declined from 1966 through 2004. Using Longlong-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 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 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.

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 significantly improvements of monitoring soil 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 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 timing and duration of 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 their~~and also the~~ spatial characteristics over China.~~across stations, based on a 0 ℃ threshold.~~ Finally, ~~W~~we ~~then~~briefly investigated the response of the near-surface soil freeze/thaw status to changes in climate conditions in 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 (0 cm). Data used for this study include daily minimum ground-surface temperatures, and mean annual air temperature 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).

Ground surface temperatures were measured by using a thermometer. The thermometer sensor has mercury ball on one end with diameter of 5 mm. It is required by the measurement standard that half of the thermometer sensor be buried in ground and the other half expose to the air. In practice, the sensor is usually buried more than half in the ground and it is colored in white to reduce solar heating. Daily minimum (maximum) temperatures were measured using a special minimum (maximum) temperature thermometer. The minimum (maximum) temperature thermometer records the daily minimum (maximum) temperature once a day although it cannot record the time when it occurs. Ground surface temperatures were also measured four times a day (02:00, 08:00, 14:00, and 20:00 Beijing Standard Time) and averaged as a daily mean. Daily minimum (maximum) temperature was reported at 20:00 Beijing Standard Time. The thermometer has an accuracy of ±0.1 ℃ and by requirements, these thermometers should be calibrated once a year. The thermometer sensors were used for the entire study period. The large majority of the stations have no location change over period of the records. However, information is not available for those stations with location change history. We believe that effect of station movement on overall outcome is very minimum. All of these measurements were conducted routinely each day by trained professional technicians at all meteorological station across China.

The daily surface temperature dataset was performed basic quality control that identified and excluded questionable data points. In details, we checked with the following two procedures. First, at daily time scale, we checked the consistency of temperature time series by cross-referencing temperature values with the day before and after the checking day. At annual time scale, we plotted and screened each individual time series to identify questionable data points and delete the statistical outliers of points out of the three standard deviations range from the long-term mean.

~~.~~Annual statistics of first date, 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 anomalies of these variables over our study period across China. A linear regression method is used to calculate trends of each indicator and to test their statistical significance. We also compared the linear trends of the mentioned variables with latitude and altitude in stations to investigate the geographic characteristics of the changes~~We also calculated the linear regression of trends of latitude, altitude, and mean annual air temperature to investigate~~

~~geographical relationships~~.

The first date of the near-surface soil freeze (FD) is defined as the first 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) is defined as the time span between the first date of freeze and last date of freeze. Because of extreme weather events, the near-surface soil may not be frozen continuously from the first date to the last date. Thus, we further define the actual number of 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 study have continuous data for the 30 yr study period. Generally, ~8 missing years (25% of the 30-yr period) are permitted in a calculation of the time-mean (Jones and Hulme, 1996). In this study, we applied some quality control approaches to ensure the reliability and consistency of results by station and year. ~~First~~Firstly, a year with at least 300 daily records (more than 75% of a year) could be utilized in the annual indices. Before we selected the threshold, we also used years with 365 daily records to calculate the indicators. Through comparison, the results used 300 days as threshold have errors of +/- 2 days. In this case, we believe that the 300-day threshold and will have very limited effects on results. However, it will give us more stations to cover more spatial areas. Secondly, We rejected the outliers, based on statistical 3σ error, by station. Finally, we selected those stations with >21 points of annual statistical data. Locations of the 636 meteorological stations are shown in Fig. 1.

3. Results

3.1 Changes in the First Day of the Near-Surface Soil Freeze

Overall, departure of FD showed ~~increased~~a ~~significantly~~significantly increase across China by nearly 5 days, or a trend of 0.10±0.03 day/yr, for the period 1956–2006 (Fig. 2a). We found that the near-surface soil started to freeze later due to a general warming in the fall season across China. The coefficient of multiple determination, R^2=0.23, means that somewhat less than one-fourth 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. Anomalies of FD ~~decreased, but insignificantly, before the 1970s (-0.20 day/yr, p = 0.14) and changes~~ during 1965–1975 are the lowest in our study period. An ~~major~~ increase started from ~~- in FD appeared after~~ the early 1970s when a short cold period was ended (0.21 day/yr). However, the greatest increase in FD (0.72±0.17day/yr) occurred after the early 1990s (Fig. 2a); FD has occurred ~10 days later since the early 1990s. R^2 = 0.59 means that somewhat more than one-half of the total variability in the FD can be explained by the regression equation. ~~For the period before the early 1990s, FD had no significant change (0.03 day/yr, p = 0.45)~~.

For our study period, the ~~stations~~ 140 stations showed a significant trend in FD (Fig. 2b). Most stations showed long-term delays of FD, except at four stations. At ~100 of the 140 stations, the delay in FD is <0.25 day/yr (histogram in Fig. 2b). When comparing stations in west China and east China (east and west of 110 °E), we found greater delays in FD in the west than in the east. FD at stations surrounding or on the Qinghai-Tibetan Plateau was delayed by >0.5 days/yr (Fig. 2b), primarily due to the higher average altitude in those regions.

3.2 Changes in the Last day of Near-Surface Soil Freeze

In China, LD declined significantly over the period 1956–2006, by >7 days, or a trend of -0.15 ± 0.02 day/yr (Fig. 3a). This indicates that warming spring seasons result in an earlier end to soil freeze. Somewhat less than 50% of the total variability in the LD can be explained by our regression. Variations in LD are distributed over two periods: before and after the early 1990s. Prior to the early 1990s, LD occurred slightly earlier. Anomalies during 1965–1980 are the highest over our study period. The rapid advancement of LD appeared after the early 1990s, with a linear trend of –0.58 ± 0.14 day/yr; i.e., LD has occurred earlier (by ~ 9 days) since the early 1990s.

LD changed significantly at 36% (229 stations) of the study stations (Fig. 3b). This percentage is greater than that of the stations with significantly delayed FD. Most stations show a long-term advancement in LD. At ~140 stations, LD was advanced by ~ –0.30 day/yr (see the histogram in Fig. 3b). We found that changes in west China were generally larger than those in east 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 frost and an earlier ending of the last spring frost over our study period.

3.3 Changes in the Duration of Near-Surface Soil Freeze

Over the period from 1956 through 2006, DR was shortened by almost 13 days, or –0.25 ± 0.04 day/yr (Fig. 4a). ~~DR increased, but statistically insignificantly, from 1956 through 1970 (–0.27 day/yr, P = 0.18).~~ Anomalies during 1966–1980 were higher 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 ±0.21 day/yr) (Fig. 4a), by almost 16 days. The overall variation in DR (–0.25 day/yr) is similar to the variation in FD (0.10 day/yr) and LD (–0.15 day/yr). For example, the increase in DR (13 days) corresponds to the change in FD (5 days) plus the change in LD (7 days). An earlier last freeze in spring might contribute to more than half of the shortening of the DR.

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

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

It is important to realize that near-surface soil may not be frozen continuously during the period from the first date to last date 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 ± 0.03 day/yr) for the period 1956–2006 (Fig. 5a). The trend in NF is similar but smaller than that in DR (compare to Fig. 4a). A statistically ~~in~~significant increase in NF 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 day/yr since early 1990s (Fig. 5a). The actual number of freeze days in near-surface soil decreased by >12 days over our study period.

At 381 stations (~ 60% of the study stations), NF varied significantly during our study period (Fig. 5b). Although few stations in western China showed an increased variability in NF, almost all stations showed a significant decrease, ranging from –0.50 to –0.20 day/yr (histogram in Fig. 5b). 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: the Qinghai-~~Tibet~~Tibetan 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~~Tibetan 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.

3.5 Variations in Soil Freeze with Latitude and Altitude

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 China, altitude is statistically correlated to FD and NF (slope of 0.~~10~~13 and -0.063; Fig. 6~~a~~), so that the first date of soil freeze ~~is~~toward more later in higher-altitude regions. Similarly, trends in NF relate significantly to altitude. Higher-altitude regions have ~~lower NF values~~greater decrease in NF.

In east China, latitude correlates with LD, DR, and NF, but altitude correlates to NF (Fig. 6~~b~~). Low-latitude stations are more sensitive to freeze/thaw timing and duration because soil at more southerly latitudes remains closer to the freezing point in cold seasons. Under warming climatic 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. 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.

3.6 Effects of Air Temperature on Soil Freeze

Air temperature is an important factor in near-surface soil freeze dynamics. We calculated changes in air temperature at Chinese meteorological stations and correlated this with FD, LD, DR, and NF.

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 $\pm$0.76, –3.93 $\pm$0.82, –7.65 $\pm$1.25, and –6.55 $\pm$0.99, respectively, demonstrating that the 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 freeze by several days. Similar differences in R^2 exist between DR and NF.

4. Discussion

We calculated four indicators of near-surface soil freeze from 1956 through 2006 across China. Our results indicate that the first date and last date of near-surface soil freeze occurred later and earlier, respectively, than normal, thereby resulting in a decrease in the duration and number of days of the near-surface soil freeze.

FD was delayed by ~5 days (0.10 day/yr) over the entire study period. 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 indicate a later FD from the early 1990s to 2006 over China (trend is 0.72 day/yr), than Li et al. (2012) results from the Qinghai-Tibetan Plateau (10 days, ~0.50 day/yr) from 1988 to 2007. (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 ~7 days earlier (0.15 day/yr) over our study period. Li et al. (2012) showed a later date of soil freeze (by ~14 days; ~ 0.70 day/yr) from 1988 to 2007. We found more change in FD in China since the early 1990s (0.58 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 the entire study period.

Our results indicate that DR and NF decreased 13 and 10 days, respectively, from 1956 to 2006 and have decreased sharply since the early 1990s. There is also 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). 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 aArctic 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.

Our results indicated that urbanization may play an important role in decrease of the near-surface soil freeze days in China over the past three decades. To further explore the impact of urbanization on soil freeze, we used data and information of urban expansion in China from 1990 through 2010 (Wang et al., 2012). The urban built-up areas were manually interpreted using Landsat TM/ETM+ in the 1990s, 2000s and 2010s, which have a spatial resolution of 30 m. The interpretation processes were mainly performed by three experienced operators and revised by the high-resolution images in Google Earth. The interpreted urban areas were finally integrated by 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%), median rate (200% - 500%), and high rate (>500%) of urban expansion regions (Fig. 8). We then calculated the regional anomalies of the number of soil freeze days (Fig. 9). For all three regions, there were significant decreasing trends in the near-surface soil freeze days since 1956 (Fig. 9). For the low and median rate regions, the trends in NF were approximately -0.19 day/yr; while for the high rate regions, the trend was about -0.27 days/yr, approximately 42% larger than the other two regions. It showed a similar phenomenon to Fig.5b (spatial trend patterns of NF from 1956 through 2006 across China). Meanwhile, interannual variations were also significantly large in high rate regions (Fig. 9). However, an important issue occurred roughly before and after 1990. Here we chose 1990 as the breakpoint because (1) 1990 was the starting year of urban expansion data and information available (Wang et al., 2012), and (2) 1990 was close to the breakpoint as shown in Fig.5a.

We found NF changed insignificantly in all three regions before 1990 and significantly decreased after 1990 (Fig. 9). The NF was decreased sharply and continuously even though air temperature had a warming hiatus from approximately 1998 (Easterling et al., 2009). It showed that natural forcing (air temperature) may not be the major factor to affect NF. Further analysis indicated that after 1990, NF in the regions with the lower rate of urban expansion decreased at a rate of about –0.86 day/yr, while NF in regions with high rate of urban expansion showed a statistically insignificant change over the same period (Fig. 9).

Based on results from the above analysis, regions with large expansion rate had a significant long-term (1956-2006) decreasing trend in NF, while regions with low and median expansion rates, the decrease in NF was also significant but their magnitudes were reduced almost by one-third (Fig. 9). This is because the regions with the high urban expansion rates are large cities along the east coast of China.

These regions were relatively more developed since the mid 1950s, resulting in the greater long-term impact of urban expansion over the past five decades on the near-surface soil freeze, superimposed on the 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 the climate warming hiatus effect, while urban effect may be minimal because the urban expansion was mainly occurred around the edges of the large cities and meteorological stations were not moved. For regions with low and median expansion rates, the long-term decrease trends in NF may mainly reflect the impact of climate warming with relatively limited urban expansion effect because these regions are located far inland and less developed. Meteorological stations in these regions were installed in the 1950s and generally located away from small and median cities by several kilometers to avoid the urban effect on meteorological observations. However, over the period from 1990 through 2006, the magnitude of the decreasing trends in NF increased sharply (Fig. 9) this may be due to the urban expansion was close to and probably far beyond the meteorological stations, resulting in substantial heat island impact on the near-surface soil freeze.

~~5.~~ Soil profiles, snow cover, and other factors all might be the important issues to near-surface soil freeze/thaw states. Unfortunately, we don’t have enough and valid materials of soil parameters in all stations especially the dynamics of these soil parameters. Despite we have some observations of snow depth in meteorological stations; the duration of snow cover on the ground is always short. Thus its effects on the near-surface soil freeze/thaw status also are limited. We have also examined the relationship between NAO (seasonal mean from December to February) and our indicators (not shown). Our results indicated barely significant in first date, last date and number of days, and only a statistically significant relationship between winter NAO and duration. It shows that effects of NAO on our indicators exist but may be limited at least in a way of statistical results.

~~6.~~5. Summary

We investigated variations in four indicators (the first date, last date, duration, and number of days) of near-surface soil freeze, from 1956 through 2006, across China. We examined the spatial characteristics and statistical relationship between these indicators and air temperature. Our results are summarized as follows:

- The first date of near-surface soil freeze was delayed by ~5 days (0.10 ± 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 near-surface soil freeze has occurred ~7 days earlier (0.15 ± 0.02 day/yr) over our study period. Near-surface soil freeze occurred earlier by of –0.58 ± 0.14 day/yr since the early 1990s.
- The duration of near-surface soil freeze decreased 13 days from 1956 through 2006. It has decreased by ~15 days since the early 1990s.
- The number of the near-surface soil freeze days decreased by ~10 days (–0.20 ± 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~~Tibetan Plateau and the lower reaches of the Yangtze Basin.

- Air temperature significantly influences all four soil freeze indicators, and correlates best with indicators of duration, such as duration or number of days.

Near-surface soil 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.

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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 refereed from Zhang, Y., et al. 2014.

Fig. 2. (A) Composite variations of FD 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 FD from 1956 through 2006 across China; center-top is histogram of changes in FD.

Fig. 3. (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.

Fig. 4. (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.

Fig. 5. (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.

Fig. 6. Trends of FD, LD, DR and NF at ~~(A)~~ west stations (the first row, longitude ≤ 110 °E) and ~~(B)~~ east stations (the second and third rows, longitude >110 °E) against latitude (°N) and altitude (10^3~~k~~m a.s.l.). We show only graphs passed significant test at least 95% confidential level. Solid cycles are data points, and lines are linear fitted lines. Symbol * indicates a significant trend at 95% confidential level.

Fig. 7. Relationship between of air temperature and (a) FD, (b) LD, (c) DR, and (d) NF from 1956 through 2006 across China. The solid circles are individual data points, and the lines are linear regression. Symbol * indicates a significant trend at 95% confidential level.

Fig. 8. Rates of urban expansion from 1990s through 2010s. (Reclassified from Wang et al. (2012))

Fig. 9. Regional changes of NF in regions with different urbanization rates (left). Black lines and red lines depict respectively the linear regression for the period after 1990 and the period since 1956. Symbol '*' indicates a statistically significant at 95% confidential level. Rights are number of stations used to create each time-series.