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

T. Zhang[1,2] , K. Wang[1] , and X. Zhong[3]

[1] College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China
[2] National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, Colorado 80309-0449, USA
[3] Laboratory of Remote Sensing and Geospatial Science, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

Correspondence to: T. Zhang (tjzhang@lzu.edu.cn)

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).

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. 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 long-term data from three stations in Indiana, USA, Sinha et al.

(2008) 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 at 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 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, last date, duration, and actual number of days 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. 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. In addition, we used Quantile-Quantile method to examine the distribution of residual is normal in order to ensure our linear hypothesis should be appropriate statistically (John, 2006; David, 2009). (To keep the paper short we did not include the results from statistical examinations.)

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. 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 a 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 during 1965–1975 are the lowest in our study period. An increase started from 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 our study period, the 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 were 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). 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 significant increase in NF occurred since the early 1970s. During the period from 1971 through the early 1990s, NF decreased slightly (–0.27 day/yr). The NF decrease for the period from 1971 through the end of our study period is –0.34 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-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-Tibetan Plateau (Cheng and Wu, 2007; Li et al., 2012; Wu and Zhang, 2008). However, it should be noted that the warming observed 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 0.13 and -0.063; Fig. 6), so that the first date of soil freeze toward more later in higher-altitude regions. Similarly, trends in NF relate significantly to altitude. Higher-altitude regions have greater decrease in NF.

In east China, latitude correlates with LD, DR, and NF, but altitude correlates to

NF (Fig. 6). 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 ± 0.76, –3.93 ± 0.82, –7.65 ± 1.25, and –6.55 ± 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 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.

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.

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.

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-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.

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).

References

Anandhi, A., Perumal, S., Gowda, P., Knapp, M., Hutchinson, S., Harrington, J., Jr., Murray, L., Kirkham, M., and Rice, C.: Long-term spatial and temporal trends in frost indices in Kansas, USA, Climatic Change, 120, 169-181, 10.1007/s10584-013-0794-4, 2013.

Barichivich, J., Briffa, K. R., Myneni, R. B., Osborn, T. J., Melvin, T. M., Ciais, P., Piao, S., and Tucker, C.: Large-scale variations in the vegetation growing season and annual cycle of atmospheric CO2 at high northern latitudes from 1950 to 2011, Global Change Biol., 19, 3167-3183, 10.1111/gcb.12283, 2013.

Cheng, G. D., and Wu, T. H.: Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau, J. Geophys. Res. Earth Surf., 112, F02S03, 10.1029/2006jf000631, 2007.

Cherkauer, K. A., and Lettenmaier, D. P.: Hydrologic effects of frozen soils in the upper Mississippi River basin, J. Geophys. Res. Atmos., 104, 19599-19610, 10.1029/1999JD900337, 1999.

CMA: Daily surface climatic dataset in China. China Meteorological Data Sharing Service System: Beijing, China, http://cdc.cma.gov.cn/, 2007a.

CMA: Specifications for surface meteorological observation, Part13: Measurement of soil temperature, China Meteorological Press: Beijing, China, 2007b.

Cornelissen, J. H. C., Van Bodegom, P. M., Aerts, R., Callaghan, T. V., Van Logtestijn, R. S. P., Alatalo, J., Stuart Chapin, F., Gerdol, R., Gudmundsson, J., Gwynn-Jones, D., Hartley, A. E., Hik, D. S., Hofgaard, A., Jónsdóttir, I. S., Karlsson, S., Klein, J. A., Laundre, J., Magnusson, B., Michelsen, A., Molau, U., Onipchenko, V. G., Quested, H. M., Sandvik, S. M., Schmidt, I. K., Shaver, G. R., Solheim, B., Soudzilovskaia, N. A., Stenström, A., Tolvanen, A., Totland, Ø., Wada, N., Welker, J. M., Zhao, X., and Team, M. O. L.: Global negative vegetation feedback to climate warming responses of leaf litter decomposition rates in cold biomes, Ecol. Lett., 10, 619-627, 10.1111/j.1461-0248.2007.01051.x, 2007.

David, F.: Statistical models: theory and practice (revised version), Cambridge University Press, Cambridge, United Kingdom, 2009.DeConto, R. M., Galeotti, S., Pagani, M., Tracy, D., Schaefer, K., Zhang, T., Pollard, D., and Beerling, D. J.: Past extreme warming events linked to massive carbon release from thawing permafrost, Nature, 484, 87-91, 10.1038/nature10929, 2012.

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

Edwards, K. A., and Jefferies, R. L.: Inter-annual and seasonal dynamics of soil microbial biomass and nutrients in wet and dry low-Arctic sedge meadows, Soil Biol. Biochem., 57, 83-90, 10.1016/j.soilbio.2012.07.018, 2013.

Entekhabi, D., Njoku, E. G., Houser, P., Spencer, M., Doiron, T., Yunjin, K., Smith, J., Girard, R., Belair, S., Crow, W., Jackson, T. J., Kerr, Y. H., Kimball, J. S., Koster, R., McDonald, K. C., O'Neill, P. E., Pultz, T., Running, S. W., Jiancheng, S., Wood, E., and Van Zyl, J.: The hydrosphere State (hydros) Satellite mission: an Earth system pathfinder for global mapping of soil moisture and land freeze/thaw, IEEE Trans. Geosci. Rem. Sens., 42, 2184-2195, 10.1109/TGRS.2004.834631, 2004.

Gilichinsky, D., and Wagener, S.: Microbial life in permafrost: A historical review, Permafrost Periglac., 6, 243-250, 10.1002/ppp.3430060305, 1995.

Heimann, M., and Reichstein, M.: Terrestrial ecosystem carbon dynamics and climate feedbacks, Nature, 451, 289-292, 2008.

Henry, H. A. L.: Climate change and soil freezing dynamics: historical trends and projected changes, Climatic Change, 87, 421-434, 10.1007/s10584-007-9322-8, 2008.

IPCC: Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on

Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535pp, 2013. doi:10.1017/CBO9781107415324.

IPCC-TGICA: General Guidelines on the use of Scenario Data for Climate Impact and Adaptation Assessment, Version 2. Intergovernmental Panel on Climate Change, Task Group on Scenarios for Climate Impact Assessment, 71pp, http://www.ipcc-data.org/guidelines/TGICA_guidance_sdciaa_v2_final.pdf, 2007.

Jarvis, A, Reuter, H, Nelson, A, Guevara, E.: Hole-filled SRTM for the globe Version 4. Available from the CGIAR-SXI SRTM 90m Edition, http://srtm.csi.cgiar.org, 2008.

John, R.: Mathematical statistics and data analysis (3rd edition), Cengage Learning, United States, 2006.

Jones, P., and Hulme, M.: Calculating regional climatic time series for temperature and precipitation: methods and illustrations, Int. J. Climatol., 16, 361-377, 10.1002/(SICI)1097-0088(199604)16:4<361::AID-JOC53>3.0.CO;2-F, 1996.

Kimball, J. S., McDonald, K. C., and Zhao, M.: Spring Thaw and Its Effect on Terrestrial Vegetation Productivity in the Western Arctic Observed from Satellite Microwave and Optical Remote Sensing, Earth Interact., 10, 1-22, 10.1175/EI187.1, 2006.

Koven, C. D., Ringeval, B., Friedlingstein, P., Ciais, P., Cadule, P., Khvorostyanov, D., Krinner, G., and Tarnocai, C.: Permafrost carbon-climate feedbacks accelerate global warming, Proc. Natl. Acad. Sci. Unit. States Am., 108, 14769-

14774, 10.1073/pnas.1103910108, 2011.

Kumar, N., Grogan, P., Chu, H., Christiansen, C., and Walker, V.: The Effect of Freeze-Thaw Conditions on Arctic Soil Bacterial Communities, Biology, 2, 356-377, 10.3390/biology2010356, 2013.

Li, X., Jin, R., Pan, X., Zhang, T., and Guo, J.: Changes in the near-surface soil freeze–thaw cycle on the Qinghai-Tibetan Plateau, Int. J. Appl. Earth Obs., 17, 33-42, 10.1016/j.jag.2011.12.002, 2012.

Lloyd, J., and Taylor, J.: On the temperature dependence of soil respiration, Funct. Ecol., 315-323, 1994.

Mastepanov, M., Sigsgaard, C., Dlugokencky, E. J., Houweling, S., Strom, L., Tamstorf, M. P., and Christensen, T. R.: Large tundra methane burst during onset of freezing, Nature, 456, 628-630, 10.1038/nature07464, 2008.

Menzel, A., Jakobi, G., Ahas, R., Scheifinger, H., and Estrella, N.: Variations of the climatological growing season (1951–2000) in Germany compared with other countries, Int. J. Climatol., 23, 793-812, 10.1002/joc.915, 2003.

Niu, G.-Y., and Yang, Z.-L.: Effects of Frozen Soil on Snowmelt Runoff and Soil Water Storage at a Continental Scale, J. Hydrometeorol., 7, 937-952, 10.1175/JHM538.1, 2006.

Rempel, A. W.: Hydromechanical Processes in Freezing Soils, Vadose Zone J., 11, 10.2136/vzj2012.0045, 2012.

Schimel, J. P., and Mikan, C.: Changing microbial substrate use in Arctic tundra soils through a freeze-thaw cycle, Soil Biol. Biochem., 37, 1411-1418, 10.1016/j.soilbio.2004.12.011, 2005.

Schuur, E. A., Vogel, J. G., Crummer, K. G., Lee, H., Sickman, J. O., and Osterkamp, T. E.: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra, Nature, 459, 556-559, 10.1038/nature08031, 2009.

Sinha, T., and Cherkauer, K. A.: Time Series Analysis of Soil Freeze and Thaw Processes in Indiana, J. Hydrometeorol., 9, 936-950, 10.1175/2008JHM934.1, 2008.

Su, Z., Wen, J., Dente, L., van der Velde, R., Wang, L., Ma, Y., Yang, K., and Hu, Z.: The Tibetan Plateau observatory of plateau scale soil moisture and soil temperature (Tibet-Obs) for quantifying uncertainties in coarse resolution satellite and model products, Hydrol. Earth Syst. Sci., 15, 2303-2316, 10.5194/hess-15-2303-2011, 2011.

Tagesson, T., Mölder, M., Mastepanov, M., Sigsgaard, C., Tamstorf, M. P., Lund, M., Falk, J. M., Lindroth, A., Christensen, T. R., and Ström, L.: Land-atmosphere exchange of methane from soil thawing to soil freezing in a high-Arctic wet tundra ecosystem, Global Change Biol., 18, 1928-1940, 10.1111/j.1365-2486.2012.02647.x, 2012.

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.

Wu, Q., and Zhang, T.: Recent permafrost warming on the Qinghai-Tibetan Plateau, J.

Geophys. Res. Atmos., 113, D13108, 10.1029/2007JD009539, 2008.

Yang, K., Qin, J., Zhao, L., Chen, Y., Tang, W., Han, M., Lazhu, Chen, Z., Lv, N., Ding, B., Wu, H., and Lin, C.: A Multiscale Soil Moisture and Freeze–Thaw Monitoring Network on the Third Pole, Bull. Am. Meteorol. Soc., 94, 1907-1916, 10.1175/BAMS-D-12-00203.1, 2013.

Zhang, T., Barry, R. G., Gilichinsky, D., Bykhovets, S., Sorokovikov, V., and Ye, J.: An amplified signal of climatic change in soil temperatures during the last century at Irkutsk, Russia, Climatic Change, 49, 41-76, 10.1023/A:1010790203146, 2001.

Zhang, Y., Li, B., and Zheng, D.: A Discussion on the Boundary and Area of the Tibetan Plateau in China (DBATP), DOI:10.3974/geodb.2014.01.12.V1, 2014.

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.

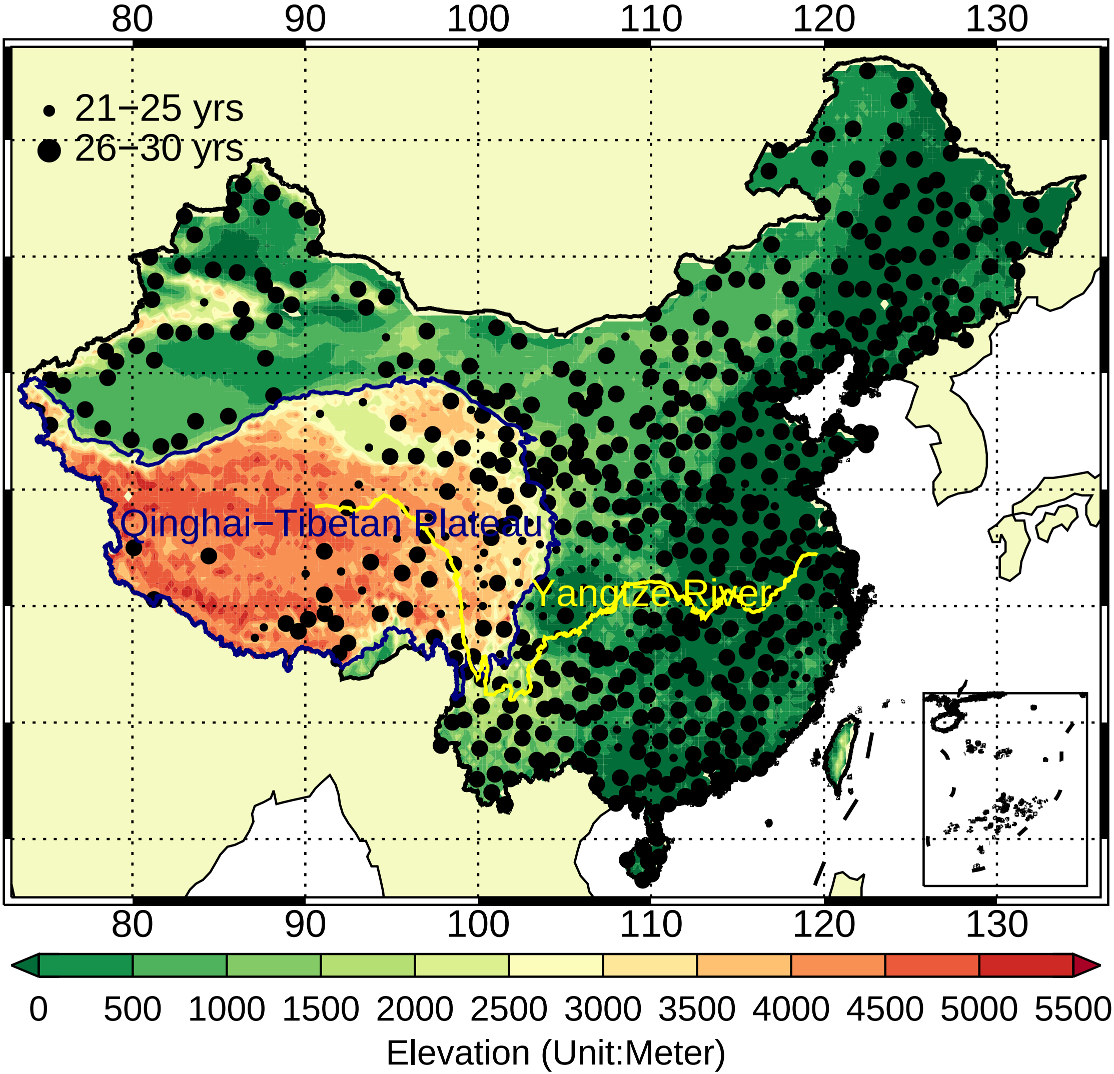
Fig. 6. Trends of FD, LD, DR and NF at west stations (the first row, longitude ≤ 110 ˚E) and east stations (the second and third rows, longitude >110 ˚E) against latitude (˚N) and altitude (10^3m a.s.l). We show only graphs passed significant test at least 95% confidential level. Solid cycles are data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

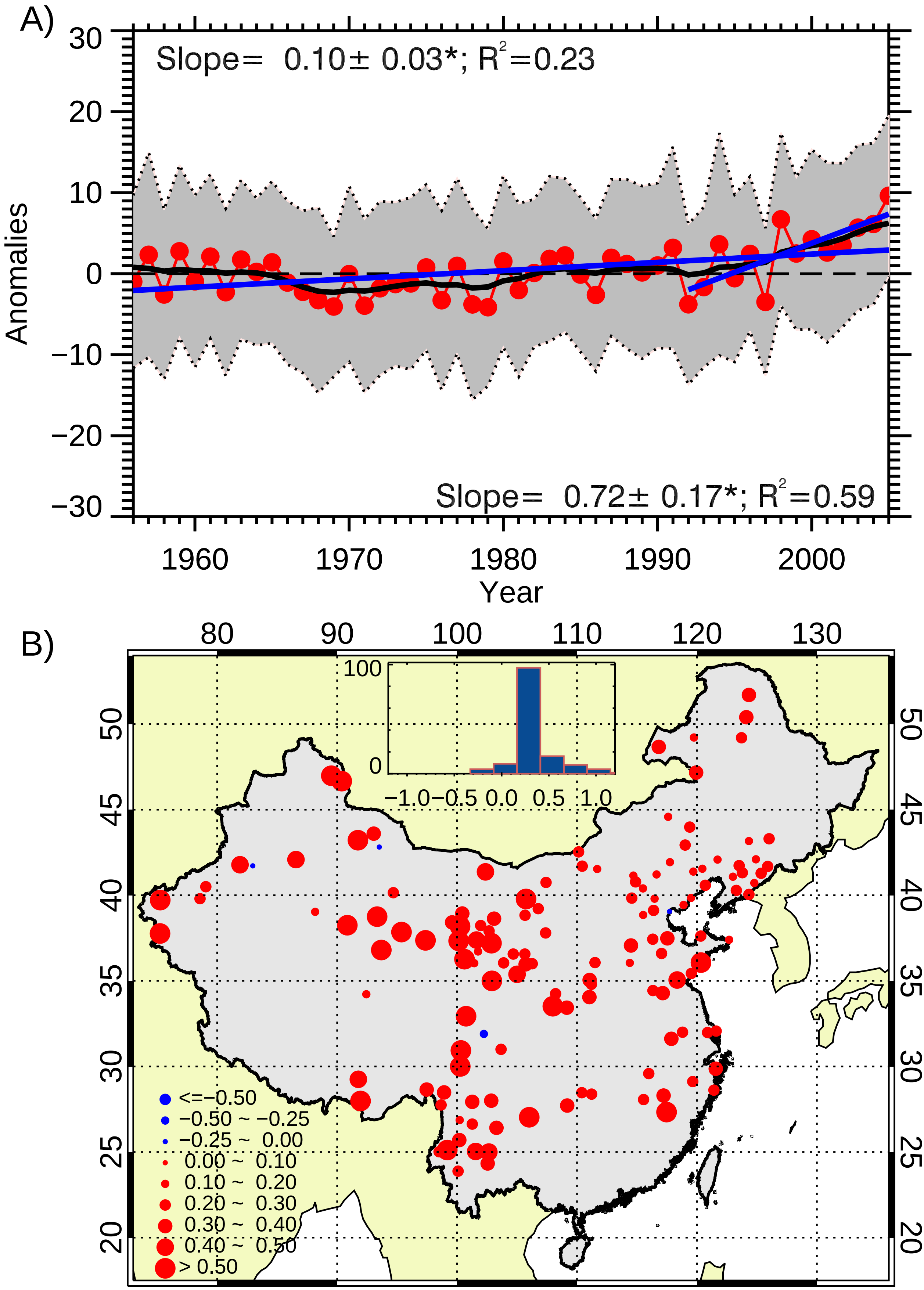
Fig. 7. Relationship between of air temperature and (a) FD, (b) LD, (c) DR, and (d) NF from 1956 through 2006 across China. The solid circles are individual data points, and the lines are linear regression. Symbol * indicates a significant trend at 95% confidential level.

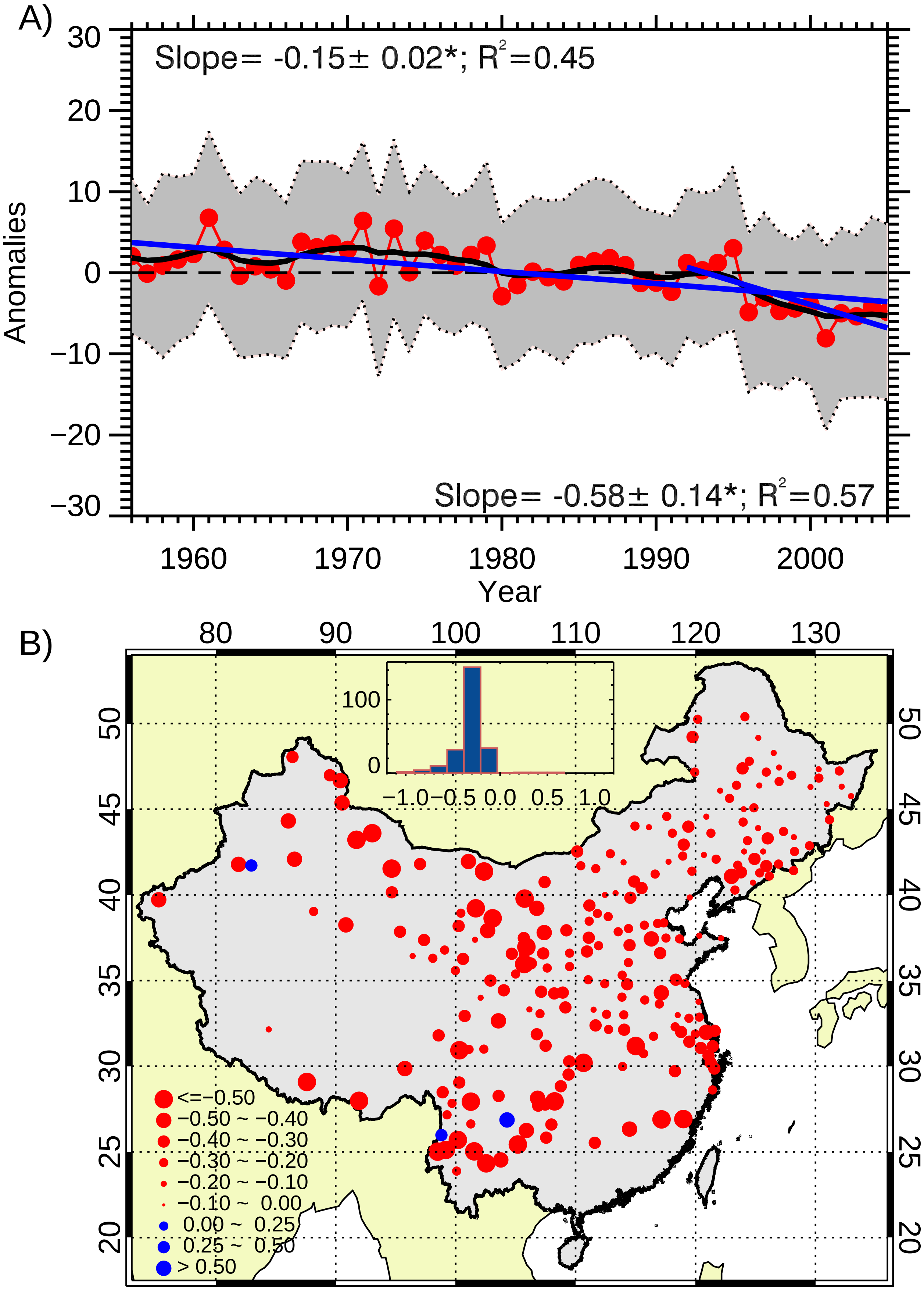
Fig. 8. Rates of urban expansion from 1990s through 2010s. (Reclassified from Wang

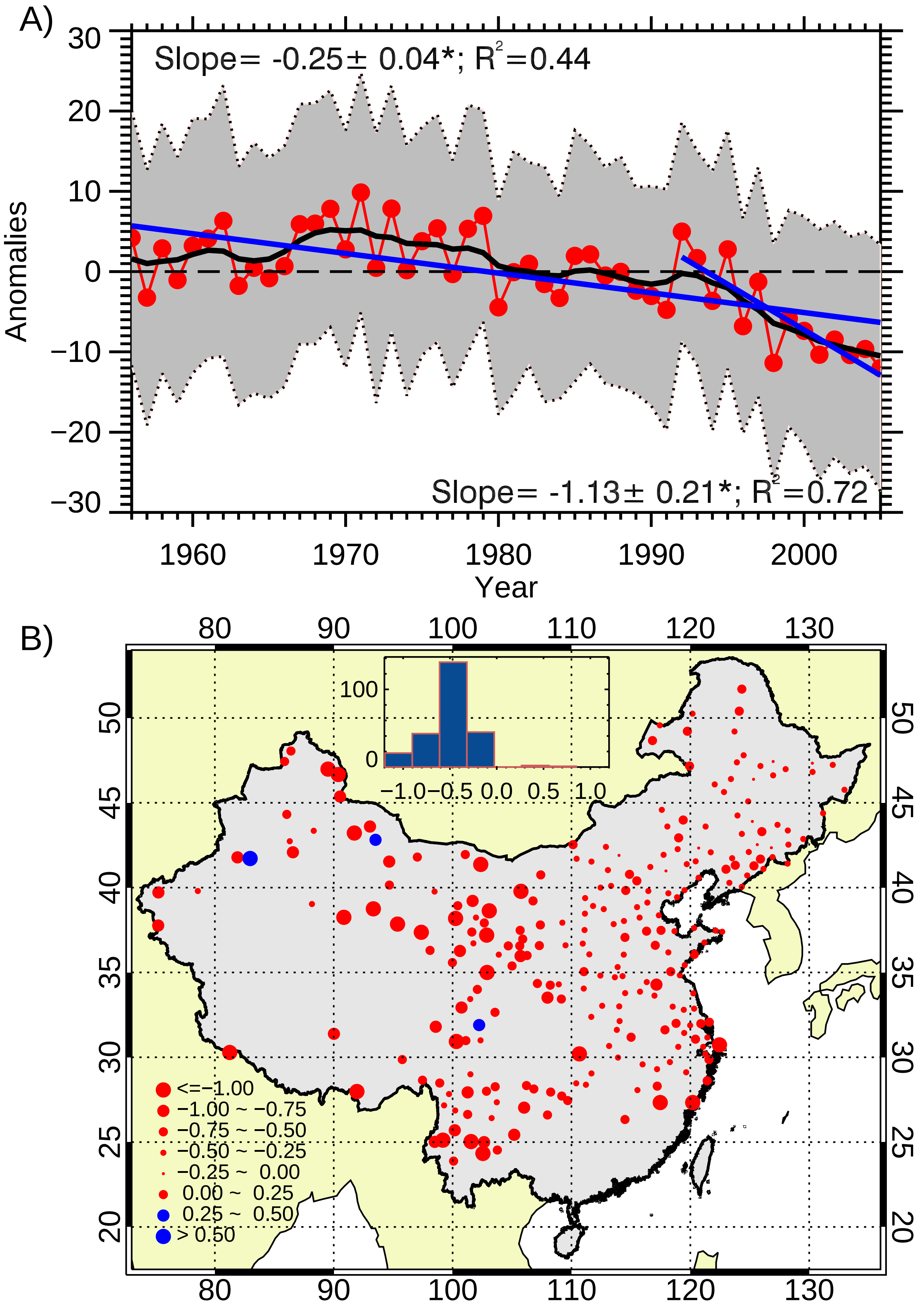
et al. (2012))

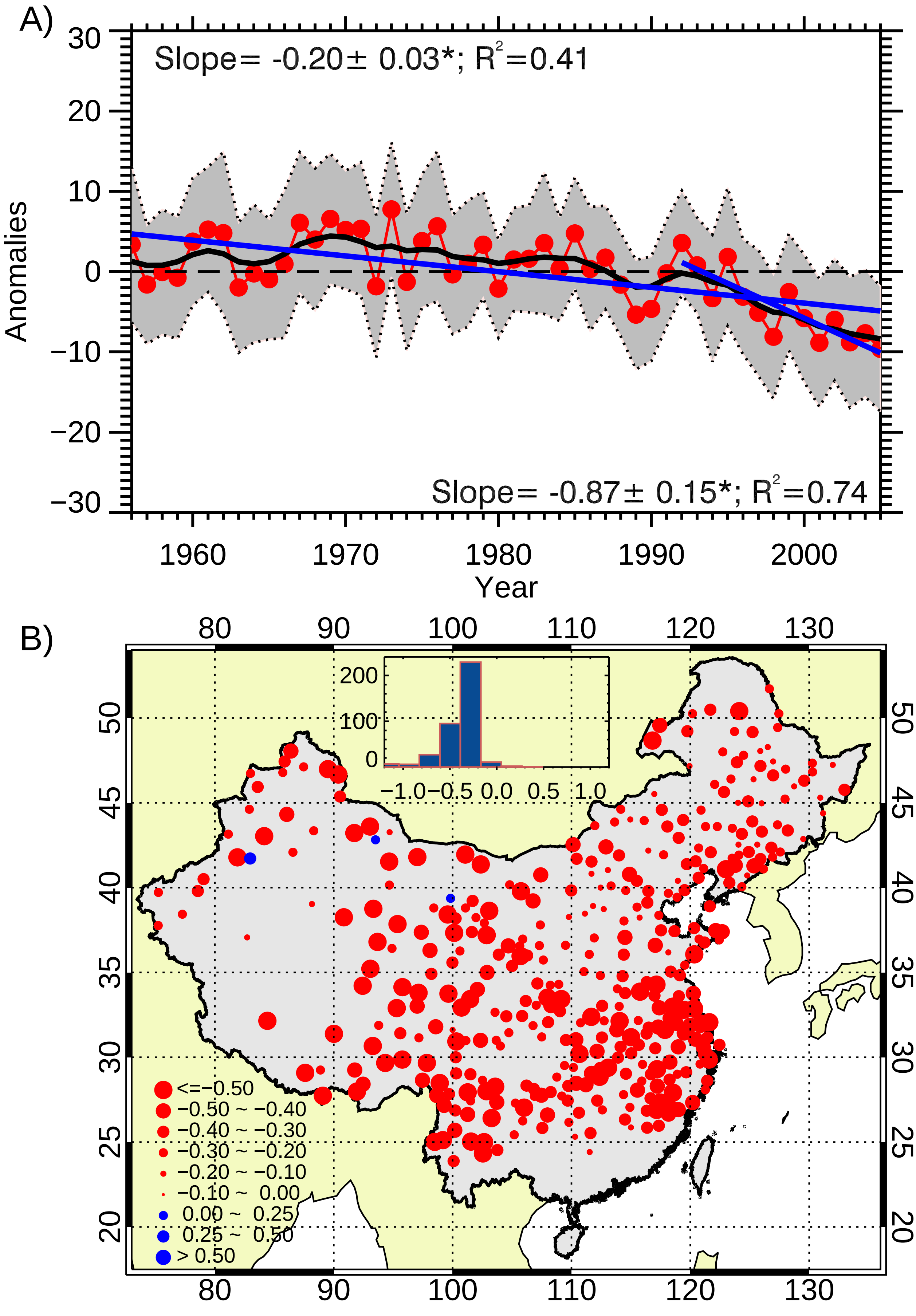
Fig. 9. Regional changes of NF in regions with different urbanization rates (left). Black lines and red lines depict respectively the linear regression for the period after 1990 and the period since 1956. Symbol '*' indicates a statistically significant at 95% confidential level. Rights are number of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


80
90
100
110
120
130
50
45
40
35
30
25
20
● 21−25 yrs
● 26−30 yrs
Qinghai−Tibetan Plateau
Yangtze River
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
Elevation (Unit:Meter)

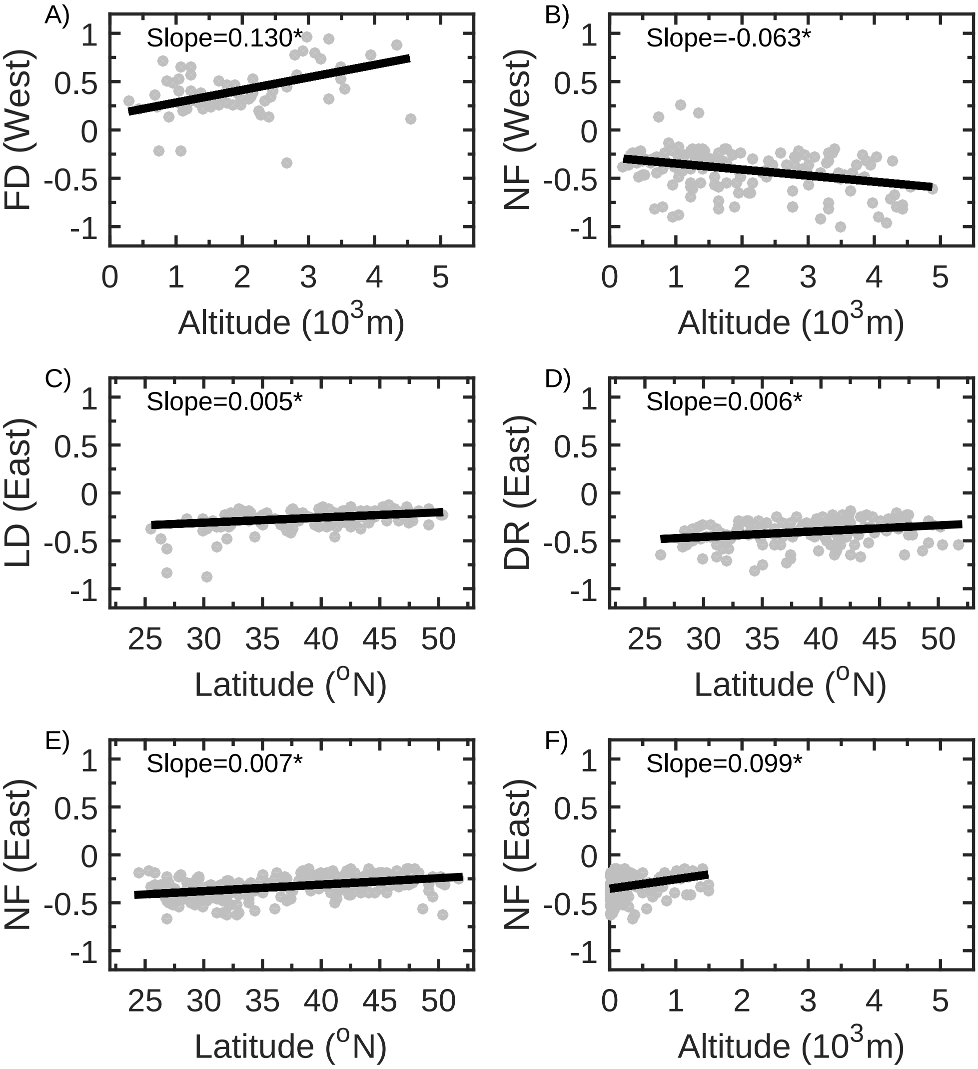

A)
Slope= 0.10± 0.03*; R²=0.23
Slope= 0.72± 0.17*; R²=0.59
Anomalies
30
20
10
0
−10
−20
−30
1960
1970
1980
1990
2000
Year
B)
80
90
100
110
120
130
50
45
40
35
30
25
20
100
0
−1.0
−0.5
0.0
0.5
1.0
<=−0.50
−0.50 ~ −0.25
−0.25 ~ 0.00
0.00 ~ 0.10
0.10 ~ 0.20
0.20 ~ 0.30
0.30 ~ 0.40
0.40 ~ 0.50
> 0.50

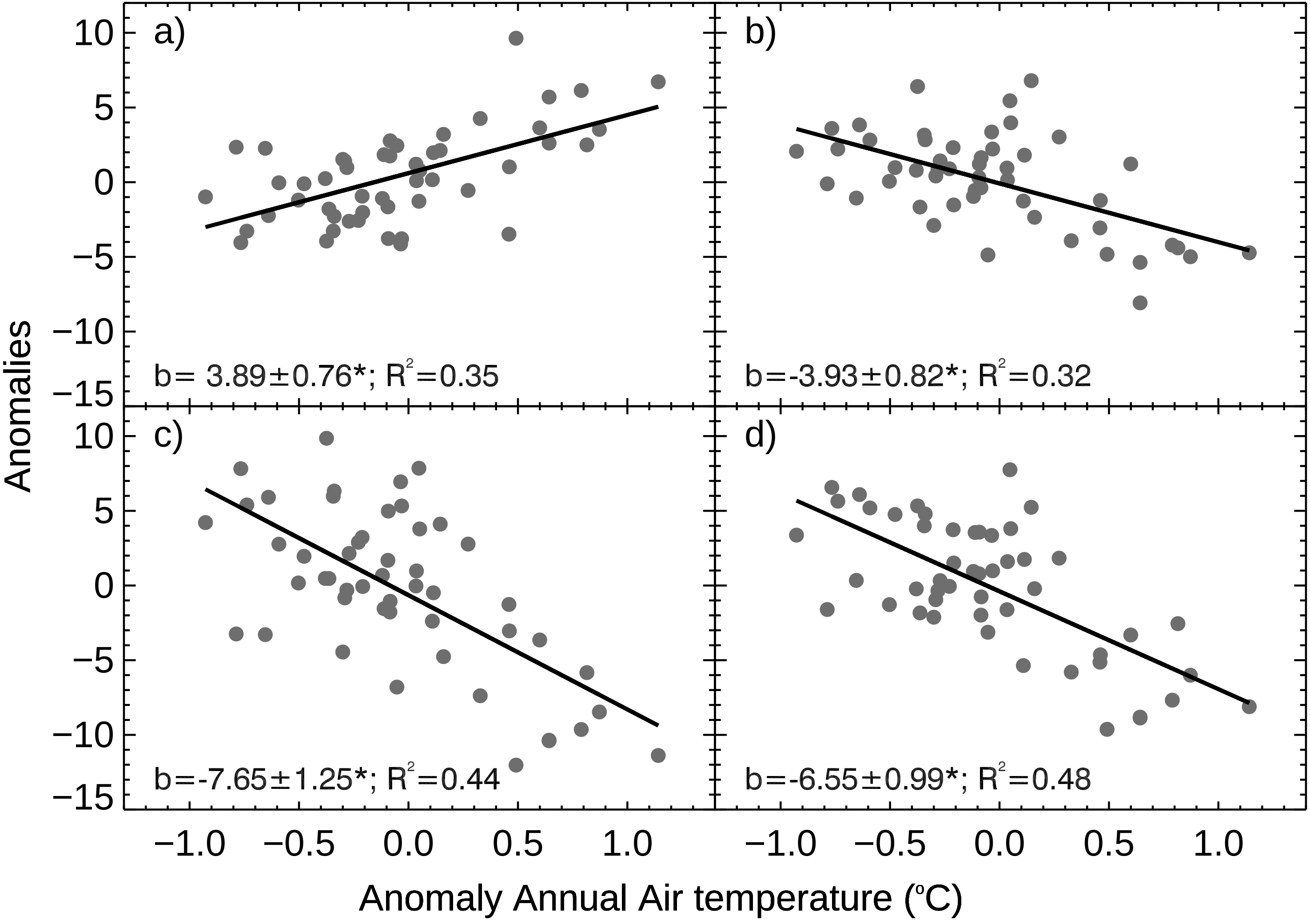

A)
Slope= -0.15± 0.02*; R²=0.45
Slope= -0.58± 0.14*; R²=0.57
Anomalies
30
20
10
0
−10
−20
−30
1960
1970
1980
1990
2000
Year
B)
80
90
100
110
120
130
50
45
40
35
30
25
20
100
0
−1.0
−0.5
0.0
0.5
1.0
<=−0.50
−0.50 ~ −0.40
−0.40 ~ −0.30
−0.30 ~ −0.20
−0.20 ~ −0.10
−0.10 ~ 0.00
0.00 ~ 0.25
0.25 ~ 0.50
> 0.50

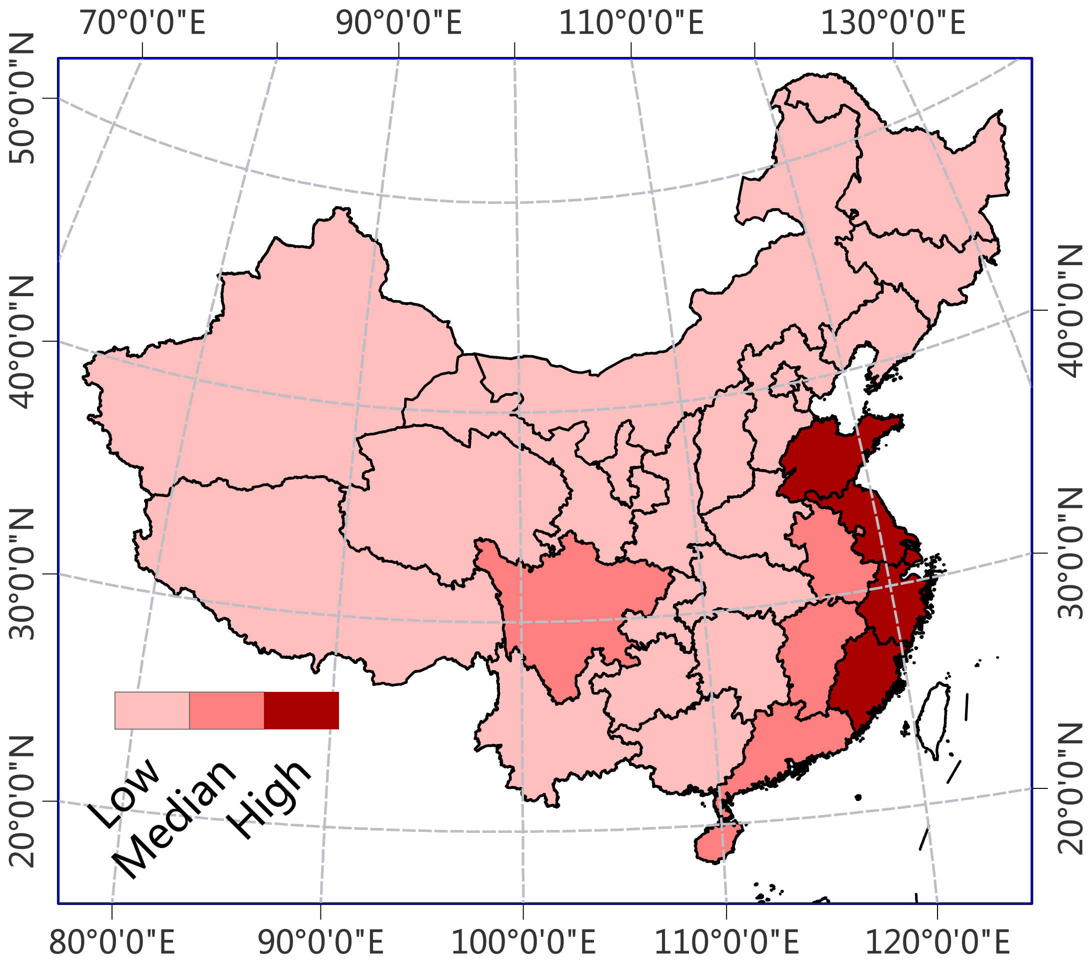

A)
Slope= -0.25± 0.04*; R²=0.44
Slope= -1.13± 0.21*; R²=0.72
Anomalies
30
20
10
0
−10
−20
−30
1960
1970
1980
1990
2000
Year
B)
80
90
100
110
120
130
50
45
40
35
30
25
20
100
0
−1.0
−0.5
0.0
0.5
1.0
<=−1.00
−1.00 ~ −0.75
−0.75 ~ −0.50
−0.50 ~ −0.25
−0.25 ~ 0.00
0.00 ~ 0.25
0.25 ~ 0.50
> 0.50

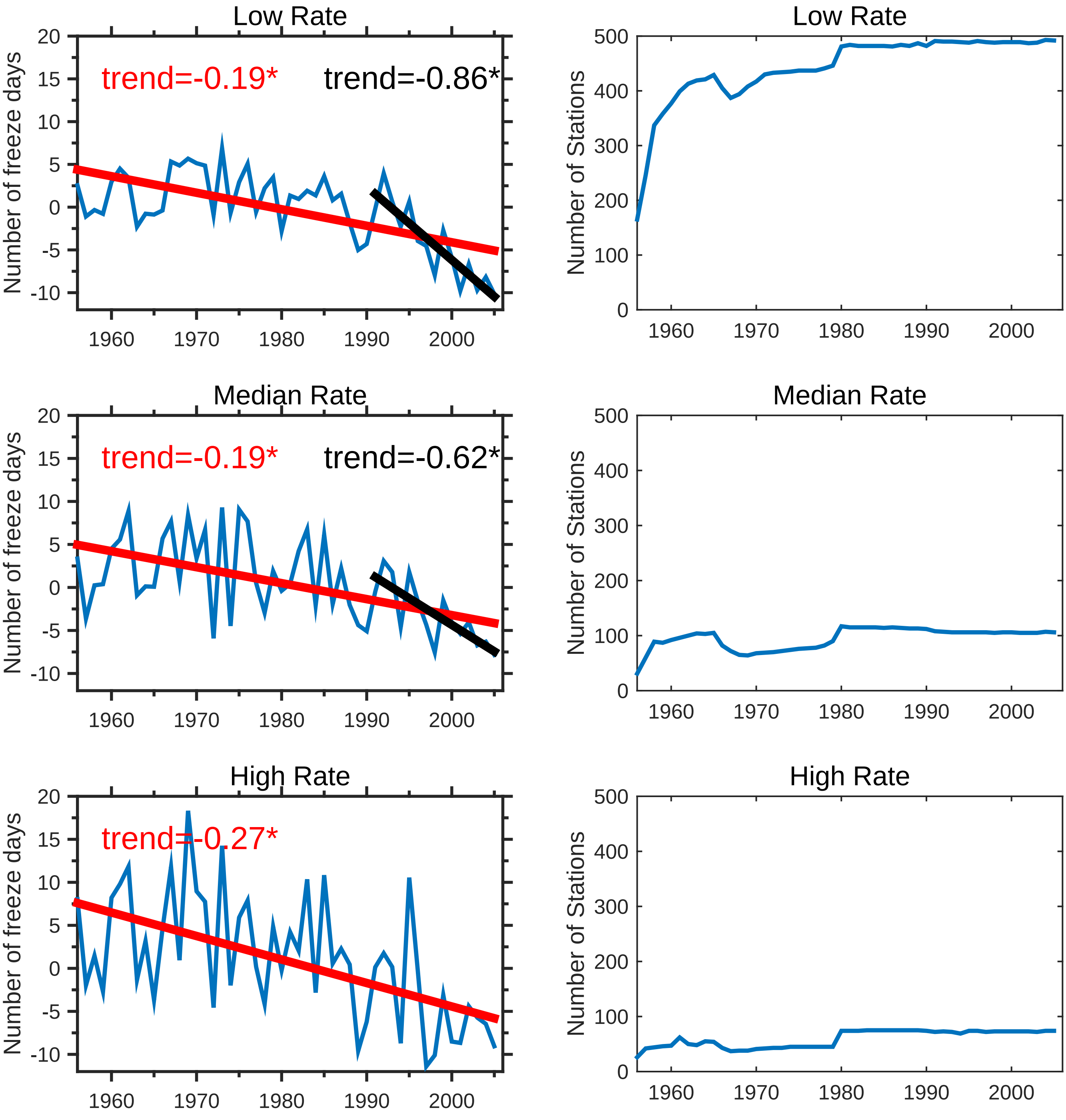


A)
Slope= -0.20± 0.03*; R^2=0.41
Slope= -0.87± 0.15*; R^2=0.74
Anomalies
30
20
10
0
−10
−20
−30
1960
1970
1980
1990
2000
Year
B)
80
90
100
110
120
130
50
45
40
35
30
25
20
200
100
0
−1.0
−0.5
0.0
0.5
1.0
<=−0.50
−0.50 ~ −0.40
−0.40 ~ −0.30
−0.30 ~ −0.20
−0.20 ~ −0.10
−0.10 ~ 0.00
0.00 ~ 0.25
0.25 ~ 0.50
> 0.50


A)
Slope=0.130*
FD (West)
Altitude (10^3m)
B)
Slope=-0.063*
NF (West)
Altitude (10^3m)
C)
Slope=0.005*
LD (East)
Latitude (^oN)
D)
Slope=0.006*
DR (East)
Latitude (^oN)
E)
Slope=0.007*
NF (East)
Latitude (^oN)
F)
Slope=0.099*
NF (East)
Altitude (10^3m)
1
0.5
0
-0.5
-1
0
1
2
3
4
5
25
30
35
40
45
50


a)
b)
c)
d)
b= 3.89±0.76*; R²=0.35
b=-3.93±0.82*; R²=0.32
b=-7.65±1.25*; R²=0.44
b=-6.55±0.99*; R²=0.48
10
5
0
−5
−10
−15
−1.0
−0.5
0.0
0.5
1.0
Anomalies
Anomaly Annual Air temperature (ºC)


70°0'0"E
90°0'0"E
110°0'0"E
130°0'0"E
50°0'0"N
40°0'0"N
30°0'0"N
20°0'0"N
40°0'0"N
30°0'0"N
20°0'0"N
Low
Median
High
80°0'0"E
90°0'0"E
100°0'0"E
110°0'0"E
120°0'0"E


Low Rate
trend=-0.19*
trend=-0.86*
Median Rate
trend=-0.19*
trend=-0.62*
High Rate
trend=-0.27*
Number of freeze days
20
15
10
5
0
-5
-10
1960
1970
1980
1990
2000
Number of Stations
500
400
300
200
100
0