The Cryosphere Discuss., 8, 3785–3809, 2014
www.the-cryosphere-discuss.net/8/3785/2014/
doi:10.5194/tcd-8-3785-2014

The Cryosphere
Discussions
Open Access

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

Received: 27 May 2014 – Accepted: 2 July 2014 – Published: 15 July 2014

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

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The near-surface soil freeze/thaw status is an important indicator of climate change. Using data from 636 meteorological stations, with a 0 °C 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 ($0.10 \pm 0.03\,\mathrm{day\,yr^{-1}}$) and the last datewas advanced 7 days ($0.15 \pm 0.02\,\mathrm{day\,yr^{-1}}$) 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 °C 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 °C to +0.5 °C (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. Long-term data from three stations in Indiana, USA, 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). 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 °C to 0 °C (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 °C) 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 soil freeze across China, and also the spatial characteristics across stations, based on a 0 °C threshold. We then 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 °C 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).

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 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 °C. 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 °C. 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 °C.

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, a year with at least 300 daily records (more than 75 % of a year) could be utilized in the annual indices. 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, FD increased significantly across China by nearly 5 days, or a trend of $0.10 \pm 0.03\,\mathrm{day\,yr^{-1}}$, 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. FD decreased, but insignificantly, before the 1970s ($-0.20\,\mathrm{day\,yr^{-1}}$, $p = 0.14$) and changes during 1965–1975 are the lowest in our study period. A major increase in FD appeared after the early 1970s (0.21 day yr^{-1}). However, the greatest increase in FD (0.72 ± 0.17 day yr^{-1}) 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^{-1}, $p = 0.45$).

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^{-1} (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 day yr^{-1} (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^{-1} (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 appearedafter the early 1990s, with alinear trend of -0.58 ± 0.14 day yr^{-1}; 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^{-1} (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 dramatically 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 $-0.25 \pm 0.04\,\text{day}\,\text{yr}^{-1}$ (Fig. 4a). DR increased, but statistically insignificantly, from 1956 through 1970 ($-0.27\,\text{day}\,\text{yr}^{-1}$, $P = 0.18$). Anomalies during 1966–1980 were higher over the entire study period. The most significant decrease in DR appeared mainly after the 1970s ($-0.43\,\text{day}\,\text{yr}^{-1}$). Since the early 1990s, DR has decreased sharply ($-1.13 \pm 0.21\,\text{day}\,\text{yr}^{-1}$) (Fig. 4a), by almost 16 days.The overall variation in DR ($-0.25\,\text{day}\,\text{yr}^{-1}$) is similar to the variation in FD ($0.10\,\text{day}\,\text{yr}^{-1}$) and LD ($-0.15\,\text{day}\,\text{yr}^{-1}$). 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 $< -0.50\,\text{day}\,\text{yr}^{-1}$ (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 $\leq 0\,^{\circ}\text{C}$.

NF decreased by almost 10 days ($-0.20 \pm 0.03\,\text{day}\,\text{yr}^{-1}$) 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 insignificant increase in NF occurred from 1956 to 1970 ($0.30\,\text{day}\,\text{yr}^{-1}$,

$P = 0.10$), but NF decreased after the early 1970s. During the period from 1971 through the early 1990s, NF decreased slightly ($-0.27\,\mathrm{day\,yr^{-1}}$, $P = 0.02$). The NF decrease for the period from 1971 through the end of our study period is $-0.34\,\mathrm{day\,yr^{-1}}$, with a decrease of $-0.87\,\mathrm{day\,yr^{-1}}$ 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 ($\sim 60\,\%$ 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 $-0.20\,\mathrm{day\,yr^{-1}}$ (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: Qinghai-Tibet Plateau in the west, and the lower reaches of the Yangtze River in east China. Previous studies have indicated that more warming has more pronounced effects in high-altitude regions, such as the Qinghai-Tibet Plateau (Cheng and Wu, 2007; Li et al., 2012; Wu and Zhang, 2008). However, it should be noted that the warming observede in the lower reaches of the Yangtze River is probably a result of urbanization.

3.5 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; Fig. 6a), so that the first date of soil freezeis later in higher-altitude regions. Similarly, trends in NF relate significantly to altitude. Higher-altitude regions have lower NF values.

In east China, latitude correlates with LD, DR, and NF, but altitude correlates to NF (Fig. 6b). 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 thatthe timing and duration of near-surface soil freeze correlates with increasing air temperature. Correlations with FD and LD are smaller than those of DR and NF. In addition, we found that R^2 of soil freeze timing (FD and LD) is less than R^2 of soil freeze duration (DR and NF). This implies that air temperature is a more effectively indicator of freeze duration (i.e., DR and NF). The probable reason for this is that the timing statistics used in this study may be influenced by extreme weather events in some years. For example, an incidental cold event in the fall could delay or advance the first soil freezeby several days. Similar differences in R^2 exist between DR and NF.

4 Discussion

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 ($0.10\,\mathrm{day\,yr^{-1}}$) 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^{-1}), than Li et al. (2012) results from the Qinghai-Tibetan Plateau (10 days, ~ 0.50 day yr^{-1}) 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^{-1}) over our study period Li et al. (2012) showed a later date of soil freeze (by ~ 14 days; ~ 0.70 day yr^{-1}) from 1988 to 2007. We found more change in FD in China since the early 1990s (0.58 day yr^{-1}). The last freeze date in Kansas, USA, occurred earlier (by 0.01–0.19 day yr^{-1}) 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^{-1} 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^{-1} 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 (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 growng 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.

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 ($0.10 \pm 0.03\,\mathrm{day\,yr^{-1}}$) 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 ($0.15 \pm 0.02\,\mathrm{day\,yr^{-1}}$) over our study period. Near-surface soil freeze occurred earlier by of $-0.58 \pm 0.14\,\mathrm{day\,yr^{-1}}$ 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 ($-0.20 \pm 0.03\,\mathrm{day\,yr^{-1}}$) for the period 1956–2006. The decrease in the number of freeze days has been $-0.87 \pm 0.15\,\mathrm{day\,yr^{-1}}$ since the early 1990s. There are two regions in China with the most changes in NF: the Qinghai-Tibet Plateau and the lower reaches of the Yangtze Basin.

- Air 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. 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 Jr., J., Murray, L., Kirkham, M., and Rice, C.: Long-term spatial and temporal trends in frost indices in Kansas, USA, Climatic Change, 120, 169–181, doi:10.1007/s10584-013-0794-4, 2013.

Baker, D. G. and Ruschy, D. L.: Calculated and measured air and soil freeze–thaw frequencies, J. Appl. Meteorol., 34, 2197–2205, doi:10.1175/1520-0450(1995)034<2197:CAMAAS>2.0.CO;2, 1995.

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, Glob. Change Biol., 19, 3167–3183, doi: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.-Ea. Surf., 112, F02S03, doi: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, doi:10.1029/1999JD900337, 1999.

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, doi:10.1111/j.1461-0248.2007.01051.x, 2007.

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, doi:10.1038/nature10929, 2012.

DeLuca, T. H., Keeney, D. R., and McCarty, G. W.: Effect of freeze–thaw events on mineralization of soil nitrogen, Biol. Fertil. Soils, 14, 116–120, doi:10.1007/BF00336260, 1992.

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, doi: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 T. Geosci. Remote, 42, 2184–2195, doi:10.1109/TGRS.2004.834631, 2004.

Fitzhugh, R., Driscoll, C., Groffman, P., Tierney, G., Fahey, T., and Hardy, J.: Effects of soil freezing disturbance on soil solution nitrogen, phosphorus, and carbon chemistry in a northern hardwood ecosystem, Biogeochemistry, 56, 215–238, doi:10.1023/A:1013076609950, 2001.

Gilichinsky, D. and Wagener, S.: Microbial life in permafrost: a historical review, Permafrost Periglac., 6, 243–250, doi: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, doi:10.1007/s10584-007-9322-8, 2008.

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

Kim, Y., Kimball, J. S., McDonald, K. C., and Glassy, J.: Developing a global data record of daily landscape freeze/thaw status using satellite passive microwave remote sensing, IEEE T. Geosci. Remote, 49, 949–960, doi:10.1109/TGRS.2010.2070515, 2011.

Kim, Y., Kimball, J. S., Zhang, K., and McDonald, K. C.: Satellite detection of increasing Northern Hemisphere non-frozen seasons from 1979 to 2008: implications for regional vegetation growth, Rem. Sens. Environ., 121, 472–487, doi:10.1016/j.rse.2012.02.014, 2012.

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, doi:10.1175/EI187.1, 2006.

Knorr, W., Prentice, I. C., House, J. I., and Holland, E. A.: Long-term sensitivity of soil carbon turnover to warming, Nature, 433, 298–301, doi:10.1038/nature03226, 2005.

Knox, J. C.: Agricultural influence on landscape sensitivity in the Upper Mississippi River Valley, Catena, 42, 193–224, doi:10.1016/S0341-8162(00)00138-7, 2001.

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, P. Natl. Acad. Sci. USA, 108, 14769–14774, doi: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, doi: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, doi: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, doi:10.1038/nature07464, 2008.

McDonald, K. C., Kimball, J. S., Njoku, E., Zimmermann, R., and Zhao, M.: Variability in springtime thaw in the terrestrial high latitudes: monitoring a major control on the biospheric assimilation of atmospheric CO_2 with spaceborne microwave remote sensing, Earth Interact., 8, 1–23, doi:10.1175/1087-3562(2004)8<1:VISTIT>2.0.CO;2, 2004.

McDonald, K. C. and Kimball, J. S.: Estimation of surface freeze–thaw states using microwave sensors, in: Encyclopedia of Hydrological Sciences, edited by: Anderson, M. G. and McDonnell, J. J., John Wiley & Sons, Ltd, UK, 783–797, 2005.

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, doi:10.1002/joc.915, 2003.

Mintz, Y. and Serafini, Y. V.: A global monthly climatology of soil moisture and water balance, Clim. Dynam., 8, 13–27, doi:10.1007/BF00209340, 1992.

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, doi:10.1175/JHM538.1, 2006.

Poutou, E., Krinner, G., Genthon, C., and Noblet-Ducoudré, N.: Role of soil freezing in future boreal climate change, Clim. Dynam., 23, 621–639, doi:10.1007/s00382-004-0459-0, 2004.

Rempel, A. W.: Hydromechanical processes in freezing soils, Vadose Zone J., 11, doi: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, doi:10.1016/j.soilbio.2004.12.011, 2005.

Schimel, J., Kielland, K., and Chapin III, F.: Nutrient availability and uptake by tundra plants, in: Landscape Function and Disturbance in Arctic Tundra, Springer, Germany, 203–221, 1996.

Schuur, E. A., Bockheim, J., Canadell, J. G., Euskirchen, E., Field, C. B., Goryachkin, S. V., Hagemann, S., Kuhry, P., Lafleur, P. M., and Lee, H.: Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle, BioScience, 58, 701–714, doi:10.1641/B580807, 2008.

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, doi: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, doi:10.1175/2008JHM934.1, 2008.

Smith, N. V., Saatchi, S. S., and Randerson, J. T.: Trends in high northern latitude soil freeze and thaw cycles from 1988 to 2002, J. Geophys. Res. Atmos., 109, D12101, doi:10.1029/2003JD004472, 2004.

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, doi: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, Glob. Change Biol., 18, 1928–1940, doi:10.1111/j.1365-2486.2012.02647.x, 2012.

Viterbo, P., Beljaars, A., Mahfouf, J.-F., and Teixeira, J.: The representation of soil moisture freezing and its impact on the stable boundary layer, Q. J. Roy. Meteor. Soc., 125, 2401–2426, doi:10.1002/qj.49712555904, 1999.

Walker, G.: A world melting from the top down, Nature, 446, 718–221, doi:10.1038/446718a, 2007.

Wang, G., Hu, H., and Li, T.: The influence of freeze–thaw cycles of active soil layer on surface runoff in a permafrost watershed, J. Hydrol., 375, 438–449, doi:10.1016/j.jhydrol.2009.06.046, 2009.

Williams, P. J. and Smith, M. W.: The Frozen Earth: Fundamentals of Geocryology, Cambridge University Press, Cambridge, UK, 1989.

Wu, Q. and Zhang, T.: Recent permafrost warming on the Qinghai-Tibetan Plateau, J. Geophys. Res. Atmos., 113, D13108, doi: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, B. Am. Meteorol. Soc., 94, 1907–1916, doi:10.1175/BAMS-D-12-00203.1, 2013.

Zhang, T. and Armstrong, R. L.: Soil freeze/thaw cycles over snow-free land detected by passive microwave remote sensing, Geophys. Res. Lett., 28, 763–766, doi:10.1029/2000GL011952, 2001.

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, doi:10.1023/A:1010790203146, 2001.

Zhang, T., Barry, R. G., and Armstrong, R. L.: Application of satellite remote sensing techniques to frozen ground studies, Polar Geogr., 28, 163–196, doi:10.1080/789610186, 2004.

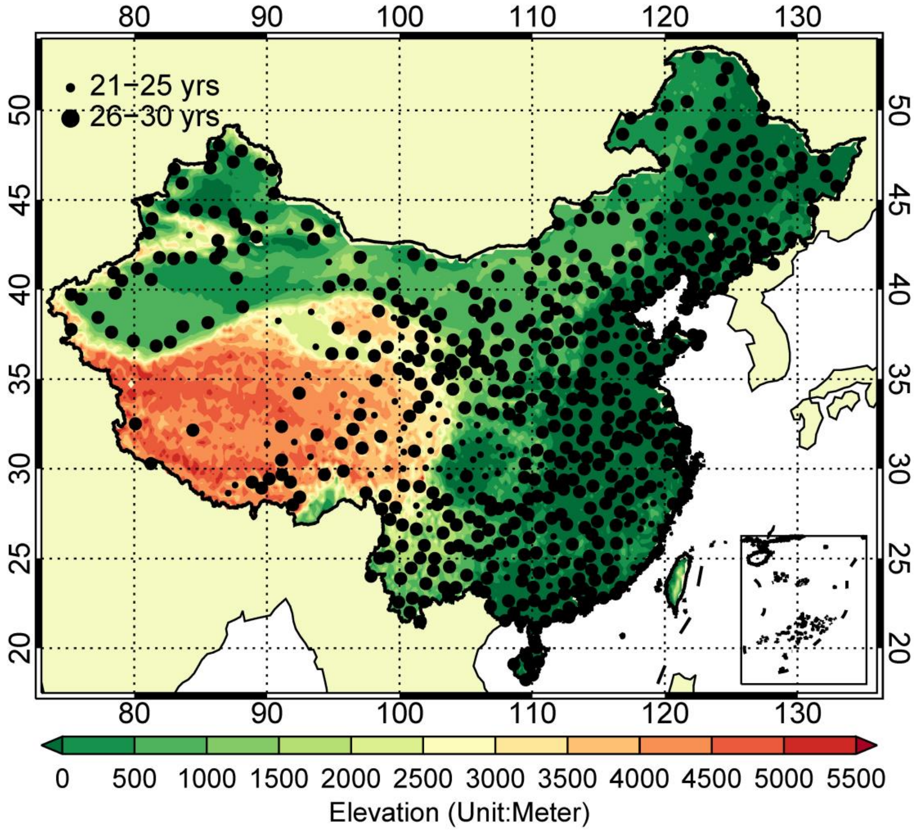

Figure 1. Map of meteorological stations across China used in this study. Background reflects elevation, and sizes of circles reflect data availability during the period from July 1971 to June 2001.

TCD
8, 3785–3809, 2014

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

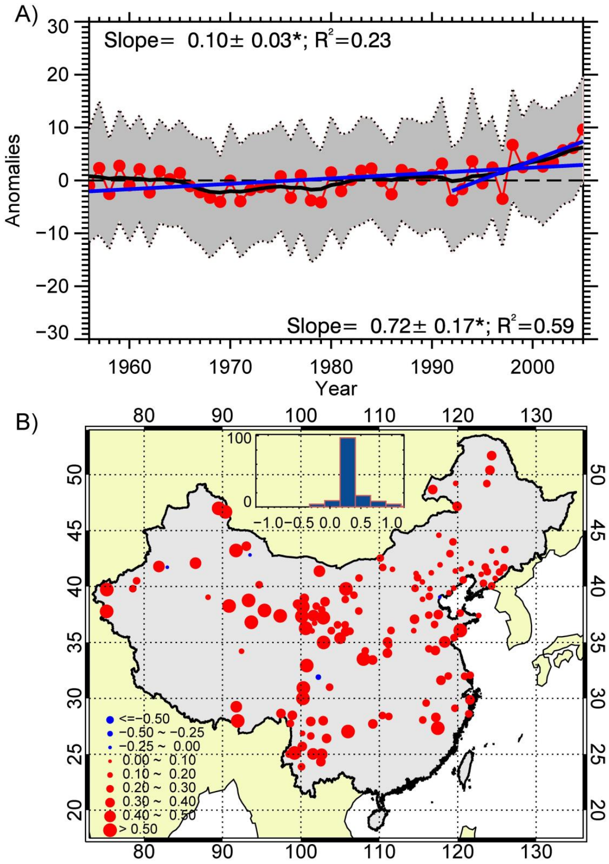

Figure 2. (A) Composite variations of FD from 1956 through 2006 across China. The red line with solid circles is data line. Blue lines are linear trends, and black line represents a low-pass filter with a cut-off frequency of 0.09. Symbol * indicates a significant trend at 95 % confidential level. **(B)** Changes in FD from 1956 through 2006 across China; center-top is histogram of changes in FD.

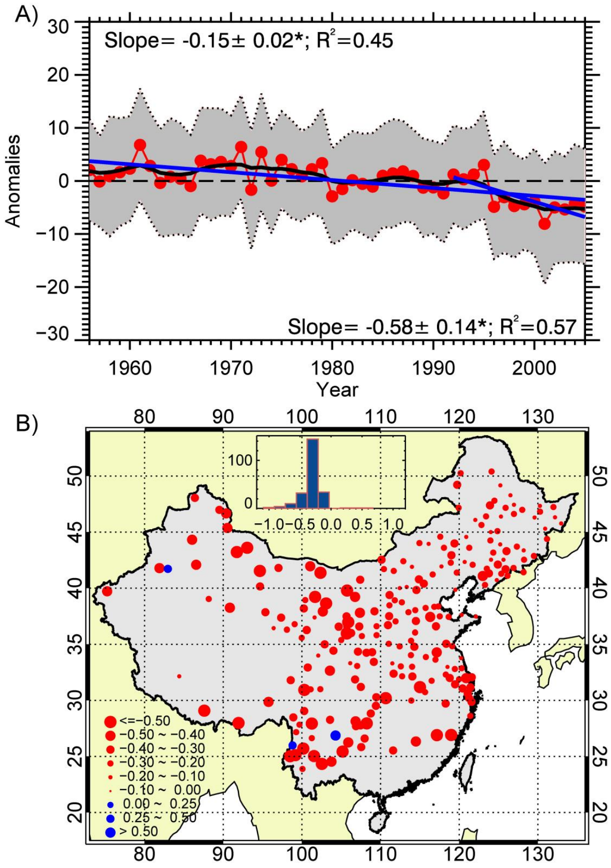

Figure 3. (A) Composite variations of LD from 1956 through 2006 across China. The red line with solid circles is data line. Blue lines are linear trends, and black line represents a low-pass filter with a cut-off frequency of 0.09. Symbol * indicates a significant trend at 95 % confidential level. **(B)** Changes in LD from 1956 through 2006 across China; center-top is histogram of changes in LD.

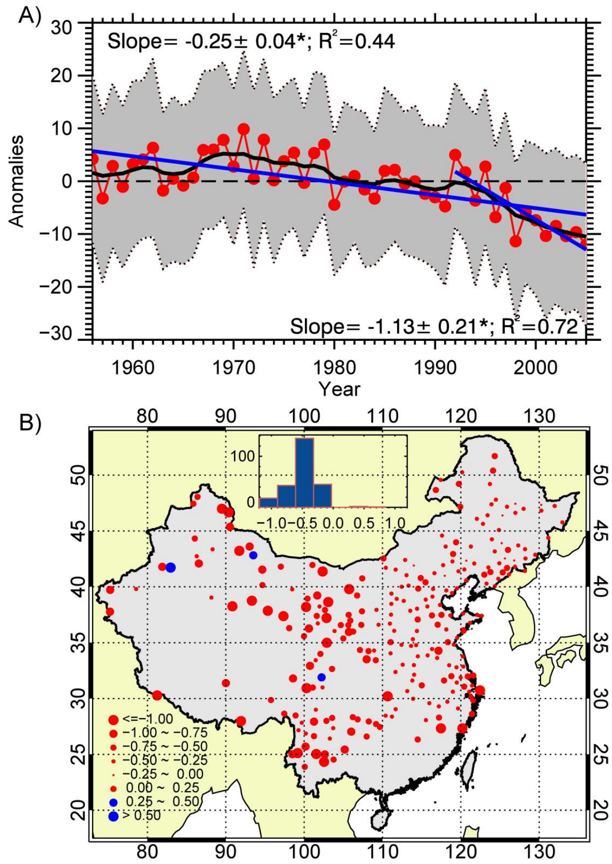

Figure 4. (A) Composite variations of DR from 1956 through 2006 across China. The red line with solid circles is data line. Blue lines are linear trends, and black line represents a low-pass filter with a cut-off frequency of 0.09. Symbol * indicates a significant trend at 95 % confidential level. **(B)**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

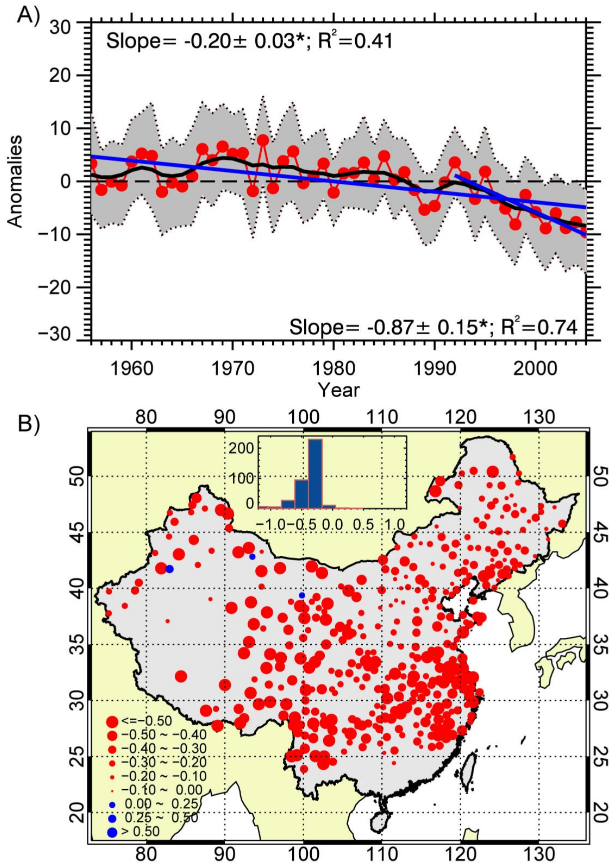

Figure 5. (A) Composite variations of NF from 1956 through 2006 across China. The red line with solid circles is data line. Blue lines are linear trends, and black line represents a low-pass filter with a cut-off frequency of 0.09. **(B)** Changes in NF from 1956 through 2006 across China; center-top is histogram of changes in NF.

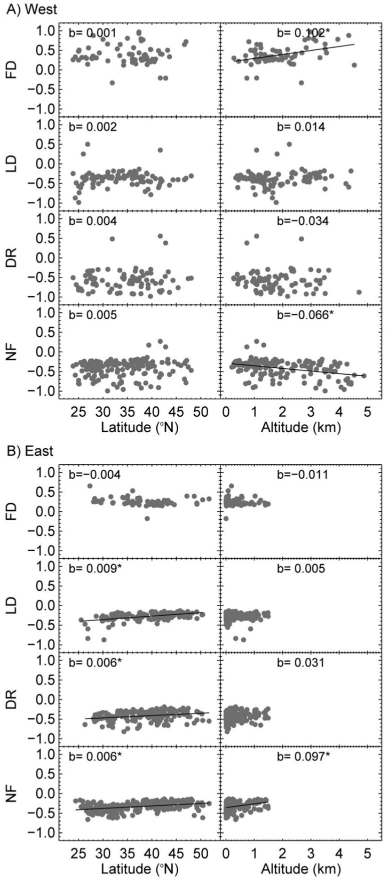

Figure 6. Trends of FD, LD, DR and NF at **(A)** west stations (longitude ≤ 110° E) and **(B)** east stations (longitude > 110° E) against latitude (° N) and altitude (km a.s.l.). Solid cycles are data points, and lines are linear fitted lines. Symbol * indicates a significant trend at 95 % confidential level.

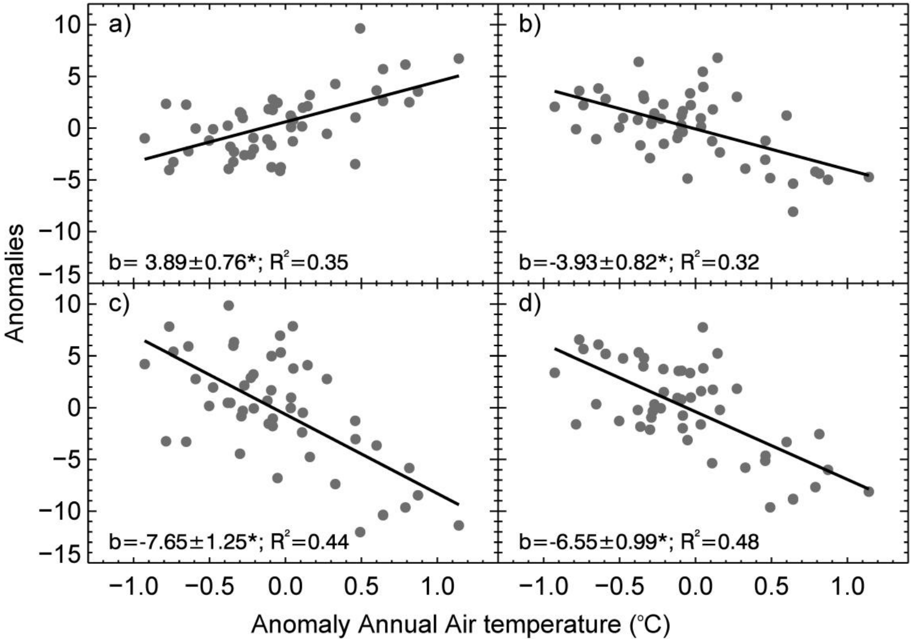

Figure 7. Relationship between of air temperature and **(a)** FD, **(b)** LD, **(c)** DR, and **(d)** NF from 1956 through 2006 across China. The solid circles are individual data points, and the lines are linear regression. Symbol * indicates a significant trend at 95 % confidential level.