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Comprehensive Assessment of Seasonally Frozen Ground Changes in the Northern Hemisphere Based on Observations

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Key Points:

- A comprehensive station database with soil temperature observations for the entire Northern Hemisphere is assembled
- The temporal and spatial characteristics of seasonally frozen ground in response to climate change are quantified
- Seasonal soil freeze/thaw status is sensitive to climate change and mainly driven by air temperature changes and latitude

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Abstract

Seasonally frozen ground (SFG) in the Northern Hemisphere (NH) plays a significant role in the earth system via changes in the freeze-thaw cycle. Previous studies primarily focus on permafrost; however, the SFG response to climate change on a hemispheric scale is uncertain due to a lack of observations. We rectify this with a newly assembled comprehensive database of 1,220 stations with daily observations. To quantify the spatiotemporal characteristics of SFG in response to climate change, we calculate eight variables with these observations: the first date of soil freeze (FFD), freezing duration (FDR), maximum freeze depth (MFD), the date of maximum freeze depth (MFDD), the last date of soil thaw (TLD), thawing duration (TDR), freeze-thaw duration (FTDR), and actual number of freezing days (AD). During the variables' common 1986–2005 period, MFD decreased 8.9 cm (9% change). FFD was later by 5.3 days (2% change), MFDD and TLD were earlier by 14.5 days (27% change) and 24.7 days (22% change), respectively, and FDR and TDR decreased by 9 days (11% change) and 4.6 days (10% change). FTDR and AD decreased 18.1 days (14% change) and 12.1 days (10% change), respectively. The spatial pattern of freeze-thaw variables depends on latitude and elevation, and varies by climatic zone: FTDR increases, going from the warm temperate climate, to the arid climate, and the snow and polar climates. The variability in freeze-thaw changes is mainly driven by air temperature and latitude, while precipitation, soil moisture, snow depth, and elevation are relatively insignificant at the hemispheric scale.

Plain Language Summary

Although seasonally frozen ground (SFG) covers 51% of the continental land areas in the Northern Hemisphere (NH), few studies have focused on this cryospheric parameter largely due to a prior lack of data. We remedy this by assembling a comprehensive database of over a thousand stations with daily soil temperature observations. We present a hemispheric-scale assessment of SFG changes across the NH, to provide a better understanding of the spatial and temporal variability and its potential driving factors. We define eight variables to comprehensively describe all aspects of SFG variability during 1986–2005, and find earlier thawing, later freezing, shallower freeze depths, and an overall shorter freezing period and longer thawed period. These changes are mostly due to a warming climate, with spatial patterns that correspond to latitude and climate regions. These findings can be useful to inform future variability, as climate continues to change.

1. Introduction

Frozen ground, an important component of the cryosphere, plays a significant role in local to global atmospheric circulation, climate, hydrology, and terrestrial ecosystems by affecting the energy, water, and carbon cycles (Derksen et al., 2012; Friedlingstein et al., 2006; Luo et al., 2020; Schmidt et al., 2011; Walvoord & Kurylyk, 2016). The development of frozen ground is affected by many factors, both anthropogenic and natural. In turn, freeze-thaw processes also influence many of earth's systems because almost all ecologic, hydrologic, pedologic, and biologic activities occur within this seasonal soil freeze layer. The annual freeze-thaw cycle of soils affects the variability of surface and ground water, and directly changes the hydrothermal properties of soil and thus impacts vegetation (Peng et al., 2016; Shiklomanov & Nelson, 2002). Because the near-surface soil freeze status determines the infiltration ability, hydraulic conductivity, and permeability, it affects the redistribution of water into the soil profile. Soil freezing reduces the hydraulic conductivity, leading to either more runoff due to decreased infiltration, or higher soil moisture content due to restricted drainage (Zhang et al., 2005).

Due to the impermeability, water storage, and evaporation inhibition of frozen ground, the existence of a frozen layer and the freezing/thawing process are directly related to soil moisture, which has crucial importance for agriculture. The freeze depth, freezing time, and thawing rate of soils play an important role in the growth of vegetation, determine the length of the growing period, and the ultimate crop yield (Peng et al., 2020; Shur & Jorgenson, 2007; Zhou et al., 2018). The moisture retention of a frozen layer increases the soil moisture content in cold regions, which impacts the moisture availability during spring planting time. The amount of moisture affects the growth and harvest of crops, thereby affecting the development of local agricultural production (Baïz et al., 2008; Maximov et al., 2008; Sugimoto et al., 2002). Seasonal freeze-thaw processes can be accompanied by frost heave and thaw settlement, resulting in surface deformation and potential infrastructure damage of, e.g., roads and thus impact the safety of traffic. In cold regions, special considerations are thus required before designing any infrastructure and must consider the influence of frozen ground on the project, taking appropriate preventive measures to ensure the stability of the frozen ground (Wu et al., 2016; Zhang et al., 2008). Therefore, it is crucial to have a comprehensive understanding of seasonally frozen ground (SFG) changes.

According to working group I of the IPCC's sixth assessment report, the global surface temperature in the first 20 years of the 21st century was 0.99 °C (0.84–1.10 °C) higher than during 1850–1900. The global surface temperature of the most recent decade, from 2011 to 2020, was 1.09 °C (0.95–1.20 °C) higher than from 1850 to 1900 (IPCC, 2021). Under a warming climate, freeze-thaw changes in frozen ground will impact and threaten ecological systems, engineering structures, and even human life (Baumann et al., 2009; Serreze et al., 2000). Previous work mainly focused on the response of permafrost to climate change, such as the area extent of permafrost, active layer thickness, permafrost temperature, etc. Permafrost in high latitude and elevation regions is degrading at varying rates, and the thickness of the active layer is increasing (Brown & Romanovsky, 2008; Frauenfeld et al., 2004; Peng et al., 2018; Romanovsky et al., 2010). SFG covers 50.5% of Northern Hemisphere (NH) land areas (Zhang et al., 2003), corresponding also to areas where most of the human population are concentrated. SFG is affected by seasonal changes within a few meters of the surface, freezing in winter and thawing in summer. It thereby directly impacts the energy exchange between the atmosphere and the surface, and is sensitive to climate change, responding very quickly. Despite its vast extent and importance, area changes in SFG have received very little attention, with most work either focusing on specific regions, or only on depth changes (Frauenfeld & Zhang, 2011; Frauenfeld et al., 2004; Peng et al., 2016, 2017; Zhang et al., 2003). SFG on the Tibetan Plateau follows the expected distribution characteristics of climatic zones: the average freeze depth in the subfrigid zone, ~142 cm, was deeper than in the temperate (85 cm) and subtropical zones (6 cm). In these same temperature zones, freeze depth deepened significantly with decreasing moisture (Luo et al., 2020). Evaluating seasonal freeze depth in the Eurasian high latitude areas for 1930–2000 revealed a statistically significant trend of −4.5 cm/decade and a net change of −31.9 cm (Frauenfeld & Zhang, 2011). Not only is the maximum freezing depth an important indicator of the response of SFG to climate change, but the dates of the first freeze and last thaw, the duration of the freezing and thawing periods, and the number of days of actual freezing all characterize the freezing state of near-surface soils. These additional variables can more comprehensively describe the entire process of seasonal freezing and thawing, so as to better quantify the response of the entire freeze/thaw cycle of SFG to climate change, and explore its interactions within the earth-atmosphere system. Previous studies thus mostly focused on one or two aspects of SFG, and only on local or regional scales. Until now, no holistic assessment of SFG changes on a hemispheric scale has been performed.

Given the importance of SFG, its extensive distribution, and its role in climate change processes, it is particularly important to quantify freeze-thaw changes and the spatiotemporal characteristics of SFG at the hemispheric scale. We obtain long-term observations from 1,220 meteorological stations covering the NH, in addition to multiple environmental indicators (air temperature, soil temperature, precipitation, snow depth, soil moisture content) and geographic factors (latitude, elevation). Eight variables are derived to represent freeze-thaw processes, which are analyzed to statistically quantify their spatial distribution and temporal variability. We thereby comprehensively evaluate the response of SFG to climate change, and assess its potential drivers.

2. Data and Methods

2.1. Soil Temperature

Daily soil temperature data are used to characterize the freeze-thaw status of SFG. A total of 1,220 stations covering the NH are collected for China, Russia, Finland, USA, and Canada (Figure 1). The period of record and

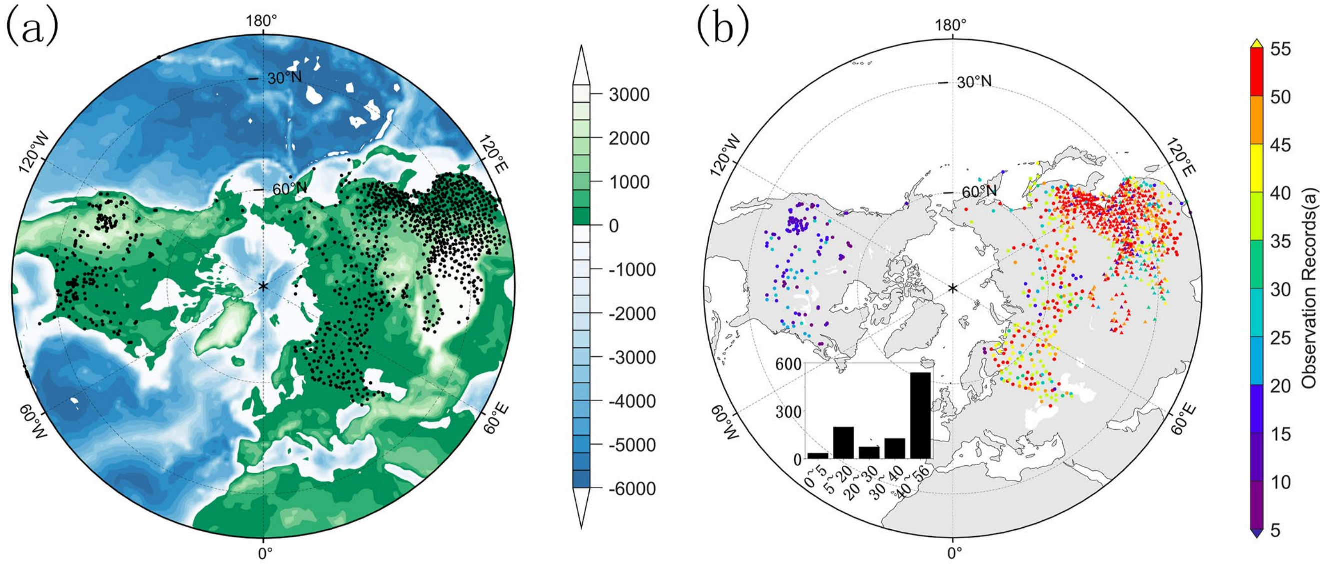

Figure 1. Map of the 1,220 observations in the Northern Hemisphere (NH) based on (a) locations and elevation (m), and (b) years with soil temperature observations; the histogram provides a count of stations with recording period. Stations with soil temperature at 0 cm are represented by triangles.

observing depth of these station records is inconsistent. A total of 635 sites are available in China from the China Meteorological Administration (2015) of which 394 sites contain 0-cm soil temperature, with depths below the surface of: 0.05, 0.1, 0.15, 0.2, 0.4, 0.5, 0.8, 1.6, and 3.2 m. There are 264 sites in Russia from the World Data Center, and their 12 soil temperature observation depths are 0.02, 0.05, 0.1, 0.15, 0.2, 0.4, 0.6, 0.8, 1.2, 1.6, 2.4, and 3.2 m. In the United States, 208 sites are available from the National Water and Climate Center. Their depths of soil temperature observations are 0.05, 0.1, 0.2, 0.5, and 1.0 m. There are 32 sites in Canada are from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC), with inconsistent depths of soil temperature observations: some sites have only two depths, and others have nine depths from 0.005 to 2.5 m. A total of 81 stations in Finland, from the Finnish Meteorological Institute, also have inconsistent soil temperature observation depths; 20 stations have to be excluded because they have soil temperature at only one depth. The other stations have measurements for 2–16 depths, from 0 to 3 m.

Site observations on the Eurasian continent date back to the 1950s and 1960s. China has the earliest observations, beginning in 1951, but observations end in 2006. Russia began observations in 1963, and their data are available until 2015. The U.S. data are available from 1993 to 2021 and Canada and Finland for 1996–2014 and 2000–2021, respectively. About 92% of sites have records for >10 years (Figure 1b). After screening all the sites and excluding those on permafrost and stations without measurements, 975 sites are ultimately available for this study.

2.2. Meteorological Data

Meteorological data include air temperature, precipitation, snow depth, and soil moisture content. These variables are related to each of the freeze-thaw state variables, thereby assessing their potential impacts on SFG. Many of the station records (Section 2.1) also include daily air temperature and daily precipitation, except the Eurasian stations do not provide soil moisture and the stations on the American continent do not have daily snow depth. Annual mean temperature and annual cumulative precipitation are calculated from the daily observations. The annual mean snow depth is calculated based on the daily snow depth during 1 July to 30 June. Soil moisture content is measured at 5-cm depth. If there are >10% missing daily observations during any year, the data from that year are not included in the statistics.

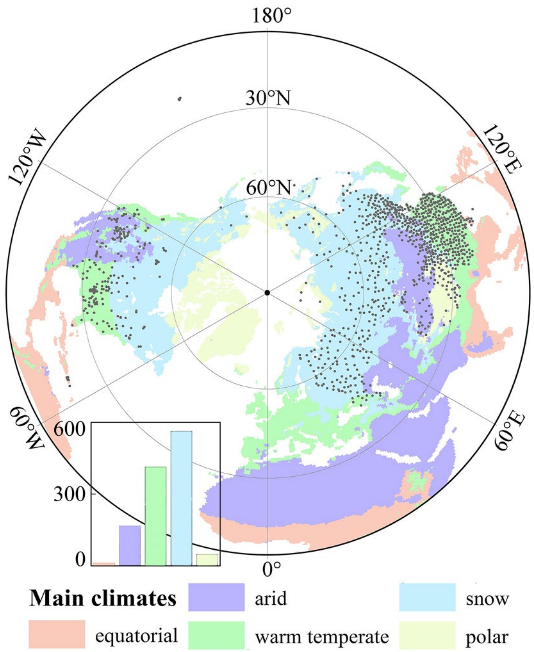

Figure 2. Five main climatic zones of the Northern Hemisphere (NH) derived from the Köppen-Geiger classification system. The histogram shows the number of stations in each climatic zone.

2.3. Climate Zone Data

To provide further context for the distribution of SFG, the Köppen-Geiger climate classification system is used to categorize the NH into climatic zones and statistically assess the freeze-thaw processes for the different climate zones. The Köppen-Geiger climate classification (http://koeppen-geiger.vu-wien.ac.at/) is based on temperature, precipitation, and vegetation. The global land area is divided into five main climate zones, i.e., equatorial, arid, warm temperate, snow, and polar climate (Figure 2).

2.4. Methods

SFG is defined as any soil or rock material near the surface that is frozen in the cold season and thawed in the warm season, but with its frozen state lasting <1 year. Unlike the active layer, SFG freezes in one direction and thaws in both directions. One freeze-thaw cycle is defined as the period from autumn and winter of 1 year to spring and summer of the next year. To quantify the response of SFG to climate change, we calculate eight variables that characterize the freeze-thaw status: the first date of soil freeze (FFD), freezing duration (FDR), maximum freeze depth (MFD), date of maximum freeze depth (MFDD), last date of soil thaw (TLD), thawing duration (TDR), freeze-thaw duration (FTDR), and actual number of freezing days (AD). To show the freeze-thaw process and explain the definitions of the eight freeze-thaw state variables, Xu et al. (2022) simulated a complete freeze-thaw process profile diagram of SFG (Figure 3). The FFD is the first day of autumn freezing. As the temperature continues to decrease, the soil continues to freeze downward until the MFD is reached. This day is defined as the MFDD. Then the temperature rises and the frozen soil begins to thaw in both directions, converging to a certain depth. After that, no frozen soil remains. The last day of freezing in the next spring is defined as the TLD. The FDR is the number of days from FFD to MFDD, and the TDR is the number of days from MFDD to TLD. The number of days between FFD and TLD is defined as the FTDR. Because freezing and thawing always occurs at the beginning of autumn, the AD is defined as the number of days in which the daily freezing depth is not zero. Using these eight freeze-thaw variables, the freeze-thaw status of SFG can be analyzed in detail.

If the MFD is deeper than the lowest depth of soil temperature observation, the true MFD cannot be calculated and the data for that year are discarded. When calculating a multiyear average and multiyear trends of each freeze-thaw state variable, only stations with a record length of 5 or more years are used. If, throughout the available record, a site's deepest soil temperature observations are continuously negative, the site is considered to be located on permafrost. Conversely, if the deepest available soil temperatures are continuously positive, the site is considered to be located on nonpermafrost (Frauenfeld et al., 2004; Peng et al., 2020). When determining FFD, the soil temperature at the top soil layer cannot be missing, otherwise the data for that year are discarded. Given the availability of soil temperature observations, in China we use the 0-cm soil temperature, and in other areas the 2-cm or 5-cm depths are used.

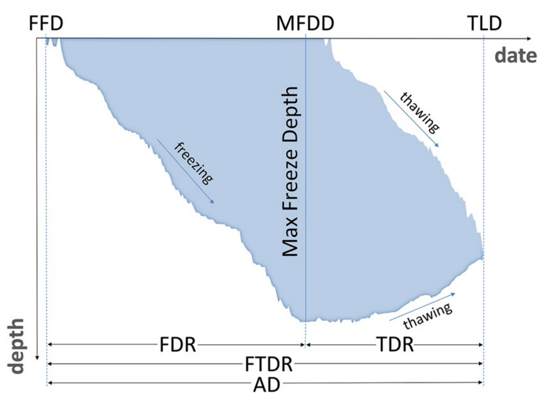

Figure 3. Schematic of the freeze-thaw process of seasonally frozen soil.

Finally, we use linear regression to calculate trends of each freeze-thaw state variable. To explore the relationships between SFG and the potential driving factors for the NH, Pearson correlation is used to quantify the association between environmental (temperature, precipitation, snow depth, and soil moisture) and geographic factors (latitude and elevation) with the freeze-thaw state variables. The 90% confidence level is used to establish significance for all statistical tests.

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3. Results

3.1. Spatial Pattern of SFG

The spatial distribution of the various freeze-thaw state variables based on the long-term average shows a gradual increase from low to high latitudes and from low to high elevations (Figure 4). The hemispheric average value of the FFD is day 329 ± 29 (late November), of which 145 stations (26%) show frozen ground in October, 220 stations (39%) in November, the ground at 105 stations (19%) began to freeze in December, and 91 stations (16%) in January of the next year. In China, freezing occurs before or after December, based on the dividing line of the Qinling and Huaihe Rivers. In North America, the FFD occurs in December at the low elevations in the east, and in November at the high elevations in the west, due to the elevations greater than 3,000 m in the North American Cordillera, including the Rocky Mountains in western North America. Due to the lack of measurements of shallow soil temperature at stations in Russia, the FFD, FDR, and the FTDR cannot be calculated.

The MFD can reach 316 cm, and the minimum, in the low latitude areas, is only 2 cm. The hemispheric average of the MFD is 90 ± 73 cm. The MFD of 114 stations (18%) is <20 cm, 301 stations (47%) between 20 and 100 cm, 158 stations (25%) are within 100–200 cm, and 71 stations (11%) with MFD greater than 200 cm are located in Siberia, the Qinghai-Tibet Plateau, and in northeastern China. The freezing depth at stations in the Siberian mountains and plateaus is >200 cm. Compared with the stations on the Siberian plain and the Eastern European plain at the same latitude, the freezing depth is only about 100 cm. The freezing depth in North America is generally <75 cm.

The hemispheric average value of the MFDD is day 49 ± 28 (mid-February). At 212 stations (33%), it occurs from December to January (of the next year), 203 stations (31%) experienced the maximum freezing depth in February, 176 stations (27%) in March, and 53 stations (8%) in April or May. In Siberia at high latitudes, MFDD occurs the latest, on the 129th day (early May). The MFDD is generally reached as early as the 354th day (end of December) in the Rocky Mountains in North America.

Similarly, the hemispheric average of the TLD is day 96 ± 45 (early April). At 146 stations (26%), TLD is in January or February, at 237 stations (43%) in March or April, at 148 stations (27%) in May or June, and at 20 stations (4%) in July or August. The Siberian Plateau thaws the latest, by mid-August, the North American region thaws from low latitudes in January to midlatitudes in April, and some stations in Canada thaw in May.

The hemispheric averages of FDR and TDR are 75 ± 44 and 41 ± 19 days, respectively. The FDR is generally longer than the TDR in a freeze-thaw cycle. It is also worth noting that, the lower the latitude, the shorter the TLD. The longest thawing period is in the Siberian Plateau, the Qinghai-Tibet Plateau, and Northeast China. The longest TDR lasts 99 days and the shortest only 2 days in the NH. The hemispheric average of the AD is 105 ± 66 days. The freezing days at 206 stations (27%) are within 60 days, at 361 stations (48%) between 3 and 5 months, at 173 stations (23%) between 6 and 8 months, and greater than 244 days at 14 stations (2%). Especially in the Siberian Plateau at high latitude, AD can be up to 325 days. The FTDR ranges from <1 month at low latitudes to 7 months in the midlatitudes. The FTDR is longer at high latitudes and elevations, e.g., the Siberian Plateau, Qinghai-Tibet Plateau, and Northeast China, and about 4 months in the North American Cordillera including the Rocky Mountains in western North America. These preliminary results thus verify the latitudinal and elevation dependence of each freeze-thaw status variable.

3.2. SFG in Climate Regions

The freeze-thaw cycle of SFG shows a distinct distribution in the five climatic zones (Figure 5 and Table 1). In the warm temperate climate area, the ground freezes the latest. The FFD occurs in December. The MFD is the shallowest, mostly <25 cm. The TLD occurs the earliest, and all thawing is completed by February (of the next year). The AD are the shortest, generally <2 months. The arid climate area begins to freeze in early November, with an MFD of about 80 cm. Thawing is completed in March (of the next year), and the AD can last for 4 months. Finally, there is little difference between the boreal snow climate and the polar climate. Freezing occurs at the end of October, and the MFD is 100–200 cm. Freezing can last until the end of May, and the AD are up to 6 months. The TLD, MFDD, and AD are later and longer in the boreal snow climate zone than in the polar climate zone. Most of the stations in the polar climate zone are located on the Qinghai-Tibet Plateau, which is in the middle

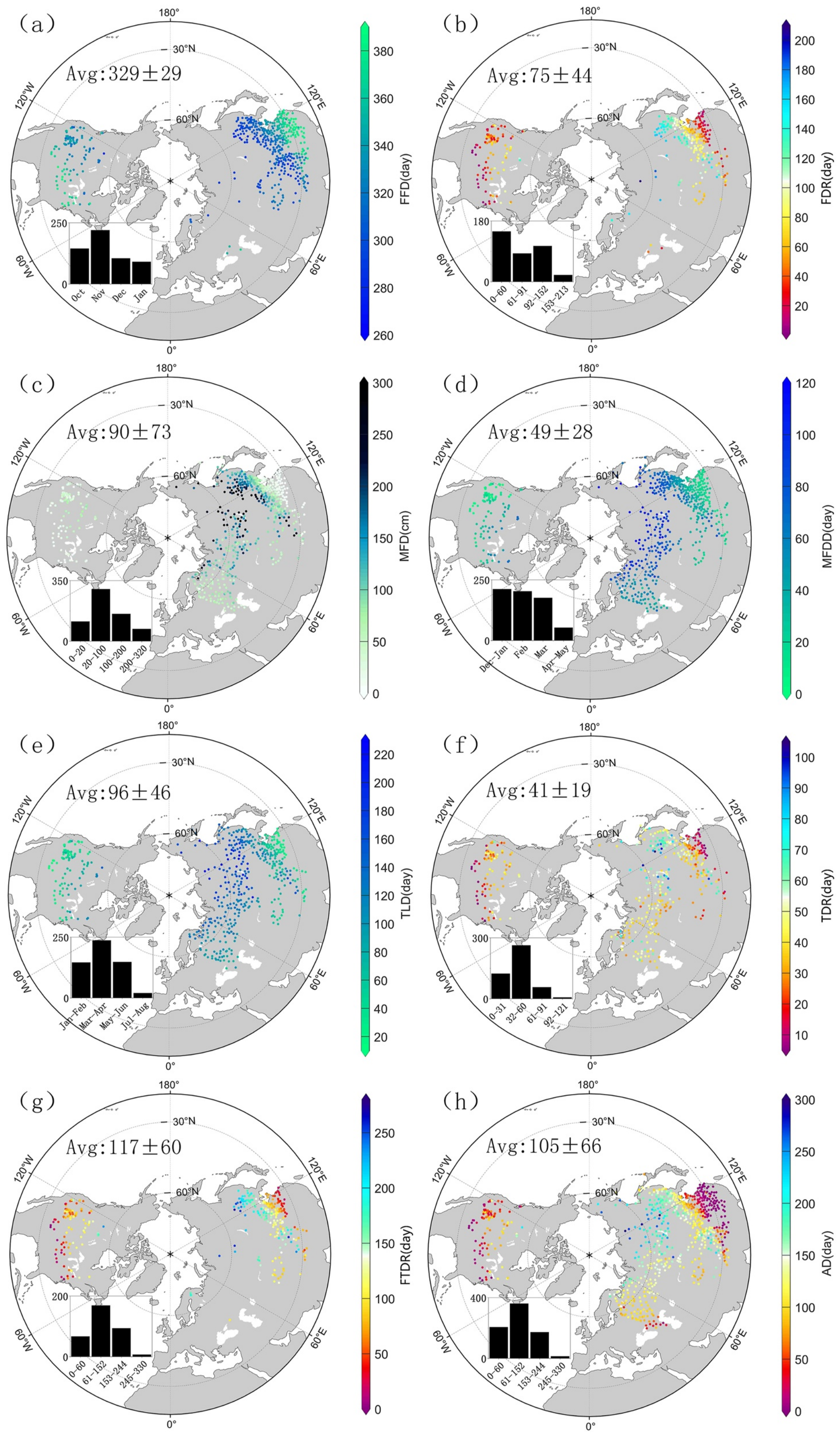

Figure 4. The long-term average spatial distribution of freeze-thaw state variables in the Northern Hemisphere (NH): (a) the first date of soil freeze (FFD), (b) freezing duration (FDR), (c) maximum freeze depth (MFD), (d) the date of maximum freeze depth (MFDD), (e) the last date of soil thaw (TLD), (f) thawing duration (TDR), (g) freeze-thaw duration (FTDR), and (h) actual number of freezing days (AD). The insets show the number of stations in each range.

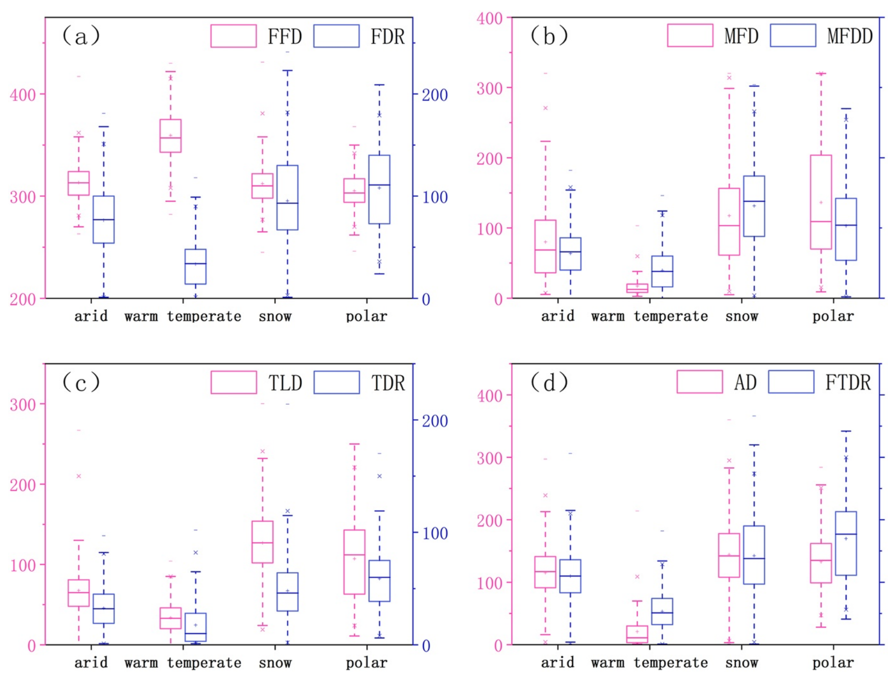

Figure 5. Comparison of the eight freeze-thaw status variables in the different climatic zones.

latitude region and has greater solar radiation than the high latitudes, resulting in the advance of the freeze-thaw cycle and a reduction in the days. The equatorial climate does not develop SFG.

3.3. Trends of SFG

The long-term trends of the freeze-thaw status variables (Figure 6) indicate that at most stations in the NH, the FFD is delayed (69% of stations), the TLD advances (77% of stations), the MFD decreases (79% of stations), the MFDD is advanced (73% of stations), the days of FDR and TDR decreased (72% and 61% of stations, respectively), and the FTDR and AD similarly decreased (72% and 74% of stations, respectively). All of these trends are indicative of climate warming, with the positive trend in FFD and the negative trends in all other freeze-thaw status variables. The magnitude of annual changes in freeze-thaw days at most stations is between −0.5 and +0.5 days. Greater changes occur in high latitude and high elevation areas, such as the Qinghai-Tibet Plateau, Northeast China, Siberia, Eastern Europe, and the Rocky Mountains. The magnitude of MFD change is <−4 cm/a. At the North American stations, there is no obvious pattern to the spatial distribution of trends, perhaps due to the inconsistent length of the station time series, adding uncertainty to the trends.

We next focus on time series trends for a common 20-year period from 1986 to 2005, because the station data in this period are relatively complete, but decline in the 2010s (Figure 7). Despite high interannual variability, there is an increase in FFD and the other variables decrease at varying magnitudes. On the hemispheric scale, FFD occurs later at an average change of 0.26 days/year from 1986 to 2005. The MFD decreased at a rate of 0.44 cm/a, the MFDD is delayed at a rate of 0.72 days/a, the TLD advanced at a rate of 1.23 days/a, the FTDR decreased 0.91 days/a, and the AD decreased by 0.60 days/a. TDR and FDR experienced the largest changes, decreasing by 0.45 and 0.23 days/a, respectively.

To better show the degree of change in the long-time series of freeze-thaw variables in the NH, we also calculated the net change as a percentage relative to the climatology (Figure 8). Among the significant results, the FFD

Table 1
The Regional Average Values of Eight Freeze-Thaw State Variables in Different Climate Zones

	Arid	Warm temperate	Snow	Polar
FFD (days)	313.3 ± 16.9	359.4 ± 23.2	312.2 ± 20.5	305.2 ± 16.3
FDR (days)	76.5 ± 34.6	33.6 ± 22.0	95.3 ± 43.7	108.0 ± 38.7
MFD (cm)	80.1 ± 56.8	17.1 ± 13.0	117.5 ± 72.9	136.3 ± 86.9
MFDD (days)	31.9 ± 19.8	19.7 ± 15.2	65.7 ± 29.9	51.5 ± 28.2
TLD (days)	67.6 ± 36.5	33.6 ± 20.2	126.8 ± 44.2	107.1 ± 47.3
TDR (days)	32.6 ± 18.4	17.5 ± 18.6	48.0 ± 25.9	58.8 ± 27.4
FTDR (days)	109.7 ± 43.0	53.2 ± 30.6	142.4 ± 62.5	169.8 ± 61.6
AD (days)	115.0 ± 41.7	20.9 ± 24.6	144.2 ± 57.2	132.6 ± 45.1

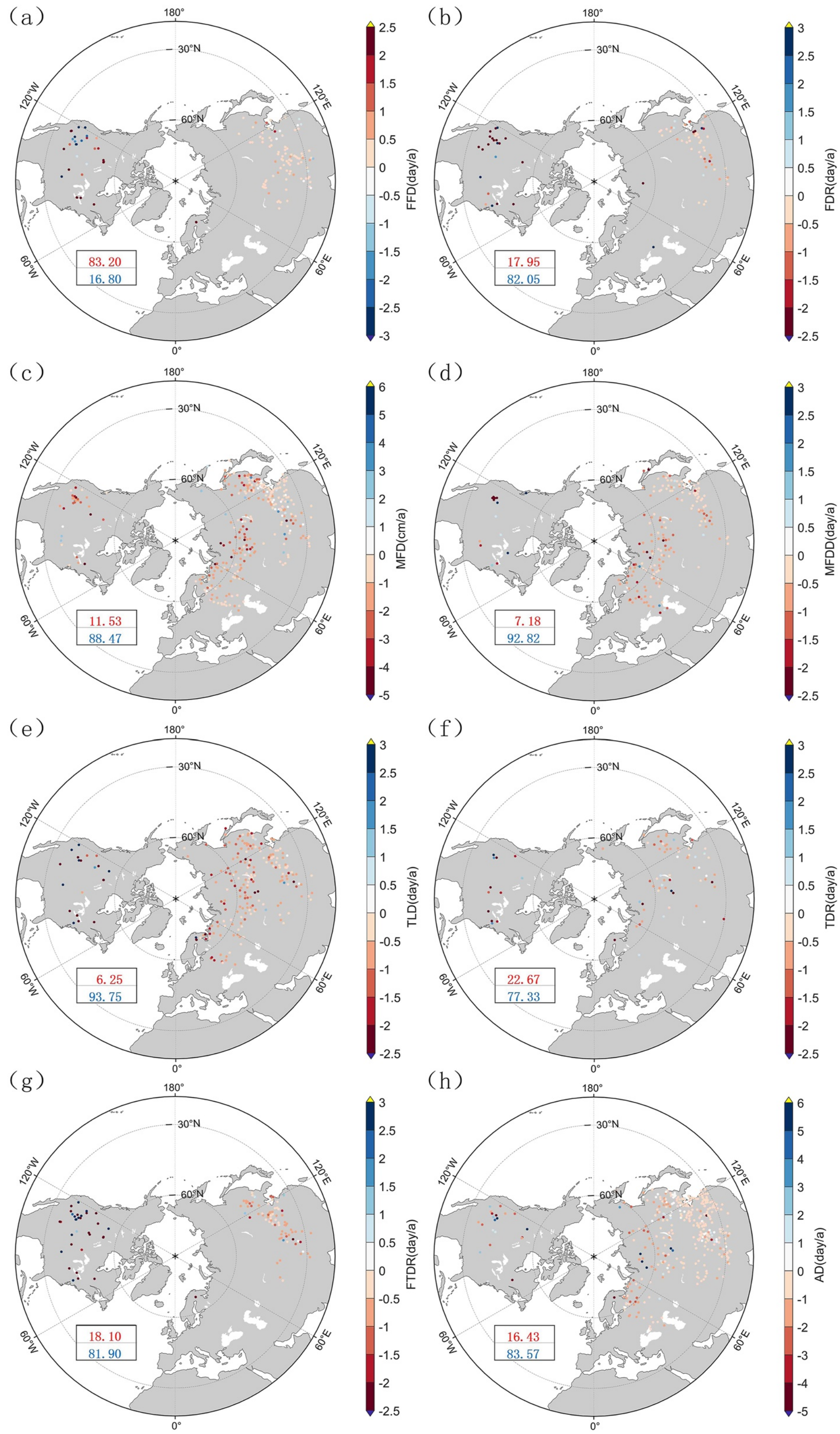

Figure 6. Long-term trend of each freeze-thaw state variable at each station in the Northern Hemisphere (NH): (a) the first date of soil freeze (FFD), (b) freezing duration (FDR), (c) maximum freeze depth (MFD), (d) the date of maximum freeze depth (MFDD), (e) the last date of soil thaw (TLD), (f) thawing duration (TDR), (g) freeze-thaw duration (FTDR), and (h) actual number of freezing days (AD). The table represents the significant positive trends (red) and significant negative trends (blue).

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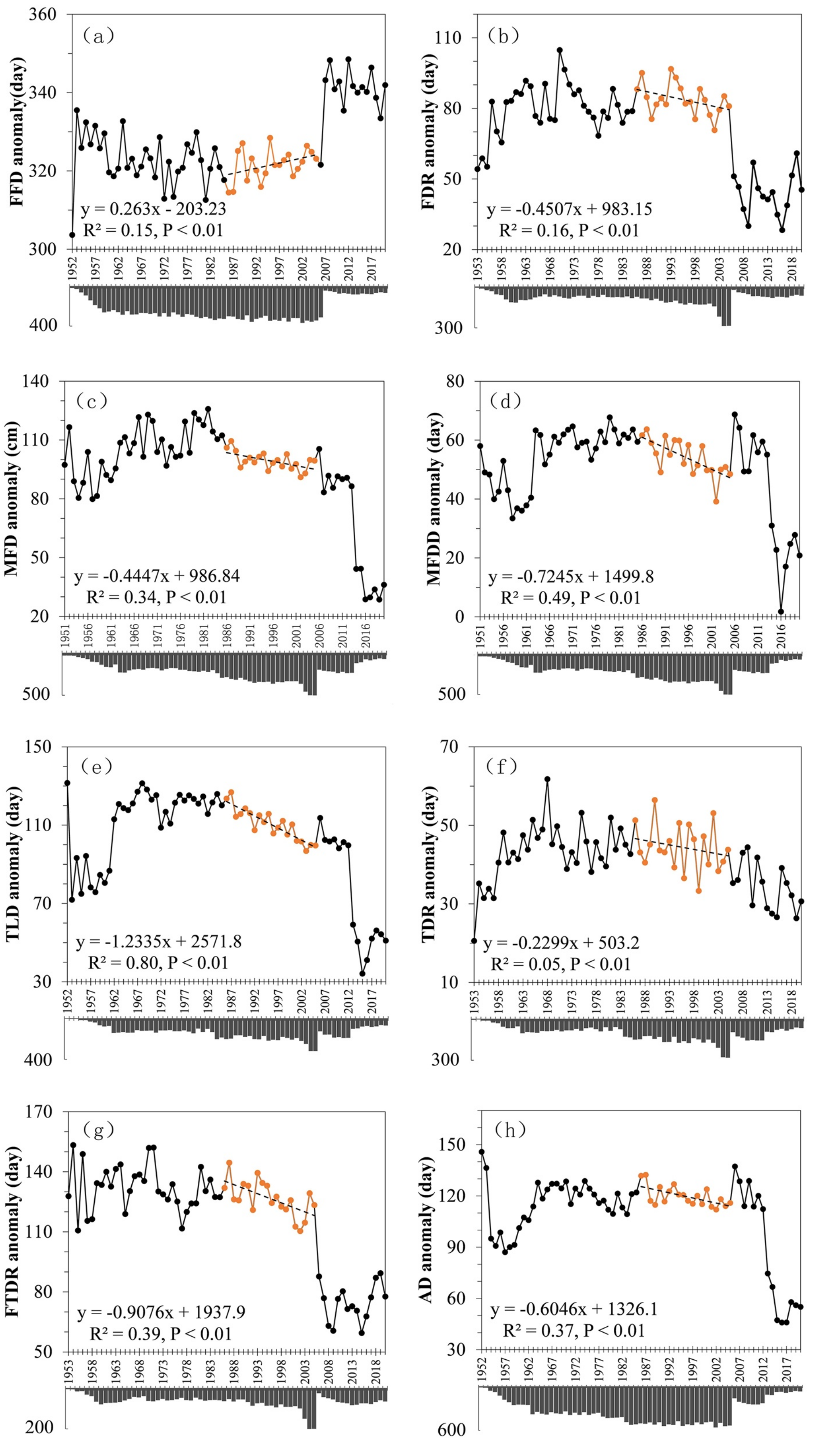

Figure 7. Time series of freeze-thaw state variables in the Northern Hemisphere (NH): (a) the first date of soil freeze (FFD), (b) freezing duration (FDR), (c) maximum freeze depth (MFD), (d) the date of maximum freeze depth (MFDD), (e) the last date of soil thaw (TLD), (f) thawing duration (TDR), (g) freeze-thaw duration (FTDR), and (h) actual number of freezing days (AD). The orange symbols indicate the common trend period from 1986 to 2005.

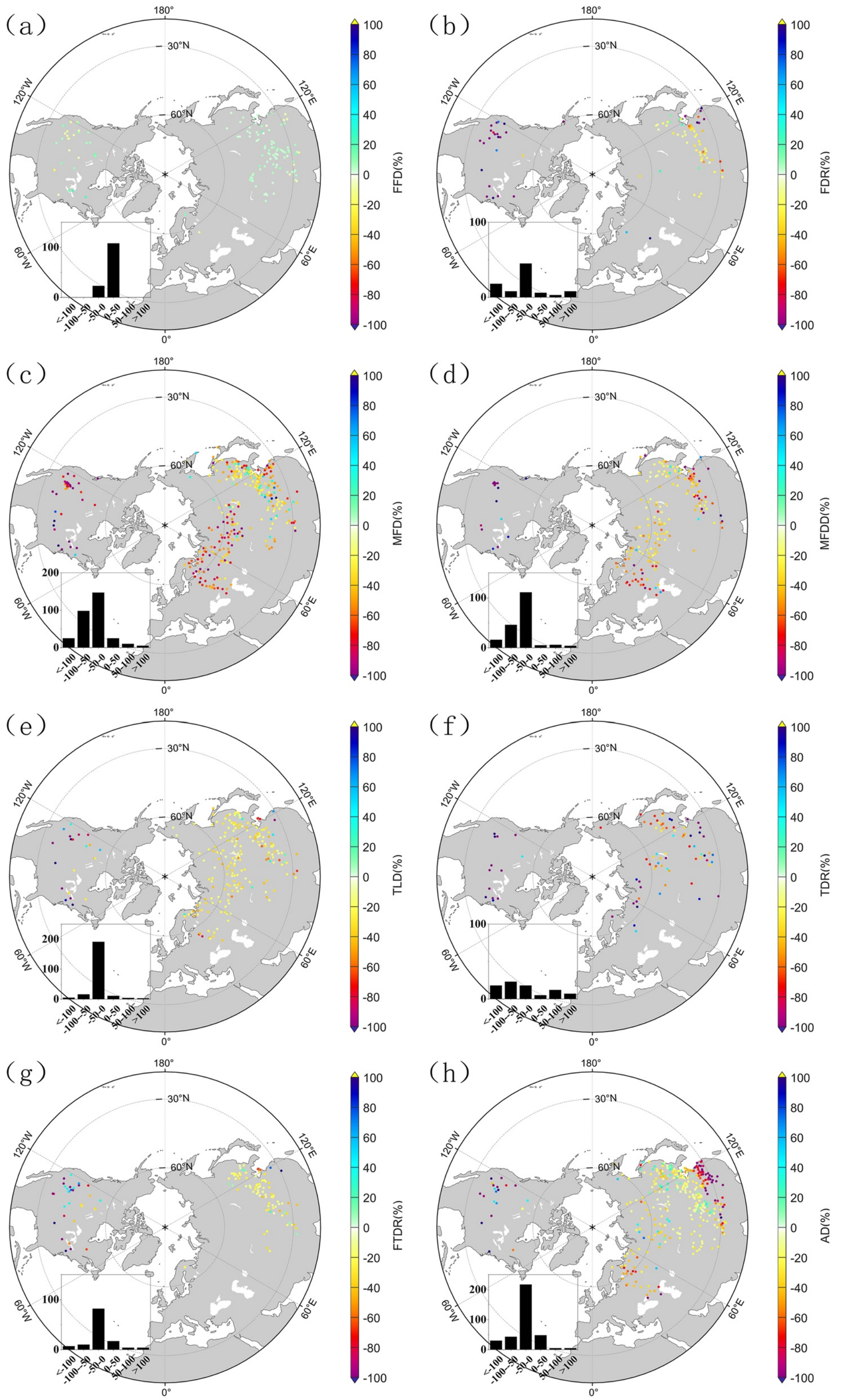

Figure 8. Long-term change degree of each freeze-thaw state variable at each station in the Northern Hemisphere (NH): (a) the first date of soil freeze (FFD), (b) freezing duration (FDR), (c) maximum freeze depth (MFD), (d) the date of maximum freeze depth (MFDD), (e) the last date of soil thaw (TLD), (f) thawing duration (TDR), (g) freeze-thaw duration (FTDR), and (h) actual number of freezing days (AD). The insets show the number of stations in each range.

10.1029/2022JD037306

(82% of stations) was delayed by an average of 5.7%. The MFD of 87% stations was decreased, and 32% of the stations had a greater degree of change between −50% and −100%. The MFDD and TLD of 92% stations advanced. At 81% of the stations, the FDR decreased. The FTDR and AD of 80% and 83% stations decreased, respectively. For 71% of the stations, the TDR showed a negative percentage, meaning fewer days. The larger percentages of change at low latitudes and low elevations are due to the small base values of freeze-thaw variables in these regions.

4. Discussion

4.1. Potential Driving Variables

Soil freeze-thaw status is affected by climate warming and environmental change (Zhang et al., 2001). Therefore, the change in freeze-thaw processes is the result of the interactions between the atmosphere and soil (Peng et al., 2016; Wang et al., 2015, 2019). This study focuses on four variables, i.e., temperature, precipitation, snow depth, and soil moisture to explore their relationship with the freeze-thaw variables.

4.1.1. Annual Air Temperature

For annual air temperature, 83.4% of the stations indicate positive correlations with FFD (Figure 9). The days of FDR, MFD, MFDD, TLD, FTDR, and AD were negatively correlated with air temperature at 75–78% of stations. Interestingly, for TDR days, only 52% of the stations were positively correlated with air temperature, and 48% of the stations were negatively correlated with air temperature. Many of the negatively correlated stations are located in low latitude areas, while most positive-correlation stations are in the high latitudes. This could be due to the short freeze period in the low latitudes with higher annual air temperature, and vice versa in colder regions (Figure 4). The earlier MFDD leads to an increase in the TDR. Due to climate warming, a large amount of long wave radiation is transmitted from the atmosphere to the ground, increasing the soil temperature. Heat accumulation increases in the soil, which directly affects the freeze-thaw status and decreases both the MFD and FDR (Peng et al., 2017).

Comparing the response of freeze-thaw status to air temperature in each climate zone (Figure 10), soil freeze-thaw in the polar climate zone is most affected, and correlations are all greater than 0.8. The correlation between freeze-thaw variables and air temperature is the smallest in the warm temperate zone, with $R = 0.31$. For an annual average temperature increase of 1 °C, MFD decreases by 21 cm, FFD is delayed by 4 days while TLD advances 12 days, and the AD is reduced by 12 days. The warm temperate climate zone has the smallest response to air temperature. The MFD decreases by <3 cm, FFD is delayed by 5 days, TLD advances by 2 days, and the AD decreases by 6 days when the annual average temperature increases by 1 °C. For the same 1 °C change in the snow climate and the arid climate, MFD decreases by 9 and 14 cm, FFD is delayed by 4 and 3 days, TLD advances by 7 days in both regions, and AD decreases 8 and 9 days, respectively. Results in these climate zones indicate that the freeze-thaw process is more sensitive to climate change in polar areas.

4.1.2. Annual Precipitation

At the hemisphere scale, there is no relationship between precipitation and the freeze-thaw variables. We therefore focus on the climate regions, where FFD is positively correlated with precipitation in all four zones. The greater the precipitation, the later the freezing occurs. The other three freeze-thaw status variables in the four climatic zones are negatively correlated with precipitation (Figure 11). Thus, the greater the precipitation, the smaller the MFD, the earlier the TLD, and the shorter the AD. The precipitation regressions with MFD show a rate of −0.14 cm/mm in the polar climate zone, FFD with a rate of 0.02 days/mm in the warm temperate climate zone, TLD with a rate of −0.04 days/mm in the snow climate zone, and AD with a rate of −0.08 days/mm in snow climate zone. As the FFD occurs in autumn, this suggests that the more precipitation, the greater the soil moisture content and the greater the latent heat flux, which delays the soil freeze-up. This results in a shortening of the freeze-thaw cycle. On the other hand, during the thawing period, an increase in precipitation leads to an accelerated thawing rate because liquid water is warmer and increases the energy content of the soil. Therefore, increased moisture will shorten the days of the entire soil freeze-thaw process, but it will prolong the soil FTDR to a certain extent in the arid climate zone (Luo et al., 2020).

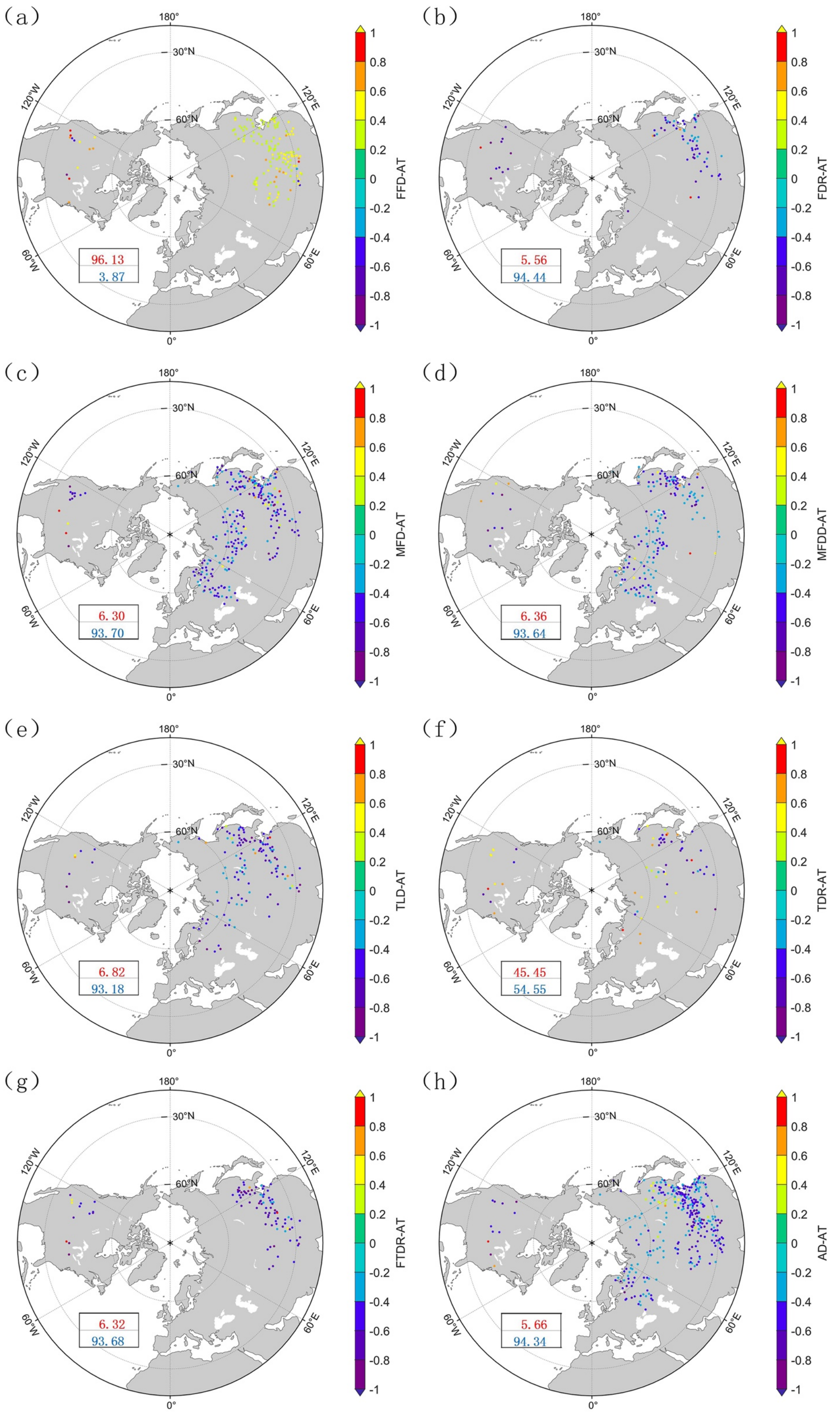

Figure 9. Correlation between each freeze-thaw state variable and annual average temperature in the Northern Hemisphere (NH): (a) the first date of soil freeze (FFD), (b) freezing duration (FDR), (c) maximum freeze depth (MFD), (d) the date of maximum freeze depth (MFDD), (e) the last date of soil thaw (TLD), (f) thawing duration (TDR), (g) freeze-thaw duration (FTDR), and (h) actual number of freezing days (AD). The tables show the frequency of significant positive correlations (red) and significant negative correlations (blue).

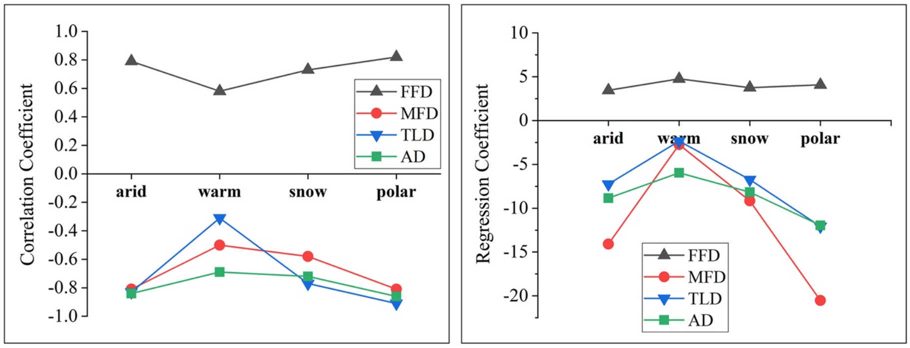

Figure 10. Correlation and regression coefficient between air temperature in each climate zone and (a) the first date of soil freeze (FFD), (b) maximum freeze depth (MFD), (c) the last date of soil thaw (TLD), and (d) actual number of freezing days (AD).

4.1.3. Snow Depth

Negative correlations between the freeze-thaw variable and snow depth are concentrated in high latitudes, with positive correlation in low latitudes (Figure 12). There is a negative relationship between snow depth and the freeze-thaw variable in Siberia and northeast China, with correlations generally <−0.4.

TLD is negatively correlated with snow depth in the high latitudes, e.g., northern Asia and northeast China, with positive correlations in low latitude and low elevation areas, e.g., eastern Europe, the Tarim Basin, and other low latitude regions in China. These relationships can probably be attributed to the thermal insulation effect of snow. In areas of shallow snow depths (low latitude/elevation areas), snow has a cooling effect. Because of snow's high albedo, net radiation at the surface is reduced, resulting in less heat absorbed by the soil (Zhang et al., 2005).

Similar correlation results with snow depth are also found in the climate zones (Figure 13). In the snow climate and the arid climate zone, FFD is negatively correlated with snow depth, with regression coefficients of −0.97 and −0.77 days/cm, respectively. Relationships in the polar climate and warm temperate climate are not statistically significant. Likely, because FFD occurs in autumn when the snow first covers the ground, the fresh but shallow snow depth has a high albedo, which has a cooling effect on the surface (Zhang et al., 2005).

In the polar climate zone, MFD is negatively correlated with snow depth, with a regression coefficient of −0.76 cm/cm. The annual snow thickness in northern Asia is up to 66 cm which, due to the low thermal conductivity of snow, plays a role in thermal insulation to the soil. However, there is a positive correlation with a regression coefficient of 0.80 cm/cm in the warm climate zone, due to the cooling effect of a thin snow cover.

The TLD and AD in each climate zone are positively correlated with snow depth. The associated changes in TLD due to snow depth in each climate zone, from high to low, are 3.32 days/cm (arid climate), 0.79 days/cm (warm

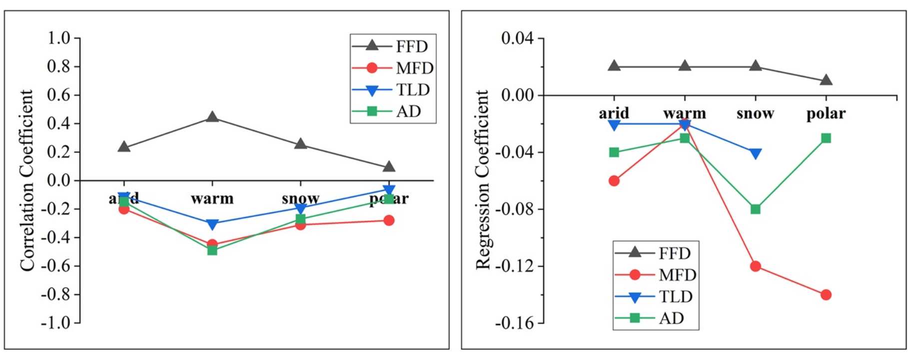

Figure 11. Correlation and regression coefficient between precipitation in each climate zone and (a) the first date of soil freeze (FFD), (b) maximum freeze depth (MFD), (c) the last date of soil thaw (TLD), and (d) actual number of freezing days (AD). Insignificant results are not displayed.

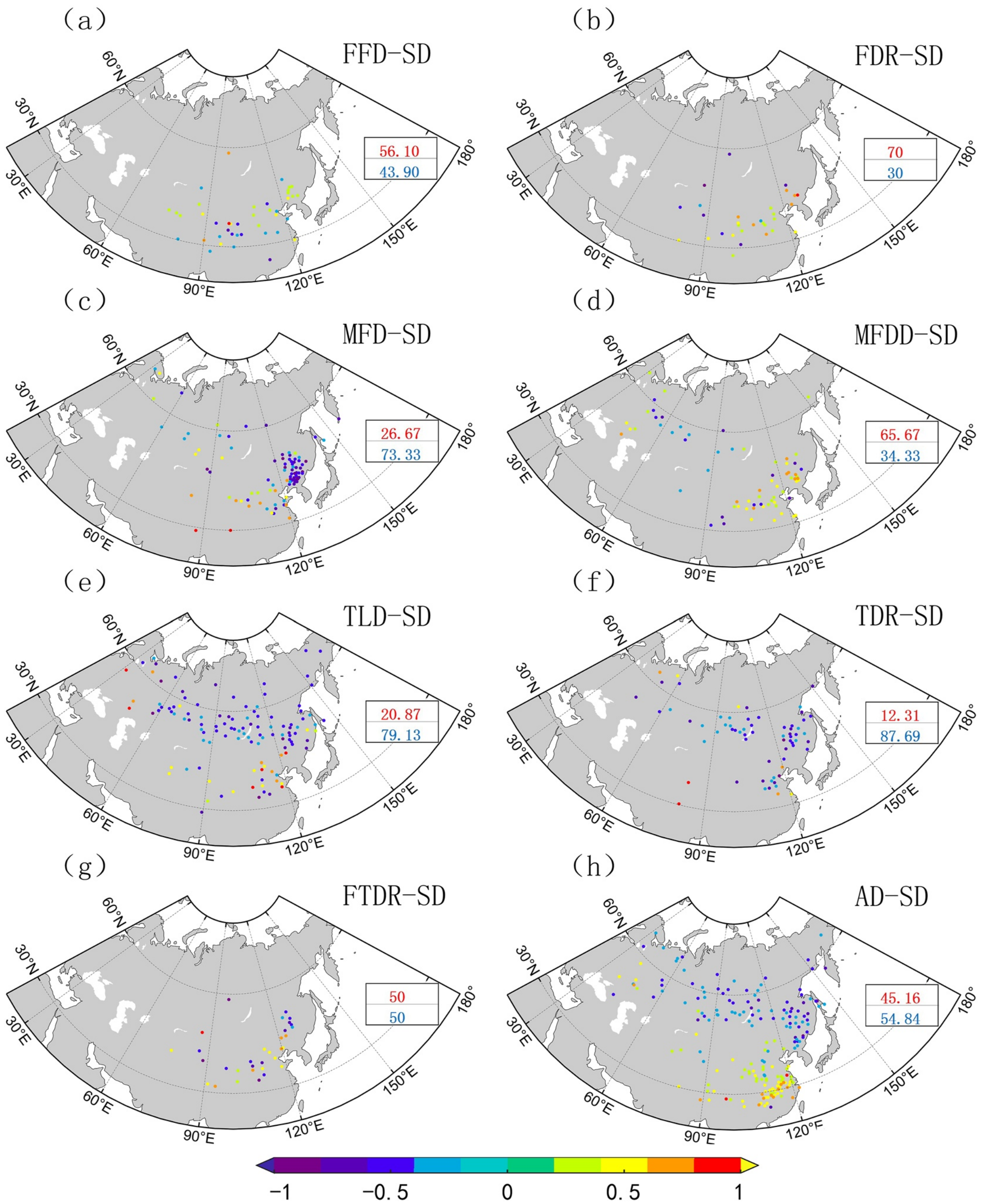

Figure 12. Correlation between each freeze-thaw state variable and annual average snow depth in the Northern Hemisphere (NH): (a) the first date of soil freeze (FFD), (b) freezing duration (FDR), (c) maximum freeze depth (MFD), (d) the date of maximum freeze depth (MFDD), (e) the last date of soil thaw (TLD), (f) thawing duration (TDR), (g) freeze-thaw duration (FTDR), and (h) actual number of freezing days (AD). The tables show the frequency of significant positive correlations (red) and significant negative correlations (blue).

temperate climate), 0.46 days/cm (snow climate), and 0.43 days/cm (polar climate). For AD, it is 1.78 days/cm (arid climate), 0.67 days/cm (warm temperate climate), 0.52 days/cm (snow climate), and no change in the polar climate. In these four climatic zones, the deeper the snow, the stronger the thermal insulation effect on the soil.

4.1.4. Soil Moisture

To determine the potential effect of soil moisture on freeze-thaw status, we establish the correlations (Figure 14). The percentages of sites that are negatively correlated are 45.5% (FFD), 50% (FDR), 84.6% (MFD), 66.7%

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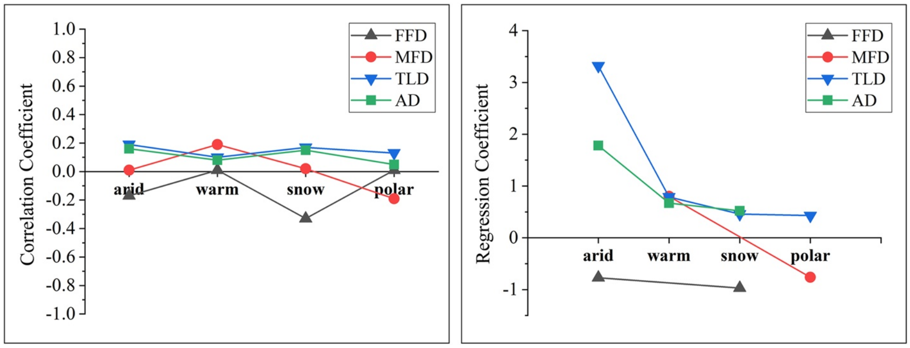

Figure 13. Correlation and regression coefficient between snow depth in each climate zone and (a) the first date of soil freeze (FFD), (b) maximum freeze depth (MFD), (c) the last date of soil thaw (TLD), and (d) actual number of freezing days (AD). Insignificant results are not displayed.

(MFDD), 63.6% (TLD), 70% (TDR), 55.6% (FTDR), and 77.8% (AD), but most are not significant. For each variable, the correlation in the arid climate zone was opposite to that from the other two climate zones (Figure 15). Soil moisture is not available in the polar climate zone. The strength of the association was strongest in the arid climate zone, then the warm temperate climate zone, and then the snow climate zone (except FFD). Generally, the results indicate that the greater the soil moisture content, the smaller the freeze-thaw variable in the warm temperate and snow climate zone, and vice versa in the arid climate zone. The probable reasons are that, during the freezing stage, more liquid water freezes into ice, more latent heat needs to be released, which results in a later FFD. Also, soil with greater soil moisture has a higher heat capacity and thus needs to absorb more energy to promote phase change, which causes the freezing depth to decline. Thus, the TLD will occur earlier and the FTDR will be shortened. Finally, during the thawing stage, soil with high soil moisture will also have a high ice content, which thaws slower compared with the arid soil. Thus, the TLD is delayed, which prolong the days of the entire freeze-thaw process (Luo et al., 2016).

4.1.5. Geographic Factors

Geographical factors are also important, and dominate the spatial patterns of the freeze-thaw process. Thus, the correlations between latitude and elevation with each freeze-thaw status variable are considered (Figure 16). The entire freeze-thaw process is prolonged (advanced FFD, delayed TLD, increased AD) and the MFD is increased, with an increase of latitude and elevation. The correlation between each variable and elevation is lower, the maximum R being -0.37 with FFD, indicating that freeze-thaw status it is not strongly affected by elevation at the hemisphere scale. Furthermore, these stations do not have a large elevation range. On the other hand, the increase of latitude corresponds to a decline in the intensity of solar radiation, which reduces the surface temperature and thus the transmission of heat from the surface into the ground.

4.2. Limitations and Future Work

This study assembled the most comprehensive set of long-term SFG observations in the NH, conducted a detailed assessment, and discussed the spatiotemporal characteristics and potential influencing factors. However, there are still some limitations, which should be acknowledged. For example, freeze-thaw processes are jointly affected by many factors, not only the geographical and climatic factors included here. These include other potential factors such as soil texture, vegetation cover, terrain, and solar radiation (Gao et al., 2016; Mishra & Riley, 2014). However, due to the lack of reliable data, their impact on SFG is still unknown. Future work could focus on these nonclimatic factors, to supplement the existing field observations (Frauenfeld & Zhang, 2011; Frauenfeld et al., 2004).

Projections of SFG changes could be useful for climate change, agriculture, etc. (Chang et al., 2018; Han et al., 2018; Wang et al., 2019). Although observations are critical in exploring the current status of seasonally freeze-thaw processes, additional, improved data sets would also be important to better project these changes in the future. Similarly, establishing the exact mechanisms of these SFG changes requires more detailed observations and simulations. Because SFG is affected by many factors combined (Chen et al., 2014; Luo et al., 2018),

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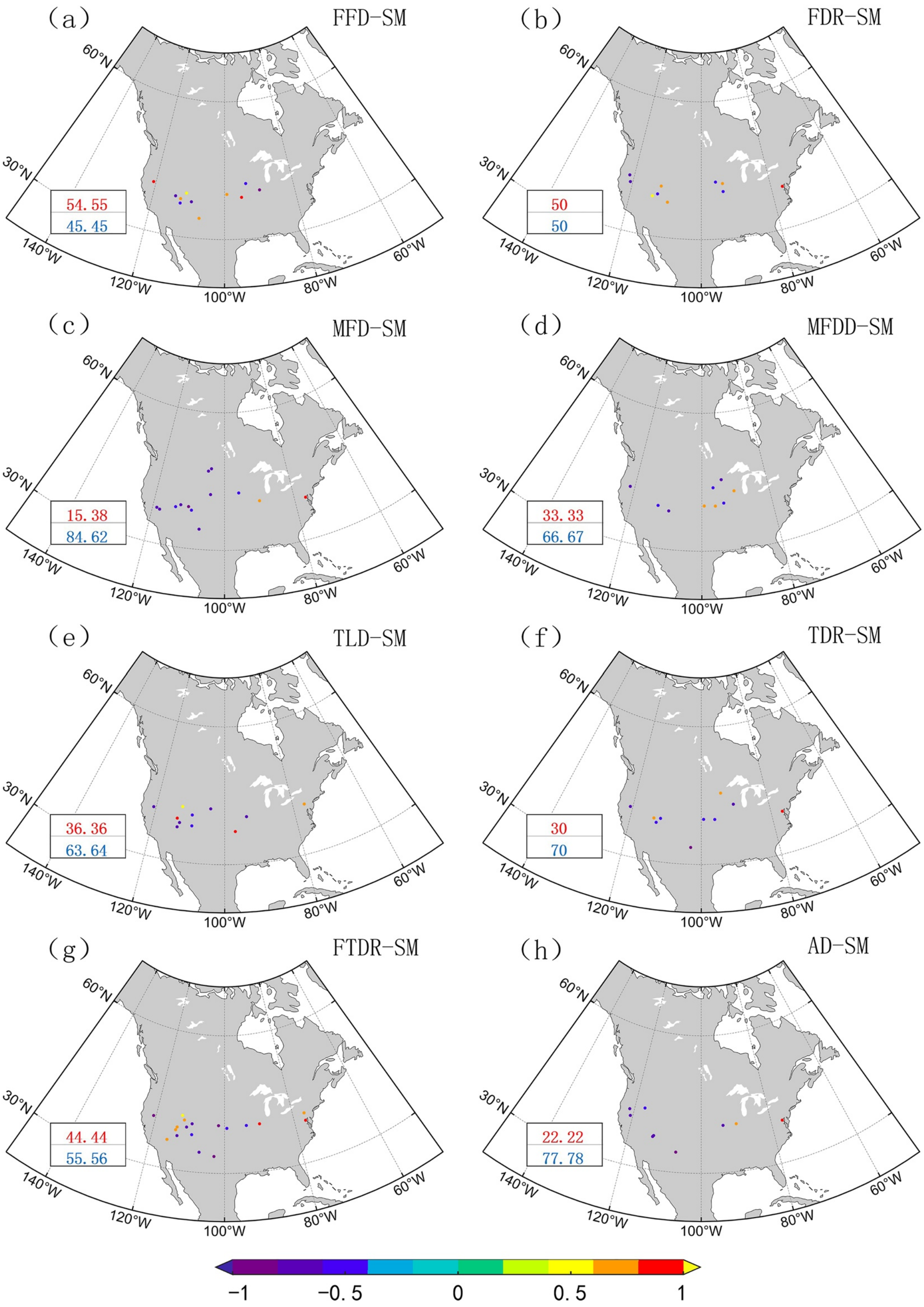

Figure 14. Correlation between each freeze-thaw state variable and annual average soil moisture content in the Northern Hemisphere (NH): (a) the first date of soil freeze (FFD), (b) freezing duration (FDR), (c) maximum freeze depth (MFD), (d) the date of maximum freeze depth (MFDD), (e) the last date of soil thaw (TLD), (f) thawing duration (TDR), (g) freeze-thaw duration (FTDR), and (h) actual number of freezing days (AD). The tables show the frequency of significant positive correlations (red) and significant negative correlations (blue).

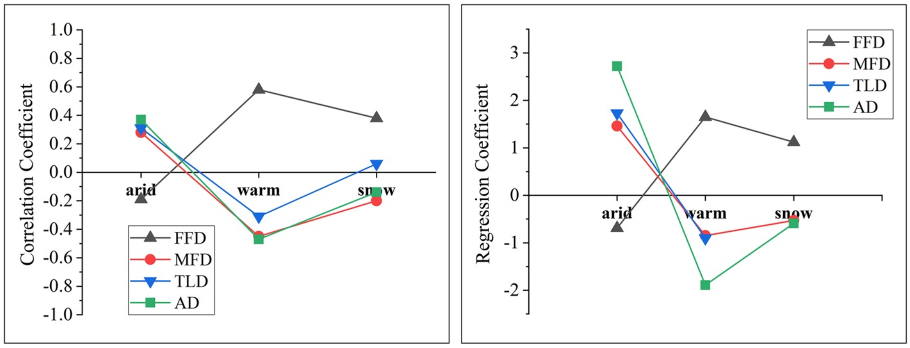

Figure 15. Regression between soil moisture in each climate zone and (a) the first date of soil freeze (FFD), (b) maximum freeze depth (MFD), (c) the last date of soil thaw (TLD), and (d) actual number of freezing days (AD).

it is important to quantify the joint and individual effects of each factor. Finally, an important limitation is the necessity of ground surface temperature at 0 cm in determining freeze-thaw processes of SFG. Because measurements are recorded at different depths in different countries, this brings about uncertainties at the hemisphere scale. Similarly, the uneven distribution of stations will introduce uncertainty to the spatial patterns.

5. Summary and Conclusions

We conducted a comprehensive assessment of the freeze-thaw processes based on long-term historical time series of 1,220 stations in the NH, including their temporal and spatial variability, comparisons in different climate zones, and their potential drivers. The following conclusions can be drawn:

1. The spatial distribution of the various freeze-thaw status variables based on the long-term average shows a gradual increase from low to high latitudes and from low to high elevations. The hemispheric average value of the FFD is day 329 ± 29 (late November), the MFD is 90 ± 73 cm, the MFDD is day 49 ± 28 (mid-February), the TLD is day 96 ± 45 (early April), the FTDR is 117 ± 60 days, the AD is 105 ± 66 days, and FDR and TDR are 75 ± 44 and 41 ± 19 days, respectively. The distribution of the multiyear mean of the eight freeze-thaw status variables corresponds to the major climatic zones. The FTDR from shortest to longest is: warm temperate, arid, snow, and polar climate. The warm temperate zone is found at low latitudes (southern China and southern North America) and low elevations (western Europe), and this climate zone is characterized by high temperatures and rainfall, with the warm and humid conditions not being conducive to the development of SFG. In contrast, the snow and polar climates are located at high latitudes (circumpolar regions) and high elevations (Qinghai-Tibet Plateau), where the climate is cold and permafrost develops, thus the FTDR of SFG at the periphery of the permafrost region is longer.
2. At the hemisphere scale, eight freeze-thaw status variables are estimated to quantify SFG variability. The long-term trends of the freeze-thaw status variables indicate that at most stations in the NH, the FFD is delayed (69% of stations), the TLD occurs earlier (77% of stations), the MFD decreases (79% of stations), the MFDD is earlier (73% of stations), the FDR and TDR shorten (72% and 61% of stations, respectively), and the FTDR and AD are similarly decreased (72% and 74% of stations, respectively). From 1986 to 2005, the 20-year net change in each variable shows a 5.3 days delayed FFD, a 9.0 days shorter FDR, 8.9 cm shallower MFD, 14.5 days earlier MFDD, 24.7 days earlier TLD, 4.6 days shorter TDR, 18.2 days shorter FTDR, and 12.1 days fewer AD. In high latitude and elevation regions, the trend in each freeze-thaw variable is largest, indicating the region's sensitivity to climate change.
3. Different climatic and environmental factors were explored as potential driving variables of the freeze-thaw process changes. The FFD is positively correlated with air temperature and precipitation, the MFD, FTDR, and AD are negatively correlated with air temperature and precipitation. Thus, higher temperatures and moisture shorten the freeze-thaw process in soils. Similarly, the freeze-thaw variables and snow depth on the Eurasian continent are negatively correlated in the high latitudes, and positively correlated in the lower latitudes. The insulation effect of snow on the freeze-thaw process does not weaken with decreasing snow depth. In low latitude and low elevation areas, where annual average snow depth is shallow, snow plays a cooling role. In the US, the correlations in the arid climate zone were opposite to those in the other two climate zones. In the

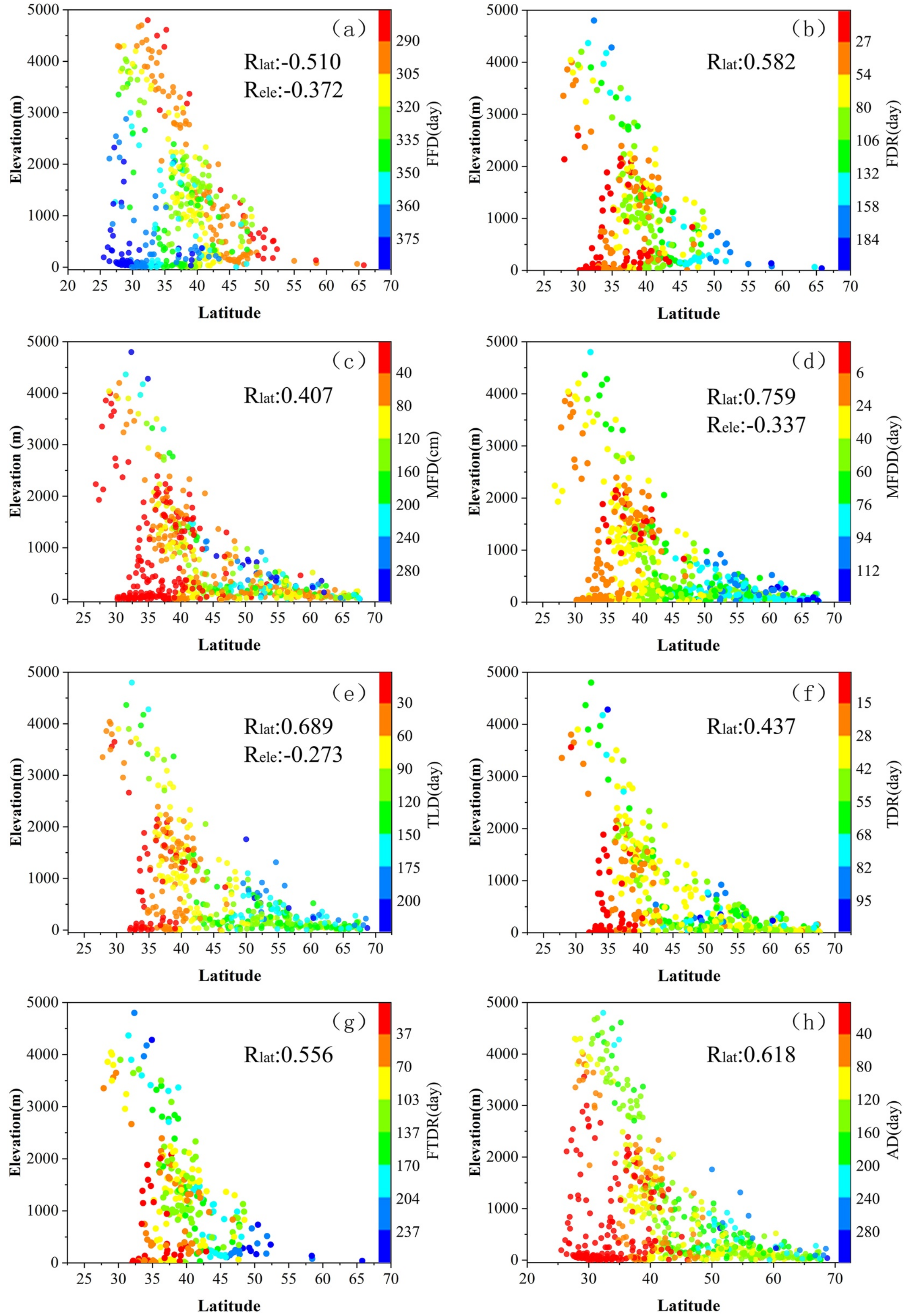

Figure 16. Variation and correlations between latitude (R_{lat}) and elevation (R_{ele}) in the Northern Hemisphere (NH) with the first date of soil freeze (FFD), (b) freezing duration (FDR), (c) maximum freeze depth (MFD), (d) the date of maximum freeze depth (MFDD), (e) the last date of soil thaw (TLD), (f) thawing duration (TDR), (g) freeze-thaw duration (FTDR), and (h) actual number of freezing days (AD). Only significant correlations are shown.

arid climate zone, the soil moisture content is negatively correlated with FFD, and positively correlated with MFD, TLD, and AD. The spatial distribution of SFG is also influenced by latitude and elevation, with stations at high latitude and elevation being characterized by early freezing, deep freezing depths, late thawing, and more freezing days.

Data Availability Statement

Daily mean air temperature, ground surface temperature, soil temperature, and snow depth [dataset] are available to scientific researchers in China via application from the China Meteorological Administration (2015), http://data.cma.cn/en/. Russian station observations [dataset] are from the Russian Research Institute for Hydro-Meteorological Information-World Data Center (2015), http://meteo.ru/data/. Meteorological station data for the United States [dataset] are available from the National Water and Climate Center (Soil Climate Analysis Network, 2021, https://www.nrcs.usda.gov/wps/portal/wcc/home/snowClimateMonitoring/soilClimateConditions/). Station observations for Canada [dataset] are available from the Fluxnet-Canada Research Network-Canadian Carbon Program via (Fluxnet Canada Team, 2016, https://doi.org/10.3334/ORNLDAAC/1335/). Station observations for Finland [dataset] from the Arctic Space Centre can be downloaded from (Finnish Meteorological Institute's Arctic Space Centre, 2021, https://litdb.fmi.fi/).

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