

Recent dynamics of soil thermal regime under changing climate in northern Eurasia

Liangzhi Chen

ACADEMIC DISSERTATION

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Abstract

Soil is one of the most critical components in Earth systems in connecting the lithosphere, hydrosphere, atmosphere, and biosphere. The responsiveness of soil temperature to climatic changes has been tackled in a number of studies. However, a timely understanding of the recent shallow-depth soil temperature evolution in response to changing climate and environment at inter-annual time scale over northern Eurasia is inadequate and needed for assessing the land-atmosphere thermal interactions and consequences at a broad spatiotemporal scale. This thesis backs up the aforementioned knowledge gaps by 1) quantifying and contrasting soil temperature changes in northern Eurasia and subregions; 2) investigating discordant changes in soil and air temperatures and their links with environmental changes; 3) assessing and examining the stability of soil-air temperature coupling at an inter-annual time scale and the underlying mechanisms.

This thesis demonstrated that shallow-depth soil temperature significantly increased over the region since the 1970s in terms of the annual mean, maximum, and minimum soil temperatures. However, the warming rates were spatially heterogeneous at different depths and over the subregions divided by the extent of frozen ground. In the region as a whole, the average increases in the annual mean, maximum and minimum temperatures ranged between 0.30–0.31, 0.33–0.44, and 0.24–0.25 °C/decade, respectively, at multiple depths. As such, the overall faster increase in the annual maximum temperature than minimum temperature led to an increase in intra-annual variability of soil temperature over the years.

The soil temperature changes were consistently smaller than the air temperature changes except in the seasonal frost area at a depth of 0.2 m. Such discordant changes in soil and air temperatures led to inter-annual variations of soil-air temperature

difference over the period. Furthermore, the environmental changes essentially explained the variability of temperature difference. Among the examined variables, changes in the snow cover characters showed overriding effects. Other environmental changes such as surface net solar radiation, liquid precipitation, and soil moisture had comparatively smaller impacts but still significant, which cannot be ignored at some ground depths.

It is also revealed that coupling, which is defined as the linear regression slope between the mean annual soil and air temperatures, was not a stable property and significantly decreased from 1984 to 2013. The declined coupling was likely due to the compound effects of changing thawing/freezing-degree days of air temperature and snow cover

characteristics. The findings further question the rationality of using air temperature to proxy soil temperature (or vice versa) at inter-annual and long-term time scales.

This thesis provides a thorough picture of the recent shallow-depth soil temperature evolution in response to climate changes and related consequences over northern Eurasia. The findings will help understand land-atmosphere thermal interactions and the role of environmental components at inter-annual and long-term time scales. Considering soil temperature as a critical parameter for Earth systems research, the findings can be referred to and implemented for various aims, such as climate projection, land-surface model development, and agricultural management.

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List of original publications

- I. Chen, L., Aalto, J., Luoto, M. (2021).** Significant shallow–depth soil warming over Russia during the past 40 years. *Global and Planetary Change*, 197, doi: 10.1016/j.gloplacha.2020.103394
- II. Chen, L., Aalto, J., Luoto, M. (2021).** Decadal changes in soil–atmosphere temperature differences linked with environmental shifts over northern Eurasia. *Journal of Geophysical Research: Earth Surface*, 126, e2020JF005865. doi:10.1029/2020JF005865
- III. Chen, L., Aalto, J., Luoto, M. (2021).** Observed decrease in soil and atmosphere temperature coupling in recent decades over northern Eurasia. *Geophysical Research Letters*, 48, e2021GL092500. doi:10.1029/2021GL092500.

The publications are referred to in the text by their roman numerals.

Author’s contribution to the publications

Activities	I	II	III
Original idea	LC, JA, ML	LC, JA, ML	LC
Data compilation	LC	LC	LC
Data analyses	LC, JA	LC	LC
Results interpretation	LC, JA, ML	LC, JA, ML	LC, JA, ML
Writing – original draft	LC	LC	LC
Writing – comments & revisions	LC, JA, ML	LC, JA, ML	LC, JA, ML

LC, JA, and ML refer to Liangzhi Chen, Juha Aalto, and Miska Luoto, respectively.

Abbreviations

AMSD	annual mean of the daily snow depth
Beta (β)	coupling between MAAT and MAST (equivalent to the slope of the linear regression between MAST and MAAT) in a specified time
Delta T (ΔT)	difference between annual mean air and soil temperature (MAST–MAAT)
FDD	freezing degree days (sum of daily air temperature that below 0 °C)
GAMM	generalized additive mixed model
LAI	leaf area index
MAAT	mean annual air temperature
m a.s.l	meters above sea level
MAST	mean annual soil temperature
m b.s.l	meters below sea level
Rainfall	annual liquid precipitation
SCD	annual snow cover duration (sum of the days that snow cover exists)
SEM	standard error of mean
SolarRad	surface net solar radiation (equivalent to the solar radiation reached to the surface minus the amount reflected the surface)
SSD	annual sum of the daily snow depth
TDD	thawing degree days (sum of the mean daily air temperature above 0)
Tmax	annual maximum soil temperature
Tmin	annual minimum soil temperature
Trange	annual variability of soil temperature
VWC	volumetric water content

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1 Introduction

The shallow–depth soil temperature is closely related to ambient air temperature and affected by the processes occurring near the land–atmosphere interface. Soil temperature impacts various biogeophysical and biogeochemical functions, such as ground hydrothermal fluxes (Luo et al., 2003; Makarieva et al., 2019), vegetation root growth (Porter & Gawith, 1999), and soil organic carbon balance (Davidson & Janssens, 2006; Fernández-Martínez et al., 2019). Thus, it is of great importance and interest in broader disciplines such as biodiversity, agriculture, forest management, and urban development.

In a warming climate, soil temperature has been changing, especially in northern Eurasia, where the climatic warming is faster than the global average during the last few decades (Blunden & Arndt, 2019; IPCC, 2013; Wisser et al., 2011). The ground in northern Eurasia experiences freeze-thaw cycles during summer and winter seasons and encompasses the world’s largest permafrost area, which is defined as the ground that temperature remains below 0 °C for at least two consecutive years and known to be sensitive to climate

change (AMAP, 2017; Brown et al., 1997; Smith & Brown, 2009). Over the past 30–35 years, the warming rate of the permafrost over northern Eurasia was similar to that in North America, whereas the warming rate in 2006–2017 was most notable in northern Eurasia (at 0.33 ± 0.16 °C) than in North America (at 0.23 ± 0.11 °C) (Biskaborn et al., 2019; Blunden & Arndt, 2019; Drozdov et al., 2015).

Compared with the research focusing on the permafrost area, the seasonal frost area – where the ground experiences at least 15 days of freezing per year – has received less attention (Frauenfeld & Zhang, 2011; Zhang, 2005). Soil temperature in the seasonal frost area is generally more responsive to the air temperature than in the permafrost area, mainly due to longer snow cover duration and thicker snow cover depth, which insulates soil temperature against ambient air temperature (Barnett et al., 1988; Zhang, 2005). However, how and at what rate the ground temperature over the seasonal frost area has changed in contrast to that over the permafrost area is less addressed, which is vital in providing benchmark data of soil temperature dynamics in the seasonal

frost and permafrost areas. Moreover, compared with the mean annual soil temperature (MAST), the extreme (maximum and minimum) soil temperatures have been comparatively less studied, mainly due to data limitations in spatiotemporal coverage. The extreme ground temperatures determine the freeze-thaw depth and timing in the ground (Anderson et al., 2019; Frauenfeld et al., 2004), which influences the latent heat processes and further affects soil hydrothermal state, soil carbon balance, and vegetation growth. Furthermore, the variability of shallow-depth soil temperature (the range between maximum and minimum temperature) is critical for soil biodiversity, vegetation composition, and abiotic and biotic functions within the soil (Adriaenssens et al., 2017; Anderson et al., 2019; Jiang et al., 2016). Hence, it is important to examine the changes in extreme annual ground temperatures in response to the changing climate.

In situ data scarcity is a major barrier to disentangle shallow-depth soil temperature evolution and its response to climatic changes at a large spatiotemporal scale. By applying multiple statistical methods, this thesis incorporates the most up-to-date in situ

measurements and reanalyzed environmental attributes to answer how shallow-depth soil temperature has responded to the climatic changes in northern Eurasia and its mechanisms and consequences since the 1970s.

1.1 Soil temperature regime in cold regions

Soil temperature closely responds to air temperature with a time delay that increases with soil depth. The variations of soil temperature in a specific period decrease as the depth increases. For instance, diurnal variations of soil temperature are mostly damped out at a depth of 30–50 cm, mainly depending on soil composition (Hirota et al., 2002; Jacobs et al., 2011). In particular, soil temperature variations and responsiveness to air temperature can be affected by land covers, such as seasonal snow cover and vegetation (Fisher et al., 2016; Hinkel, 1997; Sokratov & Barry, 2002).

Shallow-depth soil temperature is an integrator of the processes and their interactions occurring near the land-atmosphere interface and involves broader disciplines such as climatology, hydrology, biogeography, and socioeconomics. Hence, it significantly affects land-climate hydrothermal

fluxes, root development, subsurface soil carbon balance, and human activities. In turn, the environmental elements and anthropogenic activities also modulate spatiotemporal variations of soil temperature directly or indirectly (Aalto et al., 2018; Edmondson et al., 2016; Peng et al., 2016; Sokratov & Barry, 2002).

Soil temperature of the ground that freezes and thaws seasonally or remains frozen perennially is a critical attribute in cryospheric research (Romanovsky et al., 2002). The permafrost temperature refers to the temperature measured at a depth where the seasonal variations are negligible or within the accuracy of the instrument, which is one of the essential climate variables (ECV) (Bojinski et al., 2014; Romanovsky et al., 2010a). In shallow depth of the permafrost ground, the active layer (the soil layer above the permafrost that freezes and thaws each year) thickness is primarily determined by shallow–depth soil temperature, and more frequent energy and mass exchanges with the atmosphere and vegetation occur within the active layer rather than the underlain permafrost (e.g., Romanovsky & Osterkamp, 2000). As such, energy flux through the active layer is decisive for the existence of permafrost, and thus shallow–depth soil

temperature is a useful premonition for underlain permafrost changes. In the seasonal frost area, shallow–depth soil temperature is essential for the hydrology and microclimate of seasonally frozen soils, which has greater agricultural and socio-economic impacts due to denser human activities than in the permafrost area (Gautier et al., 2009; Hjort et al., 2018; Melvin et al., 2017).

In situ observation of soil temperature over a long period and large spatial scale is costly and time–consuming. Spatiotemporal coverage of the current monitoring networks and schemes used for measurements vary among countries (or regions). Over the frost–related areas in the Northern Hemisphere, the most extensive multilayer soil temperature monitoring is conducted across northern Eurasia at 458 meteorological stations (Gilichinsky et al., 1998). Meanwhile, other climatic variables such as air temperature, snow cover depth, and precipitation are also measured at some stations. This systematic monitoring was initiated in the middle of the last century by the All-Russian Research Institute of Hydrometeorological Information-World Data Centre (RIHMI-WDC), and most of the stations stay active.

1.2 Soil temperature changes in a warming climate

There is an undisputed globally climatic warming at a time scale associated with soil temperature changes (Blunden & Arndt, 2019). The Arctic (70–90°N) warming is two to three times faster than the global average since the 1950s, so-called Arctic amplification (Cohen et al., 2014). Besides, the observed Arctic amplification during 1950–2012 extends further south than CMIP5 models simulated beyond the Arctic region to central Asia, especially in the winter season, suggesting that trends in soil temperature over the subarctic region (50–70°N) derived from Earth system models might be underestimated (IPCC, 2013; van Oldenborgh et al., 2013). Thus, it is imperative to benchmark the current status and evolution of soil temperature over this region.

For the last 30–40 years, the warming rate of the permafrost varied regionally, in particular, the most significant warming of the permafrost from 2008/2009 to 2016 was observed in northern Eurasia (over 0.90 °C) among the global boreholes (AMAP, 2017; Biskaborn et al., 2019). In relatively shallow ground (0–3.2 m), MAST at 1.6 m depth increased at 0.26 °C/decade during 1956–1990, while MAAT

increased 0.29 °C/decade in eastern Siberia (Romanovsky et al., 2007). The fastest warming of soil temperature (0–3.2 m) occurred in the central and southern regions of Siberia, accompanied by increased active layer thickness (Romanovsky et al., 2007). Nevertheless, the synthesis studies on soil temperature change in the seasonal frost area and in contrast with that in the permafrost area are rare and urgently needed for providing timely information on recent soil temperature evolution against the extent of frozen ground (Frauenfeld & Zhang, 2011; Zhang, 2005).

Extreme weather and events have been changing globally since the mid-20th century in terms of frequency and intensity (Donat et al., 2013; IPCC, 2013). For instance, the fifth assessment report of the intergovernmental panel on climate change (IPCC AR5) concludes that it is *very likely* (90–100% probability) that the number of cold days and nights decreased while the number of warm days and nights increased at a global scale (IPCC, 2013). The extreme soil temperatures are likely to be affected by the weather extremes, whereas knowledge of such responsiveness and consequences is limited to some characterization case

studies and inadequately known at a large spatiotemporal scale (Luo et al., 2020; Matyshak et al., 2017).

The frozen ground contains an enormous amount of soil organic carbon, more than twice the amount currently in the atmosphere (Tarnocai et al., 2009). An increase in soil temperature degrades permafrost, thus exposing and releasing preceding frozen carbon to the atmosphere in the form of greenhouse gases, such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (NO₂), and further leads to a higher atmospheric temperature (Marushchak et al., 2011; Reay et al., 2018; Turetsky et al., 2020). In turn, climatic warming would cause more greenhouse gases to be released, creating positive feedback beyond the regional but global Earth system (Koven et al., 2011; Schuur et al., 2013, 2015). Moreover, the permafrost stores nearly twice as much mercury as all other soils, the ocean, and the atmosphere combined, and this mercury is vulnerable to release with permafrost degradation and further poses unknown consequences to the environment (Schuster et al., 2018).

Notably, the role of soil temperature on the frost-related ground goes beyond ecology and geography but also into engineering. An increase in soil

temperature leads to permafrost degradation and thickening of the active layer, which has been demonstrated to risk some human infrastructures (Hjort et al., 2018; Shiklomanov et al., 2017). Overall, the changes in frost-related soil temperature and other cryosphere components, such as snow cover, glacier, and their interactions, can also generate positive feedback to Earth system changes and increase the rate and uncertainties of global change (Diro & Sushama, 2020; Groisman et al., 2017).

1.3 Role of environmental variables on soil temperature

Soil temperature is highly sensitive to climate change, but the response may be complex and spatiotemporally heterogeneous. In the frost-related ground, shallow-depth soil thaws and freezes annually, and thus the soil temperature is altered by land surface energy and moisture fluxes (Aalto et al., 2018; Iijima et al., 2010; Luo et al., 2020; Subin et al., 2013). Essentially, all processes involving hydrothermal exchanges are influential on soil temperature, but the strength of the influences varies at different time scales and soil depths due to the heterogeneity in hydrothermal fluxes with depth and soil composition. However, the

quantitative and comparative studies on environmental impacts on soil temperature at different depths are inadequate, especially on an inter-annual basis at a large spatiotemporal scale.

In the frost-related area, the insulation function of snow cover on soil temperature is vital, especially for fresh snow with a low density (Apaloo et al., 2012; Bartlett et al., 2005; Peng et al., 2016; Sokratov & Barry, 2002; Way & Lewkowicz, 2018; Tingjun Zhang, 2005). If the air is colder than the soil, the snow cover will reduce heat transfer upwards, which could reduce the freeze depth of soil, slow down the freeze of the active layer and protect the ground from cooling. The opposite influence emerges if the air is warmer than the soil. The overall consequences of the snow cover impacts on soil temperature depend on the timing of snowfall, thickness, and duration of snow cover (Smith et al., 2012; Zhang, 2005). At a longer time scale, for instance, decades, the change in soil temperature can be decoupled with the change in air temperature due to temporal variations of snow cover characteristics. For example, in eastern Siberia, the faster soil warming (at a depth of 1.6 m) than air at some sites was attributed to a positive trend in snow cover thickness (Romanovsky et al.,

2007). In particular, if the snow cover is relatively thin (e.g., winter snow depth ranges up to 30 cm), the sensitivity of ground temperature to the variations in snow cover thickness is very significant; however, a primary thickness varies at individual sites.

Soil moisture in the frost-related ground undergoes phase changes (from water to ice, or vice versa) seasonally, introducing substantial freeze-thaw latent heat effects on shallow-depth soil temperature (Andresen et al., 2020; Cheruy et al., 2017; O'Donnell et al., 2009). As the permafrost degrades, the formerly frozen ground that features low hydraulic conductivity would be transferred to be drainable, further modulating soil moisture distribution and soil temperature (Young et al., 2020; Zhang et al., 2001). At long-term scales, changing precipitation and evaporation alter soil moisture content, resulting in the changes in soil thermal conductivity and heat capacity, which further is likely to contribute to soil temperature trends (Bintanja & Andry, 2017; Bintanja & Selten, 2014; O'Donnell et al., 2009; Subin et al., 2013).

Vegetation regulates the soil thermal regime by root development and surface energy partitioning by the canopy that reflects/absorbs solar radiation and

holds snowfall (e.g., Bonan, 2015; Forzieri et al., 2020). Removal of vegetation increases soil temperature in the summertime and seasonal freeze-thaw depth in the frost-related ground (Blok et al., 2010; Loranty et al., 2018). Further, as an essential land cover element, vegetation intensively interacts with precipitation, soil moisture, and air temperature by evapotranspiration processes (Byrne & O’Gorman, 2015; Zhou et al., 2021). In a changing climate and associated vegetation dynamics (Linscheid et al., 2020; Macias-Fauria et al., 2012; Piao et al., 2020), the influence of long-term vegetation changes on soil temperature regime needs to be quantified (Loranty et al., 2018). Yet, the influence of environmental variables on soil temperature at relatively fine timescales (on a daily and seasonal basis) has been widely addressed, whereas the compound studies that concurrently incorporate critical environmental variables are limited, especially at a large spatiotemporal scale in the frost-related area (Aalto et al., 2018; Iijima et al., 2010). Moreover, northern Eurasia has recently undergone drastic climatic changes (Blunden & Arndt, 2019; Groisman et al., 2017), causing alterations in, for example, precipitation

(Bintanja & Andry, 2017), snow cover characteristics (Zhong et al., 2018), soil moisture (Dai et al., 2004), and vegetation (Piao et al., 2020). Considering the close interactions between soil temperature and environmental variables and the great importance of soil temperature in many disciplines, soil temperature trends and related mechanisms should be better assessed.

1.4 Objectives

This thesis assessed the changes in shallow-depth (0.2–3.2 m) soil temperature under a changing climate and roles of environmental changes, such as snow cover, liquid precipitation, and vegetation over the past three to four decades in northern Eurasia. The main aims are to develop our understanding of land–climate interactions and highlight current and potential consequences facing the future climate. In detail, this thesis will

1. Quantify and contrast the changes in shallow-depth soil temperature in terms of the annual mean, extreme, and variability of soil temperature at multiple depths over subregions divided by the extent of frozen ground (Paper I).
2. Clarify the responsiveness of soil temperature to air temperature changes

and the role of the environmental changes on trends of the temperature difference between air and soil (Paper **II**).

3. Assess the temporal stability of the coupling between soil and air temperatures at an inter-annual scale and uncover key mechanisms (Paper **III**).

Three research papers address these objectives.

In Paper **I**, trends in multilayer soil temperatures collected from 457 stations during 1975–2016 were investigated. Beyond the mean annual ground temperature, trends in the annual extreme (maximum and minimum) and intra-annual variability of soil temperatures are also examined. The regional trends are assessed by aggregating the results of individual stations. Further, the study examines and compares trends in soil temperature over the subregions distinguished by the extent of frozen ground. Meanwhile, the role of snow cover, latent heat due to freeze-thaw cycles on soil temperature, and the temperature difference between soil and air are discussed.

In Paper **II**, first, the relationships

between the trends in temperature difference and environmental variables are regressed using the linear least-squares method against multiple depths and subregions. Then, the influences of the environmental changes on temperature difference trends are quantified by GAMM, which can capture not only linear but also nonlinear relationships between the response and explanatory variables (Hastie & Tibshirani, 1990; Wood, 2017).

In Paper **III**, first, coupling between MAAT and MAST is derived from a 15-year running window during 1984–2013. Then trends in the coupling at individual stations are computed as slopes of the linear regressions from a set of running windows in the period. Regional changes in coupling are assessed by aggregating the results from all sites. Furthermore, the coupling between two sets of years, which is evenly divided based on the magnitudes of investigated environmental variables in a 20-year running window, are compared to reveal the underlying mechanisms of the weakened inter-annual relationship between MAST and MAAT.

2 Materials and Methods

2.1 Study region

The study region covers the land between ca. 28°E in the west, the Pacific Coast in the east, ca. 42°N in the south, and the Arctic Ocean coast in the north (Figure 1). The region encompasses a broad range of climatic conditions, topography, biomes, and ground thermal regimes. The MAAT ranges from lower than -15 °C in central Siberia to 15 °C in the Black Sea Coastal area (Groisman et al., 2017). The annual precipitation ranges from 150 mm in the Siberian tundra to 2000 mm in coastal areas of Kamchatka and the Black Sea (Hijmans et al., 2005). The elevation ranges from 28 m b.s.l at the Caspian Sea, ca. 100 m a.s.l in West Siberian Plain, on average of 500–700 m a.s.l in Central Siberian Plateau, to 5642 m a.s.l at Mount Elbrus. The cool–temperate and cold boreal forests dominate the vegetation of the region. The balance of regional land cover is occupied by xerophytic shrublands and grasslands at the southern boundary of the boreal forest and a sequence of tundra biomes, from high and low–shrub tundra at the polar treeline to cushion–forbs lichen and moss in the most extreme polar climate zones in the north (Goetz et al., 2011).

Most of the ground freezes in winter, while the length of the freezing period varies spatially at different depths (Frauenfeld et al., 2004). The region comprises the world’s largest permafrost area, which is defined as the ground that temperature remains below 0° C for at least two consecutive years (Brown et al., 1997), while the seasonal frost ground, soil that experiences at least 15 days of freezing per year occupies the rest of the areas beyond the permafrost area.

Over the past few decades, the regional climate has been changing considerably. For instance, the MAAT increased by 0.37 °C/decade during 1975–2011 (Groisman et al., 2017). The rising air temperature regulates cryospheric components, including permafrost degradation (Biskaborn et al., 2019; Streletskiy et al., 2015; Zhang et al., 2001), declined thickness of seasonally frozen ground (Frauenfeld et al., 2004; Frauenfeld & Zhang, 2011; Shiklomanov et al., 2017) and glacier melt (Bennett et al., 2015). However, the knowledge of how shallow-ground temperature responded to climate change in a long period and mechanisms are relatively limited, which is of great importance considering the effects of

energy flux near the land–atmosphere interface on soil carbon balance and

vegetation growth, hydrological regimes, and human infrastructure stability

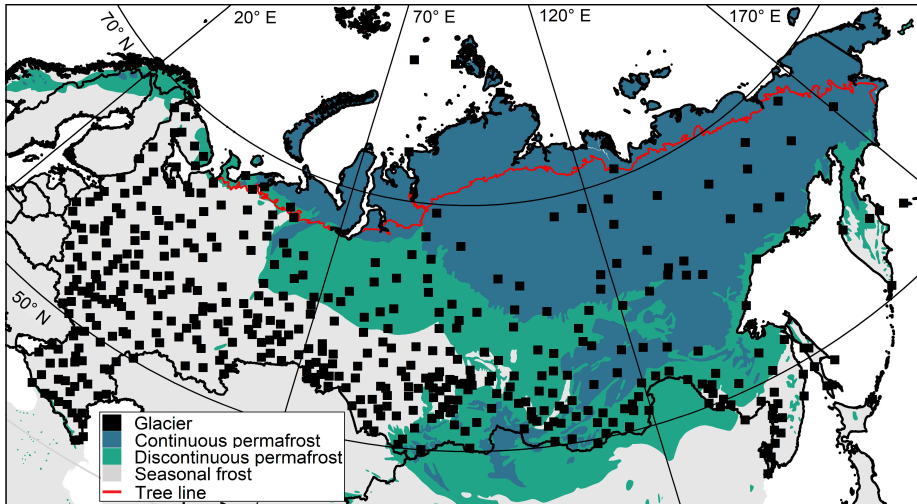


Figure 1. Distribution of observational stations used in this thesis ($n = 457$). The background map of the permafrost zonation (continuous permafrost area: the extent of permafrost $\geq 90\%$; discontinuous permafrost area: $0\% < \text{extent of permafrost} < 90\%$) was obtained from the International Permafrost Association (Brown et al., 1997). The tree line was derived from the Circumpolar Arctic Vegetation Map project (Walker et al., 2005).

2.2 Meteorological and geospatial data

This thesis uses the most up-to-date in situ observations, including air, soil temperatures, snow depth, and rainfall (liquid precipitation) collected from 457 meteorological stations in northern Eurasia (Figure 1). In these datasets, the daily air temperature is an average of three-hourly observations in a calendar day, and soil temperature is measured once per day around midday local time (Bulygina & Razuvaev, 2012). The temperature observations are all within

the measurement accuracy of 0.1°C (Gilichinsky et al., 1998). Daily snow depth and rainfall are measured with an accuracy of 0.1 cm and 0.1 mm, respectively. All datasets were extracted from the All-Russia Research Institute of Hydrometeorological information – World Data Center (RIHMI-WDC). The datasets were performed with multiple quality checks before publication and the data qualified as “reliable” are used in this thesis (Paper I).

Apart from in situ observations, other environmental data from ERA5–Land

products are also used in the thesis (Table 1). The ERA5–Land provides reanalysis datasets of land variables that cover the analyzing periods of the papers (papers **II** and **III**) without gaps at a spatial resolution of 9 km (Hersbach et al., 2020). The ERA5–Land combines weather forecast models and observations across the world into a globally complete dataset based on physics laws, providing a reasonable description of the past climate.

The surface net solar radiation (SolarRad, w/m^2) from ERA5–Land is defined as the amount of solar radiation (also known as shortwave radiation reaching the surface of the Earth (both direct and diffuse) minus the amount reflected by the Earth’s surface (Hersbach et al., 2020). The volumetric water content (VWC, %) is available at three soil layers (VWC_{0.2}, VWC_{0.8}, and VWC_{1.6}) and includes both the liquid and solid (ice) water content in unfrozen and frozen soils, respectively (Balsamo et al., 2011). Vegetation is characterized by the leaf area index (LAI) from ERA5–Land, which is defined as one-half of the total green leaf area per unit of horizontal ground surface area (Monteith & Unsworth, 2013).

2.3 Data compilation

This thesis focuses on inter-annual variations of soil temperature regimes and other environmental variables. Thus, the daily in situ measurements extracted from RIHMI-WDC were computed into the annual values for analyses. Due to the data gaps where the reasons were not always recorded, a qualified year has to have a minimum of 300 days of measurements per year for computing the annual values (Papers **I–III**). The raw data downloaded from ERA5–Land were monthly-mean averages which were then computed into the annual values for analyses in Papers **II** and **III**. The annual values applied in the thesis are listed in Table 1.

Inter-annual variations of individual variables were investigated by their temporal trends that were computed as the slopes of linear least squares regressions during specified periods. The analyzing period of Paper **I** spans from 1975 to 2016, during which a minimum of 30 years’ data is needed to calculate trends in variables for each station. Then the regional soil temperature changes were quantified by aggregating the results from all sites. Moreover, soil temperature changes over the subregions divided by the extent of frozen ground (the continuous permafrost, discontinuous permafrost,

and seasonal frost) were analyzed and contrasted. The significance of trends against the null hypothesis (meaning no change occurred over time) was tested by the Wilcoxon method (Bauer, 1972). In Paper II, data collected from 1981 to 2015 were involved, which is different from Paper I due to the data availability (1981–present) of ERA5–Land products.

2.4 Statistical analyses

The relationships between paired climatic and environmental variables were examined by linear least square regressions (Paper II). However, the correlations and interactions between Earth system components are complex and nonlinear in many cases (Ghil, 2019). Thus, to quantify the effects of trends in variables on ΔT (MAST-MAAT, °C) trends, generalized additive mixed models (GAMM) were applied in Paper II. Unlike the linear regressions, GAMM captures the impact of a changing environment on the ΔT trends by smooth functions, which can be linear or nonlinear depending on the underlying patterns of the data (Hastie & Tibshirani, 1990; Wood, 2017).

The explanatory variables used in GAMMs in Paper II are trends in climatic and environmental variables,

including AMSD, SCD, SolarRad, Rainfall, VWC, and LAI, while the trend in ΔT is the response variable. Due to the nonuniformity of in situ measurements, temporal coverage of the data varies at stations. To ensure the consistency of the data used in GAMM, two criteria were followed (Paper II). First, trends of the variables at each station were derived from a common set of years. Second, the number of years used for computing trends at each site was included as a random term in GAMMs to take the effect of the different temporal coverages at sites into account in the models (Wood, 2017). Multicollinearity refers to the non-independence of predictor variables in regression analysis (Dormann et al., 2013). It is a common feature of any descriptive geophysical data and can inflate the variance of the regression parameters and hence potentially results in biased interpretations of the role of individual variables in GAMM. In Paper II, collinearities among explanatory variables were diagnosed by multiple indices, including pairwise correlations, condition index (CI) (Belsley et al., 2005; Douglass et al., 2003), variance inflation factor (Hair et al., 1995), and tolerance. The diagnostic results indicate that

Table 1. The annual variables were calculated from the daily observations and gridded monthly (grey shaded) data sets.

Variables	Definition	Calculation and /or description	Paper
MAAT	Mean annual air temperature (°C)	Arithmetic mean of the daily air temperature in a year	I II III
MAST	Mean annual soil temperature (°C)	Arithmetic mean of the daily soil temperature in a year	I II III
ΔT	Difference between MAAT and MAST (°C)	MAST–MAAT	II
SSD	The sum of annual snow depth (cm)	Arithmetic sum of daily snow depth in a year	I
AMSD	Annual mean of daily snow depth (cm)	Arithmetic mean of the daily snow depth in a year	II
SCD	Snow cover duration (days)	Length of the days when snow cover exists (>0.1 cm)	I II III
Rainfall	Annual liquid precipitation (cm)	Arithmetic sum of daily rainfall precipitation in a year	II III
SolarRad	Surface net solar radiation (w/m^2)	Absorbed solar radiation equivalent to the amount of solar radiation reaching the earth surface minus that reflected by the surface.	II III
VWC	Volumetric water content (%)	VWC _{0.2} , VWC _{0.8} , VWC _{1.6} represent the soil water content in layers of 0–0.2, 0–0.8, and 0–1.6 m, respectively.	II III
LAI	Leaf area index	One half the total green leaf area per unit of the horizontal ground surface	II III

variables that potentially distort the modeling outcomes affected by severe collinearity were not included in GAMM (Paper II).

The contribution of each explanatory variable in GAMM was characterized by relative variable importance (Thuiller et al., 2009). First, the Pearson correlation coefficients between fitted values of the models and predictions where the variable under investigation has been randomly permuted were calculated. Then, the importance of the investigated variable was simply calculated as the outcomes of correlation coefficients minus one. Consequently, the magnitude of the variable importance is constrained from 0 to 1, in which the higher the variable is, the more influential it is. The final variable importance was the average of 100 permutations.

In order to examine dynamics of the relationship between air and atmosphere temperature, Paper III analyzes inter-

annual variations of the relationship between MAST and MAAT in the region during 1984–2013. Firstly, MAST–MAAT coupling (β) was defined as the regression slope between MAST and MAAT during each 15–year moving window from 1984–2013. Then, trend in β at each site was computed as the linear regression slope from the whole running windows (16 windows overall). Further, the mechanisms of the weakened β were examined using a similar statistical method. In short, β_s derived from two sets of years which were evenly divided by the magnitude of various environmental variables for each 20–year running window were compared. As such, the more influential the variable is, the greater the difference of β between two sets of years is (Paper III). All variables were first detrended in each window before statistical analyses as we focused on the inter-annual relationship between MAST and MAAT.

3 Results

3.1 Evolution of shallow-ground temperature

Paper I demonstrated significant increases in shallow-depth soil temperatures, in which the magnitudes were spatially heterogeneous at multiple depths (Figure 2). Of the total investigated sites, over 89% showed increases in MAST, and only four, two, and two sites had decreased trends at depths of 0.8, 1.6, and 3.2 m, respectively. The fastest warming occurred in the northern Siberian permafrost area by 1.09 ± 0.20 °C/decade (mean \pm S.D., $P < 0.01$). In the region as a whole, the averaged increase rates for MAST and T_{min} from 0.8 to 3.2 m were at a similar level by 0.30–0.31 and 0.24–0.25 °C/decade, respectively. However, the increases in T_{max} declined from 0.40 to 0.33 °C/decade as the depth increases. The overall faster increase in T_{max} than T_{min} led to an increase in T_{range} , suggesting an expanded intra-annual variability of soil temperature that further has a reasonable impact on permafrost degradation, root growth, soil carbon balance, and ground hydrological regime.

In the subareas featuring different frozen

ground, soil temperature changes varied with depth and attribute (Figure 3). At depths of 0.8 and 1.6 m, the increase in MAST over the continuous permafrost area was the most pronounced, followed by those observed over the seasonal frost and discontinuous permafrost areas, whereas it was the slowest at a depth of 3.2 m. Moreover, the changes in the extreme soil temperatures showed different patterns spatially at multiple depths. The increase in T_{max} over the discontinuous permafrost area was less in the shallower levels than the deeper varying from 0.31–0.35 °C/decade, but the opposite was the case for T_{min} ranging from 0.35–0.27 °C/decade. However, in the seasonal frost area, trend in T_{max} diminished from 0.40 to 0.32 °C/decade with depth, while the increase in T_{min} enhanced from 0.19 to 0.25°C/decade. Consequently, the changes in T_{range} declined over the seasonal frost region with depth but enhanced in the discontinuous permafrost area.

3.2 Discordant increases in soil and air temperatures and the consequences

The regression analyses demonstrated that MASTs (0.8 m) were systematically

smaller than MAATs and, on average, accounted for 0.64 of MAATs in the region (Paper I). The coupling (MAST/MAAT) was close to zero when the site had a longer SCD and thicker

SSD. However, at a few extreme cold sites (averaged MAAT is around $-10\text{ }^{\circ}\text{C}$) located in the continuous permafrost, the coupling was high at 0.94 despite the thick snow cover (Paper I).

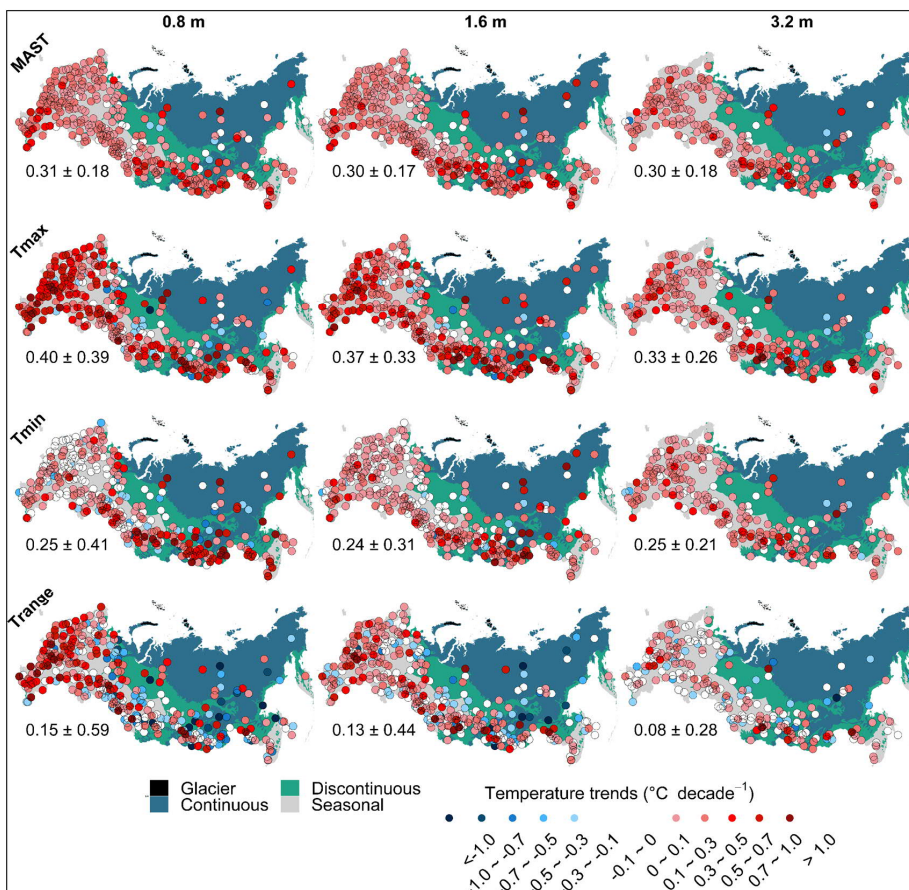


Figure 2. Spatial distribution of trends in four soil temperature parameters at multiple depths during 1975–2016 in northern Eurasia (Paper I). There are 315, 319, and 213 sites at depths of 0.8, 1.6, and 3.2 m, respectively.

During the past decades, the changes in soil temperature followed air temperature changes, but the warming rates were inconsistent (Figure 4). Over the subareas based on the extent of

frozen ground, warming rates in MASTs were, in general, lower than those in MAATs, except in the seasonal frost area where MAST at 0.2 m ($0.44\text{ }^{\circ}\text{C}/\text{decade}$) increased faster than

MAAT (0.36 °C/decade). The most notable difference in warming rates between MAST and MAAT emerged in the discontinuous permafrost area at a depth of 0.2 m by 0.15 °C/decade and 0.27 °C/decade, respectively.

The discordant trends in air and ground temperature led to ΔT , which varied inter-annually during the period. The

averaged trends in ΔT were slightly smaller than 0 °C/decade ranging from -0.05 to -0.02 °C/decade with depths, suggesting that the temperature difference between MAAT and MAST was in decline but at a minor rate (Figure 4). Nevertheless, the trends in ΔT were spatially heterogeneous, ranging from over -1 to 1 °C/decade at different depths.

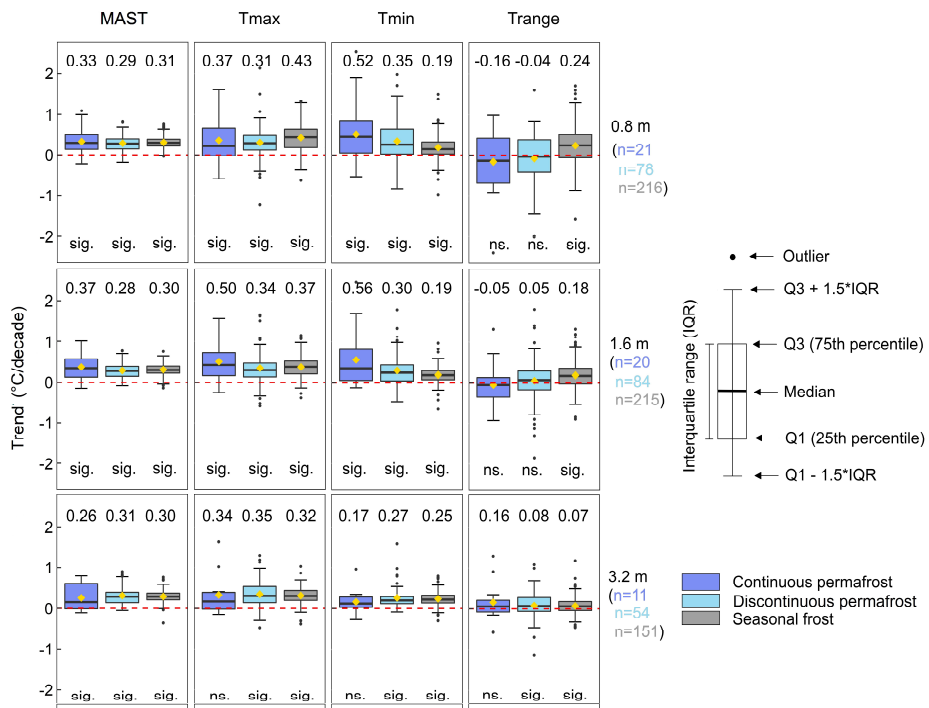


Figure 3. Variations of trends in soil temperature at multiple depths over the subareas divided by the extent of frozen ground (Paper I).

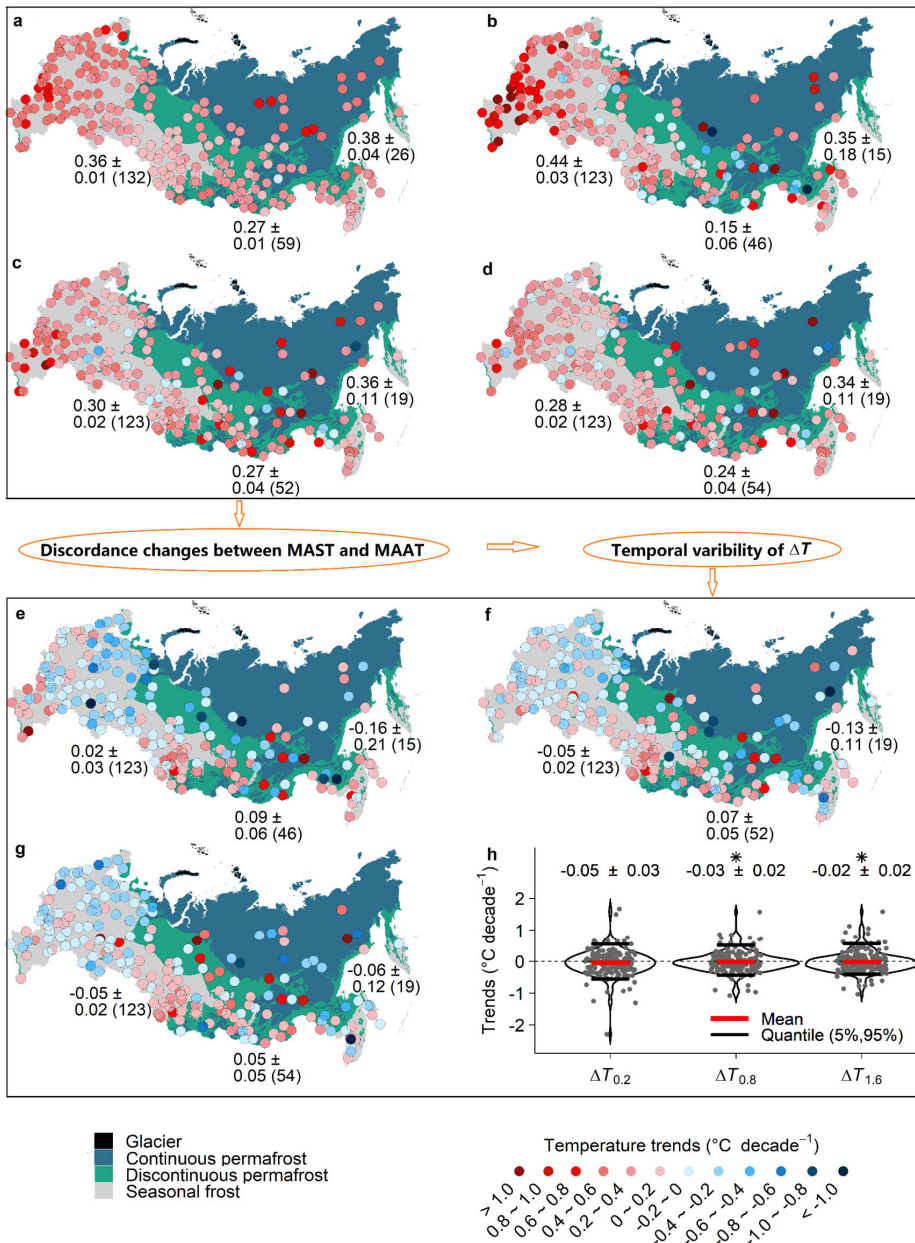


Figure 4. The discordant trends in MAST and MAAT led to the temporal variability of ΔT during 1981–2015 (Paper II). The figures (a–d) in the upper panel depict trends in MAAT, MAST_{0.2}, MAST_{0.8}, and MAST_{1.6}, respectively. The figures (e–g) in the lower panel depict trends in $\Delta T_{0.2}$, $\Delta T_{0.8}$, and $\Delta T_{1.6}$, respectively, while figure h shows variations of trends in figures e–g.

3.3 Factors controlling trends of ΔT

Trends in ΔT at individual sites closely responded to the local climatic and environmental changes. The results of statistical analyses suggest that the alteration in snow cover was a major factor in affecting ΔT trends. Over the region, trends in AMSD had closer relationships with trends in ΔT at the deeper ground than the upper by the explained variance ranging from 30.2% to only 4.3% in linear regressions (Paper II). However, trends in SCD explained the largest ΔT trends by 19.1% at a depth of 0.8 m, followed by depths of 1.6 and 0.2 m.

The results from multivariate analyses are generally consistent with the linear regression results but shed light on the influences of other environmental changes (Figure 5). Trends in SolarRad significantly related to the trends in ΔT at all depths, but the relationship weakened as the depth increases. Trends in rainfall had no significant relationships with ΔT trends by linear regressions, whereas they played the

second most important factor for $\Delta T_{0.2}$ trends by GAMM. Soil moisture systematically decreased over the region by 0.48–0.58% at multiple levels, which was significantly and nonlinearly related to ΔT trends. The change in vegetation showed no significant relationships with ΔT trends at shallower levels but was significant at 1.6 m.

Multivariate analyses by GAMM demonstrated the highly nonlinear responsiveness between trends in ΔT and other environmental variables. The response curves between trends in ΔT and AMSD and VWC are largely above the null (meaning the no changes in ΔT), suggesting that the changes in annual mean snow cover thickness and soil moisture were mainly associated with the increases in ΔT (meaning the faster warming of soil than air). However, the response curves from trends in SolarRad, Rainfall, and LAI are largely below null, indicating that the decreased ΔT involves more environmental changes such as the changes in solar radiation, liquid precipitation, and vegetation.

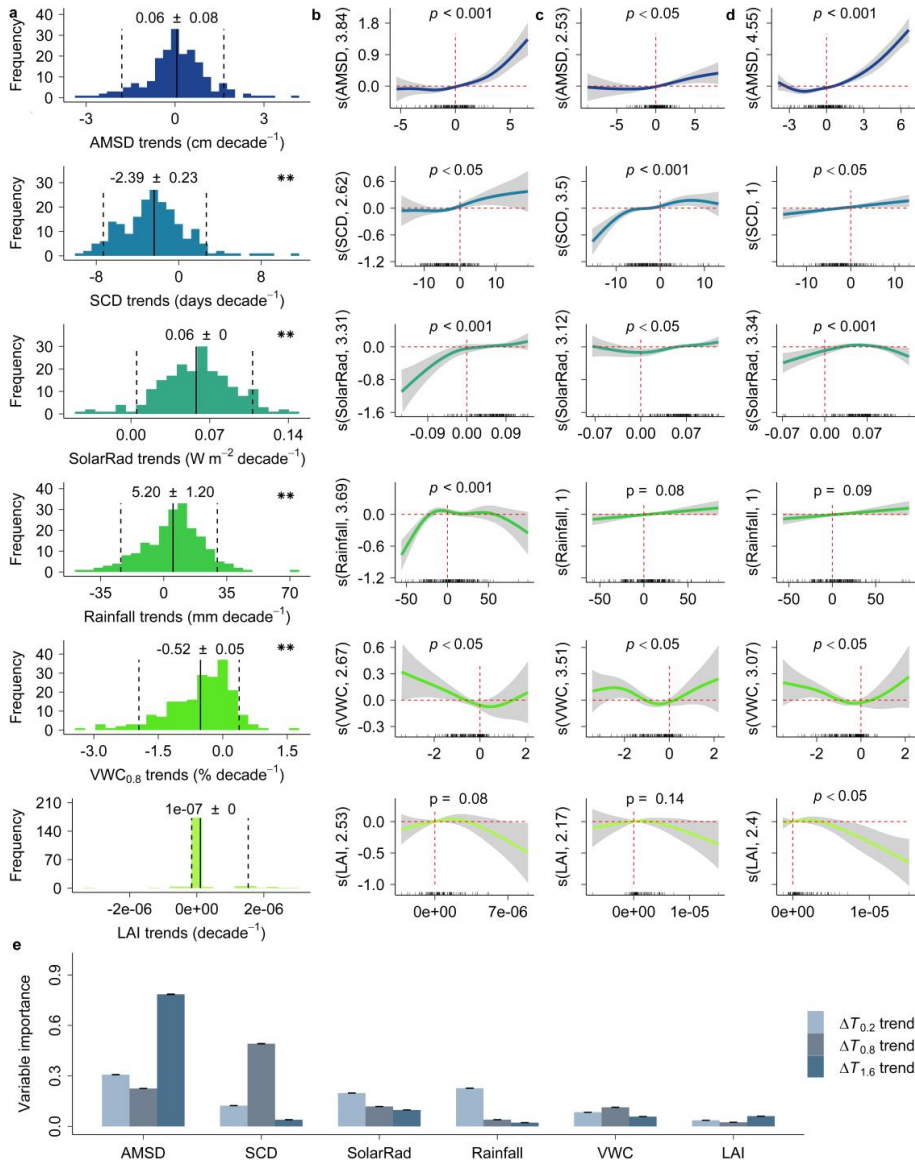


Figure 5. Histograms (a) display temporal trends in the environmental variables at 217 sites during 1981–2015 (Paper II). Average trends are reported with SEM (Mean ± SEM) in subplots. Dashed lines indicate the 5th and 95th percentiles. The significance of the averaged trend against null was marked with asterisks that none (or two) indicate $p > 0.05$ (or $p < 0.0001$). Figures (b)–(d) show response curves between trends in ΔT (b. $\Delta T_{0.2}$; c. $\Delta T_{0.8}$; d. $\Delta T_{1.6}$) and the environmental variables based on GAMM. Shades represent 95% confidence intervals and red dashed lines ($y = 0$ and $x = 0$) indicate nulls. Figure (e) shows relative importance for each variable with a 95% confidence bar over 100 permutations.

3.4 Decreased air-ground temperature coupling

The results of Paper III demonstrated that the relationship between MAST and MAAT was not a stable property, and β decreased from 1984 to 2013 over northern Eurasia (Figure 6). The $\beta_{0.2}$ decreased from 0.48 for the first 15 years (1984–1998) to 0.36 for the last 15 years (1999–2013) in the region, and a similar reduction in β was also observed at a depth of 1.6 m. During 1984–1998, 80% of the sites had significant $\beta_{0.2}$, while only 53% of the sites remained significant during 1999–2013. At 1.6 m, even over half of the sites lost the significance of $\beta_{1.6}$ from 67% during 1984–1998 to 33% during 1999–2013. The mechanisms of the weakening air–ground temperature relationship were examined by a unique statistical

framework. The β for the group with greater AMSD is systematically lower than that for the group with smaller AMSD, but the differences diminish as the depth increases (Figure 7). Similarly, the difference of β between groups divided by the magnitude of TDD is notable. However, the effect of FDD on β is less clear and masked by seasonal snow cover as an insulation layer. Nevertheless, in the last couple of windows, it is also noticeable that β for the group with greater FDD is consistently smaller than that of the group with lower FDD. SolarRad also plays a role in determining β , and the differences in the β between two groups are generally smaller than those derived by different TDD. However, there are slight differences in β during the two groups divided based on Rainfall (Figure 7).

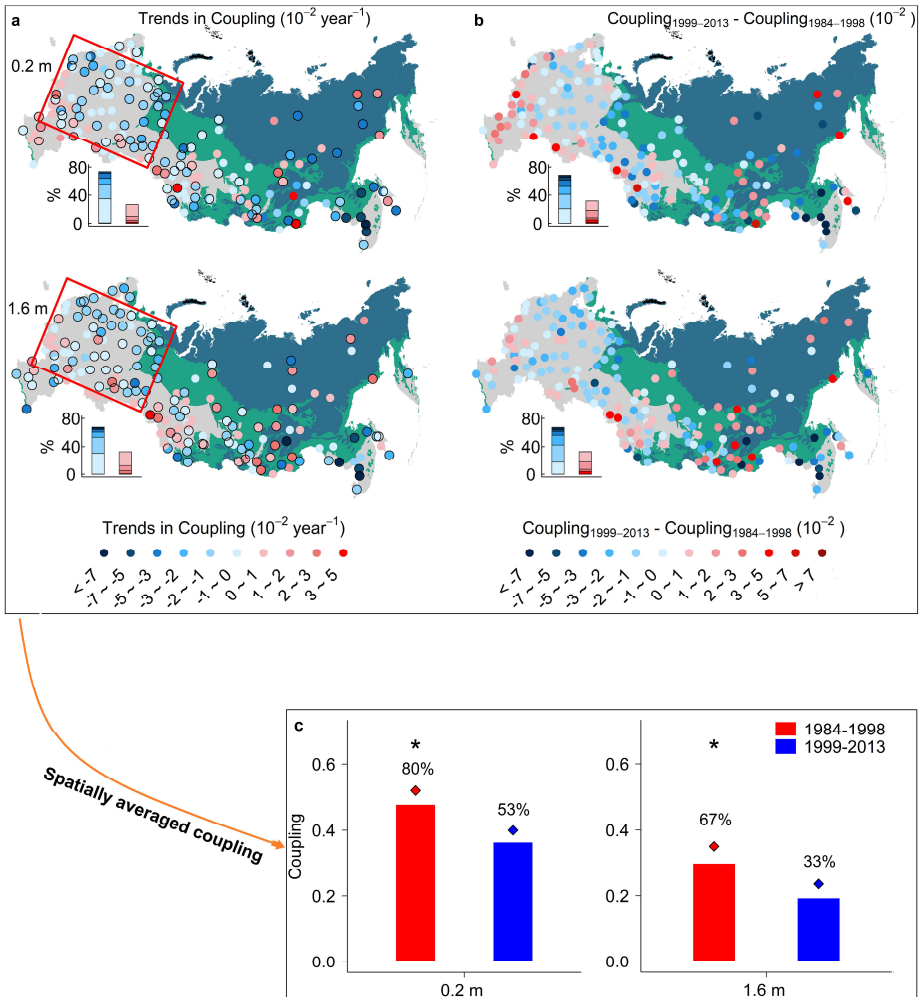


Figure 6. The weakened coupling (β) of MAST and MAAT during 1984–2013 at the shallower (0.2 m) and deeper (1.6 m) ground (Paper III). Panel a and b depict trends in β and the difference of β computed for the last (1999–2013) and first (1984–1998) 15 years during the period, respectively. Black-edged circles indicate that trends are statistically significant ($P < 0.05$). Panel c shows spatially averaged β during the first and last 15 years. The numbers at the top of each bar are the percentage of significant stations.

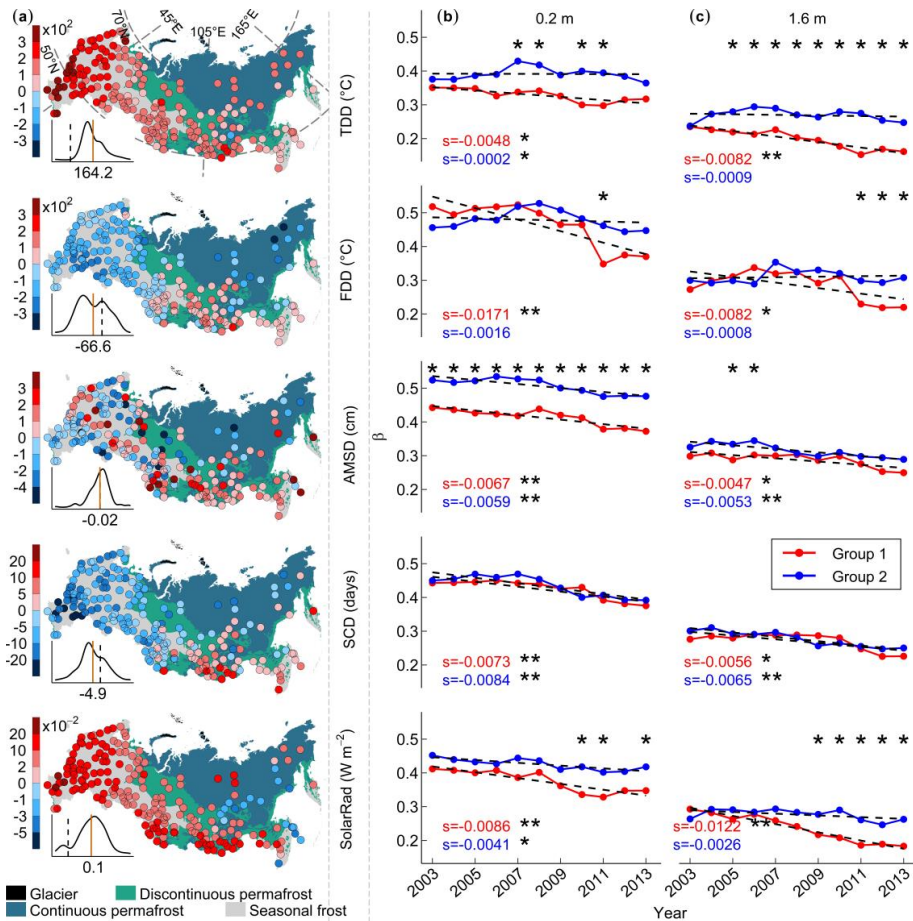


Figure 7. Change and comparison of β in different climatic and environmental conditions (Paper III). (a). The difference in the climatic variables between 1999–2013 and 1984–1998. The sub-density plots depict the distribution of the variables’ differences, while the black dashed and solid orange lines represent the null (meaning no change) and mean values, respectively. (b and c). Comparison of the changes in β in different climatic conditions. The x-axis shows the last year of each 20-year running window (e.g., 2013 stands for a running window from 1994 to 2013). For each 20-year window, we divided the 20 years into two groups based on the magnitudes of TDD, FDD, AMSD, SCD, and SolarRad: one group consists of 10 years with greater values (red, Group 1), while the other group (blue, Group 2) includes the remaining 10 years with smaller values. The difference between the two groups was assessed by the paired t-test and indicated with asterisks ($P < 0.05$) at the top. The numbers in b and c are linear regression slopes, and the asterisks indicate the significance level of the regressions (one for $P < 0.05$, two for $P < 0.001$).

4 Discussion

Understanding the recent shallow–depth soil temperature evolution in the context of a changing climate is critical for assessing land–climate thermal interactions, validating outputs of land surface models. In the frost–related area over northern Eurasia, despite soil temperature having been documented for decades and receiving reasonable attention, the knowledge of recent soil temperature evolution at multiple depths and underlying environmental drivers are inadequate at continental and decadal scales. This thesis provides a comprehensive view of decadal soil temperature evolution and its interactions with the changing environment by quantifying and contrasting the changes in soil temperature across subareas featuring different extents of the frozen ground; linking the changes in soil temperature and environmental conditions under climate change; assessing the coupling of air and ground temperatures over northern Eurasia since the 1970s.

4.1 Recent shallow–depth soil temperature change

In northern Eurasia, the soil depth measured at depths of 0.8, 1.6, and 3.2 m significantly increased in terms of

MAST, T_{min} , T_{max} during 1975–2016. The warming rates of soil temperature were analyzed to be spatially heterogeneous at different depths. The results provide valuable benchmark data of multilayer soil temperatures for Earth system models as insufficient soil depth in the models has been criticized (Phillips, 2020). The average increase in MAST and T_{min} were similar at depths by 0.30–0.31 °C/decade and 0.24–0.25 °C/decade, respectively. However, the increase of T_{max} diminished from 0.40 to 0.33 °C/decade as depth increases. The overall faster increases in T_{max} than T_{min} in the region led to an increase in T_{range} , which could affect biogeochemical and biogeophysical functions near the land–atmosphere interface (e.g., Davidson & Janssens, 2006; Jiang et al., 2016).

In subareas divided by the different extent of frozen ground, the changes in soil temperature were different. At depths of 0.8 and 1.6 m, the increases in MAST and T_{min} in the continuous permafrost area were faster than in the discontinuous permafrost and seasonal frost areas, which can be attributed to the different strengths of freeze–thaw latent heat effects across subareas

(Romanovsky et al., 2010a). For the deeper borehole temperature, studies also attribute the discrepancy of the warming magnitudes in the continuous and discontinuous permafrost areas to the different latent heat effects over the areas (Biskaborn et al., 2019; Smith et al., 2012).

The changes in snow cover characteristics closely respond to soil temperature changes by impeding the energy exchange between land and atmosphere during the winter (e.g., Zhang, 2005). Trends in snow cover thickness and soil temperature had a positively significant relationship (Paper I). Notably, the sites with decreased MAST were associated with declined SSD and SCD, which is in line with previous studies (e.g., Gądek & Leszkiewicz, 2010; Romanovsky et al., 2007). Meanwhile, trends in snow cover and Trange had significantly negative relationships, suggesting that future intra-annual variability of soil temperature may continue to increase under the current and a projected retreat of snow cover in northern Eurasia (Bormann et al., 2018; Bulygina et al., 2011).

4.2 Environmental impacts on trends in air and soil temperatures

Soil temperature is closely related to

ambient air temperature and also other environmental components, such as snow cover (Bartlett et al., 2005; Way & Lewkowicz, 2018; Zhang, 2005), soil moisture (O'Donnell et al., 2009; Subin et al., 2013), rainfall (Iijima et al., 2010; Ye et al., 2015). However, there was no significant relationship between trends in MAST and MAAT in the permafrost area (Paper II). Such decadal inconsistent changes in air and soil temperatures led to temporal variations of ΔT over northern Eurasia, which responded to concurrent environmental changes.

Snow cover characteristics have been changing considerably over the region (Paper II and AMAP, 2017; Bulygina et al., 2011). The change in snow cover showed an overriding effect on ΔT trends (Figure 5). The SCD decreased over the region, especially in late spring, while the changes in AMSD were spatially heterogeneous (details in supplementary material in Paper II). This supports the previous studies concluding that the maximum water equivalent and maximum snow cover depth have increased over most of the region (Bulygina et al., 2011). Inconsistent changes in snow cover thickness and duration make the influence of snow cover on soil and air temperature

relationships complex (Peng et al., 2016; Zhang, 2005). The results of Paper II suggest that the change in AMSD was more influential on ΔT trends compared with the change in SCD. It is also noted that the response curves of trends in snow cover and ΔT are largely above null (Paper II, meaning no changes in ΔT), indicating that the changes in snow cover mainly contribute to the increase in ΔT rather than the decrease. The effect of snow cover on soil temperature may differ depending on the time frame of interest (Bartlett et al., 2004). On a daily and monthly basis, the net effect of snow cover on soil temperature can either be positive or negative by nonlinear relationships among snow cover thickness, duration, and onset timing (Aalto et al., 2018; Sokratov & Barry, 2002; Zhang et al., 1997). On an annual basis, the seasonal snow cover mainly positively affects soil temperature in the high latitude region (Bartlett et al., 2006; Gądek & Leszkiewicz, 2010).

Compared with the changes in snow cover, other environmental changes had relatively less impact on ΔT trends at decadal scales. The increase in SolarRad significantly contributes to ΔT trends, and the influential strength decreases as the depth increases. At different time scales, soil temperature may respond to

the other environmental variables dissimilarly. In cold regions, the abrupt rainfall precipitation in pre-winter seasons significantly raises the daily soil temperature at shallow levels, whereas it can decrease MAST of the frost-related soil (e.g., Luo et al., 2020; Iijima et al., 2010; Zhu et al., 2017). However, the potential for subsequent soil warming due to the abrupt rainfall is very sensitive to the initial hydrological conditions of soil if which are relatively moist, rainfall does not necessarily generate warming of soil (Subin et al., 2013). At a decadal scale, Paper II demonstrates that the increase in rainfall precipitation has a strong influence on trends in $\Delta T_{0.2}$, but the relationships are not significant at deeper levels (0.8 and 1.6 m).

The changes in vegetation only showed a significant relationship with ΔT trends at 1.6 m. Nevertheless, detailed information about vegetation at each station was not recorded, and the grasses removal for maintenance purposes at some stations might introduce anthropogenic trends to soil temperature variations (Gilichinsky et al., 1998).

Within soil in the frost-related ground, soil moisture, together with substrate materials, affect soil temperature by controlling the soil thermal capacity and strength of the freeze-thaw latent heat

influence on a seasonal basis (Apaloo et al., 2012; Ashcroft & Gollan, 2013; Cheruy et al., 2017; O'Donnell et al., 2009; Throop et al., 2012). Although the future liquid precipitation in high latitudes is predicted to increase (Bintanja & Andry, 2017), the net effect of soil moisture on soil temperature on an annual basis is uncertain due to the likely increase of evapotranspiration (Hinzman et al., 2005) and possible increased drainage due to the degrading permafrost (Andresen et al., 2020; Avis et al., 2011). The results of Paper II demonstrate that the long-term changes in soil moisture have minor but significant effects on ΔT trends at multiple depths.

4.3 Declined coupling of air and soil temperatures

During 1984–2013, the inter-annual relationship between MAST and MAAT was not stable and significantly decreased, especially in the western part of the region (Figure 6). The number of sites with significant β reduced substantially, warning us that using MAAT to proxy MAST could lead to bias, which is likely to be amplified if the β continues to be weakened with ongoing climate change (IPCC, 2013; Krasting et al., 2013).

By contrasting β_s of two groups divided

by the magnitudes of the environmental variables, the results of Paper III demonstrate that changes in TDD and SCD were primarily responsible for the declined β . The change in MAAT seems not an important role in declined β . This is partly because of the masked effects of FDD on β due to the snow cover insulation. However, FDD is likely to turn to play a significant role in affecting β with the projected retreat of snow cover in the region in the future, which leads to a gradual diminishing of the mask function of snow cover on FDD's impact on β (Bokhorst et al., 2016; Krasting et al., 2013; Lawrence & Slater, 2010). The snow cover attributes, especially SCD, have a positive relationship with FDD. As such, the warmer winter and consequent snow cover retreat may increase β . However, due to TDD's negative effect on β , the compound effects of TDD, FDD, and snow cover on β largely depend on the strength of individual influence, which is still little known and will be uncertain in the future climate considering the interactions and feedback among the variables. Future efforts should be devoted to quantifying and contrasting the individual influence of the changes in TDD, TDD, and snow cover on the β variations.

The changes in rainfall might not be a significant factor in the weakened β at an inter-annual time scale. Nevertheless, β of the group with higher annual soil moisture is slightly higher than the group with lower annual soil moisture. Further, the influence of rainfall–soil moisture mechanisms on β may change in the region, where more liquid precipitation is expected in the future climate (Bintanja & Andry, 2017; Eltahir, 1998). The results of this thesis consistently highlight the key role of snow cover in land–atmosphere thermal interactions at three- to four-decadal scales. This could be especially critical for northern Eurasia, where the changes of snow cover attributes (thickness, duration, and onset timing) have been occurring and projected to continue as well as the deemed nonlinear relationships among the snow cover attributes (Bartlett et al., 2004; Krasting et al., 2013). However, the role of other environmental components (liquid precipitation, soil moisture, vegetation) on the thermal balance between land and atmosphere can also be critical and should be counted considering the changing climate and close interactions among the components.

4.4 Future perspective

This thesis improves the understanding of the decadal evolution of shallow–depth soil temperature in response to and interactions with climatic and environmental changes. Apart from the contribution, it also raises some critical concerns and research questions worth paying attention to in the future. As the sites involved in this thesis are relatively limited and unevenly distributed, especially over the high northeastern part of the region, the results may contain some uncertainties for the regional analyses. Due to the deemed warming amplification that is projected to continue, the Earth system in the Arctic and subarctic may change unprecedently (Cohen et al., 2014). Further efforts to maintain and enhance the current monitoring network could enrich the datasets and generate more robust analyses of soil temperature change and its links with climatic and environmental dynamics.

Moreover, the role of different snow cover attributes (timing, duration, and thickness) varies, targeting the different spatiotemporal scales. The results of Paper III highlight that snow cover thickness plays a significant role in leading changes in β , but snow cover duration is not as significant. In the future, more detailed and multi-angle

studies on this issue are recommended. The effects of environmental variables on the interactions of soil and air temperatures may be different (both the magnitude and direction) at different spatiotemporal scales. For example, snow cover mostly has a positive impact on MAST as an insulator, whereas it can either positively or negatively impact soil temperature on a daily or monthly basis (Bartlett et al., 2006; Romanovsky et al., 2007; Zhang et al., 1997; Zhang et al., 2018). Similar is the case for other environmental variables, such as rainfall precipitation, and vegetation (Bonan, 2015; Loranty et al., 2018; Luo et al., 2020). Future efforts should focus on improving the knowledge of the impacts of the environmental changes on soil–air temperature coupling at long time scales in the future climate.

Beyond the investigated environmental variables, soil organic matter has been demonstrated to be influential on soil temperature by affecting soil texture and moisture-holding capacity, whereas how soil temperature would respond to soil organic matter changes in a long period is little known (Decharme et al., 2016; Zhu et al., 2019). This is mainly due to the limitation in spatiotemporal coverage of soil organic matter series. Further effort could be devoted to establishing the long-term soil organic matter monitoring network and addressing the responsiveness and interactions between soil temperature and temporal soil organic matter changes, especially in high latitudes where climate warming is faster than the global average.

5 Concluding remarks

Understanding land–climate thermal interactions – by assessing the recent trends in soil and air temperatures and the role of environmental changes – is essential to provide timely benchmark data for Earth system models and references to policymakers. This thesis demonstrates that soil temperature warming occurs across all attributes (the annual mean, maximum, and minimum temperatures), and the warming rates vary over subareas divided by the extent of frozen ground.

This thesis identifies spatially widespread discordant trends in air and soil temperatures. The consequential inter-annual variability of the temperature difference between air and soil temperatures is closely related to environmental changes. The role of the environmental variables on soil temperature may be different depending on spatiotemporal interest. This highlights the importance of paying more attention to the long-term interactions of the environmental components involved in land–atmosphere thermal interaction

processes in the future climate.

This thesis illustrates that coupling between mean annual soil and air temperature is not stable and significantly decreases at an inter-annual scale. Temporal variations of the coupling are sensitive to snow cover changes and warming of the air temperature during the snow-free season. The coupling variations can also be affected by winter warming in the future, which combines the impacts of the changes in snow cover conditions. These findings are important for generating more reliable Earth system models and climate projections in the future.

Overall, this thesis contributes to understanding recent land–atmosphere thermal interactions in response to the environmental changes in northern Eurasia. Furthermore, the benchmarked shallow–depth soil temperature changes, the role of the environmental variables in affecting relationships between soil and atmosphere temperatures discussed herein have implications for future studies on climate attribution and land–atmosphere thermal interactions.

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