LETTER

Recent regional warming across the Siberian lowlands: a comparison between permafrost and non-permafrost areas

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Abstract
The northern mid-high latitudes experience climate warming much faster than the global average. However, the difference in the temperature change rates between permafrost and non-permafrost zones remains unclear. In this study, we investigated the temporal changes in temperature means and extremes across the Siberian lowlands (<500 m) over the past six decades (1960–2019) using in situ observations and reanalysis data. The results show that permafrost zones (0.39 °C/decade) have warmed faster than non-permafrost zones (0.31 °C/decade). The minimum values of the daily maximum (TXn) and minimum (TNn) temperatures changed faster than their maximum values (TXx, TNx), suggesting that low minimum temperatures increase faster, as evidenced by the considerably higher warming rate in the cool season (October–April, 0.43 ± 0.10 °C/decade, n = 126) than that in the warm season (May–September, 0.25 ± 0.08 °C/decade, n = 119). The change rates of TXx and TNx in permafrost areas were 2–3 times greater than those in non-permafrost areas; however, over the last ten years, TXx and TNx in non-permafrost areas showed decreasing trends. Moreover, faster-warming permafrost regions do not exhibit a faster increase in surface net solar radiation than slower-warming non-permafrost regions. While our findings suggest that carbon emissions from thawing soils are likely a potential driver of rapid warming in permafrost-dominated regions, the potential feedback between ground thawing and climate warming in permafrost regions remains uncertain.

1. Introduction
The Arctic has warmed by 2 °C–3 °C since the late 19th century, a rate that is much faster than the global mean (~0.8 °C) for the same period (Overland et al 2014, Post et al 2019). This phenomenon is known as Arctic amplification (Sereze and Barry 2011). Currently, the Arctic is experiencing an abrupt and sustained period of climate warming (Jansen et al 2020), and research has verified that decreases in surface albedo due to the losses of snow cover and sea ice (Screen and Simmonds 2012, Chen and Wang 2021) and increases in shortwave radiation (Previdi et al 2020) are the main forces driving Arctic warming. Permafrost (i.e. perennially frozen ground) is a sensitive indicator of climate change (French 1999, Ding et al 2019). Recent observations have demonstrated that permafrost is warming globally (Romanovsky et al 2007, Oliwa and Fritz 2018, Biskaborn et al 2019) and that this warming process
is occurring faster than expected (Vaks et al 2020). Moreover, permafrost is one of the largest carbon reservoirs on Earth (Zimov et al 2006, Hugelius et al 2014, Schuur et al 2018, Wang et al 2020), containing nearly twice as much carbon as the current atmosphere (Trumbore 2009, Guo et al 2018). Therefore, permafrost degradation has the potential to amplify climate warming due to the release of carbon and methane from thawing sediments (Walter et al 2006, Schaefer et al 2014, Mu et al 2019, Turetsky et al 2020). Particularly in warmer climates, permafrost feedback is expected to become increasingly positive (Yumashev et al 2019). Nonetheless, how fast climate warming is occurring in permafrost-dominated regions and whether the warming rates differ between permafrost and non-permafrost zones remain unclear.

Siberia, which spans the middle to high latitudes of the Northern Hemisphere, is covered by different types of permafrost, from isolated patches to continuous permafrost (Brown et al 2002, Obu et al 2019). Siberia is experiencing considerable changes in climate, and its warming rate (1.39 °C/100 years) even exceeded that of the Arctic (1.28 °C/100 years) during 1881–2010 (Groisman et al 2013). Under a warming climate, cold ice-rich permafrost is expected to thaw quickly (Nitzbon et al 2020), leading to the rapid formation of thermokarst slides and lakes (Farquharson et al 2019, Lewkowicz and Way 2019). Continuous permafrost likely thaws faster than other types of permafrost, as evidenced by the fact that continuous permafrost warmed almost twice as fast as discontinuous permafrost at a global scale during 2007–2016 (Biskaborn et al 2019).

Recently, increasing evidence has indicated that the warming rate is amplified with elevation in mountainous regions (e.g. the Tibetan Plateau) through a phenomenon known as elevation-dependent warming (Qin et al 2009, Rangwala et al 2013, Pepin et al 2015, Guo et al 2016, Williamson et al 2020). Furthermore, at the basin scale in Siberia, Wang et al (2021a) showed that climate warming in colder basins occurs much faster than in warmer basins. Considering these phenomena, we pose the following question: Is the rate of climate warming in permafrost-dominated regions closely associated with the areal extent of permafrost? We hypothesize that climate warming occurs faster in permafrost zones (especially the continuous permafrost zone) than in non-permafrost zones. To answer this question, we collected daily 2 m air temperature data from 129 meteorological stations (figure 1) across Siberia (between 50° N and 70° N) for 1960–2019; the low elevations (<500 m a.s.l.) of these stations weakened the influence of elevation-dependent warming (Wang et al 2016). The main objectives of this study were to (a) quantify the trends of annual and extreme temperatures in both permafrost and non-permafrost zones across the Siberian lowlands and (b) identify the potential mechanisms responsible for climate warming in permafrost-dominated northern high-latitude regions.

2. Materials and methods

2.1. Data

The permafrost distribution was obtained from the Circum-Arctic Map of Permafrost and Ground-Ice Conditions (Version 2) (Brown et al 2002). Four different permafrost development zones were considered: continuous permafrost (>90% coverage), discontinuous permafrost (50%–90% coverage), sporadic and isolated permafrost (0%–50% coverage) and non-permafrost zones. With the help of data from the Global 30 Arc-Second Elevation (GTOPO30) digital elevation model provided by the USGS (USGS 1996, Earth Resources and Science 2017), areas with elevations above 500 m a.s.l. were excluded.

Daily 2 m air temperature data from 129 low-elevation (<500 m a.s.l.) meteorological stations in Siberia (figure 1, supplementary table S1 available online at stacks.iop.org/ERL/17/054047/mmedia) for 1960–2019 were obtained from the Russian Meteorological Station database (Bulygina et al 2020). Nineteen of the 129 stations were relocated in the past 60 years; however, most were relocated within 3 km of the previous stations (supplementary table S1). The numbers of meteorological stations situated in continuous permafrost, discontinuous permafrost, sporadic and isolated permafrost, and non-permafrost zones are 33, 4, 38, and 54, respectively.

Nine of the 129 meteorological stations with soil temperature observations (supplementary figure S1) were selected for detailed analysis, and these stations were divided into three groups by permafrost regionalization. Three stations (World Meteorological Organization (WMO) Nos. 24966, 24738, and 23274) are located in continuous permafrost zones, two (WMO Nos. 23955 and 23933) are located in isolated permafrost zones, and the other four (WMO Nos. 28493, 29570, 28661, and 35041) are located in non-permafrost zones. Daily soil temperature observation data for 1985–2012 at depths of 20 cm, 40 cm, 80 cm, 120 cm, 160 cm, 240 cm, and 320 cm were obtained from the Russian Meteorological Station database (Bulygina et al 2020).

We also used a gridded monthly average 2 m temperature dataset with a resolution of 0.5° from the Climate Research Unit time series (CRU TS) v. 4.04 (Harris et al 2020). The validation of yearly gridded temperature data against the observed data from 129 meteorological stations showed the good performance of CRU TS v. 4.04 temperature products (MAE (Mean Absolute Error) = 0.86 °C, RMSE (Root Mean Square Error) = 1.37 °C, NSE (Nash-Sutcliffe Efficiency) = 0.91, $R^2 = 0.93$, $n = 7670$) for the study area (supplementary figure S2). Additionally,
the gridded monthly average surface albedo and surface net solar radiation at 0.25° resolution for 1960–2019 were obtained from the ERA5 land monthly reanalysis dataset (Hersbach et al 2019, Bell et al 2020).

2.2. Temperature indices
To quantify changes in the intensity and frequency of extreme temperatures, four extreme temperature indices were selected from the 27 indices defined by the Expert Team on Climate Change Detection Monitoring and Indices (Karl et al 1999, International CLIVAR Project Office 2001, Zhang et al 2005). Indices TXx and TXn represent the maximum and minimum values of the daily maximum temperature (TX), respectively:

\[ TXx = \max(TX_{ij}) \]
\[ TXn = \min(TX_{ij}) \]

where TX is the daily maximum temperature, subscript i refers to the day, and j denotes the index of the counting period.

Indices TNx and TNn represent the maximum and minimum values of the daily minimum temperature (TN), respectively:

\[ TNx = \max(TN_{ij}) \]
\[ TNn = \min(TN_{ij}) \]

where TN is the daily minimum temperature, subscript i refers to the day, and j denotes the index of the counting period.

In this study, we calculated the extreme temperature indices based on both in situ observations and gridded data. Supplementary figure S3 shows a strong correlation between the gridded and station extreme temperature indices for 1960–2019. We used the station extreme temperature indices for further analysis.

2.3. Trend analysis
The linear trends in the annually averaged time series of the observed air temperature were calculated using ordinary least squares regression. Linear regression was evaluated using the Mann–Kendall test (Mann 1945, Kendall 1975). For all statistical tests, results with \( p < 0.05 \) were considered significant. In addition, the Sen slope estimator (Sen 2012) was used to compute the magnitude of the trend. Such trend analyses were also performed for seasonal air temperatures.

According to the monthly variations in the multiyear average temperature, we selected two typical seasons for analysis: the warm season and cool season. The warm season includes the months of May–September, when the multiyear monthly average temperature is greater than 0 °C. The cool season runs from October to April, when the multiyear monthly average temperature is lower than −10 °C (supplementary figure S4). In addition, temperature changes occurring during hot summer (June–August)
and cold winter (December–February) months by calendar month over the past 60 years were also analysed.

3. Results

3.1. Mean annual temperature trends
The observations show statistically significant increasing trends in the annual mean air temperatures at 128 of the 129 meteorological stations for 1960–2019 (supplementary table S1). The mean multiyear air temperature for the 128 meteorological stations was $-2.80 \pm 4.43 \, ^\circ\text{C}$, varying from $-13.23 \, ^\circ\text{C}$ to $4.03 \, ^\circ\text{C}$ among the stations. The air temperature change rates ranged from $0.11 \, ^\circ\text{C}/\text{decade}$ to $0.64 \, ^\circ\text{C}/\text{decade}$ among the 128 stations, with an average of $0.36 \pm 0.08 \, ^\circ\text{C}/\text{decade}$ for 1960–2019. The mean air temperature ($T, ^\circ\text{C}$) and its change rate ($k_{\text{T}}, ^\circ\text{C}/\text{decade}$) are highly correlated, exhibiting a linear relationship: $k_{\text{T}} = -0.01T + 0.32, \, R^2=0.41, \, p<0.01$ (figure 2(a)). Such a relationship is confirmed by the gridded data from the CRUTS v. 4.04 temperature products (figure 2(b)).

Spatially, the air temperature in the Siberian lowlands (<500 m a.s.l.) is highly dependent on latitude (supplementary figure S5), which is associated with the solar radiation incident of the Earth’s surface. Figure 3(a) shows a linear correlation between multiyear average surface air temperatures ($T, ^\circ\text{C}$) and surface net solar radiation ($R_n$, MJ (m$^2$ yr)$^{-1}$), following relationship $T = 0.006R_n - 21.83, \, p<0.01$. This correlation indicates that the surface air temperature in the Siberian lowlands is clearly associated with $R_n$. Over the past 60 years, the mean annual temperature trend has risen by $0.38 \pm 0.07 \, ^\circ\text{C}/\text{decade}$ ($k_{\text{T}}$) according to reanalysis data for across the Siberian lowlands, and surface net solar radiation ($R_n$) has also greatly increased with a change rate, $k_{\text{R}_n}$, of $23.27 \pm 10.71 \, \text{MJ (m}^2\, \text{decade)}^{-1}$.

Observations taken from meteorological stations show that the multiyear average temperature in the continuous permafrost zones ($n = 33$) was the lowest ($-8.63 \pm 2.89 \, ^\circ\text{C}$) among the different permafrost zones, with the highest annual temperature change rate reaching $0.42 \pm 0.07 \, ^\circ\text{C}/\text{decade}, \, p < 0.01$. The sporadic and isolated permafrost zones ($n = 38$) had an average temperature of $-2.82 \pm 2.08 \, ^\circ\text{C}$ and a change rate of $0.36 \pm 0.07 \, ^\circ\text{C}/\text{decade}, \, p < 0.01$. In contrast, the multiyear average temperature in the non-permafrost zones ($n = 54$) was $1.10 \pm 1.33 \, ^\circ\text{C}$, which is higher than $0 \, ^\circ\text{C}$, with a warming rate of $0.31 \pm 0.05 \, ^\circ\text{C}/\text{decade}, \, p < 0.01$. Note that the observations from the few stations in the discontinuous permafrost zones ($n = 4$) are not adequately reliable to represent the temperature changes over the large regions characterized by discontinuous permafrost across the Siberian lowlands. Nevertheless, the gridded data analysis demonstrated that the air temperature in the discontinuous permafrost zones generally increased faster than that in the sporadic and isolated permafrost zones but slower than that in the continuous permafrost zones (figure 2(b)).

3.2. Temperature trends of the cool and warm seasons
Increasing trends in average annual air temperature at the meteorological stations were generally observed during both the warm and cool seasons. Air temperature during the warm season displayed...
Figure 3. Relationships between (a) multiyear average temperature \( T, ^\circ C \) and surface net solar radiation \( R_n, \text{MJ/(m}^2\text{-yr)} \) and (b) the temperature change rate \( k_T, ^\circ C/\text{decade} \) and summer surface albedo change rate \( k_\alpha, 1/\text{decade} \). Solid red lines represent the fitted linear trends, light red shaded areas denote the prediction interval, and dark red shaded areas denote the 95% confidence interval.

Figure 4. Relationship between observed multiyear average temperature \( T \) and its change rate \( k_T, ^\circ C/\text{decade} \) for the cool and warm seasons. \( T_c \) and \( k_T_c \) are the multiyear temperature and its change rate in the cool season, respectively, and \( T_w \) and \( k_T_w \) are the multiyear temperature and its change rate in the warm season, respectively. Solid blue and red lines represent the fitted linear trends, light blue and red shaded areas denote the prediction intervals, and dark blue and red shaded areas mark the 95% confidence intervals.

- **Cool season (Oct.-Apr.)**
  \[
  k_T^c = -0.01 T_c + 0.30, \quad R^2 = 0.35
  \]
  \( \sigma = 0.10 \ ^\circ \text{C/decade}; \ MAE = 0.08 \ ^\circ \text{C/decade}; \ n = 126 \ (p < 0.01) \)

- **Warm season (May-Sept.)**
  \[
  k_T^w = -0.02 T_w + 0.52, \quad R^2 = 0.40
  \]
  \( \sigma = 0.08 \ ^\circ \text{C/decade}; \ MAE = 0.06 \ ^\circ \text{C/decade}; \ n = 119 \ (p < 0.01) \)

statistically significant increasing trends at 119 of the 129 meteorological stations. During the cool season, statistically significant increasing trends were observed at 126 stations. As shown in figure 4, the multiyear average temperature during the warm season was 12.42 ± 2.33 °C with a change rate of 0.25 ± 0.08 °C/decade \( (p < 0.01) \). In the cool season, the multiyear average temperature was much lower \( (-13.74 \pm 6.34 \ ^\circ \text{C}) \), while the warming rate was much higher \( (0.43 \pm 0.10 \ ^\circ \text{C/decade}, p < 0.01) \) than that in the warm season. Upon comparing the air temperature change rates of the cold winter...
(December–February) and hot summer months (June–August), we also found that the warming rate in the winter \((0.57 \pm 0.12 \, ^\circ\text{C}/\text{decade}, p < 0.01, n = 13)\) was nearly twice as high as that in the summer \((0.30 \pm 0.08 \, ^\circ\text{C}/\text{decade}, p < 0.01, n = 80)\). Moreover, the rate of warming as a function of temperature interestingly decreased much faster in the warm season \(k_{T_w} = -0.02 T_w + 0.52, p < 0.01\) than in the cool season \(k_{T_c} = -0.01 T_c + 0.30, p < 0.01\), as shown in figure 4.

3.3. Trends of extreme temperatures

Four extreme temperature indices showed increasing trends during 1960–2019 in both the permafrost and the non-permafrost zones (figure 5). The change rates of the annual temperature extremes in the permafrost zones are generally higher than those in the non-permafrost zones, except there is no statistically significant increasing trend in \(TXx\) in the non-permafrost zones, \(TNx\) among the permafrost zones is 0.58 \(^\circ\text{C}/\text{decade}, which is 21\% higher than that in the non-permafrost zones (0.48 \(^\circ\text{C}/\text{decade}\). For \(TNx\), the difference in the rate of increase between these two zones is even greater: the permafrost zones exhibit an average annual rate of increase of 0.25 \(^\circ\text{C}/\text{decade}, which is almost twice that in the non-permafrost zones (0.12 \(^\circ\text{C}/\text{decade}\). For \(TNn\), the rate for the permafrost zones increases 11\% faster than that for the non-permafrost zones. Ultimately, the change rate of \(TNn\) is the fastest among all four extreme temperature indices, followed by that of \(TXn\).

Although the rates of change in \(TNx\) and \(TXx\) are relatively low, there are notable differences between the first and last 30 year periods of 1960–2019 (supplementary table S2). During the first period (1960–1989), all four indices show an increasing or relatively stable trend (no trend). However, the extreme temperature indices show differential variations in the permafrost and non-permafrost zones during the second period (1990–2019); this is especially true for \(TNx\) and \(TXx\), which show increasing trends in the permafrost zones \((TNx: 0.08 \, ^\circ\text{C}/\text{decade, TXx: 0.16 \, ^\circ\text{C}/\text{decade}}\) but decreasing trends in the non-permafrost zones \((TNx: -0.35 \, ^\circ\text{C}/\text{decade, TXx: -0.25 \, ^\circ\text{C}/\text{decade}}\). It is worth noting that these changes have become more pronounced over the last ten years (2010–2019); e.g. the change rate of \(TNx\) was 0.39 \(^\circ\text{C}/\text{decade in the permafrost zones but reached -0.72 \, ^\circ\text{C}/\text{decade in the non-}\) permafrost zones, and this difference between the permafrost (0.61 \(^\circ\text{C}/\text{decade) and non-permafrost (-0.89 \, ^\circ\text{C}/\text{decade) zones is even greater for the change rate of TXx. At the same time, the extreme temperature differences in both zones continuously diminish from 1.68 \(^\circ\text{C (1960–1965)} to 0.30 \(^\circ\text{C (2015–2019) for TXx.\)
4. Discussion

4.1. Non-uniform climate warming

The climate of Siberia has varied significantly over the past 10,000 years (Groisman 2013), with a warming trend occurring over the past century. The largest annual air temperature anomalies relative to the 1961–1990 average were observed in 2020 during the past century, reaching 5.9 °C and 4.7 °C in western Siberia and eastern Siberia, respectively (Callaghan et al. 2021). The winter temperature anomalies in western and middle Siberia even reached 8.5 °C in the winter of 2019/2020 relative to the 1961–1990 average (Callaghan et al. 2021). This result shows that air temperature in Siberia continued to increase and reached a record level in recent years of the past century in both annual and winter air temperatures.

Our results further reveal the non-uniform rates of climate warming between seasons and regions with different areal extents of permafrost across the Siberian lowlands. Climate warming has occurred more rapidly in cool regions than in warm regions (supplementary figure S6), and the rate of warming in the permafrost zones was considerably greater than that in the non-permafrost zone. In particular, the continuous permafrost zone (where permafrost covers more than 90% of the landscape) experienced the greatest rate of warming.

Of particular importance is the fact that the rate of warming is higher during cool seasons than in warm seasons in both permafrost and non-permafrost regions. These results are consistent with those of previous studies (e.g. Serreze and Barry 2011, Xia et al. 2014, Zohner and Renner 2019) showing a higher rate of warming in the winter than in the summer at mid-high northern latitudes. The accelerated warming of the coldest temperature extreme is likely attributable to the total heat stored within the Earth’s climate system (e.g. heat leads to the warming and expansion of water and the melting of glaciers and ice), which may better reflect land surface air warming and its attributions (e.g. anthropogenic greenhouse gases) (Zhou and Wang 2016). The cooling effect from evaporation during the warm season may be an important reason for its slower warming than that of the cool season. Given the role of winter temperatures in the composition and diversity of Arctic plant communities (Bjorkman and Gallois 2020, Niittynen et al. 2020), the temperature changes during cool seasons and hidden physical feedback between land and atmosphere should be addressed further.

As a result of the complexity of permafrost-ecosystem-climate interactions (Shur and Jorgenson 2007, Grosse et al. 2016), soil temperature-depth profiles record climate change, although such records can be influenced by the onset time and duration of snow events and differences in soil thermal properties (Bartlett et al. 2004, Pozdniakov et al. 2019). Soil temperature in western Siberia can be increased by 0.1 °C–0.8 °C depending on underlying surface conditions when the annual mean air temperature increases by 1 °C (Vasiliev et al. 2008). Soil temperature records from nine meteorological stations show that the seven sites experienced temperature increases of 0.17 °C–0.83 °C between 1999–2012 and 1985–1998, with the exception of WMO station Nos. 24738 and 23933 (supplementary figure S7). In general, the soil temperatures in the non-permafrost zones were higher than those in the continuous and discontinuous permafrost zones. However, it is difficult to detect a higher rate of soil temperature warming in permafrost zones than in non-permafrost zones and vice versa. This result was obtained from only 28 years of in situ observational data from nine limited sites. Compared to changes in air temperature, changes in soil temperature are more complex and not only influenced by air temperature (Streletskiy et al. 2015) but also closely related to snowpack (Zhang 2005), soil texture, and subsurface conditions.

Nevertheless, borehole temperature measurements reveal that the surface temperature in colder northeastern Siberia (0.67 °C) increased approximately 26% more than that in warmer southwestern Siberia (0.53 °C) in the twentieth century (Pollack et al. 2003). This is consistent with the permafrost temperature observations at a global scale, which indicate that the ground temperatures in colder continuous permafrost zones have increased faster than those in warmer discontinuous permafrost zones (Biskaborn et al. 2019). Compared with colder permafrost, warmer permafrost (temperatures close to 0 °C) thaws much more slowly due predominantly to the latent heat effects associated with ice-water phase change (Romanovsky et al. 2010). Therefore, the permafrost response to climate warming is likely greater in colder permafrost than in warmer permafrost with a temperature of close to 0 °C, although vegetation succession and changing soil properties can affect permafrost-climate interactions (Shur and Jorgenson 2007).

4.2. Potential drivers of climate warming

Global surface air temperature responds proportionally to global mean radiative forcing (Boer and Yu 2003), and such proportionality is referred to as a climate feedback parameter (Gregory and Andrews 2016). The feedback between radiative forcing and surface air temperature can be positive or negative around the globe, and there is positive feedback over northern land areas (Boer and Yu 2003). Our analysis reveals that the change rate of $R_n$ in the permafrost zones is not higher than that in the non-permafrost zones, although warming occurs faster in the former than in the latter. This implies that the difference in warming rates between permafrost and non-permafrost zones may not be attributable to changes in $R_n$. Different vegetation structures and associated partitioning between latent and sensible
heat fluxes are believed to be other important reasons for the difference in warming rates between permafrost and non-permafrost zones (Bonfils et al 2012, Stiegler et al 2016).

Chapin et al (2005) demonstrated that changes in summer albedo contribute substantially to high-latitude warming trends. In the Siberian lowlands, the multiyear average summer surface albedos (from May to September) are 0.15 ± 0.02, 0.14 ± 0.03, and 0.17 ± 0.06 for non-permafrost, sporadic and isolated permafrost, and continuous and discontinuous permafrost zones, respectively. Over the past 60 years, temporal changes in α passed the significance test (p < 0.05) in approximately 89% of the areas (supplementary figure S8). The slope of the change in albedo, k_α, is −0.001 ± 0.001 1/decade in non-permafrost zones, which is less notable than the values for sporadic and isolated permafrost (−0.005 ± 0.003 1/decade) and continuous and discontinuous permafrost (−0.007 ± 0.005 1/decade) zones. As shown in figure 3(b), the faster decrease in summer albedo in permafrost zones corresponds to faster warming. This suggests that the decrease in summer albedo may be one of the factors contributing to faster warming in areas underlain by permafrost.

Northern permafrost soils, including the late Pleistocene Yedoma deposits widely distributed across central and eastern Siberia, Alaska and Yukon (Strauss et al 2021), have a large carbon pool and contain enormous amounts of organic carbon (Kuhry et al 2013). Such a carbon pool is potentially vulnerable and is highly sensitive to climate (Pi et al 2021). Current permafrost warming, which is evidenced by the increasing trends of the ALT (Park et al 2016) and soil temperature (Biskaborn et al 2019), is believed to be capable of releasing trapped carbon from permafrost soils (Zimov et al 2006). In particular, abrupt permafrost thawing of ice-rich permafrost, as is evidenced by the steady increase in the area of retrogressive thaw slump-affected regions across northern Siberia (Runge et al 2022), could transform the tundra into a substantial source of carbon dioxide and methane (Nitzsbon et al 2020, Knoblauch et al 2021). The release of permafrost carbon has the potential to create positive feedback that accelerates climate warming (e.g. Dutta et al 2006, Schaefer et al 2014, Schädel et al 2016, Bowen et al 2020, Dean et al 2020, Masyagina and Menyailo 2020, Turetsky et al 2020), and the decomposition of frozen soil carbon in permafrost is estimated to lead to additional warming of up to 0.27 °C by 2100 (McGuire et al 2018) and of 0.13 °C–1.69 °C by 2300 (MacDougall et al 2012). For ice- and organic-rich permafrost of the northeastern Siberian lowlands, the response of frozen organic carbon pools to the warming climate through thermokarst-related permafrost thaw is expected to be significant (Nitzsbon et al 2020).

At the regional scale, the feedback of permafrost degradation–carbon release–climate change may be a cause of greater warming in permafrost areas than in non-permafrost areas.

Nevertheless, air temperature change is the result of multiple physical processes that link atmospheric and oceanic heat transport, land-atmosphere exchanges, surface conditions, cloud cover, the water cycle, etc (Serreze and Barry 2011, Suni et al 2015). Given that the climate system is affected by both solar and CO₂ forcing (Smith et al 2015, Modak et al 2016, Previdi et al 2020), a possible cause of global warming is an increase in net radiation absorption due to the decrease in cloud levels (Trenberth and Fasullo 2009). However, the Arctic is projected to become cloudier in a warmer climate, and radiative feedback from Arctic clouds remains highly uncertain due to the possible increases in ice nucleating particles resulting from thawing permafrost (Creamean et al 2020). Due to our limited understanding of the formation and evolution of Arctic clouds and their contributions to greenhouse gases, future research must focus on the climate impacts of thawing permafrost through its potential to affect clouds (Creamean et al 2020).

4.3. Environmental consequences of climate warming

Warming due to extreme temperatures has amplified over land (Byrne 2021), and recent climate warming has driven rapid ecosystem responses (Saros et al 2019) and a widespread abundance of permafrost region disturbances (Nitze et al 2018) across the pan-Arctic. Fire is one of the most extensive permafrost region disturbances in Siberia and is highly associated with air temperature and drought index values (Ponomarev et al 2016). Fire activity will likely increase with climate warming (Kharuk et al 2021), and an increasing frequency of high extreme temperature days in the future will facilitate extreme fire patterns (Cardil et al 2013). Unprecedented Arctic wildfires in 2020 released 35% more CO₂ than in 2019, compounding the already difficult challenge of limiting global warming to 1.5 °C or 2 °C (Natali et al 2021). As stated in section 3.3, the rate of increase in TXx is greater in permafrost zones (0.58 °C/decade) than in non-permafrost zones (0.48 °C/decade), which suggests that wildfires are more likely to occur in permafrost zones under the influence of ongoing temperature warming.

Rapid warming also threatens cryospheric components in the pan-Arctic and accelerates permafrost degradation, as evidenced by spatial and temporal changes in the ALT under a warming climate. ALT has been predicted to increase from 102 cm (2000–2014) to 118 cm (2061–2080 RCP8.5) across the Northern Hemisphere (Aalto et al 2018). Based on the ALT
estimates for 1980–2016 from Park et al (2016), the multiyear average ALT is approximately 180 ± 89 cm, with a rate of increase of 3.0 ± 1.5 cm/decade across the Siberian lowlands. The ALT values for colder permafrost zones in the northern part of the study area are mostly less than 200 cm, while those for relatively warm permafrost in the central part of the study area generally range from 200 to 300 cm (supplementary figure S8).

In addition, governed by the Clausius–Clapeyron equation (Parsons et al 2003), increases in air temperature most likely correspond to increases in precipitation in Siberia (Chen and Wang 2021, Wang et al 2021b). Increased summer precipitation will accelerate permafrost degradation by enhancing heat transfer from warmer precipitation (Douglas et al 2020, Mekonnen et al 2021). Large-scale permafrost thawing due to climate warming (Biskaborn et al 2019) increases groundwater storage by thickening the active layer (Lamontagne-Hallé et al 2018) and enhances regional surface-groundwater interactions due to extensive permafrost loss (Evans et al 2020). The hydrological response to permafrost thawing in northern high-latitude regions is evidenced by increases in winter streamflow (Wang et al 2021a). Therefore, changes in precipitation and permafrost characteristics due to climate warming provide a plausible mechanism for the observed increases in the streamflow of Arctic rivers (Debolskiy et al 2021).

5. Conclusion

This study used both station observations and gridded surface meteorological data to analyse trends of 2 m air temperature changes in the Siberian lowlands (<500 m) from 1960 to 2019. We found that the change rates of the annual temperature and four temperature indices were higher in permafrost zones (with lower annual average temperatures) than in non-permafrost zones (with higher average annual temperatures). In addition, the change rates of the minimum values of the daily maximum and minimum temperatures were much higher than those of the maximum values of the daily maximum and minimum temperatures. A higher warming rate was also detected in the cool season than in the warm season. These results confirm the hypothesis that ‘the lower the temperatures are, the faster warming is’ in the lowlands of mid-high northern latitudes. We demonstrated that increased net surface radiation alone does not explain the notable difference in the surface air warming rate between permafrost and non-permafrost zones. Clearly, the hidden physical mechanisms of climate warming are complex and require further research. However, particular attention should be given to permafrost degradation, which has great potential to amplify global climate change through the release of soil organic carbon from the thawing of frozen sediments.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Daily air temperature and soil temperature data are archived and made publicly available through the Carbon Dioxide Information Analysis Centre at https://cdiac.ess-dive.lbl.gov/ndps/russia_daily518.html (in English, period: 1960–2010) and the Russian Meteorological Station database at http://aisori-m.meteo.ru/waisori/index.xhtml?idata=5 (in Russian, period: 2011–2019, contact e-mail: ykoftan@meteo.ru, gnzvereva@meteo.ru). The gridded monthly average 2-m temperature datasets from CRU TS v. 4.04 are accessible at https://crudata.uea.ac.uk/cru/data/5/v5/. The gridded monthly average surface albedo and surface net solar radiation datasets from ERA5 are available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means-preliminary-back-extension?tab=overview (from 1950 to 1978) and https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview (from 1979 to 2019). The Circum-Arctic Map of Permafrost and Ground-Ice Conditions (Version 2) is available at https://nsidc.org/data/ggd318. The GTOPO30 data are available at www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-30-arc-second-elevation-gtopo30?qt-science_center_objects=0#qt-science_center_objects. Special thanks are owed to Youngwook Kim from the Numerical Terradynamic Simulation Group at the College of Forestry and Conservation, University of Montana, Missoula, USA, for providing the ALT data for 1980–2016.
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