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Abstract

This study assessed trends in the variability of soil temperature (T_{SOIL}) using spatially averaged observation records from Russian meteorological land stations. The contributions of surface air temperature (SAT) and snow depth (SND) to T_{SOIL} variation were quantitatively evaluated. Composite time series of these data revealed positive trends during the period of 1921–2011, with accelerated increases since the 1970s. The T_{SOIL} warming rate over the entire period was faster than the SAT warming rate in both permafrost and non-permafrost regions, suggesting that SND contributes to T_{SOIL} warming. Statistical analysis revealed that the highest correlation between SND and T_{SOIL} was in eastern Siberia, which is underlain by permafrost. SND in this region accounted for 50% or more of the observed variation in T_{SOIL}. T_{SOIL} in the non-permafrost region of western Siberia was significantly correlated with changes in SAT. Thus, the main factors associated with T_{SOIL} variation differed between permafrost and non-permafrost regions. This finding underscores the importance of including SND data when assessing historical and future variations and trends of permafrost in the Northern Hemisphere.

Keywords: soil temperature, Russia, snow depth, air temperature, permafrost

1. Introduction

Surface air temperature (SAT) increases in the Arctic have been exceptionally fast over recent decades (Serreze et al 2009). This increased SAT has resulted in a number of changes in the Arctic system during recent decades, such as increases in ground temperatures. Permafrost warming associated with the SAT increase has been observed in the Arctic (Osterkamp 2007a, Romanovsky et al 2007, Smith et al 2010). The magnitude of permafrost warming varies regionally, but is typically 0.5–2 °C at the depth of zero annual amplitude. Changes in SAT alone do not account for the increase in permafrost temperature; a number of factors interact in complex ways (Zhang 2005, Osterkamp 2007a). Previous studies have emphasized the effect of snow on Arctic soil temperature (T_{SOIL}) (Stieglitz et al 2003, Osterkamp 2007a, Sherstiukov 2008, 2009, Lawrence and Slater 2010).

Snow depth (SND) has exhibited regional variation during recent decades, with an increase in eastern Siberia (Bulygina et al 2009) and a decrease in western North America (Schindler and Donahue 2006, Park et al 2013b). Although snow only covers the soil surface during the cold
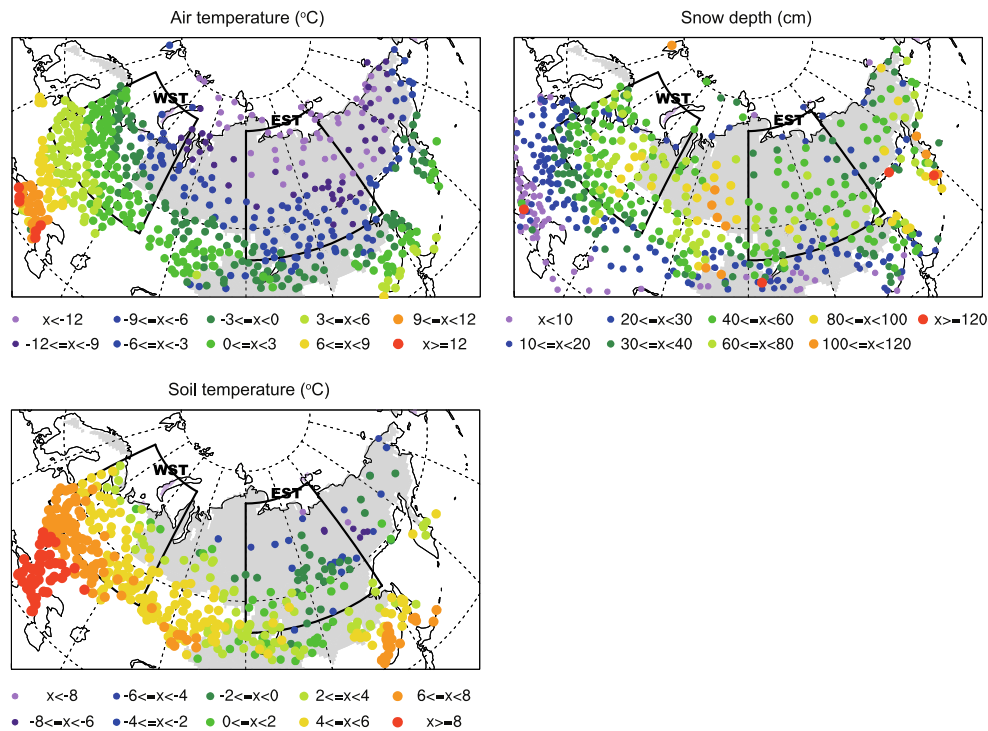
Figure 1. Map showing the geographic locations of the Russian meteorological stations that provided the data used in this study and the average values for the period of 1964–2011. Black lines indicate the western and eastern Russia regions. The gray background represents areas of permafrost.

season, the variability in snow cover has a large influence on seasonal and interannual soil thermal regimes due to the effect of insulation. Therefore, the variability of SND could result in T_{SOIL} anomalies that are inconsistent with SAT anomalies. In fact, the decreases in SND in Alaska and western Canada over recent decades (Schindler and Donahue 2010) appear to have led to decreases in T_{SOIL} (Osterkamp 2007b) and active layer thickness (Park *et al* 2013a). Despite a significant body of research and a preliminary understanding of the driving mechanisms behind the observed long-term changes in T_{SOIL}, assessing the contribution of SAT and SND to the variability of T_{SOIL} in the Arctic still involves a high degree of quantitative uncertainty.

Russia has a long history of T_{SOIL} observations at a number of meteorological stations, with some records beginning in the 1890s and many others beginning in the 1930s or 1950s (Frauenfeld *et al* 2004). Analyses of these observed data have provided useful information about changes such as the long-term deepening of the active layer (Frauenfeld *et al* 2004) and increased permafrost temperatures (Romanovsky *et al* 2007). More than half of Russia is composed of seasonally frozen non-permafrost zones, in which the maximum annual depth of soil freezing tended to be shallow from 1930 to 2000 (Frauenfeld and Zhang 2011). This geographical variation in Russia can result in regional differences in the response of T_{SOIL} to changes in climate. These regional differences could explain the possible causes of the recent permafrost warming. More generally, long-term climate and T_{SOIL} data from the Russian meteorological stations may improve our comprehensive understanding of the

conditions and future of permafrost in the Northern Hemisphere.

The main objectives of this study were to (1) assess long-term trends in the variability of T_{SOIL} using observational data collected at Russian meteorological land stations from 1921–2011, and (2) delineate factors (i.e., SAT and SND) that affect the variability and trends of T_{SOIL} at local and regional scales, and then quantitatively evaluate the contributions of these different drivers to T_{SOIL} variation.

2. Datasets and methods

The dataset used in this study is available from the All-Russian Research Institute of Hydrometeorological Information-World Data Centre (RIHMI-WDC), which includes a full set of observations collected at the hydrometeorological stations of the Roshydromet network. Daily soil temperature data from the RIHMI-WDC are available for 458 stations located across Russia (figure 1), where soil temperatures are measured at depths of 0.2–3.2 m. However, the observations at some locations have been unavoidably disturbed by grass cutting during the warm season and the removal of organic materials, mainly at agricultural sites. These disturbances may cause increased warming of the soil over time. Therefore, long-term trends in T_{SOIL} could potentially include this non-climatic component (Frauenfeld *et al* 2004).

The period of data collection varies by site, with some stations dating back to the late 1800s (Gilichinsky *et al* 1998). However, most stations on the RIHMI-WDC website have
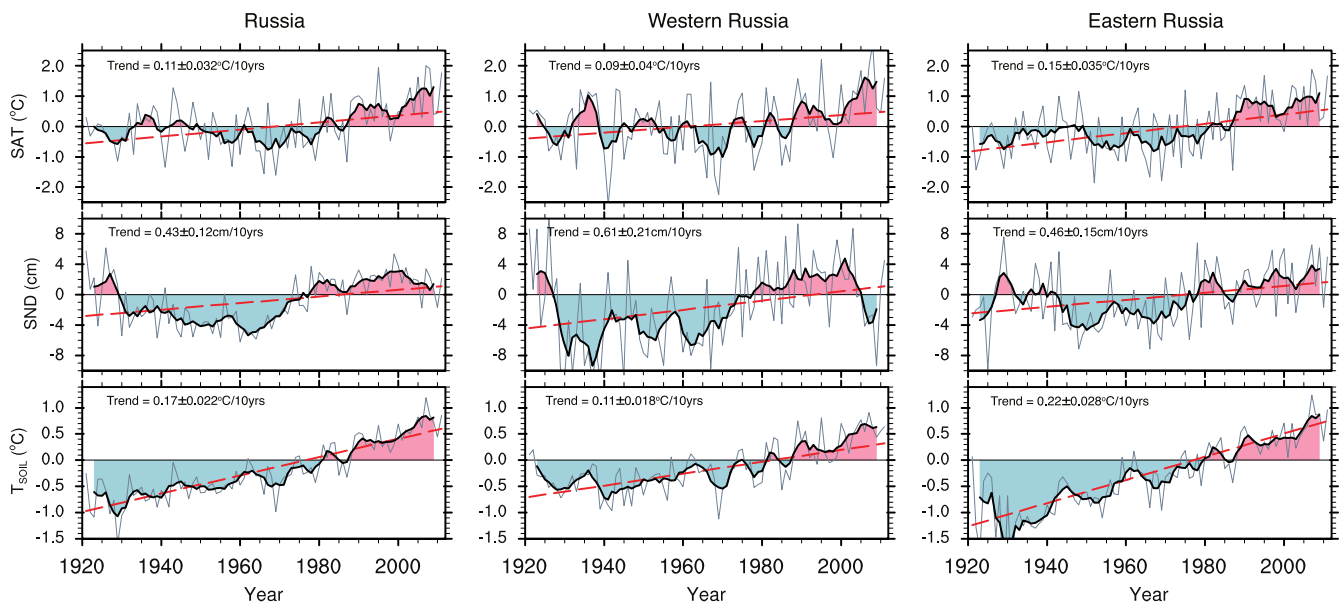
Figure 2. Composite time series of the annual SAT (top), winter SND (middle), and annual T_{SOIL} (bottom) anomalies, averaged for all Russian stations, WST, and EST. Gray lines represent annual means, black solid lines represents five-year running means, and red dashed lines represent trends.

only provided soil temperature data since 1963. Another historical T_{SOIL} dataset can be obtained from the National Snow and Ice Data Center (NSIDC), which contains monthly mean values for 423 sites across the former Soviet Union from the beginning of the instrumental observation at each station until 1990. The two datasets were combined to expand the number of stations and the time series of data for all stations. Specifically, the NSIDC monthly dataset was used as a baseline, and RIHMI-WDC data were used to supplement the data since 1990. Monthly T_{SOIL} observations from six new stations located within the Sakha Republic, Russian Federation, were also added to this dataset. For this analysis we focused on the depth of 1.6 m, for which the longest and most continuous records are available (Romanovsky *et al* 2007, Sherstiukov 2008).

The historical data for monthly SAT were compiled on the basis of *in situ* daily observations available from the RIHMI-WDC. For this study we used the monthly mean SAT from 518 stations across Russia (figure 1). Some Russian institutes have also produced extensive archives of SAT observations from Russian land stations. Bekryaev *et al* (2010) constructed a database of monthly SATs across the pan-Arctic terrestrial region north of 59°N, including this Russian data. This database includes 246 stations over the land area of Russia, 156 stations of which overlapped with the RIHMI-WDC. Consequently, SAT data from 609 stations across Russia were used for this study (figure 1). This increase in the number of stations is helpful for maintaining approximately homogeneous spatial coverage and enables the omission of records with gaps.

The RIHMI-WDC dataset also includes quality-checked daily SND observations from 598 stations across Russia. The number of active stations for SND observation varied over time, with the maximum number of stations in the 1980s after

an increase starting in the 1960s (Bulygina *et al* 2009). Some stations in European Russia and western Siberia have historical records dating from the end of nineteenth century, where the density of stations also tended to be high relative to eastern Siberia (figure 1). To reduce site density bias, we excluded data prior to 1921. The daily SND values were converted into average monthly and winter SND values for the available time period, for individual stations where daily values were available for 20 or more days in a month. This threshold of 20 days was selected because daily SND variability during the winter season is not as great as during other seasons. Winter averages were calculated from December–February. We linked the winter SND data with T_{SOIL} data from October–September to establish potential relationships between the two.

Inhomogeneity in datasets is mainly caused by changes in observational procedures and instruments, including differences in the locations where observations are made (Bulygina *et al* 2009). The use of anomalies (described below) can overcome most problems with absolute values such as those among station elevations, observation times, the methods used to calculate monthly or annual mean values, and screen types (Jones *et al* 1999). The SAT, SND, and T_{SOIL} records from each station were reduced to monthly anomalies relative to the period of 1961–2000. Monthly data were assessed for errors by identifying peaks exceeding three standard deviations and then comparing them with nearby station records (Polyakov *et al* 2003). Annual SAT and T_{SOIL} anomalies were computed only when at least six monthly values were available (Bekryaev *et al* 2010). Winter SND was averaged when two monthly anomalous values were available. We used a technique similar to the climate anomaly method (Jones *et al* 1999, Bekryaev *et al* 2010) to minimize the effect of spatially inhomogeneous data coverage on the

anomalies. Using this method, the Russian area was divided into 5° latitude and 10° longitude boxes. Anomalies of climatic variables for stations within each box were averaged, and the resulting averaged time series for each box were in turn averaged to provide a single time series at the Russian and regional scales. To compare regional differences in T_{SOIL} variability we selected two areas, western (WST: 55–75°N, 30–70°E) and eastern (EST: 55–75°N, 100–140°E) Eurasia, that are generally covered by non-permafrost and permafrost ground, respectively (figure 1).

3. Results and discussion

3.1. Interannual and decadal soil temperature variability

Figure 2 presents the composite time series of SAT, SND, and T_{SOIL} for all of Russia, WST, and EST. Jones *et al* (1999) documented two distinct warming periods in the Arctic SAT time series, from 1920–45 and from 1975 to the present. Similarly, the SAT warming since 1980 was the most significant in the Russian time series, where the maximum annual SAT anomaly reached 2 °C in 2007 (figure 2), coincident with the recorded minimum in Arctic sea ice cover. Warming over the last decade has been faster than the warming during the 1930s–40s. Polyakov *et al* (2003) reported that, for the larger area, north of 62°N, the 1938 maximum in the annual Arctic SAT anomaly was 1.69 °C, compared with the 2000 maximum of 1.49 °C. According to our analysis, however, the earlier warming was not as fast as previously reported, with only slightly positive anomalies in the 1920s and 1930s. The earlier positive anomaly was more apparent in WST than in EST. Polyakov *et al* (2003) reported that SATs in western Siberia were strongly correlated with the North Atlantic Oscillation (NAO) index, whereas the Pacific influenced eastern Siberia.

The Russian SAT time series exhibited multidecadal variability with two distinct positive phases (1930–50 and from 1980 to the present) and two negative phases (before 1930 and from 1950–80), as reported by Polyakov *et al* (2003). However, the negative phase from 1950 to 1980 was less prominent than in the pan-Arctic SAT time series considered by Serreze and Francis (2006) and AMAP (2011, pp 2–4). The T_{SOIL} time series from 1950 to the present also exhibited multidecadal variability, which appears superimposed on the background warming trend of SAT. Soil temperature is strongly dependent on SAT, and therefore T_{SOIL} trends generally follow SAT trends. The Russian T_{SOIL} anomalies changed from negative values to positive values by 1980, matching well with the SAT phase change (figure 2).

An interesting finding is that the multidecadal variability, found in SAT and T_{SOIL}, was also replicated in the composite time series of SND anomalies. The SND exhibited negative values until 1980 and then changed to positive values. These positive SND anomalies since 1980 may have further amplified T_{SOIL} warming, in combination with higher SATs. In contrast, the decrease in SND in the previous years could have enhanced the cooling of T_{SOIL}, in combination with cold
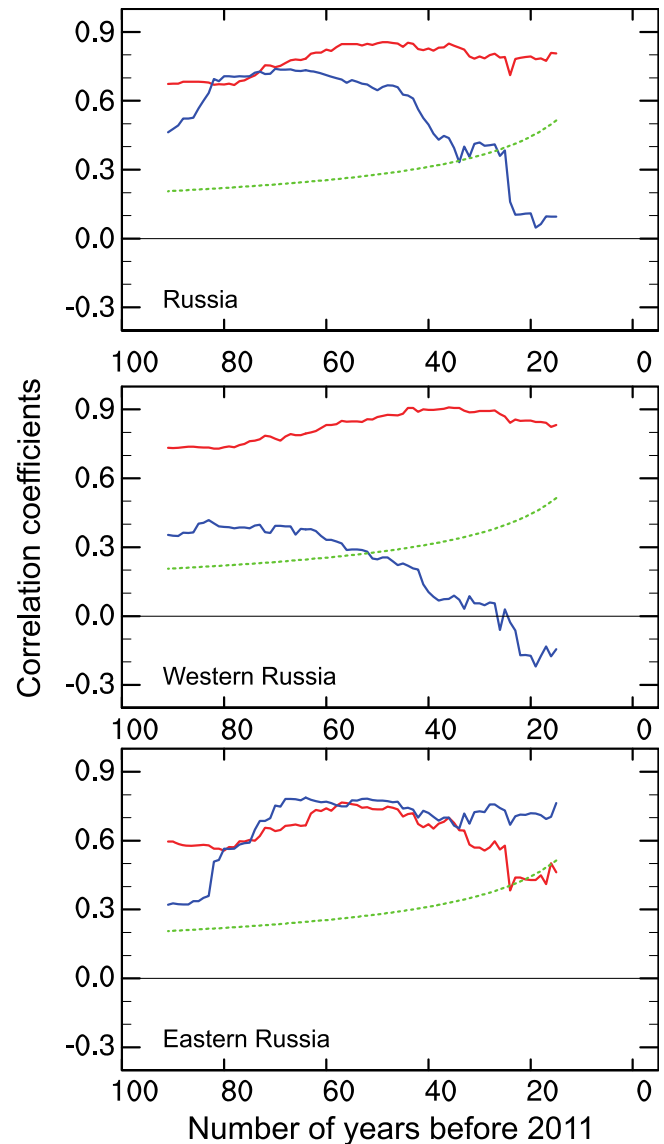

Figure 3. Correlation coefficients for the relationship of the composite time series of SAT (red) and SND (blue) to T_{SOIL} for all of Russia, WST, and EST calculated using data for a 15-year period (1997–2011) and the full record length (1921–2011), in one-year increments. Green dashed lines represent a 95% significance level.

winter SATs. The sharp decrease in SND in WST during the last decade is associated with a pause in T_{SOIL} warming in WST. Figure 2 suggests that SND may be a factor that affects the trends in T_{SOIL} variability.

3.2. Factors contributing to soil temperature variability

The correlations of SAT and SND with T_{SOIL} were calculated over periods ranging from 15 years (1997–2011) to the full record length (1921–2011), in one-year increments (figure 3). Figure 3 delineates regional differences in the main factors correlated with T_{SOIL}. T_{SOIL} in Russia was highly correlated with SAT over the entire time period, whereas the correlation between T_{SOIL} and SND has notably decreased since the 1950s, dropping below the 95% significance level during the last 25 years. Correlations in WST exhibited similar patterns
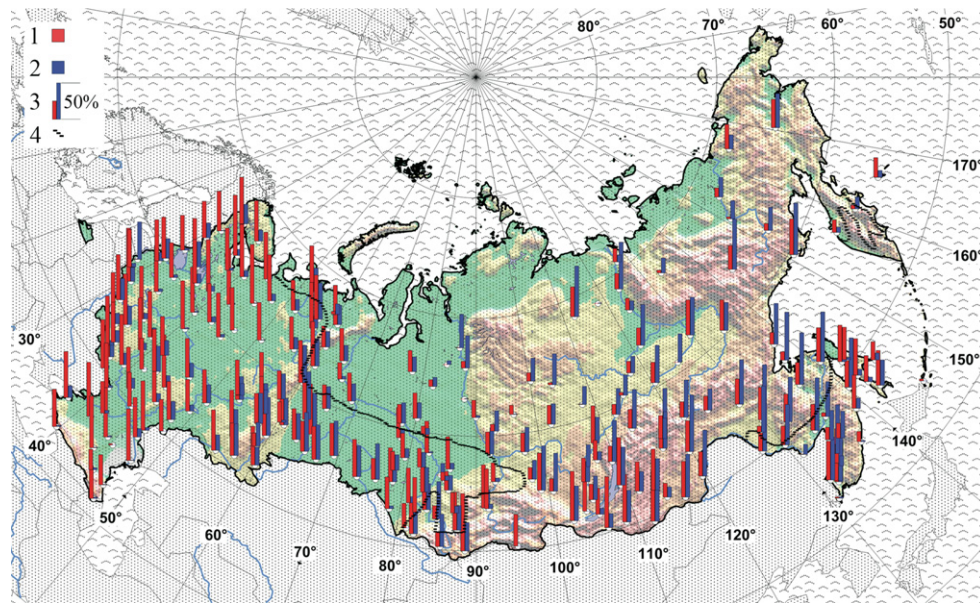
Figure 4. Proportional contributions of SAT (red) and SND (blue) to T_{SOIL} at each station computed for 1963–2011 based on multilinear regression analysis. Number 3 in the map legend represents the percent contribution of the variables. The boundary of the permafrost area is indicated by a black dashed line.
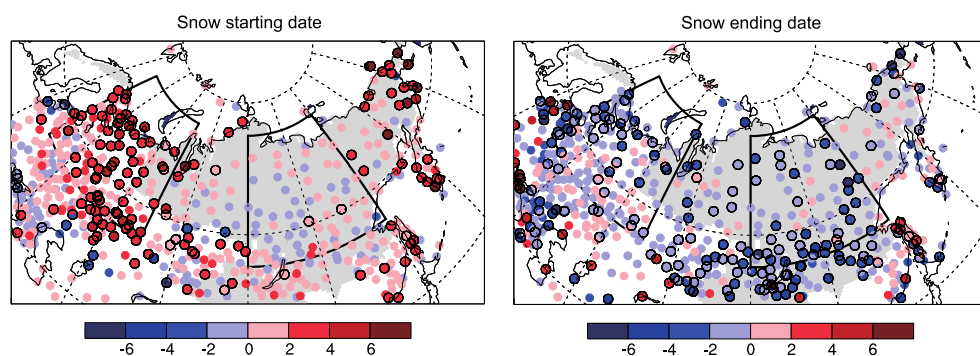

Figure 5. Trends in the start (left) and end (right) date of snow fall during the period of 1964–2011. The black circles represent stations showing a 90% significance level.

to those of the Russian time series. In WST, differences in the SAT and SND correlation values with T_{SOIL} have increased since the 1940s due to the continually decreasing correlation of SND. For Russia and WST, SAT generally explained 40–80% of the variance in the T_{SOIL} time series. In contrast, the correlation with SND in EST was similar in magnitude to that of SAT during the 1930s–1970s. The SND correlation generally maintained its previous value over recent decades, but the correlation of SAT with T_{SOIL} has decreased substantially since the 1980s when SAT significantly increased (figure 2), suggesting a higher contribution of SND to the variability of T_{SOIL}.

The regional difference in the main factors that are correlated with T_{SOIL} (figure 3) is also illustrated in figure 4, which shows the proportion of T_{SOIL} variance explained by SND and SAT at stations across Russia. These fractions were calculated using a multilinear regression analysis based on the principle of variation partitioning by regression, which can determine the contribution of explanatory variables (i.e., SAT and SND) to the variance of the dependent variable, T_{SOIL}

(Legendre and Legendre 1998). This method is useful when the explanatory variables are linearly independent. However, SND and SAT are partly intercorrelated, and the fraction of the variation in T_{SOIL} that individual SND and SAT explain could be confounded by the correlation between SND and SAT. The overlapped fraction was removed as calculating a regression between SAT and SND (Legendre and Legendre 1998).

The contribution of SAT to T_{SOIL} greatly exceeded that of SND at most WST stations (figure 4), where it accounted for more than 50% of the variance (Sherstiukov 2008, 2009). Air temperature is a primary factor affecting ground thermal regimes across all climatic zones. However, figures 3 and 4 indicate that SND is strongly correlated with T_{SOIL} in permafrost regions. Sherstiukov (2008, 2009) reported that SND in EST contributed 50% or more of the changes in T_{SOIL} (figure 4). EST is characterized by a longer freezing season (8–9 months), during which variations in seasonal snow cover greatly affect T_{SOIL}. Furthermore, the influence of SND on T_{SOIL} has tended to increase further since 1980 (figure 3)

when SAT entered the warming phase (figure 2). In the Arctic, the winter SAT has displayed a strong increase during the last few decades (Bekryaev *et al* 2010). However, EST still experiences severe freezing conditions, even though the SAT has increased. Therefore, the increased SND readily contributes to soil warming.

The winter snow in WST was generally deeper (figure 1) and displayed a larger trend toward increasing depth than that in EST (figure 2). However, the contribution of SND to T_{SOIL} was lower in WST than in EST (figures 3 and 4), which is likely associated with geographical variations of average SND and snow season. The autumn snow in WST exhibits a statistically significant trend for snow cover to start late in many stations, with a smaller change in EST (figure 5). In autumn, the earlier snow cover and the increase in SND results in more effective insulation (Zhang 2005). In contrast, the late snow cover enhances soil cooling. Although the snow fall started late, the larger snowfall in WST consequently resulted in deeper winter SND (figure 1), enhancing the insulation effect. However, a change in an area with deeper SND in the winter could have a smaller effect than the same changes in an area with shallower SND because the insulation by snow varies more strongly with depth when the depth is small. For example, Zhang (2005) reported that when the winter SND exceeds 40–50 cm, the insulation effect becomes less pronounced. Moreover, the deeper SND likely results in a late snowmelt. The high snow-related albedo and latent heat of fusion have a cooling effect on T_{SOIL}. In reality, more stations in WST than in EST exhibit a trend toward late snow disappearance in spring, although the statistical significance of this trend is low (figure 5). These snow conditions in WST offset the soil warming induced by the increased SAT.

3.3. Trends

The composite time series of the SAT anomalies for Russia, WST, and EST exhibited strong variability, with generally increasing trends appearing from 1921–2011 (figure 2). The SAT warming rate for Russia was 0.11 °C decade^{-1}. The strongest SAT warming trend was observed in EST, with a rate of 0.15 °C decade^{-1}. This rate is faster than the 0.14 °C decade^{-1} rate for the terrestrial Arctic from 1875–2008 (Bekryaev *et al* 2010). T_{SOIL} in EST also exhibited the stronger (relative to WST) warming trend, 0.22 °C decade^{-1}, which is slightly slower than the 0.26 °C decade^{-1} trend for T_{SOIL} measured at 52 meteorological stations in eastern Siberia from 1956–1990 (Romanovsky *et al* 2007). However, the T_{SOIL} trend in EST was faster than the SAT trend of 0.15 °C decade^{-1}. Similar trends were observed in both Russia and WST. This confirms the earlier regression-based results (section 3.1) suggesting the influence of snow cover. SND also exhibited positive trends in the three regions, with the strongest trend in WST (0.61 cm decade^{-1}).

Multidecadal variability in SAT, SND, and T_{SOIL} resulted in oscillatory trends (figure 6), but with obvious differences between permafrost and non-permafrost regions. SAT in WST exhibited a significant warming trend since the
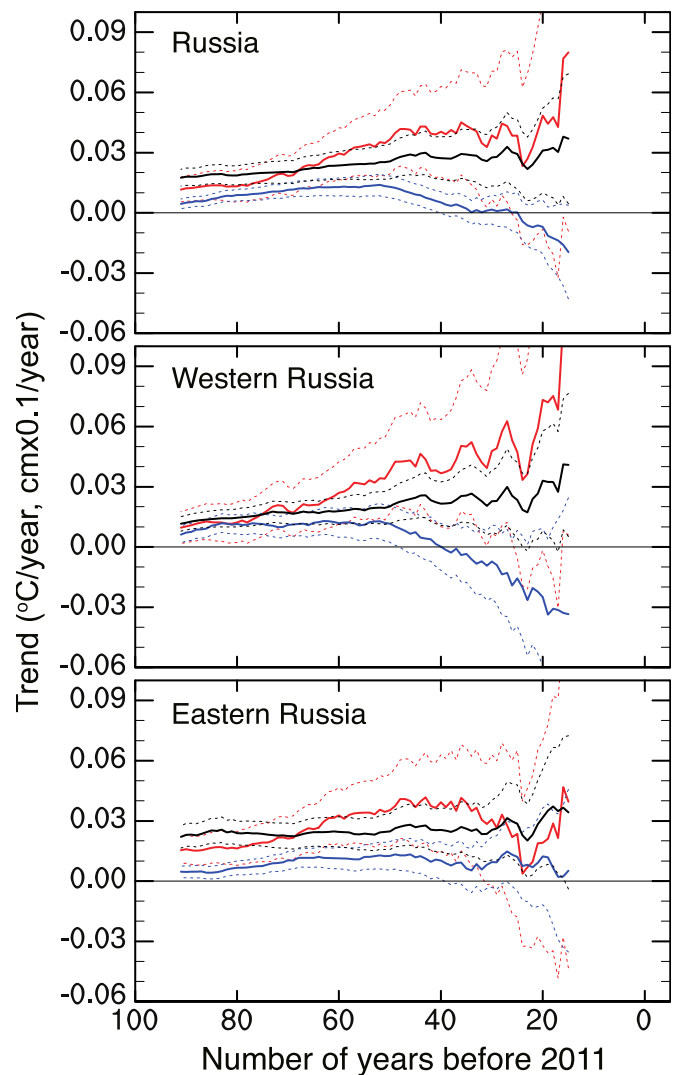

Figure 6. SAT (red, °C yr^{-1}), T_{SOIL} (black, °C yr^{-1}), and SND (blue, cm yr^{-1} × 0.1) trends and their 95% significance levels (dashed lines) in Russia (top), WST (middle), and EST (bottom) computed from their composite time series, ranging from 15 years (1997–2011) to the full record length (1921–2011), in one-year increments.

1950s, whereas the SND trend exhibited a change in sign during the same time period. Unlike in WST, SAT and SND trends in EST were positive over the entire time period, with low oscillations. Moreover, the warming tendency of SAT was not as strong in WST. The T_{SOIL} data from EST and WST revealed statistically significant warming tendencies over this time period (zero is outside the 95% confidence interval for both regions). The SAT, SND, and T_{SOIL} trends for Russia exhibited similar patterns to those for WST. Significant oscillatory behavior in SAT, SND, and T_{SOIL} trends was observed over the last 40 years in all three regions, in conjunction with an increase in Arctic air temperature (Bekryaev *et al* 2010). Furthermore, the oscillatory behavior of T_{SOIL} appears to reflect trends in factors that strongly influence the pattern of T_{SOIL} trends. It is noteworthy that the increasing T_{SOIL} rates during recent decades are exceptionally

strong over the century-scale timeframe as well as shorter subperiods.

4. Conclusion

We examined trends in the variability of SAT, SND, and T_{SOIL} during 1921–2011 using long-term observational records from Russian land meteorological stations. Those variables revealed statistically significant positive trends over the entire time period for the Russian region as well as its WST and EST subregions. Time series of their trends also exhibited oscillatory behavior over the last 40 years, when the increase in SAT was greatly accelerated. The trend of T_{SOIL} was larger than that of SAT in all three regions due to the amplified impacts of SND. The major correlators were regionally different: SAT in the seasonally freezing WST and SND in the permafrost-dominated EST. The SND in EST contributed to the highest warming rate of T_{SOIL} among the three regions; the impact of SND on T_{SOIL} in EST was more significant during the recent three decades when SAT greatly increased, suggesting the amplified impact of SND combined with SAT. In WST, the low contribution of SND to T_{SOIL} warming was due to late snow cover in autumn and late snowmelt in spring.

A key finding of this study is the regional variability of the significant impact of SND on the permafrost thermal regimes. This regional dependence is consistent with spatial variations of SND insofar as insulation varies most rapidly with SND when the depth is small. Snowfall, a primary determinant of SND, depends largely on atmospheric patterns. This dependence increases uncertainty in the magnitude of future changes in SND, which in turn introduces uncertainty into the expression of climate change, its effects on soil thermal status, and the distribution of permafrost. In reality, the eastern Siberian region has experienced an increase in SND during recent decades (Bulygina *et al* 2009, Park *et al* 2013b), which is also projected to occur under future climate change conditions (AMAP 2011). Therefore, these findings emphasize the continued importance of monitoring and predicting snow in the context of the evolving state of permafrost.

Acknowledgment

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