Spatiotemporal Variability of Snow Depth across the Eurasian Continent from 1966 to 2012

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ABSTRACT

Snow depth is one of key physical parameters for understanding land surface energy balance, soil thermal regime, water cycle, as well as assessing water resources from local community to regional industrial water supply. Previous studies by using in-situ data are mostly site-specific; data from satellite remote sensing may cover a large area or in global scale, but uncertainties remain large. The primary objective of this study is to investigate spatial variability and temporal change in snow depth across the Eurasian continent. Data used include long-term (1966-2012) ground-based measurements from 1814 stations. Spatially, long-term (1971-2000) mean snow depths of >20 cm were recorded in north-eastern European Russia, the Yenisey River basin, Kamchatka Peninsula, and Sakhalin. Annual mean and maximum snow depth increased by 0.2 cm decade^{-1} and 0.6 cm decade^{-1} from 1966 through 2012. Seasonally, monthly mean snow depth decreased in autumn and increased in winter and spring over the study period. Regionally, snow depth significantly increased in areas north of 50°N. Compared with air temperature, snowfall had greater influence on snow depth during November through March across the former Soviet Union. This study provides a baseline for snow depth climatology and changes across the Eurasian continent, which would significantly help to better understanding climate system and climate changes at regional, hemispheric or even global scales.

1 Introduction

Snow depth, snow water equivalent (SWE) and snow density are all important parameters for water resource assessment, hydrological and climate model inputs and validation (Dressler et al., 2006; Lazar and Williams, 2008; Nayak et al., 2010). Changes in snow cover, including snow depth and snow area extent, serve as an indicator of climate change because of their interactions and feedbacks with surface energy and moisture fluxes, hydrological processes, and atmospheric and oceanic circulations (Brown and Goodison, 1996; Armstrong and Brown, 2008; King et al., 2008). Changes in snow depth can have dramatic impacts on weather and climate through the surface energy balance (Sturm et al., 2001), soil temperature and frozen ground (Zhang, 2005), spring runoff, water supply, and human activity (AMAP, 2011).

During winter, the average maximum terrestrial snow cover is approximately 47 $\times 10^6$ km^2 over the Northern Hemisphere land surfaces (Robinson et al., 1993; IGOS, 2007). A large fraction of the Eurasian continent is covered by snow during the winter season, and some areas are covered by snow for more than half a year. There are long-term snow measurements and observations across the Eurasian continent with the first snow depth record dating back to 1881 in Latvia (Armstrong, 2001). These measurements provide valuable data and information for snow cover phenology and snow cover change detection. Many studies on snow depth have focused on local and regional scales over Russia (Ye et al., 1998; Kitaev et al., 2005; Bulygina et al., 2009, 2011; Brasnett, 1999) and the Tibetan Plateau (TP) (Li and Mi, 1983; Ma and Qin, 2012), and have revealed significant regional changes. It has been reported that annual mean snow depth has increased in northern Eurasia and the Arctic during the last 70 years (Ye et al., 1998; Kitaev et al., 2005; Callaghan et al., 2011a; Liston and Hiemstra, 2011) with large regional differences (Bulygina et al., 2009, 2011; Ma and Qin, 2012; Stuefer et al., 2013; Terzago et al., 2014). Changes in snow depth are primarily affected by air temperature and precipitation. Ye et al. (1998) and Kitaev et al. (2005) showed that higher air temperatures caused an increase in snowfall in winter from 1936 through 1995, and thus, greater snow depth was observed in northern Eurasia. Snow depth distribution and variation are controlled by terrain (i.e., elevation, slope, aspect, and roughness) and vegetation (Lehning et al., 2011; Grünewald et al., 2014; Revuelto et al., 2014; Rees et al., 2014; Dickerson-Lange et al., 2015). Snow depth is closely related to synoptic-scale atmospheric circulation indices such as the North Atlantic Oscillation/Arctic Oscillation (NAO/AO). Kitaev et al. (2002) reported that the NAO index was positively related to snow depth in the northern part of East European Plain of Russia and over western Siberia from 1966 to 1990, but negatively correlated with snow depth in most southern regions of northern Eurasia. You et al. (2011) demonstrated that there was a positive relationship between snow depth and the winter AO/NAO index and between snow depth and Niño-3 region sea surface temperature (SST) on the eastern and central TP from 1961 through 2005.

To increase the spatial coverage of snow depth, researchers have used different instruments (e.g., LIDAR, airborne laser scanning (ALS), and unmanned aerial systems (UASs)) (Hopkinson et al., 2004; Grünewald et al., 2013; Bühler et al., 2016) or developed and/or improved passive microwave snow algorithms (Foster et al., 1997; Derksen et al., 2003; Grippaa et al., 2004; Che et al., 2016). Although snow depth and snow water equivalent obtained from passive microwave satellite remote sensing could mitigate regional deficiency of in-situ snow depth measurements, they have low spatial resolution (25×25 km), and the accuracy is always affected by underlying surface conditions and algorithms. Using ground-based snow depth measurements over the Eurasian continent against snow depth obtained from passive microwave satellite remote sensing, Zheng et al. (2015) found that the mean percentage error was greater than 50% and can be up to 200%. Apart from remote sensing, numerical modeling is often used to obtain spatially-complete fields of snow depth and/ or snow water equivalent (SWE) (Liston and Hiemstra, 2011; Terzago et al., 2014; Wei and Dong, 2015). However, low-resolution satellite remote sensing data is used as input parameter, which can affect simulation accuracy and does not provide a sufficient time series length. Spatial interpolation is a common method for estimates in areas with sparse data. Uncertainties and potential biases in spatial interpolation can be introduced due to specific algorithms, especially in complex terrain areas. Data acquisition from large airborne equipment or aerial systems is costly and strict data use limitations apply. Hence, ground-based measurements provide currently available most accurate snow depths over long time period and a data base for verification of remote sensing and model simulations.

The objective of this study is to (i) establish snow depth climatology (1971-2000), (ii) investigate snow depth variability at various scales from 1966 to 2012, and (iii) analyze factors controlling snow depth distribution and changes over Eurasian continent. Snow depth data used in this study are daily or 10-day interval ground-based measurements from 1814 stations. Detailed description of in-situ measurements and methodology are described in Section 2 with major results, discussions, and conclusions presented in Sections 3, 4, and 5, respectively.

2 Data and Methodology

Snow depth data used in this study include daily measurements from national meteorological stations and 10-day interval measurements from snow course. Measurements of daily snow depth were conducted at 1103 meteorological stations over the Eurasian continent from 1881 to 2013 (Table 1). Snow depth was measured once a day using a graduated stake installed at a fixed point location within the station or by a wooden ruler. Snow depth was measured using the same method across the Eurasian continent, which is also one of the standard elements to be measured on a daily basis (WMO, 1996). Historical snow course data were obtained from the former Union of Soviet Socialist Republics (USSR) from 1966 to 2011. Snow course data include routine snow surveys performed throughout the accumulation season (10-day interval) and during snowmelt period (5-day interval) over the former USSR. Snow surveys were conducted over 1-2 km-long transects in both forest and open terrain around each station. Snow depth was measured every 10 m in the forest and every 20 m in open terrain. Then final snow depth at each station was determined as the average of all measurements in each snow course survey (Bulygina et al., 2011).

Daily air temperature and precipitation data were obtained from 386 meteorological stations across the former USSR from 1966 to 2010 (Table 1). Snowfall data were derived from daily precipitation and air temperature. Daily precipitation was partitioned into a solid and liquid fraction based on daily mean temperature (Brown, 2000). The solid fraction of precipitation, S_{rat}, was estimated by

$$S_{rat} = \begin{cases} 1.0 & for\ T_{mean} \le -2.0°C, \\ 0.0 & for\ T_{mean} \ge +2.0°C, \\ 1.0 - 0.25(T_{mean} + 2.0) & for\ -2.0°C < T_{mean} < +2.0°C. \end{cases} \quad (1)$$

where T_{mean} is the mean daily air temperature (°C).

Daily snowfall was obtained by daily precipitation times daily S_{rat}.

In individual measurements, both random and systematic errors inevitably occur (Kuusisto, 1984). To minimize these errors, a quality control of meteorological data was automatically undertaken prior to the datasets being stored at the Russian Research Institute for Hydrometeorological Information-World Data Center (RIHMI-WDC) (Veselov, 2002) and the National Meteorological Information Center (NMIC) of China Meteorological Administration (Ma and Qin, 2012). We implemented additional quality control using the following requirements: (1) To ensure snow depth stability, at a given location, a month with less than 15 days of snow depth measurements was deleted. (2) Stations with sudden and steep changes in snow depth were eliminated from the list. (3) The World Meteorological Organization common approach to calculate anomalies is based on a 30-years climate normal period (IPCC, 2013). In this study, we use 1971-2000 as the normal period. To ensure data continuity, stations with less than 20-years data during the 1971-2000 period were excluded. (4) At each station, we eliminated data points that exceeded two standard deviations from their long-term (1971-2000) mean. After these four steps of snow depth quality control, we used data from 1814 stations to investigate the climatology and variability of snow depth over the Eurasian continent (Fig. 1 and Table 1).

We defined a snow year starting from July 1st of a current year through June 30th of the following year to capture the entire seasonal snow cycle. Procedures and techniques for measuring snow depth may have changed over the course of station history before the 1950s. Consequently, snow depth data may not be homogeneous in the time series over the period of the record. Fortunately, there was no change in the procedure and technique of snow depth measurements since 1965 in Russia and the other countries in this study (Bulygina et al., 2009). We chose to use snow depth data from 1966 to 2012. The following variables were calculated for each station:

(1) Daily snow depth: we defined a snow cover day with snow depth equal to or greater than 0 cm according to the standard method for deriving monthly mean snow depth based on the World Meteorological Organization (WMO) climatological products (Ma and Qin, 2012). Daily snow depth is the original in-situ measurements of snow depth.

(2) Monthly mean snow depth: monthly mean snow depth was computed as an arithmetic sum of daily snow depth divided by the number of days with snow on the ground within each month.

(3) Annual mean snow depth: annual mean snow depth was calculated as an arithmetic sum of monthly mean snow depth divided by the number of available snow months for each snow year.

(4) Annual maximum snow depth: the annual maximum snow depth was defined as the maximum daily snow depth within each snow year.

(5) Long-term mean monthly snow depth: it was averaged from each monthly mean snow depth over the 1971-2000 period.

(6) Long-term mean annual snow depth: it was averaged from annual mean snow depths over the 1971-2000 period.

(7) Long-term mean maximum snow depth: it was averaged from annual maximum snow depth over the 1971-2000 period.

Anomalies of monthly, annual mean, and annual maximum snow depth from their long-term (1971-2000) mean were calculated for each station across the Eurasian continent. Composite time series of monthly and annual anomalies were obtained by using all of the available station data across the study area.

Wavelet analysis was performed to reveal the long-term low-frequency variations in snow depth over the entire study area. We applied a discrete wavelet transform, excluded the high-frequency components and then used the inverse transform to reconstruct the lower frequency signal. Any trend analysis is an approximate and simple approach to obtain what has occurred on average during the study period. A linear trend analysis provides an average rate of this change. The linear trend analysis is also a useful approximation when systematic low-frequency variations emerge even though there is a nonlinearity (Folland and Karl, 2001; Groisman et al., 2006). The linear trend coefficient of the raw snow depth was calculated to represent the rate of change at each station. The Student's t-test was used to assess statistical significance of the slope in the linear regression analysis and the partial correlation coefficients of snow depth, air temperature and snowfall, and a confidence level above 95% was considered significant in our study. The Durbin-Watson test was used to detect serial correlation of data in the time series, and the Cochrane-Orcutt test was used to correct the serial correlation. Then, the serial correlations of the new data were rechecked and trends in the time series of the corrected data were recalculated. The methods and test results are described in the appendix.

3 Results

3.1 Climatology of Snow Depth

Distributions of long-term mean annual snow depth indicate a strong latitudinal zonality. Generally, long-term mean annual snow depth increases with latitude northward across the Eurasian continent (Fig. 2). The maximum value of 109.3 cm is observed over west of the Yenisey River (dark blue circle) (Fig. 2a). In contrast, the minimum values (~0.01 cm) are observed in some areas south of the Yangtze River in China (small grey circles).

Long-term mean annual snow depth for most areas in Russia is >10 cm. Long-term mean annual snow depths are even greater in the north-eastern part of European Russia, the Yenisey River basin, the Kamchatka Peninsula, and Sakhalin with snow depths of >40 cm. Regions with the smallest long-term mean annual snow depth (<5 cm) are located in the eastern and western areas of the Caucasus Mountains. Long-term mean annual snow depth in the other areas of the former USSR is ~2-10 cm, but shallow long-term mean annual snow depths (no more than 1 cm) are observed in some southern regions of Central Asia. The long-term mean annual snow depth in the central Mongolian Plateau is lower than that in the northern areas with values of no more than 5 cm. Long-term mean annual snow depth is >3 cm in the northern part of the Tianshan Mountains, Northeast China, and some regions of the southwestern TP. In the Altay Mountains and areas of the north-eastern Inner Mongolia Plateau, long-term mean annual snow depths are >5 cm.

Long-term mean maximum snow depth (Fig. 2b) shows a similar spatial distribution pattern compared to the long-term mean snow depth pattern. The maximum value is approximately 200.2 cm in snow depth. For the majority of Russia, the long-term mean maximum snow depth is >40 cm. The regions with the long-term mean maximum snow depths of exceeding 80 cm are in the north-eastern regions of European Russia, the northern part of the West Siberian Plain, the Yenisey River basin, the Kamchatka Peninsula, and Sakhalin; in contrast, along the coast of the Caspian Sea, the long-term mean maximum snow depth is <10 cm. Most of the rest of the former USSR has a long-term mean maximum depth of >10 cm, except for some regions of the Ukraine and Uzbekistan. The long-term mean maximum snow depth is >10 cm in northern Mongolia and decreases to 6–10 cm when moving south to central and eastern Mongolia. The long-term mean maximum snow depths are high over the northern part of the Xinjiang Autonomous Region of China, Northeast China, and eastern and southwestern TP, in which they are mostly greater than 10 cm and even greater than 20 cm in some areas. For the remaining regions of China, the long-term mean maximum snow depths are relatively small and mostly less than 10 cm.

In the autumn months (September to November), the long-term mean monthly snow depth is shallow (Figs. 3a-c). Long-term mean monthly mean snow depth is <20 cm in most areas of European Russia and south of Siberia but ranges from ~20 cm to 40 cm in northern Siberia and the Russian Far East in November (Fig. 3c). Moving southward, the long-term mean monthly snow depth is less than 5 cm north of Mongolia and across China. From December to February, the long-term mean monthly snow depth increases and the snow cover extent expands significantly (Figs. 3d-f). Long-term mean monthly snow depth values are >20 cm over the former

USSR. Long-term mean monthly snow depth is still <1 cm for the majority of China, except the northern Xinjiang Autonomous Region of China, Northeast China, and south-western TP where long-term mean monthly snow depth exceeds 10 cm. The long-term mean monthly snow depth is even more than 20 cm in some places of the Altai Mountains. In spring (March through May), snow cover areas decrease significantly (Figs. 3g–i), due mainly to snow disappearance in the majority of China. However, the long-term mean monthly snow depth still exceeds 20 cm in most areas of Russia. Snow cover areas and long-term mean monthly snow depth gradually decrease in April and May. Snow cover is observed only in Russia and in the TP in June (Fig. 3j).

3.2 Variability of Snow Depth

There are long-term significant increasing trends in both annual mean snow depth and annual maximum snow depth from 1966 to 2012 over the Eurasian continent. Annual mean snow depth increases at a rate of approximately 0.2 cm decade^{-1}, whereas annual maximum snow depth increases at a rate of approximately 0.6 cm decade^{-1} (Fig. 4). Both annual mean snow depth and annual maximum snow depth exhibit a similar pattern of changes over the four decades, although the amplitude of annual maximum snow depth anomaly (approximately ±2 cm) is much larger than that of the annual mean snow depth anomaly (approximately ±1 cm). From the mid-1960s to the early 1970s, annual mean snow depth decreased slightly then increased until the early 2000s and then decreased sharply until 2012 (Fig. 4a). Annual maximum snow depth decreased by 2.5 cm from the mid-1960s through the early 1970s (Fig. 4b). There was a sharp increase of approximately 3 to 4 cm during the 1970s, then there was a large fluctuation without a significant trend from the late 1970s to the early 1990s, and finally increased again from the early 1990s through the early 2010s (Fig. 4b).

Monthly snow depth changes significantly across the Eurasian continent from 1966 through 2012 (Fig. 5). It decreases in October at a rate of approximately -0.1 cm decade^{-1} (Fig. 5a), and there are no significant trends in November and December with large inter-annual variations (Fig. 5b-c). From January through April, it shows statistically increasing trends with rates between 0.3 cm decade^{-1} and 0.6 cm decade^{-1} (Fig. 5d-g). Overall, monthly mean snow depth shows decrease in October, no trends with large inter-annual variability in November and December, and increasing trend from January to April.

Figure 6 shows the spatial distributions of linear trend coefficients of annual mean snow depth and annual maximum snow depth for each station during 1966-2012 with $p \leqslant 0.05$. The significant increasing trends (blue circles) of annual mean snow depth occur in European Russia, south of Siberia and the Russian Far East, the northern Xinjiang Autonomous Region of China, and Northeast China (Fig. 6a). In contrast, decreasing trends (red circles) are detected in western European Russia, some regions of Siberia, north of the Russian Far East, and the regions south of 40°N in China. Over the entire Eurasian continent, the most significant linear trends are observed in regions north of 50°N, indicating that the increasing rate is greater in higher latitude regions.

In October and November, there are few stations with significant increasing trends in monthly mean snow depth ($p \leqslant 0.05$) (Figs. 7a and b). The increasing trends are mainly observed in most areas across the Eurasian continent in October although the magnitudes are generally small. Over November, the increasing trends only appear in Siberia and the Russian Far East, whereas decreasing trends occur over eastern European Russia, the southern West Siberian Plain, and the northeast Russian Far East.

In winter months (December-February), there is a gradual expansion in areas with increasing trends in monthly mean snow depth variation with $p \leqslant 0.05$ (Figs. 7c–e), and this mainly occur in eastern European Russia, southern Siberia, the northern Xinjiang Autonomous Region of China, and Northeast China. In contrast, significant decreasing trends are observed in northern and western European Russia and are scattered in Siberia, the northeast Russian Far East, and northern China.

From March to May, the number of stations with significant changes ($p \leqslant 0.05$) in monthly mean snow depth decreases, especially in May because of snow melt (only

78 stations) (Figs. 7f-h). Changes in monthly mean snow depth are consistent with the trends in winter over the former USSR, but more stations with decreasing trends are found in southern Siberia. There are few stations with statistically significant trends across China; for these stations, monthly mean snow depths tend to decrease at most stations.

Overall, it presents significant increasing trends in annual mean snow depth, annual maximum snow depth and monthly mean snow depth over Eurasia, especially in European Russia, south of Siberia, the northern Xinjiang Autonomous Region of China, and Northeast China. Compared with regions south of 50°N, changes in snow depth are more significant over regions north of 50°N.

4 Discussion

4.1 Comparisons with previous results

Studies on changes in snow depth have received much attention over different regions across Eurasian continent. The present study, for the first time, investigated changes in snow depth using ground-based data and information over the Eurasian continent as a whole. We found that climatology of long-term mean annual snow depth (1971-2000) was basically consistent with the results from Ma and Qin (2012) over China. In terms of changes in annual mean snow depth, both studies showed increase in annual mean snow depth but with slight difference in magnitude. This may be caused by using a different number of stations and covering different study periods. The long-term (1971-2000) mean annual snow depth from the present study was approximately 5-10 cm higher than the results from Kitaev et al. (2005) and Bulygina et al. (2011) over northern Eurasia. These discrepancies may result from differences in the time frame of data collection, the number of stations, calculation methods, and data quality control. For example, Kitaev et al. (2005) investigated historical changes in annual mean snow depth spanning 65 years from 1936 to 2000, while the present study covered 47 years from 1966 through 2012. We intentionally did not use the earlier (1936-1965) data due primarily to data quality. The earlier Russian snow depth data were discontinuous and did not meet the data quality control requirements used. Historical changes in the hydrometeorological station locations are also a critical reason for deleting many stations from the study. Based on results from the present study, we believe that snow depth data in the early years (prior to 1965) may be questionable and changes in snow depth prior to 1965 over Russia need further in-depth investigation.

Ye et al. (1998) found that historical winter mean snow depth increased in northern Russia (1.86 cm yr^{-1}) and decreased in southern Russia at a rate of -0.23 cm yr^{-1} during 1936-1983 (Ye et al., 1998). Results from the present study were essentially consistent with Ye et al. (1998) in northern Russia; however, we found winter monthly mean snow depth increased at a rate of 0.42 cm yr^{-1} in southern Siberia during the period from 1966 to 2012. We believe that the difference is mainly due to the time periods covered by the two studies.

Liston and Hiemstra (2011) conducted snow depth assimilation using the SnowModel. Results from the SnowModel assimilations in general agree well with ground-based measurements. For example, both observations from our study and assimilations with the SnowModel (Liston and Hiemstra, 2011) presented that the peak long-term mean annual snow depth occurred more in the western portion of northern Eurasia than the Russian Far East. The similar result may be primarily because the SnowModel input data included ground-based measured air temperature, precipitation, wind conditions and in part snow depth. However, results from CMIP5 (Coupled Model Intercomparsion Project Phase 5, Terzago et al., 2014; Wei and Dong, 2015) overestimated snow depth over the TP and underestimated in forest regions. This implies that large uncertainties currently still exist in CMIP5 modeling snow depth.

4.2 Impact of Topography on Snow Depth

Topography is an important factor affecting climatology of snow depth and the main reason accounting for snow depth data inhomogeneity (Grünewald and Lehning, 2011, 2013; Grünewald et al., 2014). To explore the effects of complex terrain on snow depth over Eurasia, we conducted a linear regression analysis of annual mean snow depth with latitude, elevation and continentality (Fig. 8). Annual mean snow depth is positively correlated with latitude, i.e., generally increases with latitude (Fig. 8a). The increased rate is approximately 0.81 cm per 1°N across the Eurasian continent. A closer relationship between latitude and annual mean snow depth is found in regions north of 40°N where snow cover is relatively stable with the number of annual mean continuous snow cover days for more than 30 (Zhang and Zhong, 2014).

There is a negative correlation between annual mean snow depth and elevation across the Eurasian continent (Fig. 8b); with every 100 m increases in elevation, annual mean snow depth decreases by ~0.5 cm ($p \leqslant 0.05$). Annual mean snow depth is less than 1 cm in regions with elevation greater than 2000 m because a snow depth of 0 cm was used to calculate the annual mean snow depth. Therefore, although the TP is at a high elevation, the shallow annual mean snow depth results in a generally negative correlation between snow depth and elevation across the Eurasian continent. Snow depths were averaged at each 200 m elevation band. Annual mean snow depths are deeper in the lower elevation bands (between 0 and 600 m) across the former USSR (Fig. 8c). However, there are shallow annual mean snow depth between 600 and 1000 m due mainly to forest effect. Annual mean snow depths increase with elevation and reach to the peak at 1600 m. Annual mean snow depths show marked decrease in the highest elevation bands (2600~2900 m). There are only two stations in this band and more annual mean snow depth difference between the two stations because of terrain and climate factors. Snow is deeper in three elevation bands across China: 200~1000 m, 1600~1800 m and 2400~2600 m. Greater snow depth is attributed to more snowfall and severe cold weather in these regions. An increasing trend with elevation presents above 2600 m on the TP.

Continentality is a measure of the difference between continental and marine climates. It is roughly a measure of distance from oceans. Continentality affects precipitation, thus determines snowfall rate and snow depth. Although there is a statistically significant positive relationship between annual mean snow depth and continentality over the Eurasian continent, the Goodness of Fit is only 1% (Fig. 8d).

This indicates that the continentality may not be an important driving factor of annual mean snow depth distribution compared with latitude and elevation over Eurasia, especially on the TP.

4.3 Impact of Climate Factors on Snow Depth

In addition to the terrain factors, variations in snow depth are closely related to climate variability. To examine the relationship between snow depth and climatic factors, we calculated the long-term mean snow depth, air temperature and snowfall of 386 stations from November through March across the former USSR (Fig. 9). The period (snow cover years) spanned from 1966 through 2009 using available data. Annual mean snow depth significantly decreases with increasing air temperature ($p \leqslant 0.05$) but the Goodness of Fit of the relationship is only 16% (Fig. 9a). Compared with air temperature, snowfall exhibits a strong relationship with annual mean snow depth (Fig. 9b). The annual mean snow depth is less than 20 cm at most stations with an accumulated snowfall of <50 mm from November through March. Annual mean snow depth increases with an increase in accumulated snowfall, and the thickest annual mean snow depth of approximately 120 cm has a maximum cumulative snowfall of approximately 350 mm.

Overall, the trends in long-term air temperature, snowfall and annual mean snow depth display increasing trends from November to March (Fig. 10). This is because the increased precipitation falling as snow in cold areas where the increased temperature is still below freezing (Ye et al., 1998; Kitaev et al., 2005). Warmer air leads to a greater supply of moisture for snowfall and hence the snow depth still increases (Ye et al., 1998). Significant increasing snowfall can explain the sudden drop in bulk snow density from the mid-1990s through the early 2000s (Zhong et al., 2014): increasing snowfall should decrease the density of the surface snowpack, which lowered the bulk density of the snowpack. In addition, there are similar inter-annual variations in snowfall and heavy snowfall (daily snowfall amount is between 5-10 mm). This indicates that extreme snowfall events may be the main cause of the increase in annual mean snow depth.

The partial correlation coefficients between snow depth, air temperature and snowfall are calculated to discuss the spatial relationship among them (Fig. 11). A significant negative correlation ($p \leqslant 0.05$) between annual mean snow depth and air temperature is present in most areas of European Russia and southern Siberia (Fig 11a). However, there is no statistically significant correlation among them in northern Siberia. This is because there is no obvious effect of increasing temperature on annual mean snow depth when the air temperature is below 0 °C, which occurs in most areas of Siberia from December through March.

Compared with the previous studies (Fallot et al., 1997; Park et al., 2013), sensitivity of snow depth to air temperature and precipitation for each station show regional differences. The amount of snowfall can be affected by climate change and leads to differences in snow depth at different times (Ye et al., 1998; Kitaev et al., 2005; Ma and Qin, 2012). We find that there is a significant ($p \leqslant 0.05$) negative relationship between annual mean snow depth and air temperature in southern Siberia but not in northern Siberia. In addition to air temperature and precipitation, atmospheric circulation is a key factor affecting snowfall and snow depth change (Cohen, 2011; Zhao et al., 2013; Ye et al., 2015). Those factors above and related uncertainties may explain the regional and temporal differences in long-term mean snow depth and snow depth change.

Snow cover extent and snow cover duration have decreased in response to climate change (Bulygina et al., 2009; Brown and Robinson, 2011; IPCC, 2013; Xu et al., 2017), however, snow depth increases significantly with in situ data over Eurasia. The present study shows that there are similar inter-annual variations in annual mean snow depth and heavy snowfall, which implies that extreme snowfall may be the main reason for snow thickening.

4.4 Potential Effects of Variations in Snow Depth

Snow depth is an important factor of controlling the ground thermal regime (Goodrich, 1982; Zhang et al., 1996; Zhang, 2005; Ling and Zhang, 2005; Park et al, 2014). Studies have shown that thin snow cover resulted in a cooler soil surface, whereas thick snow cover led to a warmer soil surface (Kudryavtsev, 1992). Frauenfeld et al. (2004) indicated that the maximum snow depth by the end of winter had a significant influence on active layer depth in the following summer. Snow depth was responsible for 50% or more of the changes in soil temperature at a depth of 3.6 m in north-eastern Siberia from 1901-2009 (Park et al., 2014). Results from the present study indicated that annual mean snow depth significantly decreased on the TP and increased in Siberia. Although it is not clear what is the role (cooling or warming) of snow cover on soil thermal region on the TP, the decrease in snow depth would reduce the warming effect, offsetting the increase in permafrost temperatures (Zhang, 2012). Over Siberia, increase in snow depth would further increase permafrost temperatures (Zhang et al., 2001, 2005; Park et al., 2014), enhancing permafrost degradation over the region.

Snow cover has an important impact on the hydrological cycle (AMAP, 2011). Spring floods are generated by melting snow, and freshwater derives are from snowmelt in some snow-dominated basins (Barnett et al., 2005). Increasing snow depth may lead to frequent spring floods in northern Xinjiang and snow depth reduction can result in freshwater shortage on the TP. Furthermore, snow interacts with vegetation and in turn vegetation affects snow depth, redistribution and the vertical profile in forests or shrubs (Hedstrom and Pomeroy, 1998; Pomeroy et al., 2006). Snow also influences plant growth, high snow depth with more water amount can increase soil moisture and promote vegetation productivity (Peng et al., 2010). Therefore, increasing snow depths could contribute to forest growth in northern Eurasia and north-eastern China.

5 Conclusions

In this study, daily snow depth and snow course data from 1814 stations were used to investigate spatial and temporal changes in annual mean snow depth and annual maximum snow depth over the Eurasian continent for the period from 1966 to 2012. Our results demonstrate that greater long-term annual mean snow depth was observed in north-eastern European Russia, the Yenisey River basin, the Kamchatka

Peninsula, and Sakhalin. In contrast, the shallowest long-term annual mean snow depths were recorded in China, except for the northern Xinjiang Autonomous Region of China, Northeast China, and in some regions of the southwestern TP.

There were statistically significant trends in variations in long-term annual mean snow depth over the entire Eurasian continent. A similar increasing pattern of changes was exhibited in both long-term annual mean snow depth and long-term maximum mean snow depth, although the amplitude of the long-term maximum mean snow depth anomaly was much larger than the equivalent value for the long-term annual mean snow depth. Monthly mean snow depth in autumn presented a decreasing trend, whereas there were increasing trends during winter and spring, especially during the period of the mid-1980s through the 2000s.

Significant increasing trends in annual mean snow depth were detected in the eastern regions of European Russia, southern Siberia, the Russian Far East, the northern areas of the Xinjiang Autonomous Region of China, and north-eastern China. Decreasing linear trends were observed in most western areas of European Russia, some regions of southern Siberia, the north-eastern Russian Far East and most areas in the southern 40 °N across China.

Compared with elevation, latitude played a more important role in snow depth climatology. Variations in mean snow depth were explained by air temperature and snowfall in most areas of European Russia and some regions of southern Siberia; however, snowfall especially heavy snowfall was the main driving force of the variance of mean snow depth in the former USSR.

Appendix A: Analysis of serial correlation

In this research, the Kolmogorov-Smirnov (K-S) test was used to determine whether snow depth data followed a normal distribution. The results showed that all station data followed a normal distribution (such as annual mean snow depth for all stations, Fig. A1). We used ordinary linear regression (OLR) to detect trends in changes in snow depth. Failure to consider the serial correlation of data could lead to erroneous results when detecting the trends in a time series of snow depth, which is mainly because the probability of detecting false trends would be increased (Westherhead et al, 1998; Storch, 1999; Khaliq et al., 2009). To avoid this situation, we used the Durbin-Watson test to check the serial correlation (Neter et al., 1989; Tao et al., 2008):

$$\mathrm{d} = \frac{\sum_{t=2}^{n}(e_t - e_{t-1})^2}{\sum_{t=1}^{n} {e_t}^2} \qquad \text{(A1)}$$

where e_t was the residual estimated by the OLR, and t was the number of observations. d_1 was the lower critical value, and d_u was the upper critical value, which could be obtained through the Durbin-Watson statistic table. If $d_u \leq d \leq 4 - d_u$, a serial correlation was absent; if $d \leq d_1$ or $d \geq 4 - d_1$, a serial correlation was present.

We used the Cochrane-Orcutt method to correct the variable if the serial correlation was present (Neter et al., 1989; Tao et al., 2008):

$$X_t' = X_t - \rho X_{t-1} \qquad \text{(A2)}$$

$$Y_t' = Y_t - \rho Y_{t-1} \qquad \text{(A3)}$$

where X' was the corrected year, Y' was the corrected anomaly in time series of snow depth for each station in this research, and the autocorrelation coefficient ρ was replaced by its estimate value r:

$$\mathrm{r} = \frac{\sum_{t-2}^{n} e_{t-1} e_t}{\sum_{t-2}^{n} e_{t-1}^2} \qquad \text{(A4)}$$

Then, the Durbin-Watson test was used to check the serial correlation of the new snow depth anomalies, and recalculated the trends in the time series of new data.

The Durbin-Watson test results show that there were no serial correlations in the inter-annual trends in annual mean snow depth, maximum snow depth and monthly mean snow depth for all of the composite data ($d_u \leq d \leq 4 - d_u$) (Table A1). However, the serial correlation was present in some stations when we calculated the linear trend of annual mean snow depth, maximum depth and monthly mean snow depth for each station. The percentage of the stations with a serial correlation for annual mean snow depth and maximum depth were 18% and 21%, respectively. In the monthly test, the smallest proportion appeared in October at approximately 11%; the largest percentage of these stations for all of the stations was found in February and was up to 21%. Then, the Cochrane-Orcutt method was used to correct the variables and re-estimated the trends in long-term mean snow depth for these station (Fig. 6-7 in the text). Using the Dikson site (73.5 ºN, 80.4 ºE, 42 m a.s.l.) as an example, the serial correlation was present when the trend in annual mean snow depth was calculated. Compared with the corrected result, the variance of the previous OLR statistic was overestimated, and annual mean snow depth increased at the rate of 0.113 cm yr^{-1} (Table A2). The corrected result indicated that the variation of inter-annual mean snow depth was not significant ($P' > 0.05$). The serial correlation cannot be ignored for detecting trends in a time series of snow cover variables, which possibly invalidates the statistical test on slopes if this variable is not dealt with.

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Tables and Figures

Table 1. Sources of snow depth data

Dataset	**Spatial distribution**	**Number of stations**	**Source**
Daily snow depth	the former USSR	586	Russian Research Institute for Hydrometeorological Information-World Data Center (RIHMI-WDC) National Snow and Ice Data Center (NSIDC), University of Colorado at Boulder
	China	492	National Meteorological Information Center (NMIC) of the China Meteorological Administration
	Mongolia	25	NSIDC
Snow depth from snow courses	the former USSR	1044	RIHMI-WDC, NSIDC
Daily air temperature and precipitation	the former USSR	386	RIHMI-WDC

Table A1. Trends in snow depths with the Durbin-Watson test across Eurasia during 1966-2012

	d_1	d_u	d	$slope^*$	p^*
Mean	1.3034	1.3871	1.6435	0.02	0.0016
Maximum	1.3034	1.3871	1.8824	0.06	0.0004
October	1.3034	1.3871	2.1377	-0.01	0.0069
November	1.4872	1.5739	2.3667	0.00	0.7408
December	1.4872	1.5739	1.9684	0.02	0.0793
January	1.3034	1.3871	1.6326	0.04	0.0014
February	1.3034	1.3871	1.8469	0.06	0.0000
March	1.3034	1.3871	1.9874	0.06	0.0003
April	1.3034	1.3871	1.6754	0.03	0.0187
May	1.4872	1.5739	2.0703	0.00	0.5811

*: slope is the trend of changes in snow depth, the unit is cm yr^{-1}; p is the confidence level.

Table A2. Trends in annual mean snow depth with the Durbin-Watson test for the Dikson site during 1966-2012

ID	d_1	d_u	d	$slope$	p	d'_1	d'_u	d'	$slope'^*$	p'^*
20674	1.3034	1.3871	1.2856	0.113	0.016	1.4872	1.5739	2.0249	0.0942	0.055

*: slope' is the corrected trend of changes in snow depth, the unit is cm yr^{-1}; p' is the corrected confidence level.

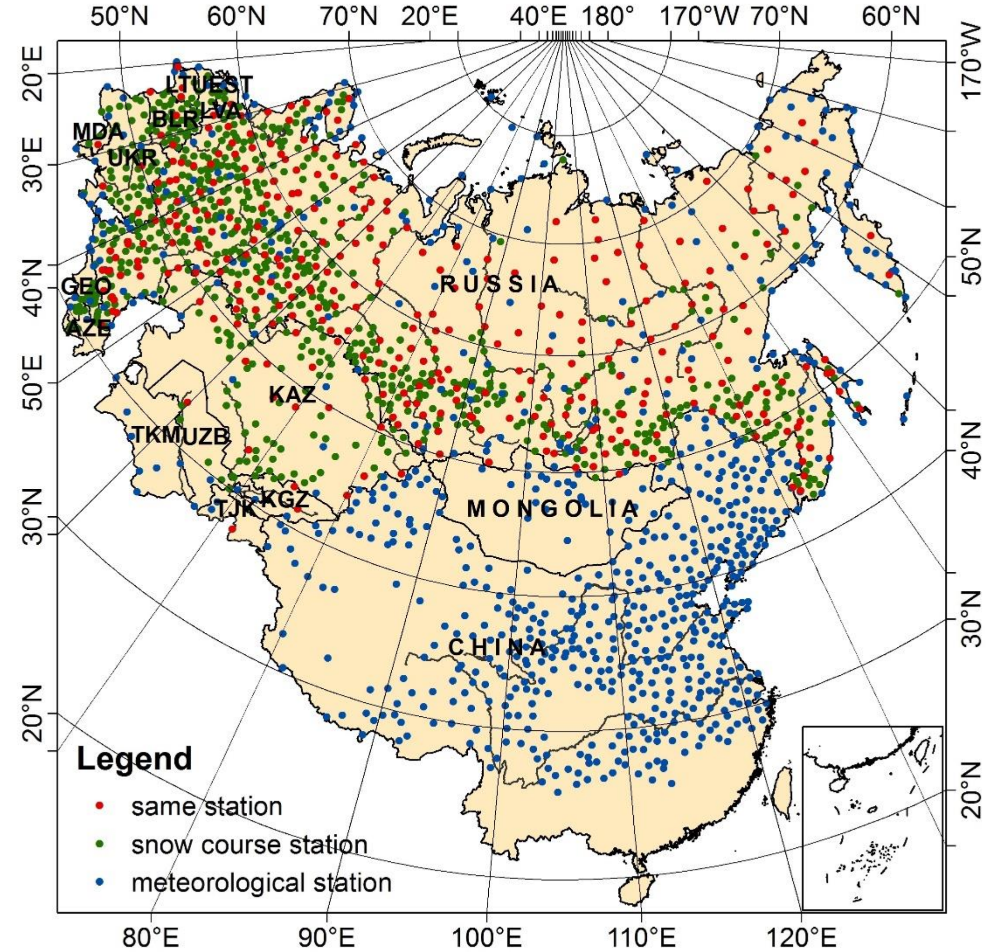


Figure 1. Geographical locations of meteorological stations and snow course survey across the Eurasian continent. The red circles represent stations where snow depth was measured at both meteorological stations and snow course surveys, the green circles show stations where snow depth was measured at snow surveys only, and the blue circles show stations where snow depth was measured at meteorological stations only. The abbreviations of countries represent separately: ARM-Armenia, AZE-Azerbaijan, BLR-Belarus, EST-Estonia, GEO-Georgia, KAZ-Kazakhstan, KGZ-Kyrgyzstan, LTU-Lithuania, LVA-Latvia, MDA-Moldova, TJK-Tajikistan, TKM-Turkmenistan, UKR- Ukraine, UZB-Uzbekistan.

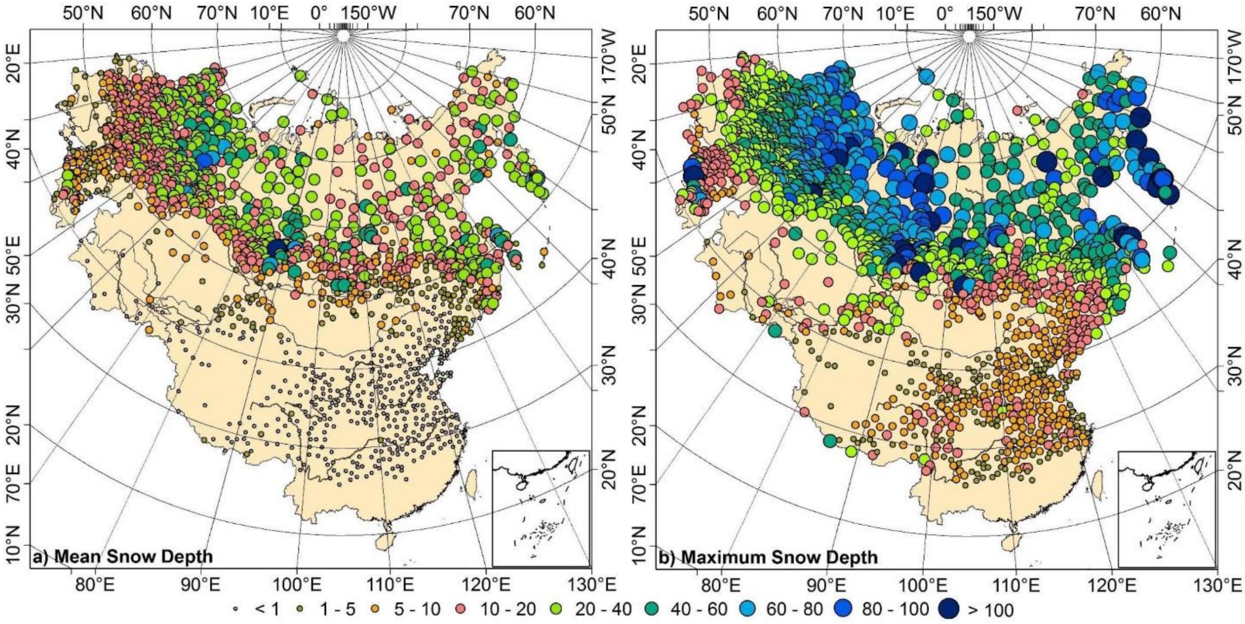
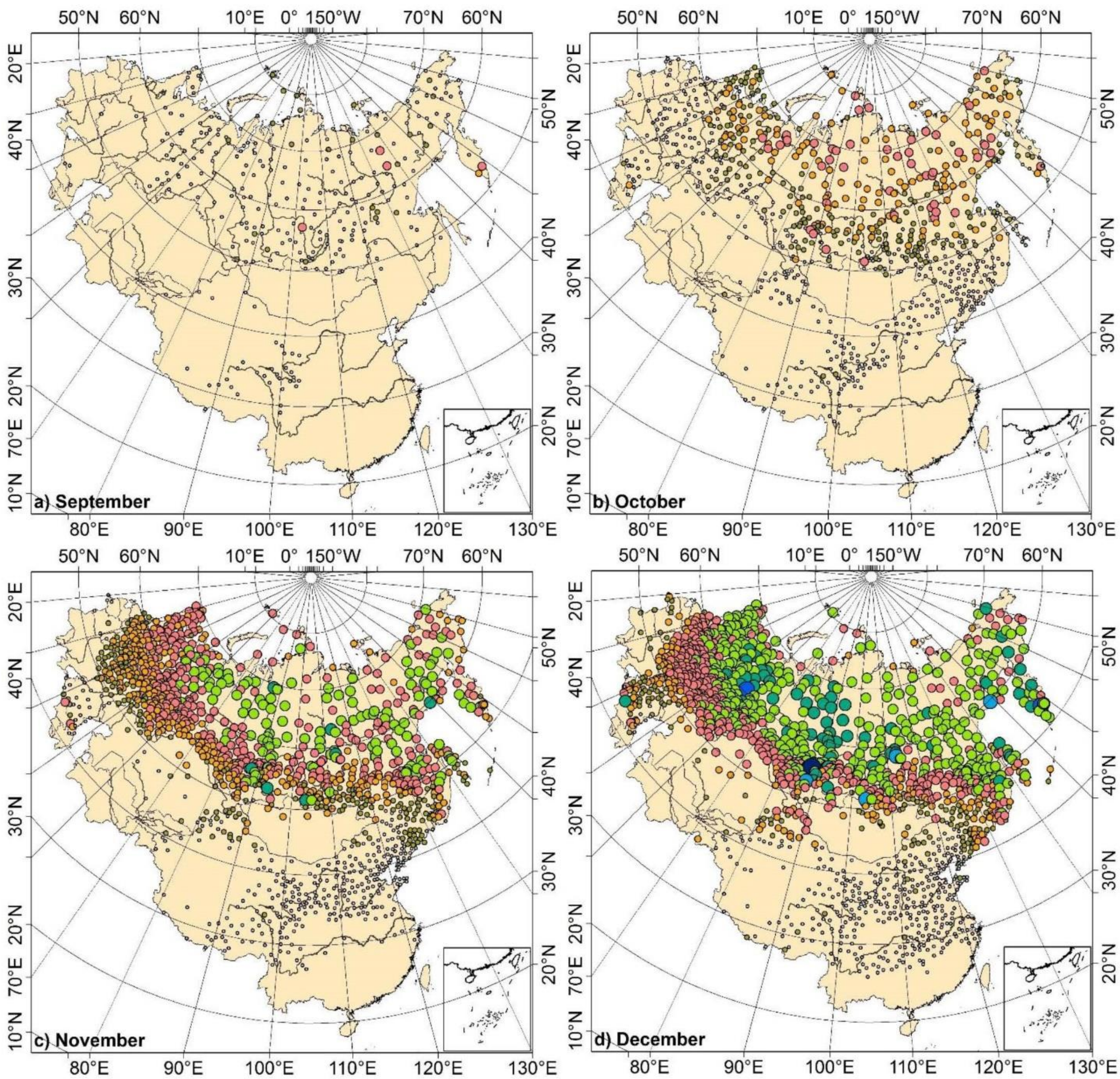


Figure 2. Long-term mean annual snow depth (a) and long-term mean maximum snow depth (b) across the Eurasian continent (cm) during the 1971-2000 period.

1



a) September
b) October
c) November
d) December
50°N
60°N
10°E
0°
150°W
70°N
60°N
20°E
40°N
30°N
20°N
70°E
10°N
50°N
40°N
30°N
20°N
80°E
90°E
100°E
110°E
120°E
130°E

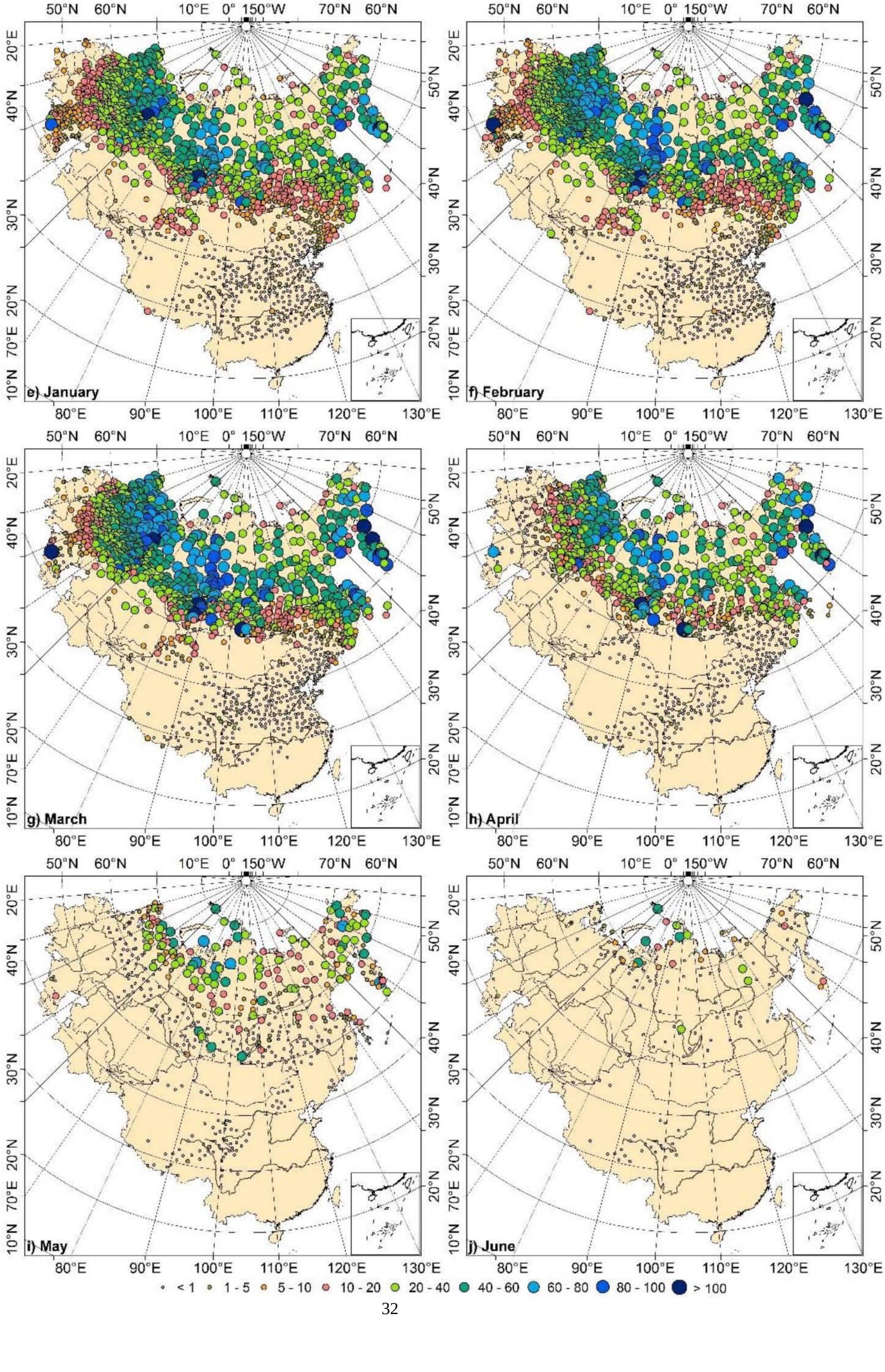

e) January
f) February
g) March
h) April
i) May
j) June
50°N 60°N 10°E 0° 150°W 70°N 60°N
20°E 40°N 30°N 20°N 70°E 10°N
50°N 40°N 30°N 20°N
80°E 90°E 100°E 110°E 120°E 130°E
< 1
1 - 5
5 - 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100

Figure 3. Long-term mean monthly snow depth (from September to June) (cm) across the Eurasian continent (cm) during the 1971-2000 period. (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, (i) May, (j) June.

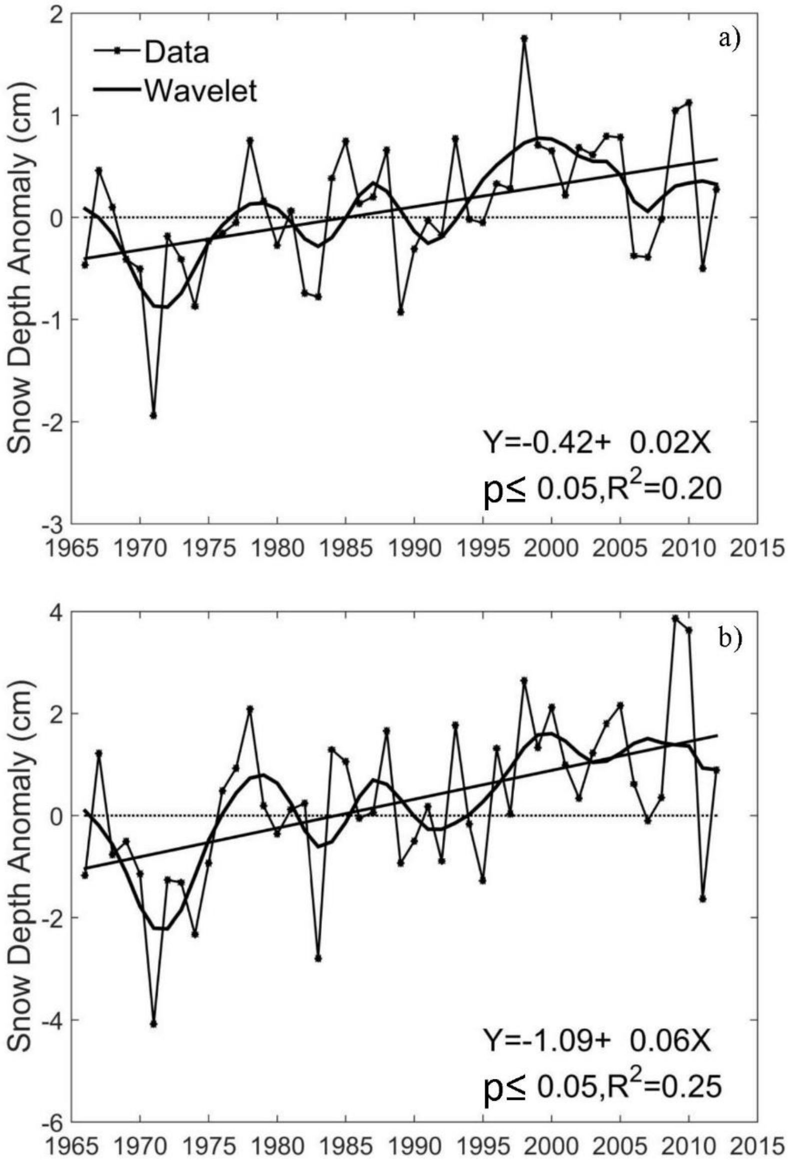
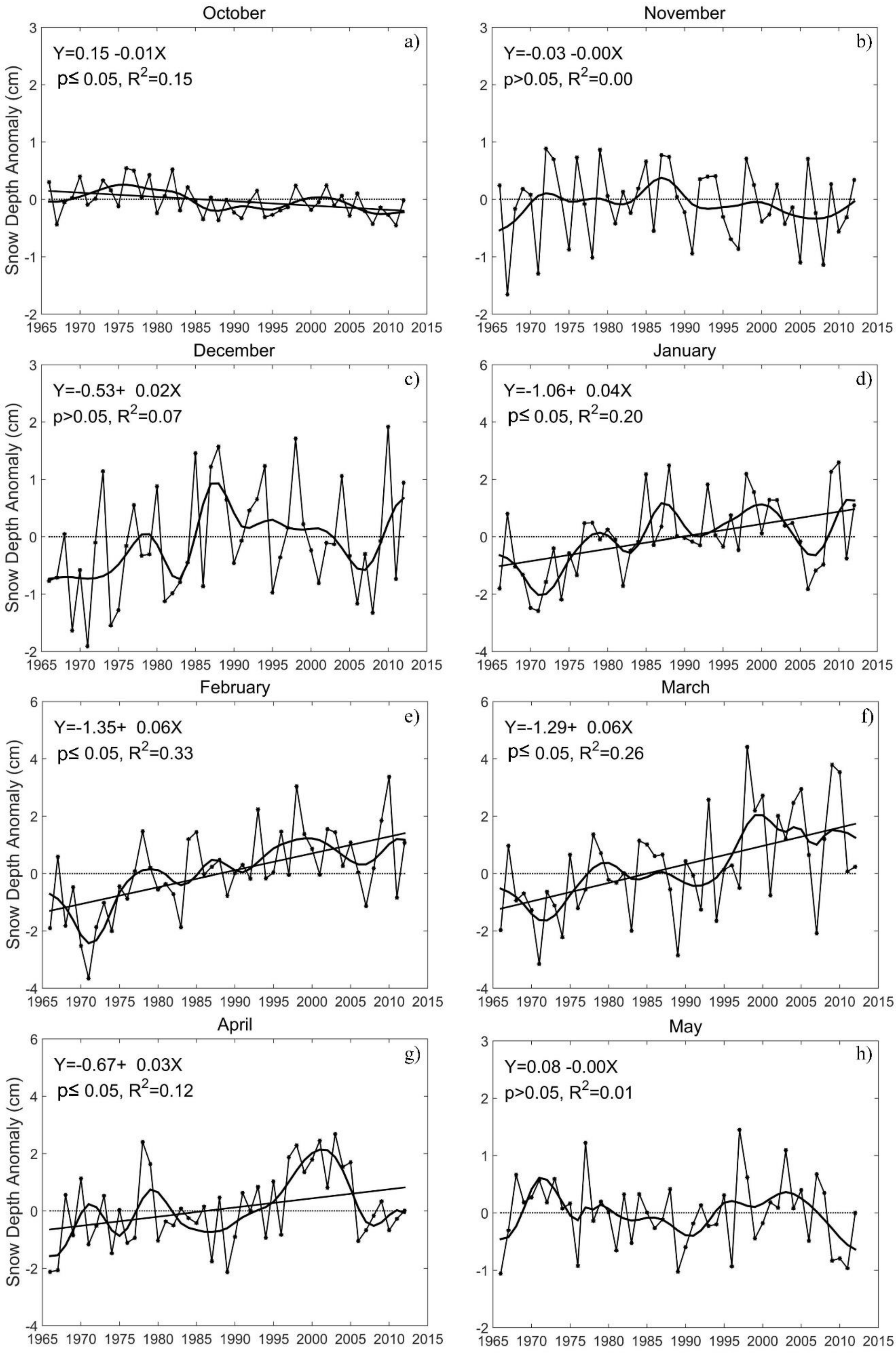


Figure 4. Composite of the anomalies of annual mean snow depth (a) and annual maximum snow depth (b) from 1966 through 2012 with respect to the 1971-2000 mean across the Eurasian continent. The composite anomaly was calculated by the sum of anomalies from all stations divided by the number of stations at a given year. The line with dots is the anomaly of snow depth; the thick curve represents the smoothed curve using wavelet analysis; the thick line presents a linear regression trend.



1

2 **Figure 5.** Composites of the anomalies of monthly mean snow depth (from October to May) from

1966 through 2012 with respect to the 1971-2000 mean across the Eurasian continent. The composite anomaly was calculated by the sum of anomalies from all stations divided by the number of stations at a given year. (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May. The line with dots is the anomaly of monthly mean snow depth; the thick curve represents the smoothed curve using wavelet analysis; the thick line presents a linear regression trend. Linear regression trend is only shown when the rate of change at the 95% level.

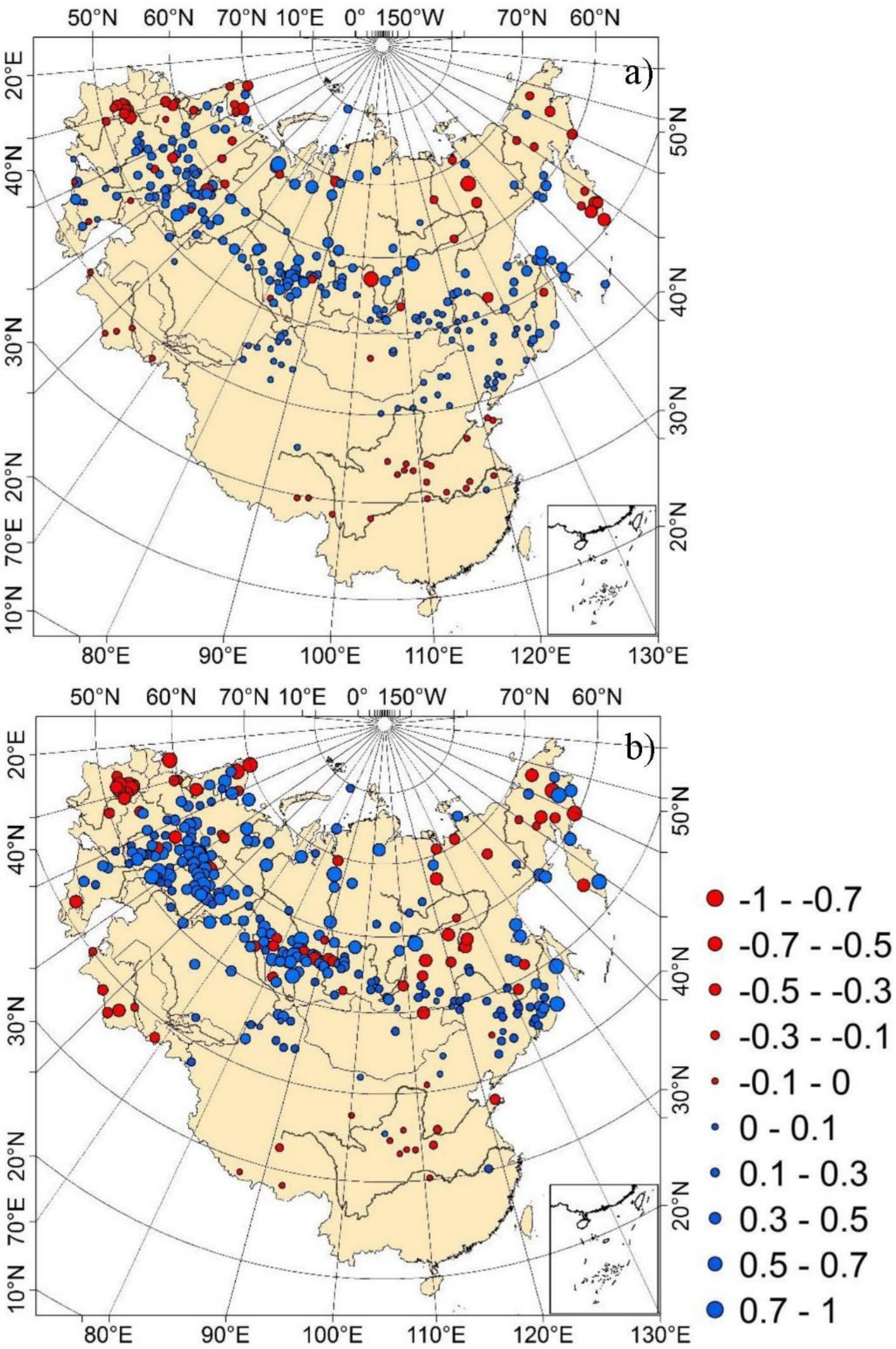
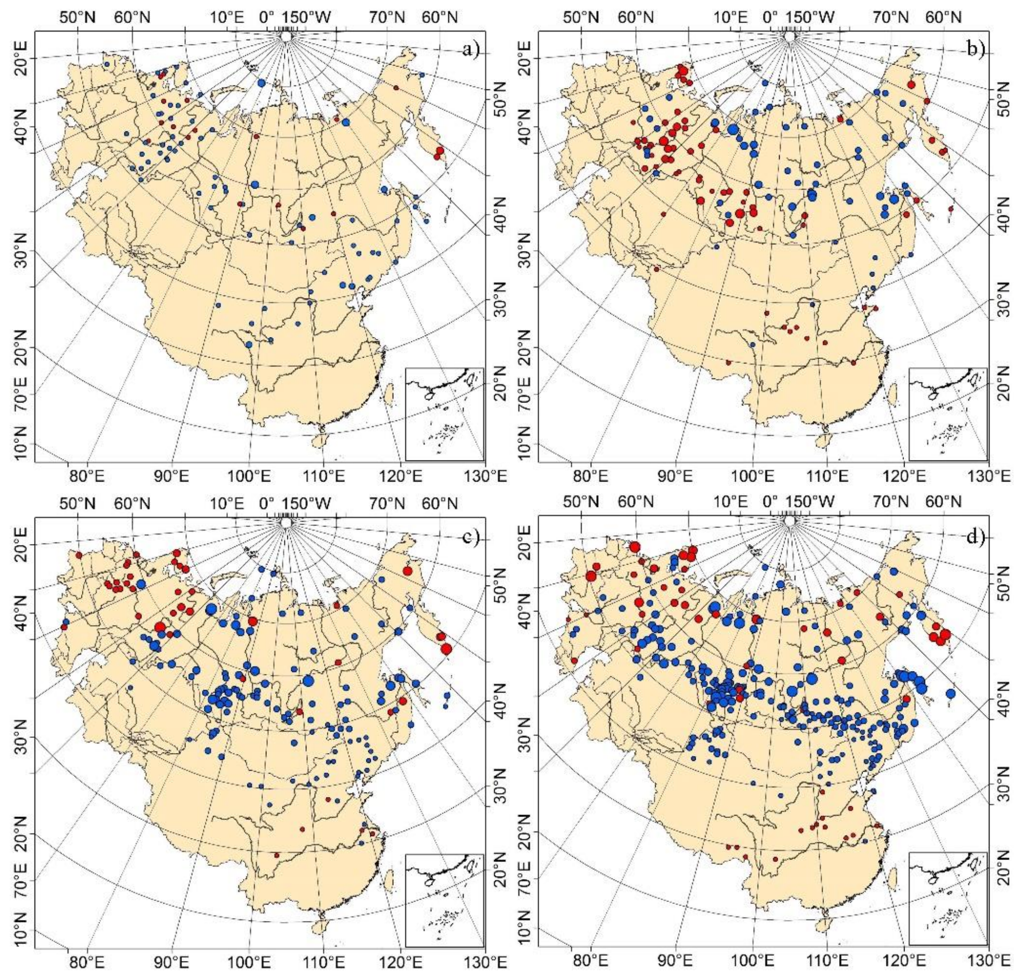


Figure 6. Spatial distribution of linear trend coefficients (cm yr^{-1}) of annual mean snow depth (a) and annual maximum snow depth (b) for each station in 1966-2012. The rate of change at the 95%

level is displayed. Red circles represent a decreasing trend, and blue circles represent an increasing trend.



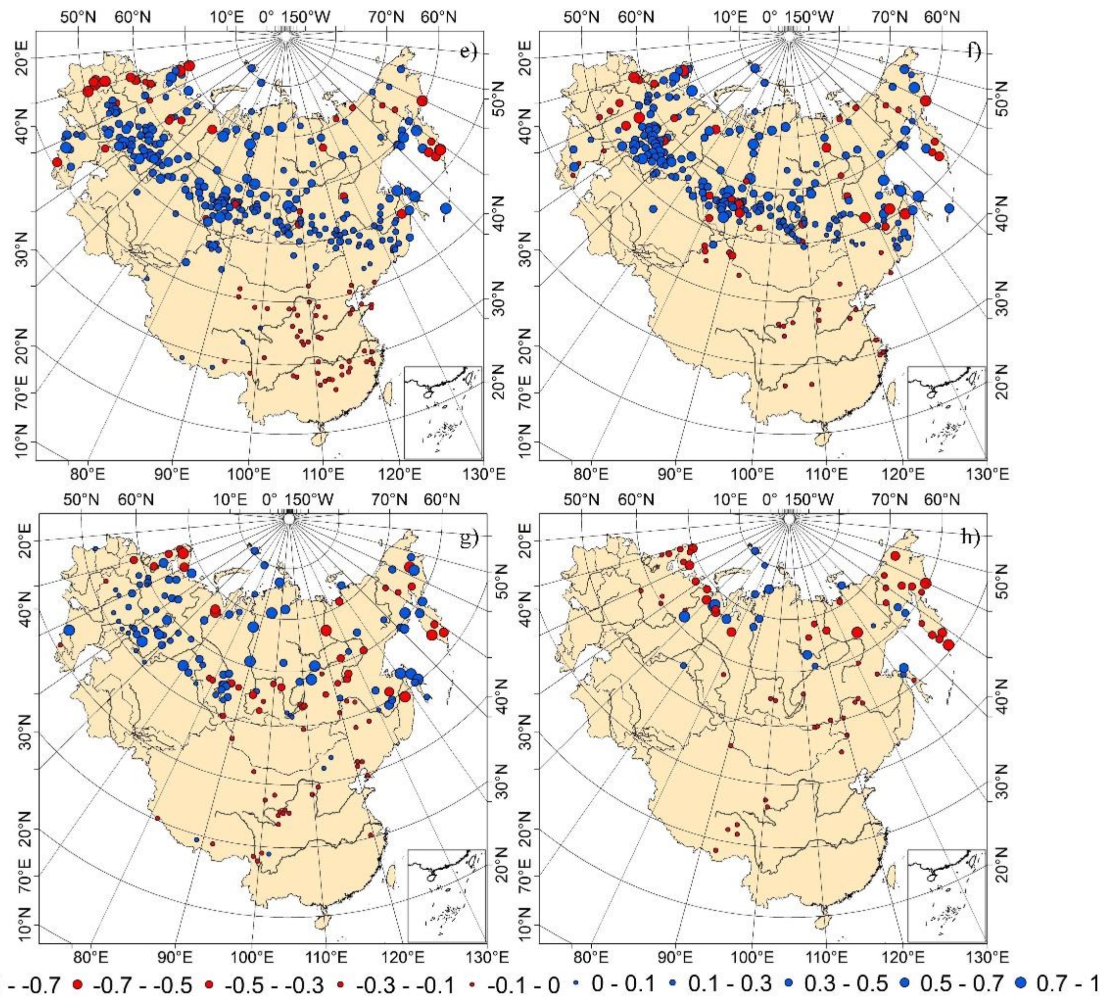


Figure 7. Spatial distributions of linear trend coefficients (cm yr^{-1}) of monthly mean snow depth (from October to May) during 1966 to 2012. (a)October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May. The rate of change at the 95% level is displayed. Red circles represent a decreasing trend, and blue circles represent an increasing trend.

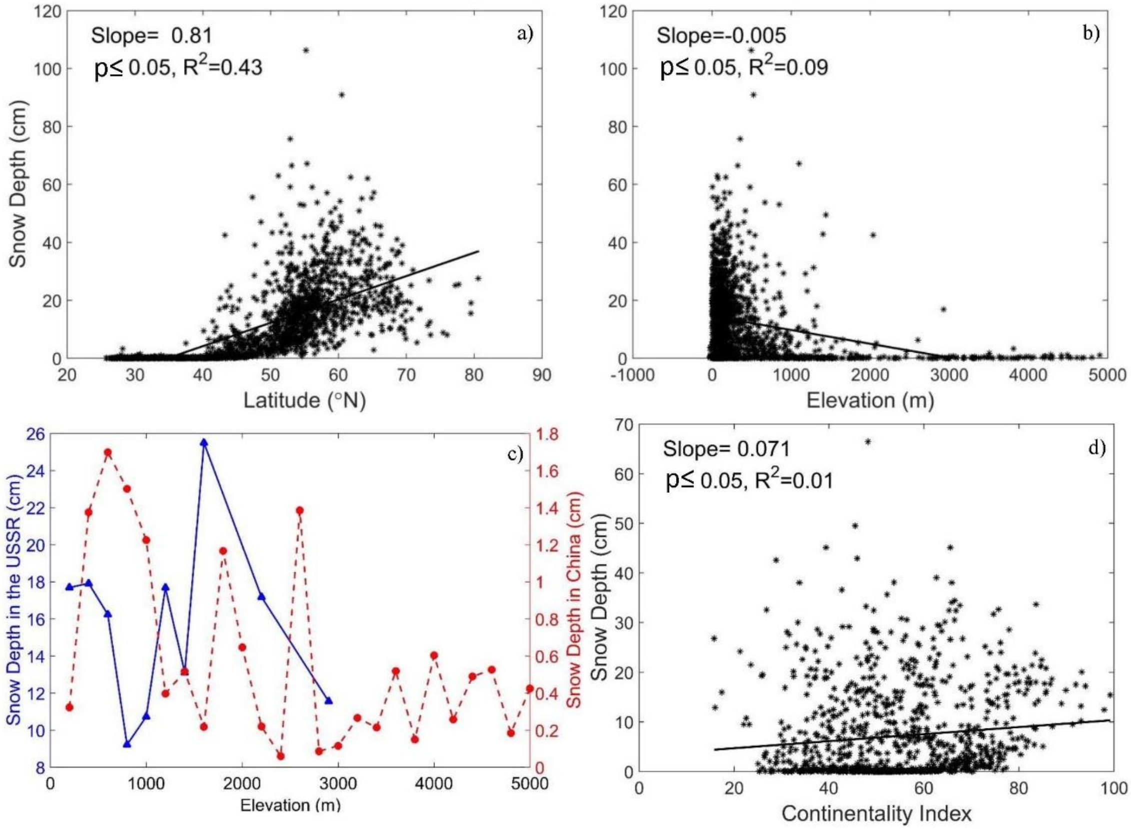


Figure 8. Relationship between annual mean snow depth and latitude (a), elevation (b and c) and continentality (d) for all stations across the Eurasian continent during 1966-2012. Asterisks show the annual mean snow depth at each station; the thick line is a linear regression trend.

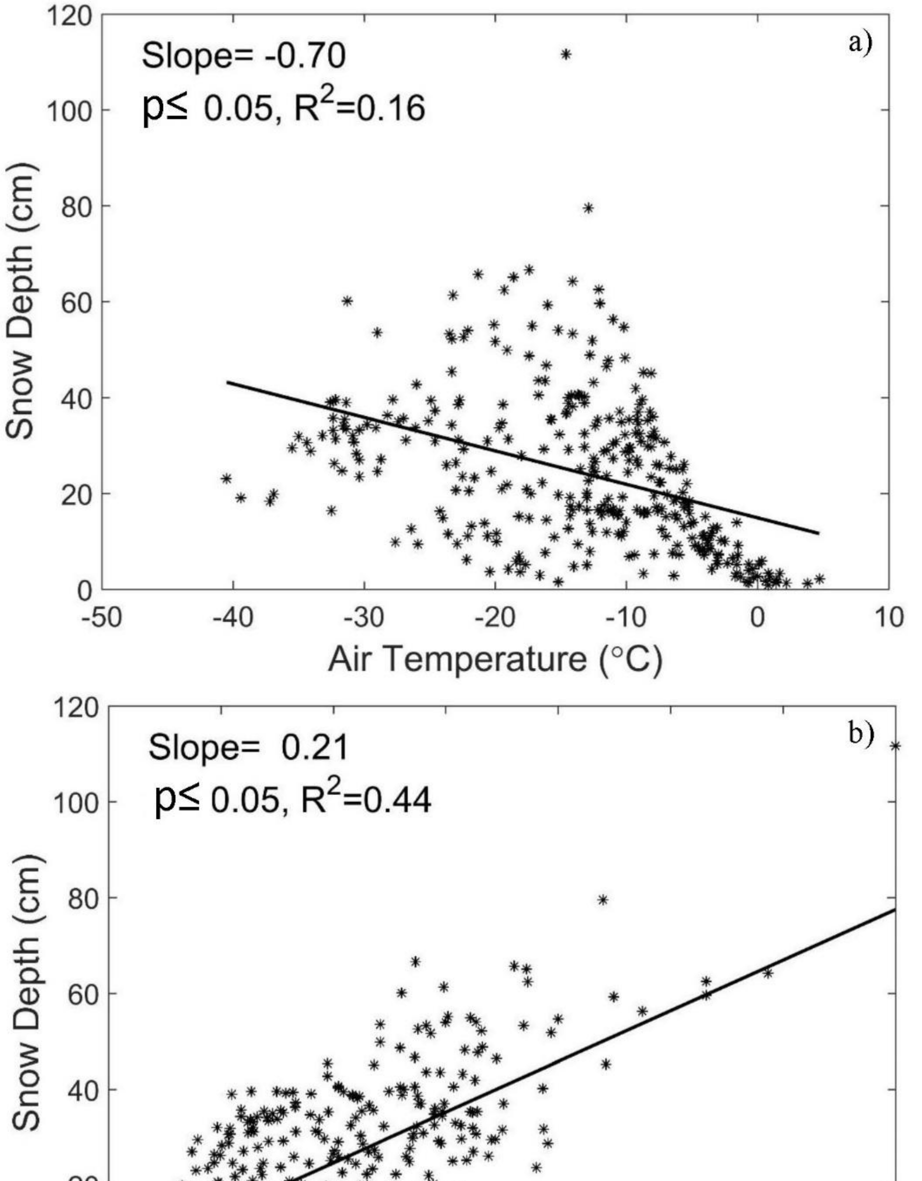


Figure 9. Relationship between annual mean snow depth and air temperature (a) and between annual snow depth and snowfall (b) from 386 stations from November through March during 1966-2009 over the USSR. The thick line is a linear regression trend.

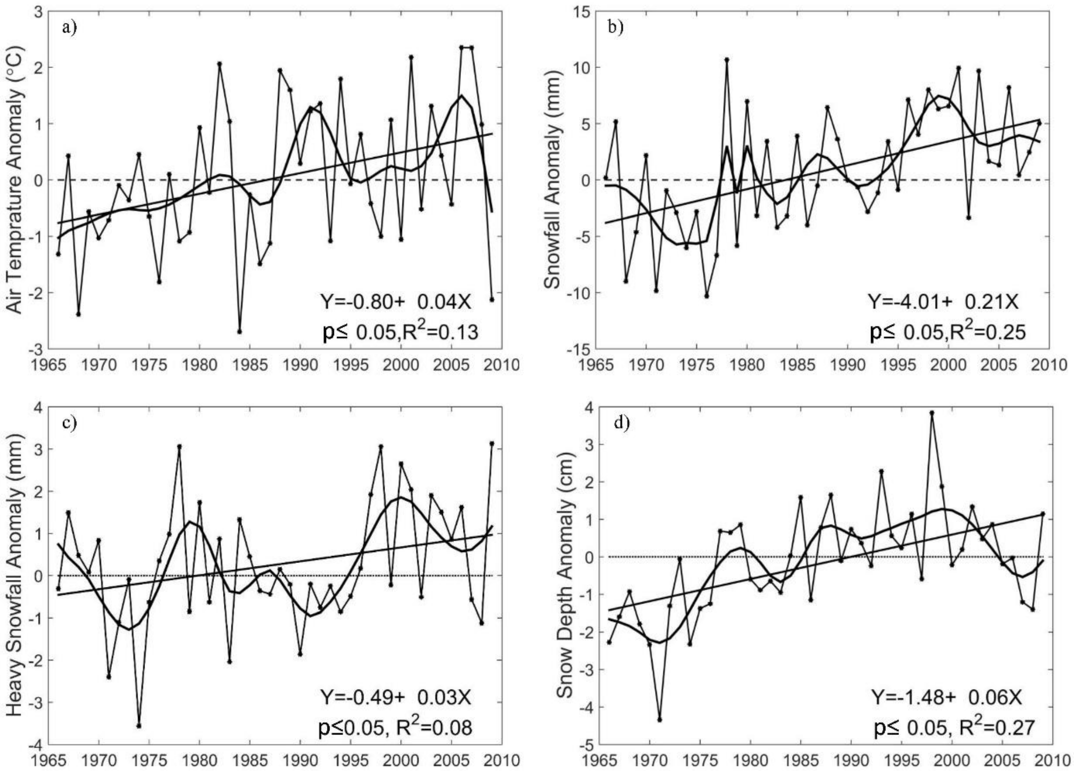


Figure 10. Composite of the anomalies of annual mean air temperature (a), annual snowfall (b), annual heavy snowfall (c) and annual mean snow depth (d) from November through March during 1966-2009 with respect to the 1971-2000 mean across the former USSR. The composite anomaly was calculated by the sum of anomalies from all stations divided by the number of stations at a given year. The line with dots is the composite of the annual means; the thick curve represents the smoothed curve using wavelet analysis; the thick line presents a linear regression trend.

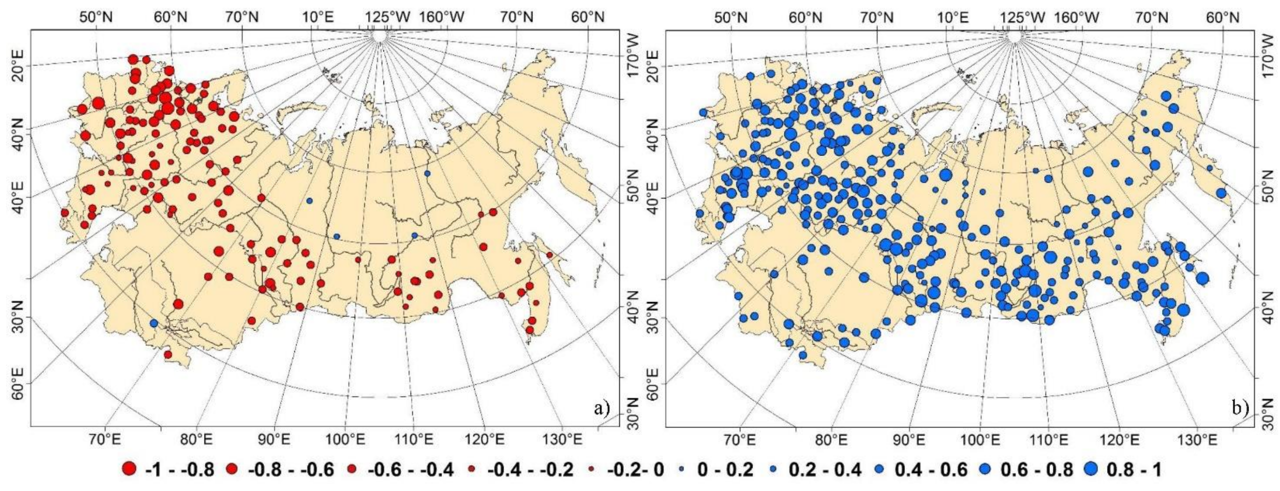


Figure 11. Spatial distributions of partial correlation coefficients between mean snow depth and air temperature (a) and between mean snow depth and snowfall (b) from November through March during 1966-2009 across the former USSR. The coefficients reaching to the 95% confidence level

are displayed. Red circles represent a negative relationship, and blue circles indicate a positive relationship.

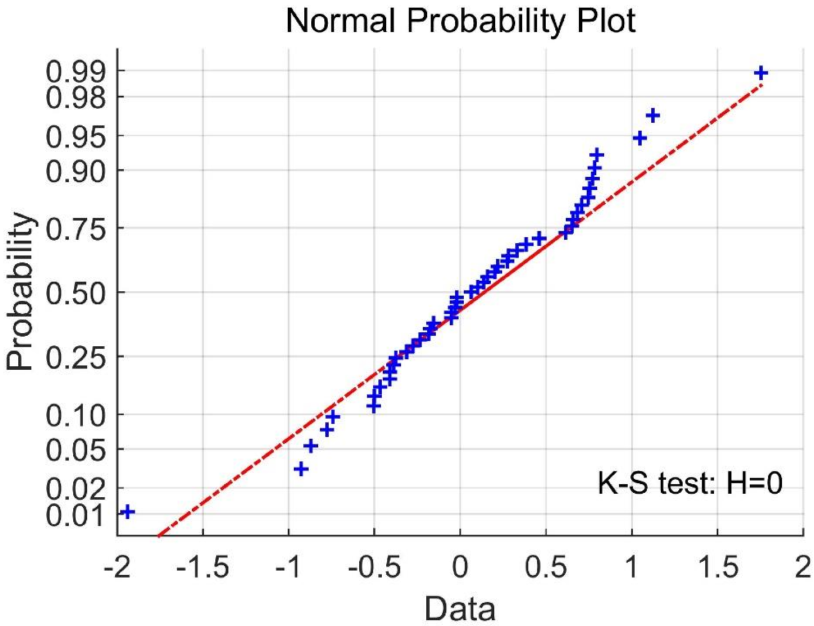


Figure A1. Normal distribution test of annual mean snow depth for all station by K-S test.