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 regimes, water cycles, as well as assessing water resources from local community to regional industrial water supply. Data and knowledge on snow in general and snow depth/snow water equivalent in particular are prerequisites for climate change studies and local/regional development planning. Past studies by using in-situ data are mostly site-specific, while data from satellite remote sensing may cover a large area or in global scale, uncertainties remain large, even misleading. In this study, spatiotemporal change and variability in snow depth was investigated using long-term (1966-2012) ground-based measurements from 1814 stations across the Eurasian continent. Spatially, 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 significantly from 1966 through 2012. Seasonally, monthly 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 more influence on snow depth and snow water equivalent during November through March across the former Soviet Union. This study provides a baseline for snow depth climatology and changes, which were significant in climate system changes over the Eurasian continent.

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 could 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 on the Tibetan Plateau (TP) (Li and Mi, 1983; Ma and Qin, 2012), which have revealed the significant regional characteristics in the changes in snow depth. 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) and showed 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 in response to global warming. Furthermore, the 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). For example, Kitaev et al. (2002) reported that the NAO index was positively related to snow depth in the northern part of the East European Plain of Russia and over western Siberia from 1966 to 1990; however, the NAO index was 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. However, most snow depth studies are at regional scale, information of snow depth at continental scale is required over the Eurasian continent.

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 by satellite remote sensing could mitigate regional deficiency of the in situ snow depth observations, 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 approximately 200%. Utilization of snow depth obtained from satellite remote sensing has large uncertainties and is impractical. Apart from remote sensing, numerical modeling is often used to obtain accurate and 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, remote sensing data with coarse-scale measurement is an important input parameter that affects simulation accuracy and does not provide a sufficient time series length. Spatial interpolation is a common method for estimates in areas with devoid data. However, uncertainty and potential bias in spatial interpolation can be introduced due to specific algorithms especially in complex terrain areas. In addition, data acquisition from large airborne equipment or aerial systems is costly and strict data use limitations apply. Ground-based measurements provide currently available and accurate snow depth over long time-series, which are critical data and information for investigating snow depth climatology and variability and can provide the data base for the verifications of remote sensing and model simulation.

The objective of this study is to develop a climatology and investigate the variability of snow depth over the Eurasian continent from 1966 to 2012. In addition, we analyse the effects of topography and climate factors (i.e., air temperature and snowfall) on the changes in snow depth over the study area. This study is unique in snow cover analysis using the most comprehensive daily snow depth observational network at continental scale over Eurasia. The dataset and methodology are described in Section 2 with the results, discussion, and conclusions presented in Sections 3, 4, and 5, respectively.

2 Data and Methodology

The data used in this study include daily snow depth, snow water equivalent (SWE), air temperature and precipitation. 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 at meteorological stations 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 since the meteorological observation standard was established by the former Union of Soviet Socialist Republics (USSR) and followed by all of the former USSR republics, Mongolia and China. Snow depth is one of the standard elements to be measured on a daily basis (WMO, 1996). Historical snow course data over the former USSR from

1966 to 2011 were also used in this study. Snow course data include routine snow surveys performed throughout the accumulation season (every ten days) and during the snowmelt period (every five days) 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 (Bulygina et al. 2011).

SWE is an important parameter that is often used in water resource evaluation and hydroclimate studies. SWE was measured using a snow tube every 100 m along the 0.5-1.0 km courses and every 200 m along the 2 km course (Bulygina et al., 2011).

Daily air temperature was measured using a thermometer, which was placed at a height of 1.5 m above the ground surface in an instrument shelter at the meteorological station (WMO, 1996). The air temperature measurement was accurate to 0.1 ℃. Air temperature was measured four times a day at 0200, 0800, 1400, and 2000 local time. The daily mean air temperature was calculated by a simple arithmetic average of the four measurements, whereas the monthly mean was based on the daily mean and the annual mean was based on the monthly mean. Precipitation was gathered and measured by a precipitation gauge and was reported with a 0.1-mm precision (Groisman and Rankova, 2001). The original precipitation data were not corrected by considering the gauge undercatch. 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 (℃).

Snow depth and SWE at each station were determined as the average value of a series of measurements in each snow course survey (Bulygina et al., 2011). 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 our study, 1971-2000 was used 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. 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). Therefore, in this study, we chose to use snow depth data from 1966 to 2012. The following variables were calculated for each station:

(1) Monthly mean snow depth: in this study, 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). According to the quality control, months having more than 15 days with snow data were used. The 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;

(2) Annual mean snow depth: an annual mean snow depth was calculated as an arithmetic sum of the monthly mean snow depth divided by the number of available snow months within each snow year. The annual mean snow depth was averaged for stations with more than 20 snow years during the 1966-2012 period;

(3) Annual mean maximum snow depth: an annual mean maximum snow depth was determined from the maximum daily snow depth in each snow year. It was calculated using the average value of the annual maximum snow depth from stations with more than 20 years of data during the 1966-2012 period.

Anomalies of monthly, annual mean, and annual mean maximum snow depth from their long-term (1971-2000) records 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. A wavelet is a wave-like oscillation with an amplitude that begins at 0, increases, and then decreases back to 0 (Graps, 1995). 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 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, 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 recalculated trends in the time series of the new data. The methods and test results were described in the appendix.

3 Results

3.1 Climatology of Snow Depth

Distributions of long-term mean snow depth indicated a strong latitudinal zonality. Generally, snow depth increased with latitude northward across the Eurasian continent (Fig. 2). A maximum annual mean snow depth of 106.3 cm was observed west of the Yenisey River (dark blue circle) (Fig. 2a). In contrast, the minimum values (~0.01 cm) were observed in some areas south of the Yangtze River in China (small grey circles).

Annual mean snow depth for most areas in Russia was >10 cm. Snow depths were 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 annual mean snow depth (<5 cm) were located in the eastern and western areas of the Caucasus Mountains. Snow depth in other areas of the former USSR was ~2-10 cm, but shallow snow depths (no more than 1 cm) were observed in some southern regions of Central Asia. The annual average snow depth in the central Mongolian Plateau was lower than that in the northern areas with values of no more than 5 cm. Snow depth was >3 cm in the northern part of the Tianshan Mountains, Northeast China, and some regions of the southwestern TP. In the Altay Mountains and some areas of the north-eastern Inner Mongolia Plateau, annual mean snow depths were >5 cm.

Annual mean maximum snow depth (Fig. 2b) showed a similar spatial distribution pattern compared to the annual mean snow depth pattern. The maximum value was approximately 201.8 cm in snow depth. For the majority of Russia, the maximum snow depth was >40 cm. The regions with maximum snow depths (exceeding 80 cm) were 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; however, along the coast of the Caspian Sea, the maximum snow depth was <10 cm. Most of the rest of the former USSR had a maximum depth of >10 cm, except for some regions of the Ukraine and Uzbekistan. Maximum snow depth was >10 cm in northern Mongolia and decreased to 6–10 cm when moving south to central and eastern Mongolia. Maximum snow depths were higher over the northern part of the Xinjiang Autonomous Region of China, Northeast China, and eastern and southwestern TP, which were mostly greater than 10 cm and even greater than 20 cm in some areas. For the remaining regions of China, the maximum snow depths were relatively small and mostly less than 10 cm.

In the autumn months (September to November), the snow depth was shallow (Figs. 3a-c). Monthly mean snow depth was <20 cm in most areas of European Russia and south of Siberia but ranged from ~20 cm to 40 cm in northern Siberia and the Russian Far East in November (Fig. 3c). Moving southward, the monthly mean snow depth was less than 5 cm north of Mongolia and across China. From December to February, the snow depth increased and the snow cover extent expanded significantly (Figs. 3d-f). Monthly snow depth values were >20 cm over the former USSR. Monthly mean snow depth was still <1 cm for the majority of China, except the northern Xinjiang Autonomous Region of China, Northeast China, and south-western TP where snow depth exceeded 10 cm. The snow depth was even more than 20 cm in some places of the Altai Mountains. In spring (March through May), snow cover areas decreased significantly (Figs. 3g–i), which was mainly because of snow disappearance in the majority of China. However, the monthly mean snow depth still exceeded 20 cm in most areas of Russia. Snow cover areas and snow depth gradually decreased in April and May. Snow cover was observed only in Russia and in the TP in June (Fig. 3j).

3.2 Variability of Snow Depth

There were long-term significant increasing trends in both annual mean snow depth and maximum snow depth from 1966 to 2012 over the Eurasian continent. Mean annual snow depth increased at a rate of approximately 0.2 cm decade^{-1}, whereas annual mean maximum snow depth increased at a rate of approximately 0.6 cm decade^{-1} (Fig. 4). Both annual mean snow depth and maximum snow depth exhibited a similar pattern of changes over the four decades, although the amplitude of maximum snow depth anomaly (approximately ±2 cm) was much larger than that of the 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). 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 in the maximum snow depth during the 1970s and then there was a large fluctuation without a significant trend from the late 1970s to the early 1990s. The maximum snow depth increased again from the early 1990s through the early 2010s.

Monthly snow depth changed significantly across the Eurasian continent from 1966 through 2012 (Fig. 5). Snow depth decreased in October at a rate of approximately -0.1 cm decade^{-1} (Fig. 5a), and there were no significant trends in November and December with large inter-annual variations (Fig. 5b-c). From January through April, snow depth showed statistically increasing trends with rates between 0.3 cm decade^{-1} and 0.6 cm decade^{-1} (Fig. 5d-g). Overall, snow depth decreased or there was no change in autumn and increased in winter and spring with large inter-annual variations over the study period.

Figure 6 shows the spatial distributions of linear trend coefficients of annual mean snow depth and maximum snow depth for each station during 1966-2012 with $p \leq 0.05$. The significant increasing trends (blue circles) of annual mean snow depth occurred 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) were detected in western European Russia, some regions of Siberia, north of the Russian Far East, and some regions to the south of 40 °N in China. Over the entire Eurasian continent, the most significant linear trends in annual mean snow depth were observed in regions north of 50 °N, which indicated that the increasing rate of annual mean snow depth was greater in higher latitude regions.

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

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

From March to May, the number of stations with significant changes (P⩽0.05) in monthly mean snow depth decreased, especially in May because of snow melt (only 78 stations) (Figs. 7f-h). Changes in monthly mean snow depth were consistent with the trends in winter over the former USSR, but more stations with decreasing trends were found in southern Siberia. There were few stations with statistically significant trends in snow depth across China; for these stations, monthly snow depths tended to decrease at most stations. Compared with regions south of 50 °N, changes in monthly mean snow depth were 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. This study, for the first time, investigated changes in snow depth using ground-based data and information over the region as a whole. Ma and Qin (2012) investigated changes in snow depth across China over period from 1957 to 2009. We found that the climatology (1966-2012) of snow depth from this study was basically consistent with that the results from Ma and Qin (2012) over China. In terms of changes in snow depth, both studies showed increase in snow depth but with slight difference in magnitude. This may be caused by using a different number of stations and covering different study periods. Over northern Eurasia, Kitaev et al. (2005) and Bulygina et al. (2011) investigated snow depth and its change. The long-term (1966-2012) mean snow depth from this 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 snow depth spanning 65 years from 1936 to 2000, while this study covered 47 years from 1966 through 2010. In this study, 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 in this study. Historical changes of the hydrometeorological station locations were also a critical reason for deleting many stations from the study. Based on results from this study, we believe that snow depth data in 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 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 this study were essentially consistent with Ye et al. (1998) in northern Russia; however, in southern Siberia where snow depth increased at a rate of 0.42 cm yr^{-1} 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 this study and assimilations with the SnowModel (Liston and Hiemstra, 2011) presented that the peak snow depth and SWE occurred more in the western portion of northern Eurasia than the western portion of the Russian Far East. This 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 modeling snow depth.

4.2 Impact of Topography on Snow Depth

Topography is an important factor affecting the climatology of snow depth and is the main reason accounting for the inhomogeneity of data (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 the annual mean snow depth with latitude, elevation and continentality (Fig. 8). Snow depth was positively correlated with latitude, i.e., snow depth generally increased with latitude (Fig. 8a). The increased rate of snow depth was approximately 0.81 cm per 1 °N across the Eurasian continent. A closer relationship between latitude and snow depth was found in regions north of 40 °N where snow cover was relatively stable with the number of annual mean continuous snow cover days at more than 30 (Zhang and Zhong, 2014).

There was a negative correlation between snow depth and elevation across the Eurasian continent (Fig. 8b); with every 100 m increase in elevation, snow depth decreased by ~0.5 cm ($P \leqslant 0.05$). Annual mean snow depth was less than 1 cm in most areas, with an elevation greater than 2000 m because a snow depth of 0 cm was used to calculate the mean snow depth. Therefore, although the TP is at a high elevation, the shallow snow depth in this area resulted in a generally negative correlation between snow depth and elevation across the Eurasian continent. Snow depths were averaged to 200 m elevation bands and then discussed the relation to elevation level for the former USSR and China. Snow depths were deeper in the lower elevation bands between 0 and 600 m across the former USSR (Fig. 8c). However, there were shallow snow accumulation between 600 and 1000 m due to most accumulation areas located in forest. Then snow depth was followed by a significant positive trend and reached a peak. Snow depths represented marked decrease in the highest elevation band (2600~2900 m). There were only two stations in this band and more snow accumulation difference between the two stations because of terrain and climate factors. Snow depths were deeper in three elevation bands across China: 200~1000 m, 1600~1800 m and 2400~2600 m. Greater snow accumulation were attributed to heavy snowfall and severe cold in these regions. An increasing trend of snow depth presented in the higher elevations above 2600 m on the TP.

There was a statistically significant positive relationship between snow depth and continentality over the Eurasian continent ($r=0.1$, $P\leqslant0.05$, Fig. 8d). This indicated that the continentality may be not an important driving factor of snow depth distribution over Eurasia, especially on the TP. Although previous studies showed that the TP's largest snow accumulation occurred in winter, precipitation during winter months was the smallest of the year (Ma, 2008). This was mainly due to the majority of annual precipitation that occurs during the summer monsoon season on the TP, which causes much less precipitation during the winter half year (or the snow accumulation season).

4.3 Impact of Climate Factors on Snow Accumulation

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. Snow depth significantly decreases with increasing air temperature ($P\leqslant0.05$) but the Goodness of Fit of the relationship was only 16% (Fig. 9a). Compared with air temperature, snowfall exhibited a strong relationship with snow depth (Fig. 9b). The mean snow depth was less than 20 cm at most stations with an accumulated snowfall of <50 mm from November through March. Snow depth increased with an increase in accumulated snowfall, and the thickest snow depth of approximately 120 cm had a maximum cumulative snowfall of approximately 350 mm.

Compared with the long-term inter-annual trends in change in snow depth, air temperature and snowfall, the variabilities in snow depth was mainly affected by the changes in snowfall. Overall, the trends in long-term air temperature, snowfall and snow depth displayed increasing trends from November to March (Fig. 10). This was because the increased precipitation fell as snow in cold areas where the increased temperature was still below freezing (Ye et al., 1998; Kitaev et al., 2005). Warmer air led to a greater supply of moisture for snowfall and hence the snow accumulation still increased (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 entire density of the snowpack. In addition, there were similar inter-annual variations in snowfall and heavy snowfall. This indicated that extreme snowfall events may be the main cause of the increase in snow depth.

The partial correlation coefficients between snow accumulation, air temperature and snowfall were calculated to discuss the spatial relationship between them (Fig. 11). A significant negative correlation ($p \leq 0.05$) between snow depth and air temperature was present in most areas of European Russia and southern Siberia (Fig 11a). The stations with negative effects of air temperature on SWE were fewer, and there were no statistically significant correlations in northern Siberia (Fig 11b). This was because there was no obvious effect of increasing temperature on snow depth when the air temperature was below 0 ℃, which occurred in most areas of Siberia from December through March.

Compared with previous studies, the sensitivity of snow depth to air temperature and precipitation for each station showed regional differences (Fallot et al., 1997; Park et al., 2013). The amount of snowfall can be affected by climate change and lead to differences in snow depth at different times (Ye et al., 1998; Kitaev et al., 2005; Ma and Qin, 2012). We found that there was a significant ($p \leq 0.05$) negative relationship between snow depth and air temperature in southern Siberia but not in northern Siberia. In addition to air temperature and precipitation, atmospheric circulation was a key factor affecting 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 decreased in response to climate change (Bulygina et al., 2009; Brown and Robinson, 2011; IPCC, 2013; Xu et al., 2017), however, snow accumulation increased significantly with in situ data over Eurasia. Our study showed that heavy snowfall may be the main reason for snow thickening, and atmospheric circulation was also an important factor.

4.4 Potential Effects of the 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). Research has 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 the 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 this study indicated that 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 accumulation reduction can result in freshwater shortage on the TP. Furthermore, snow interacts with vegetation and in turn vegetation affects snow cover accumulation, 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 maximum snow depth over the Eurasian continent for the period from 1966 to 2012. Our results demonstrate that greater long-term average snow depth was observed in north-eastern European Russia, the Yenisey River basin, the Kamchatka Peninsula, and Sakhalin. In contrast, the shallowest 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 snow depth over the entire Eurasian continent. A similar increasing pattern of changes was exhibited in both annual snow depth and maximum snow depth, although the amplitude of the maximum snow depth anomaly was much larger than the equivalent value for mean snow depth. Monthly snow depth in autumn presented a decreasing trend, whereas there were increasing trends in the variations in snow depth during winter and spring, especially during the period of the mid-1980s through the 2000s.

Significant increasing trends in 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 snow depth were explained by air temperature and snowfall in most areas of European Russia and some regions of southern Siberia and the effects of the two factors on SWE only appeared in some of these areas; however, snowfall especially heavy snowfall was the main driving force of the variance of snow depth and SWE 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 snow depth, maximum depth and monthly mean snow depth for each station. The percentage of the stations with a serial correlation for annual 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 snow depth for these station (Fig. 6-7 in the text). Using the Dikson site (73.5 °N, 80.4 °E, 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
Snow water equivalent (SWE)	the former USSR	386	RIHMI-WDC
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 was the trend of changes in snow depth, the unit was cm yr^{-1}; P was 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’ was the corrected trend of changes in snow depth, the unit was cm yr^{-1}; P’ was the corrected confidence level.

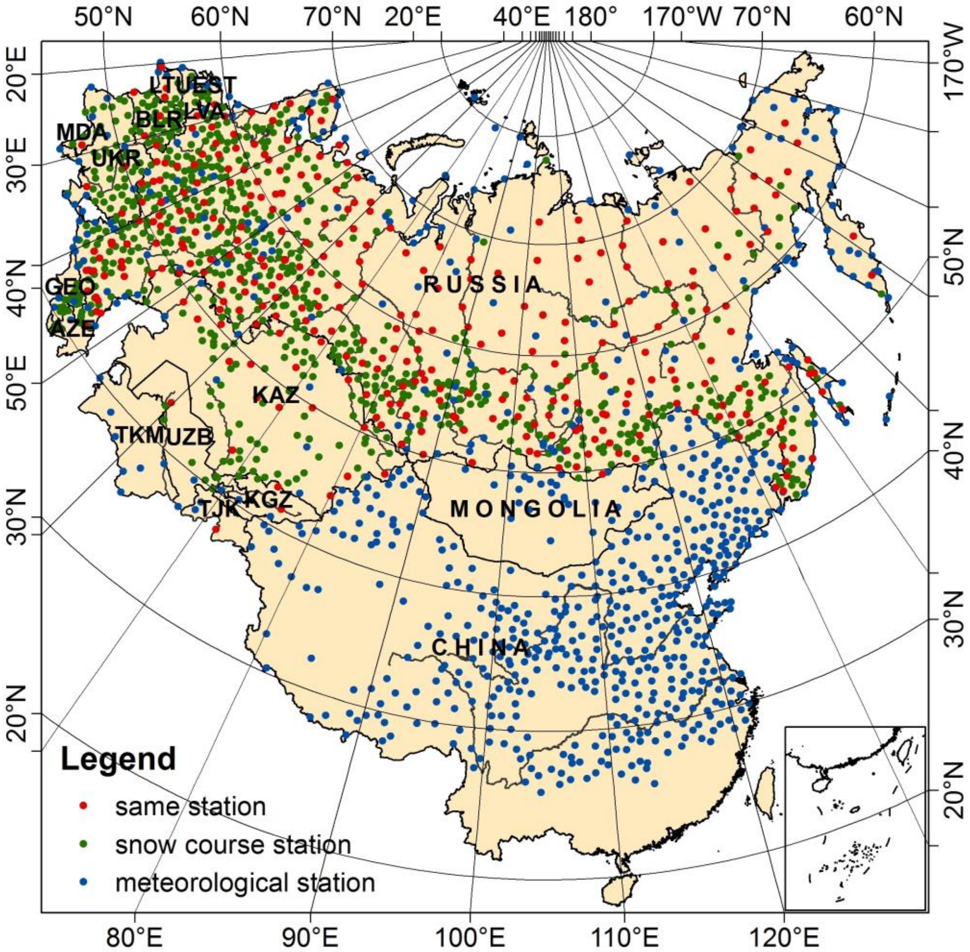


Figure 1. Geographical locations of meteorological and snow course stations across the Eurasian continent. The red circles represent stations where snow depth was measured at both meteorological stations and snow course surveys, the green circles show stations where snow depth was measured at snow surveys only, and the blue circles show stations where snow depth was measured at meteorological stations only. The abbreviations of countries represented 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.

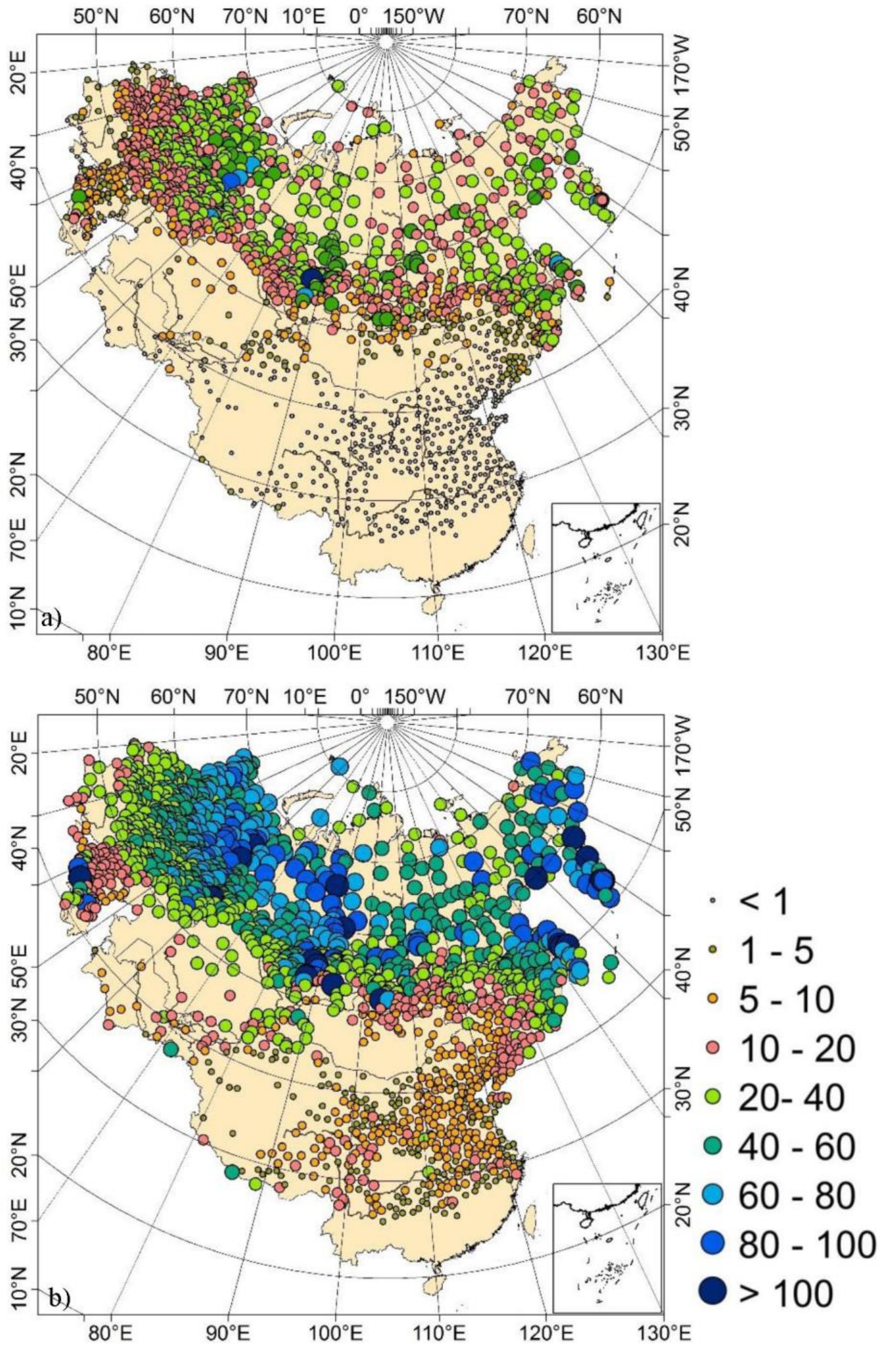
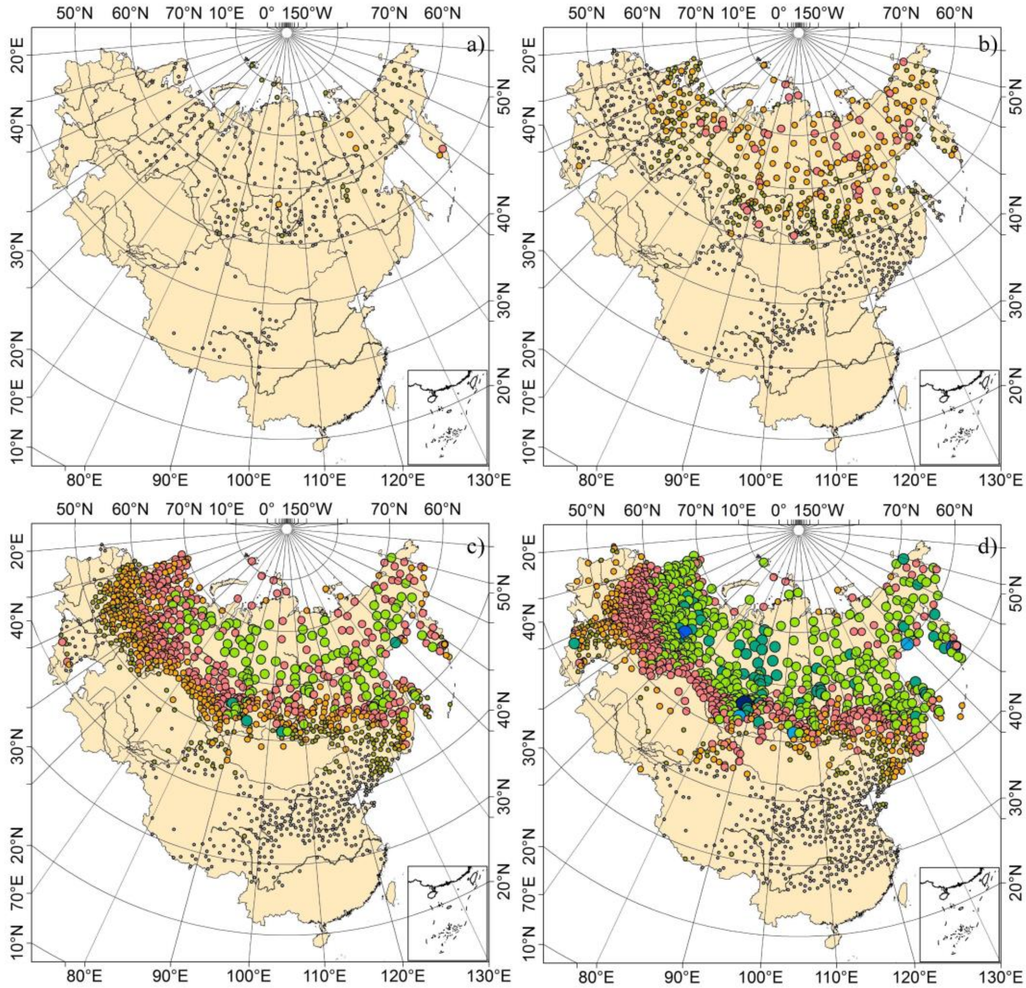


Figure 2. Annual mean snow depth (a) and maximum snow depth (b) across the Eurasian continent (cm) during 1966-2012.


a)
b)
c)
d)
50°N
60°N
70°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

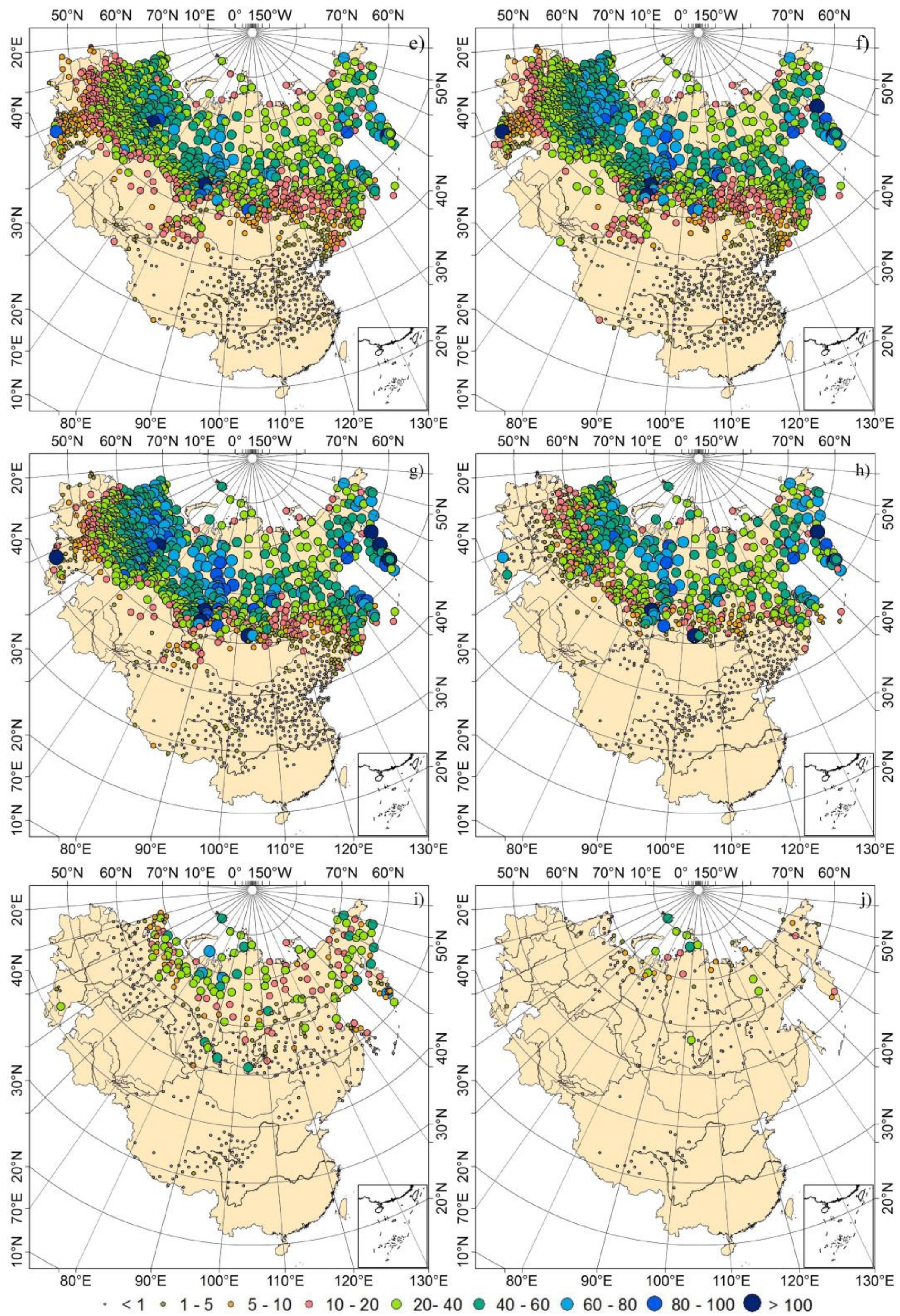


Figure 3. Monthly mean snow depth (from September to June) (cm) across the Eurasian continent (cm) during 1966-2012. (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, (i) May, (j) June.

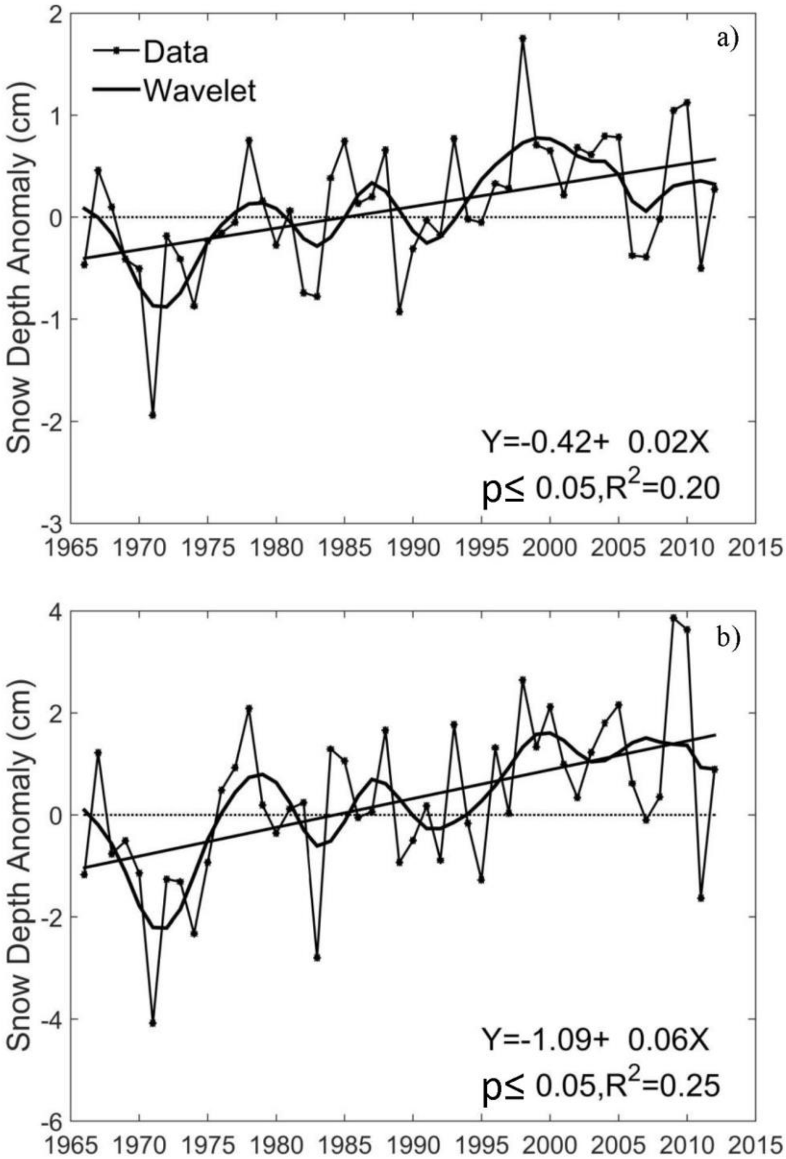


Figure 4. Composite of inter-annual variation of annual mean snow depth (a) and maximum snow depth (b) from 1966 through 2012 with respect to the 1971-2000 mean across the Eurasian continent. The line with dots is the anomaly of snow depth; the thick curve represents the smoothed curve using wavelet analysis; the thick line presents a linear regression trend.

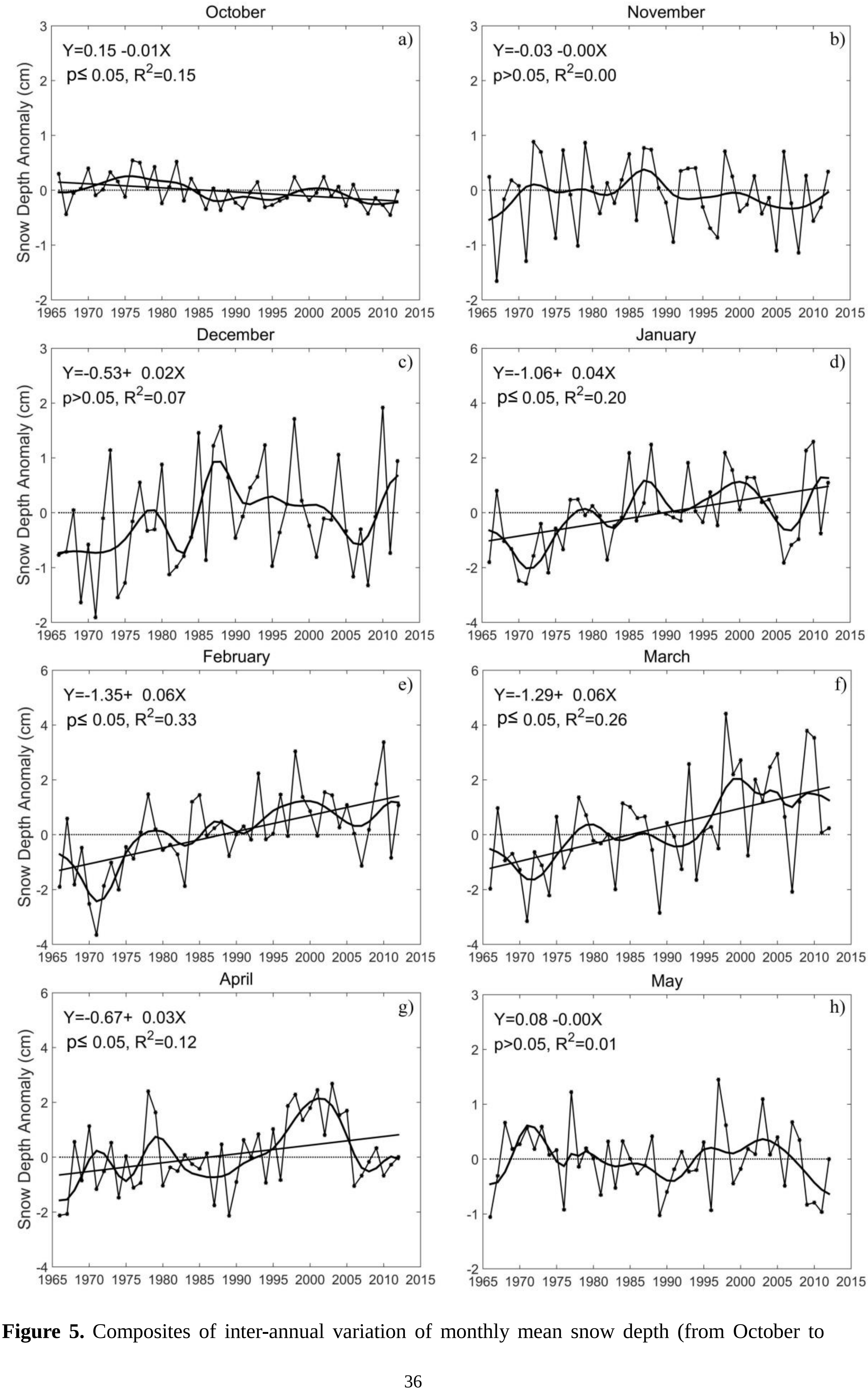


Figure 5. Composites of inter-annual variation of monthly mean snow depth (from October to

May) from 1966 through 2012 with respect to the 1971-2000 mean across the Eurasian continent. (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May. 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. Linear regression was only shown when the rate of change was at the 95% level.

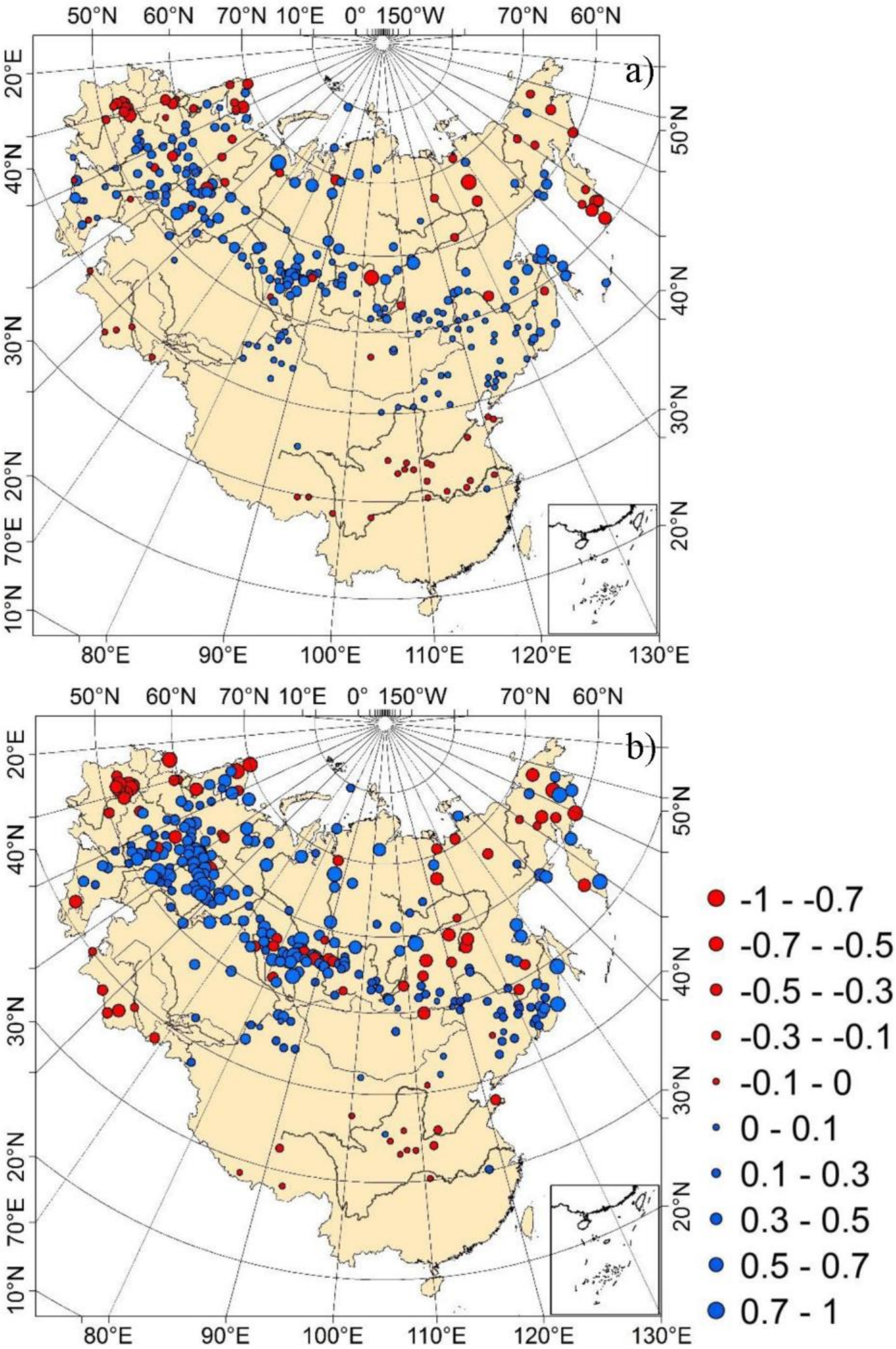
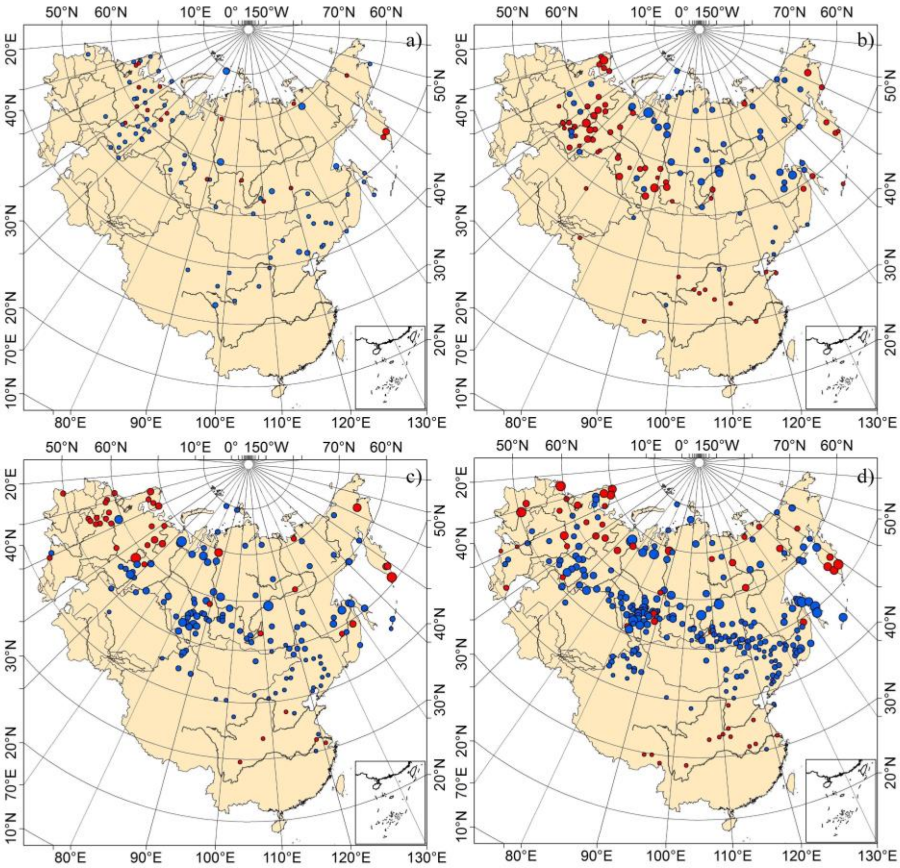


Figure 6. Spatial distribution of linear trend coefficients (cm yr^{-1}) of annual mean snow depth (a) and maximum snow depth (b) for each station in 1966-2012. The rate of change was at the 95% level. Red circles represent a decreasing trend, and blue circles represent an increasing trend.


a)
b)
c)
d)
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

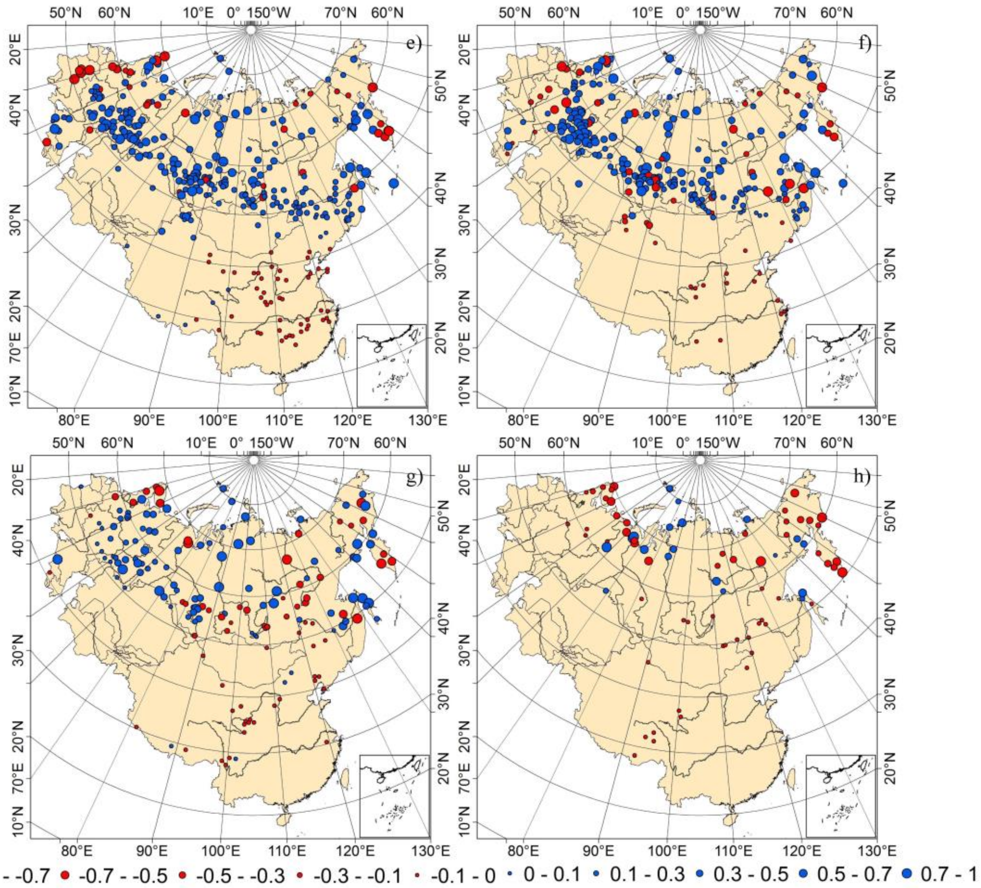


Figure 7. Spatial distributions of linear trend coefficients (cm yr^{-1}) of monthly mean snow depth (from October to May) during 1966 to 2012. (a)October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May. The rate of change was at the 95% level. Red circles represent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

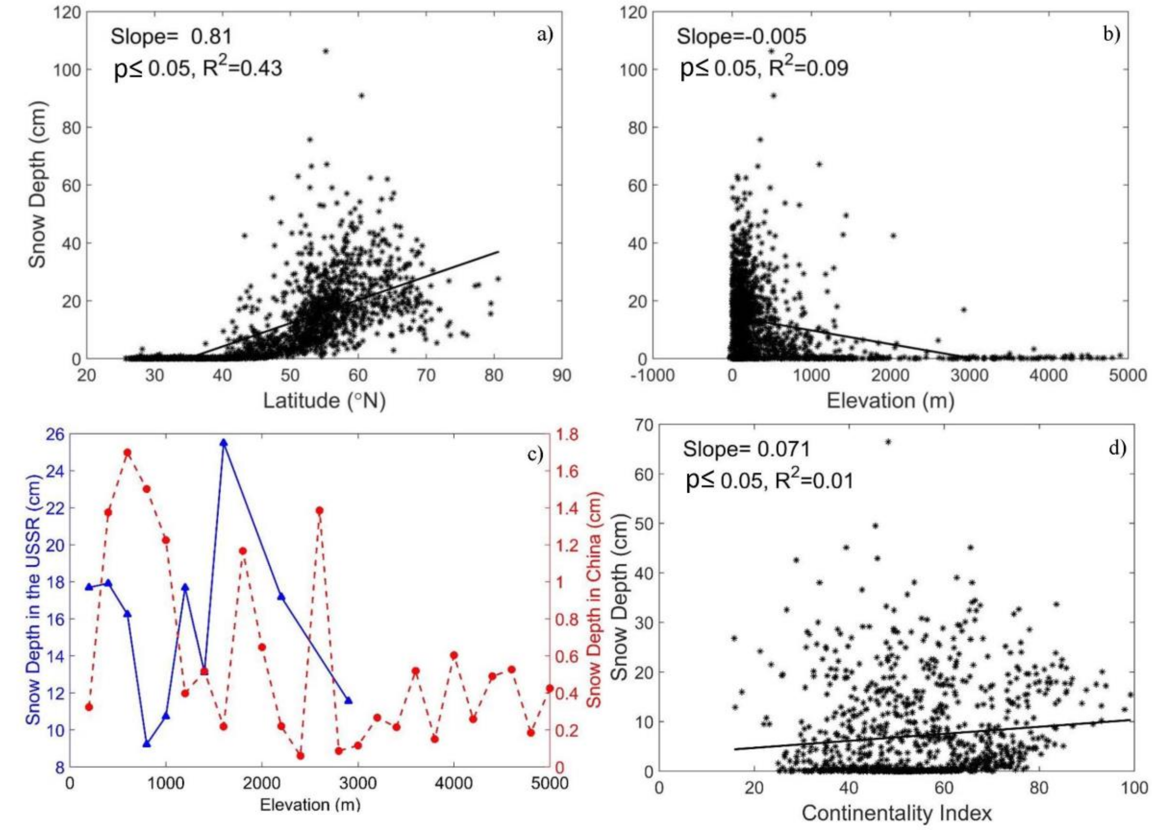


Figure 8. The relationship between annual mean snow depth and latitude (a), elevation (b and c) and continentality (d) for all stations across the Eurasian continent during 1966-2012. Asterisks show the mean snow depth of each station; the thick line is a linear regression trend.

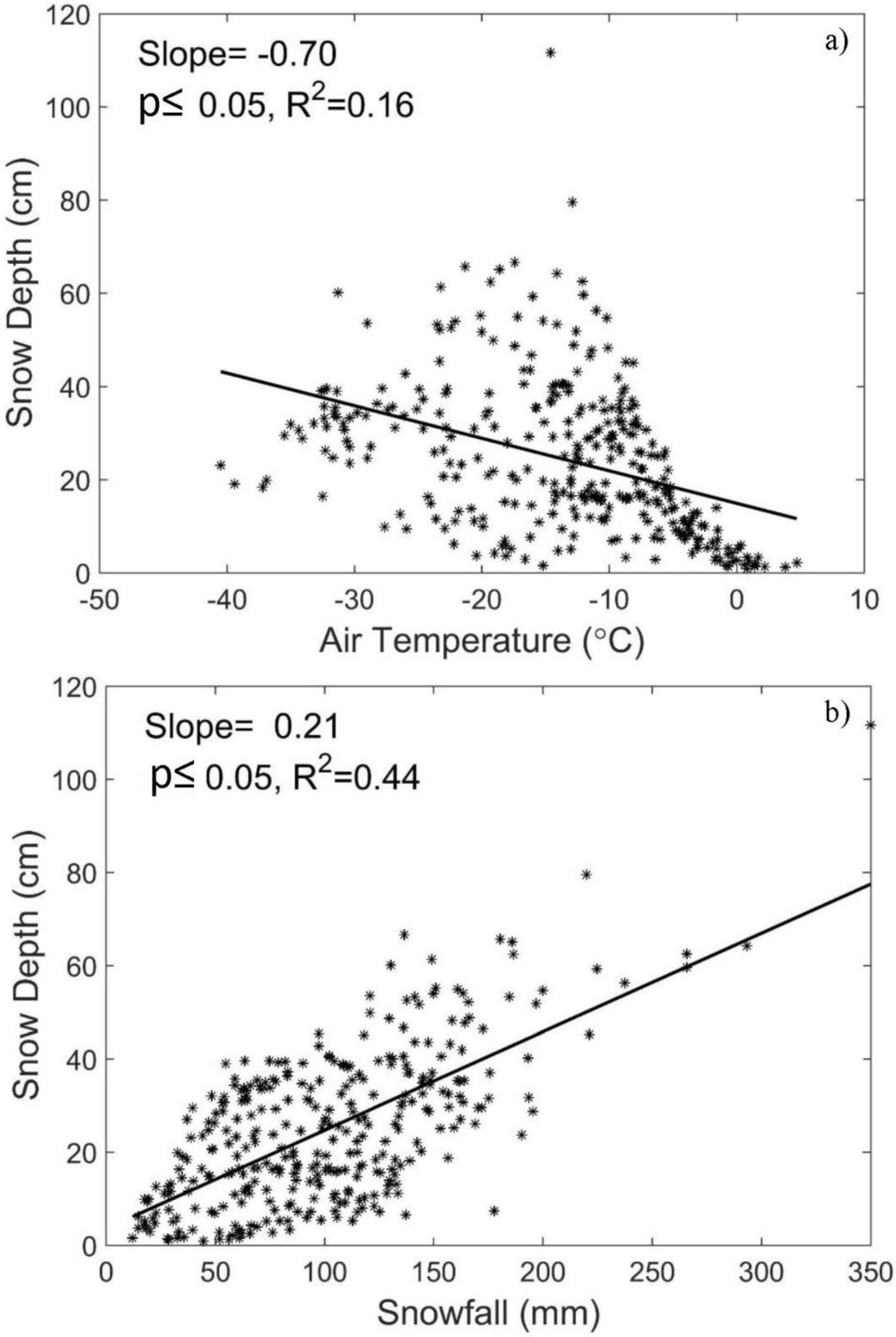


Figure 9. The relationships among annual mean snow depth, air temperature and snowfall for 386 stations from November through March during 1966-2009 over the USSR. The thick line is a linear regression trend.

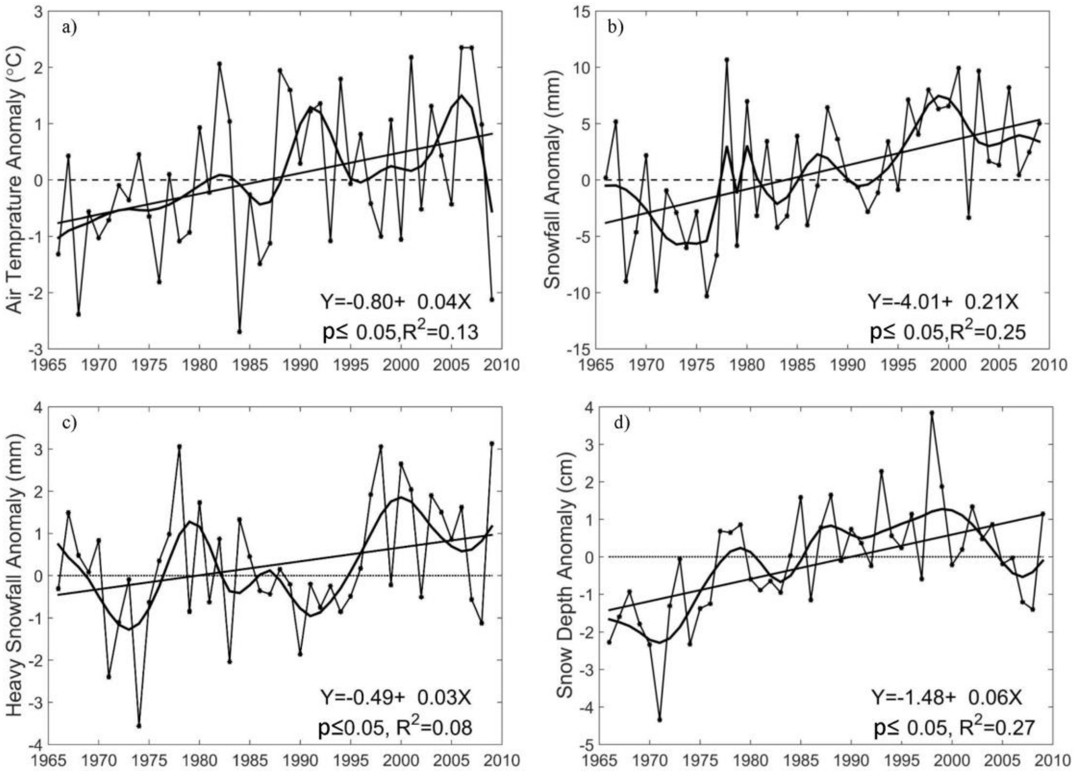


Figure 10. Composite of inter-annual variation of annual mean air temperature (a), annual snowfall (b), annual heavy snowfall (c) and annual snow depth (d) from November through March during 1966-2009 with respect to the 1971-2000 mean across the former USSR. The line with dots is the composite of the annual means; the thick curve represents the smoothed curve using wavelet analysis; the thick line presents a linear regression trend.

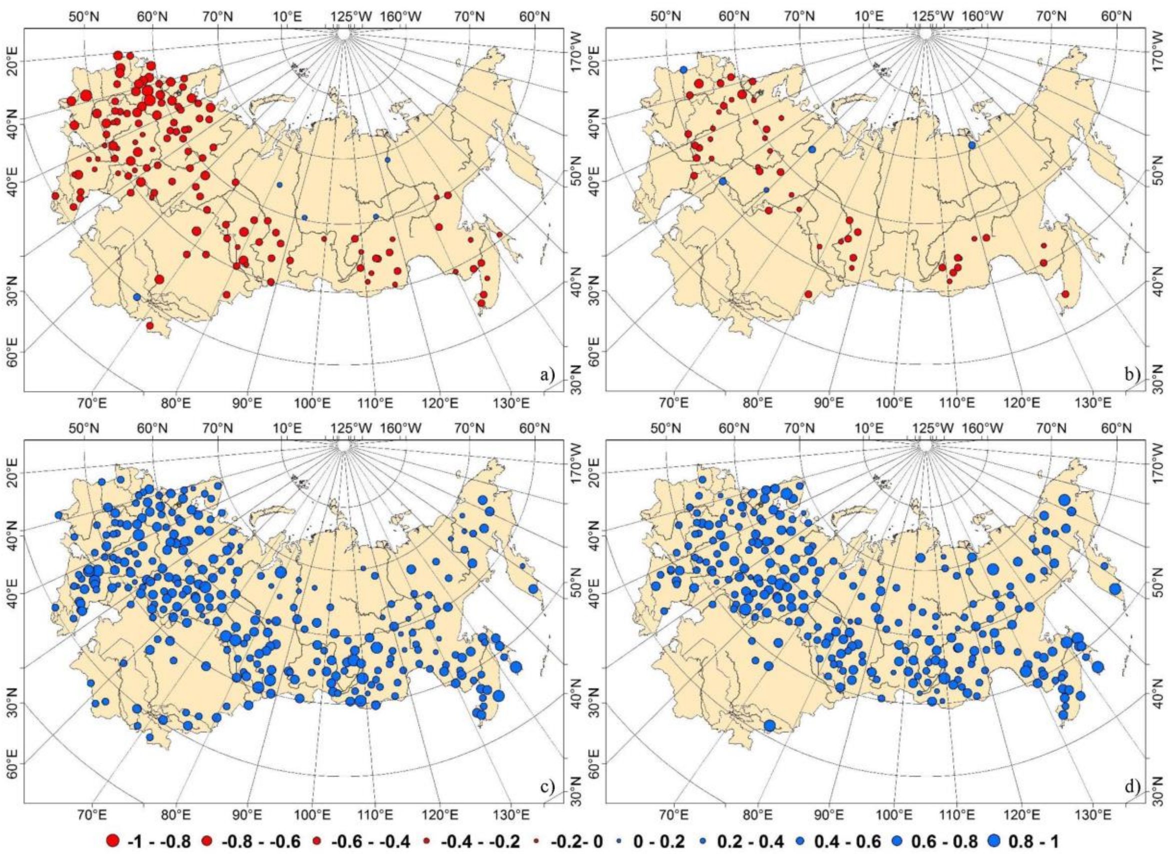


Figure 11. Spatial distributions of partial correlation coefficients of snow depth and air temperature (a), snow depth and snowfall (b), SWE and air temperature (c), SWE and snowfall from November through March during 1966-2009 across the former USSR. The coefficients reaching to 0.05 confidence level are displayed. Red circles represent a negative relationship, and blue circles indicate a positive relationship.

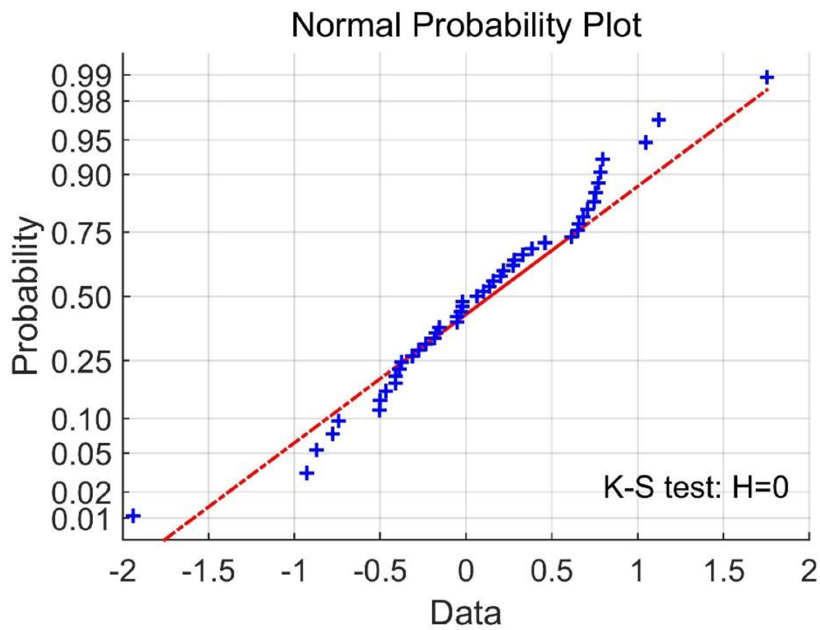


Figure A1. Normal distribution test of annual mean snow depth for all station by K-S test.