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

Xinyue Zhong[1, 3, 4], Tingjun Zhang[2], Shichang Kang[3, 6], Lei Zheng[5], Yuantao Hu[2], Huijuan Wang[2]

[1] *Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences (CAS), Lanzhou 730000, China*

[2] *Key Laboratory of Western China's Environmental Systems (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China*

[3] *State Key Laboratory of Cryosphere Science, Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou 730000, China*

[4] *Key Laboratory of Remote Sensing, Gansu Province, Lanzhou 730000, China*

[5] *Chinese Antarctic Center of Surveying and Mapping, Wuhan University, Wuhan 430079, China*

[6] *CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China*

Correspondence to: T. Zhang (tjzhang@lzu.edu.cn)

ABSTRACT

Snow depth is one of key physical parameters for understanding the land surface energy balance, soil thermal regimes, regional- and continental-scale water cycles, as well as assessing water resources. In this study, a snow depth climatology and its spatiotemporal variations were investigated using the long-term (1966-2012) ground-based measurements from 1814 stations across the Eurasian continent. Spatially, mean snow depths of >20 cm were recorded in northeastern European Russia, the Yenisey River basin, Kamchatka Peninsula, and Sakhalin. Annual mean and maximum snow depth increased significantly during 1966-2012. Seasonally, monthly snow depth decreased in autumn, and increased in winter and spring over that period of time. Regionally, snow depth significantly increased in the 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 changes in snow depth, which are significant in climate system changes over the Eurasian continent.

1 Introduction

Snow cover is a key part of the cryosphere, which is a critical component of the global climate system. Changes in snow cover serve as indicators of climate change because of its interactions and feedbacks with surface energy and moisture fluxes, hydrological processes, and atmospheric and oceanic circulation (Brown and Goodison, 1996; Armstrong and Brown, 2008; King et al., 2008). 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).

Snow depth is a basic and important parameter of snow cover, which can provide additional information related to climate, surface energy balance, soil temperature, moisture budgets, spring runoff, water supply, and human activity (Sturm et al., 2001; Zhang, 2005; AMAP, 2011). Although snow cover extent reduced with climate warming, snow depth still increased in the northern Eurasia during 1936 to 2010 (Kitaev et al., 2005; Bulygina et al., 2011). This was due to changes in the atmospheric moisture budget altering the atmospheric circulation, the warmer air led to greater moisture supply for precipitation as snowfall in winter (Ye et al., 1998; Kitaev et al., 2005; Rawlins et al., 2010). Meanwhile, snowmelt from increased snow depth may also lead to higher soil moisture in spring, which promoted enhanced precipitation with increased evapotranspiration (Groisman et al., 1994).

Using in-situ observational data from meteorological stations and satellite remote sensing data, several studies have documented changes in snow depth over the Northern Hemisphere, demonstrating that snow depth varies regionally: overall, the annual mean snow depth decreased in most areas over North America during 1946 to 2000 (Brown and Braaten, 1998; Dyer and Mote, 2006), and increased in Eurasia and the Arctic during the recent 70 years (Ye et al., 1998; Kitaev et al., 2005; Callaghan et al., 2011a; Liston and Hiemstra, 2011) but there was regional differences (Bulygina et al., 2009, 2011; Ma and Qin, 2012; Stuefer et al., 2013; Terzago et al., 2014). Changes in snow depth were 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, thus greater snow depth was observed in northern Eurasia in response to global warming. Furthermore, snow depth distribution and variation are also 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 also closely related to other large-scale atmospheric circulation indices, such as the North Atlantic Oscillation /Arctic Oscillation (NAO/AO) indices. For example, Beniston (1997) found that the NAO played a crucial role in fluctuations in the amount of snowfall and snow depth in the Swiss Alps from 1945 to 1994. Kitaev et al. (2002) reported that the NAO index is positively related to snow depth in the northern part of the East European Plain and over western Siberia during the period from 1966 to1990; however, the NAO is negatively correlated with snow depth in most southern regions of northern Eurasia. You et al. (2011) indicated that there is a positive relationship between snow depth and the winter AO/NAO index and Niño-3 region sea surface temperature (SST) in the eastern and central Tibetan Plateau (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 have developed and improved the algorithms with passive microwave (Foster et al., 1997; Derksen et al., 2003; Grippaa et al., 2004; Che et al., 2016). Although these observations can mitigate the regional deficiency of in-situ snow depth observations, the satellite data have low spatial resolution (25×25 km) and the accuracy is always affected by clouds, underlying surface conditions, and inversion algorithms; in addition, data acquisition from the large airborne equipment or aerial systems is always costly and some of them need to obtain official permission before using in some countries. Ground-based snow measurement remains the basis for verification of remote sensing and instrumental data, which can provide more accurate and longer-time-series information, and it is important for investigating climatology and variability of snow depth.

During winter, the average maximum terrestrial snow cover is nearly 47×10^6 km^2 over Northern Hemisphere lands (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 and large-scale snow cover measurements and observations across the Eurasian continent, with the first snow cover 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. In Eurasia, most studies of snow depth have mainly focused on Russia (Ye et al., 1998; Kitaev et al., 2005; Bulygina et al., 2009, 2011), the former Soviet Union (USSR) (Brasnett, 1999), and the TP (Li and Mi, 1983; Ma and Qin, 2012). However, due to the lack of data and information, there has been no integrated and systematic investigation of changes in snow depth across the entire Eurasian continent using ground-based measurements. The objective of this study is to investigate the climatology and variability of snow depth, and analyze snow depth relationships with the topography and climate factors over the Eurasian continent from 1966 to 2012. This study can provide basic information on climate system changes in the region. 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

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 at these stations on a daily basis. 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 snowmelt (every five days) period 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 also an important parameter of snow cover that is usually used in hydroclimate research. In this study, we analyzed the relationships among SWE, air temperature, snowfall and snow depth during the accumulation season (from November to March) over the former USSR where SWE data are available. SWE was measured 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 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 the following Equation (1):

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

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, quality control of the meteorological data was undertaken prior to the datasets being stored at the Russian Research Institute for Hydrometeorological Information-World Data Center (RIHMI-WDC) (Veselov, 2002). We implemented a second quality control: (1) A threshold of 15 days was selected because the snow cover duration in some areas of China was less than one month, and the data for 15 days' snow depth in a month were relatively stable. Months having less than 15 days with snow depth data were omitted from the analysis. (2) Stations with less than 20 years of data during the 1971-2000 period were excluded from the analysis. (3) At each station, data exceeding two standard deviations compared with the annual average value during 1966-2012 were omitted. In total, we used data from 1814 stations to analyze the climatology and variability of snow depth over the Eurasian continent (Fig. 1 and Table 1).

The snow cover extent is the smallest in July and August, in order to capture the entire seasonal snow cycle, we defined a snow year as the period from July 1st of a current year to June 30th of the following year. Because the procedures for taking snow observations have changed over the course of the studies period, there were some inhomogeneities in the data. However, there has been no change in the observation procedure since 1965 (Bulygina et al., 2009). Therefore, we used snow data for the snow years from 1966 to 2012 in this study. 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 way for deriving monthly mean snow depth in regular 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 the arithmetic sum of daily snow depth divided by the number of days with snow on the ground within each month.

To capture the primary long-term spatial patterns of snow cover distribution, we calculated the annual mean snow depth and annual mean maximum snow depth during 1966-2012:

(2) Annual mean snow depth: the annual mean snow depth was calculated as the 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 from the annual snow depth for ≥20 snow years during 1966-2012.

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

To overcome the systematic differences between stations related to climate/elevation and station distributions, the anomaly of snow depth from the long-term mean was used in this study. According to each 30 years as a climate reference period, the annual mean snow depths of the period 1971-2000 were computed as climate reference values in this study. We calculated the anomalies of monthly, annual mean and maximum snow depth relative to the mean for the period from 1971 to 2000 for each station and averaged the anomalies for all stations to obtain mean anomalies for the whole Eurasian continent.

Wavelet analysis was performed to reveal the long-term low-frequency variations of snow depth over the study area as a whole. 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 happened on average during the study period. Linear trend analysis provides an average rate of this change. Despite there is a nonlinearity, the linear trend analysis is also a useful approximation when a systematic low-frequency variations emerged. (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 T test was used to assess the statistical significant of the slope in the linear regression analysis and the partial correlation coefficients, and the confidence level above 95% was considered in our study. Meanwhile, to overcome the strong assumption in ordinary least squares (independent and normal distribution), we applied a Mann-Kendall (MK) test to identify the monotonic trend in snow depth. Confidence level above 95% was used to determine the statistically significant increase or decrease in snow depth. These two test methods could provide more robust and comprehensive information of the trend analysis. In order to evaluate the influence of single climatic factor on snow cover, the partial correlation coefficients were calculated and reported the relationships between snow depth, SWE, air temperature and snowfall. The way to do significant test of the correlation coefficient is same to the trend analysis, which includes T-test and MK-test.

3 Results

3.1 Climatology of Snow Depth

The distributions of long-term mean snow depth generally represented the latitudinal zonality: the snow depth for each station generally increased with the latitude across the Eurasian continent (Fig. 2).A maximum annual mean snow depth of 106.3 cm was observed in the west of the Yenisey River (dark blue circle) (Fig. 2a).

In contrast, the minimum values (~0.01 cm) were observed in some areas of the south of Yangtze River in China (small gray circles).

Annual mean snow depth for most areas in Russia was >10 cm. Depths were even greater in the northeastern part of European Russia, the Yenisey River basin, the Kamchatka Peninsula, and Sakhalin, with snow depths of >40 cm. The 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 north of the Tianshan Mountains, Northeast China and some regions of the southwestern TP. In the Altay Mountains and some areas of the northeastern Inner Mongolia Plateau, annual mean snow depths were >5 cm.

Annual mean maximum snow depth varied with the latitude (Fig. 2b), which showed a spatial distribution pattern similar to the annual mean snow depth pattern. The maximum value (~201.8 cm) was recorded in the same location as the greatest annual mean snow depth. For the majority of Russia, the maximum snow depth was >40 cm. The regions with the maximum snow depths (exceeding 80 cm) were located in the northeastern 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 Ukraine and Uzbekistan. Maximum snow depth was >10 cm in northern Mongolia, and 6–10 cm in the central and eastern parts of the country. Maximum snow depths were higher over the northern part of the Xinjiang Autonomous Region of China, Northeast China, and some regions of the eastern and southwestern TP (>10 cm). The maximum snow depth in some areas was more than 20 cm. In other regions of China, the values were relatively small, ~8 cm or less.

Monthly mean snow depth varied across the Eurasian continent (Fig. 3). The maximum monthly snow depths were recorded in northeastern European Russia, northern part of the West Siberian Plain, the Yenisey River basin, the Kamchatka Peninsula, and Sakhalin. The minimum values were observed in most areas of China.

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 the south of Siberia, but ranged from ~20 cm to 40 cm in northern Siberia and the Russian Far East in November (Fig. 3c). Monthly mean snow depth was less than 5 cm in the north of Mongolia and most regions across China. From December to February, the snow depth increased and the areas covered by snow expanded significantly (Figs. 3d-f). Most monthly snow depth values were >20 cm over the former USSR. Monthly mean snow depth was still <1 cm in most regions of China, but more than 10 cm in the northern Xinjiang Autonomous Region of China, Northeast China, and some regions of southwestern TP. The snow depth was even more than 20 cm in some places of the Altai Mountains. In spring months, the snow cover areas decreased significantly (Figs. 3g–i). 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 the TP in June (Fig. 3j).

3.2 Variability of Snow Depth

There were long-term significant increasing trends in the annual mean and maximum snow depth from 1966 to 2012 over the Eurasian continent as a whole with the increasing rates of snow depth of 0.2 cm decade^{-1} and 0.6 cm decade^{-1}, respectively (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 the maximum snow depth anomaly (about ±2 cm) was much larger than that of the mean snow depth anomaly (about ±1 cm). From the mid-1960s to the early 1970s, the annual mean snow depth decreased slightly, then it 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 3.5 cm in the maximum snow depth during the 1970s, then it fluctuating changed from the late 1970s to the early 1990s. The maximum snow depth increased again from the early 1990s through the early 2010s.

The Mann-Kendall statistical curves of annual and maximum snow depth were consistent with the linear trend analysis (Fig. 5). The increasing trend of annual snow depth reached to the 0.05 confident level in the late 1980s and from the early 1990s to the mid-1990s; it reached to the 0.01 confident level in the late 1990s. The decreasing trend reached to the 0.05 confident level from the early 2000s through the mid-2000s. The intersection of the UF curve and UB curve appeared in the mid-1970s, it indicated that the rising trend was an abrupt change during this period. The abrupt change point of the maximum snow depth was in the mid-1980s, then it increased significantly ($p \leqslant 0.05$) from the early 1990s through the mid-1990s, and it reached to the 0.01 confident level from the late 1990s to the early 2010s.

Statistically significant trends of variations in monthly snow depth occurred from 1966 through 2012 except for November, February, and May (Fig. 6). During the snow cover formation period (October and November), the monthly snow depth decreased slightly (Figs. 6a-b). There was a significant decreasing trend of monthly snow depth in October, with a rate of decrease of approximately 0.1 cm decade^{-1} (Fig. 6a).

Inter-annual variations of monthly snow depth were more significant in the winter months (Figs. 6c-e). Snow depth was below its long-term mean value from the mid-1960s through the mid-1980s, and then it was above the long-term mean. There were statistically significant increasing trends in monthly snow depth in January and February, and similar inter-annual variations in snow depth for these two months during the period from 1966 to 2012 (Figs. 6d, e). Monthly snow depth sharply decreased by about 2 cm prior to the early 1970s, then increased by 2-2.5 cm until the late 1970s. Monthly snow depth displayed a fluctuating increase from the late1970s through 2012.

Significant increasing trend of monthly snow depth also appeared in March and April, the rate of increase being about 0.6 cm decade and 0.3 cm decade, respectively

(Figs. 6f-g). The trend of monthly snow depth in March was consistent with the change in winter from the mid-1960s through the late 1970s, then it was stable until the early 1990s (Fig. 6f). Monthly snow depth rapidly increased by 2.5 cm from the mid-1990s through the late 1990s, then it decreased slightly. Snow depth presented fluctuant increasing trend during the mid-1960s through the early 1980s (Fig. 6g). Subsequently, snow depth sharply increased by about 3 cm from the mid-1980s to the early 2000s. It declined rapidly during the early 2000s through 2012.

In order to identify the monotonic trend in monthly snow depth, we conducted the MK test (Fig. 7). In October, snow depth represented a decreasing trend and it reached to the 0.05 confident level only after 2010. The statistically significant changes of monthly snow depth in November during the period of the late 1980s through the early 2000s, though it was not statistically significant with the linear regression. From December through March, there were increasing trends in monthly snow depth and the abrupt change point appeared in the mid-1970s. In the linear regression analysis, the variation of snow depth was not significant in December. However, the results of M-K test showed that the increasing trend of monthly snow depth reached to the 0.01 confident level during the mid-1980s through the late 1990s, and then it decreased during the 2000s. From January to March, monthly snow depth increased significantly ($p \leqslant 0.01$) from the mid-1980s to the early 2010s. In April, the statistically significant increase was found from the late 1990s to the late 2000s, and it reached to the 0.01 confident level after 2000. Consistent with the linear regression, the trend in monthly snow depth was not significant in May.

Figure 8 shows the spatial distributions of linear trend coefficients of annual mean snow depth and maximum snow depth for each station during 1966-2012, with $p \leqslant 0.05$. The significant increasing trends (blue circles) of annual mean snow depth occurred in most of European Russia, the south of Siberia and the Russian Far East, the northern Xinjiang Autonomous Region of China, and Northeast China (Fig. 8a). In contrast, decreasing trends (red circles) were detected in western European Russia, some regions of Siberia, the north of Russian Far East, and some regions to the south of 40 °N across China. Over the entire Eurasian continent, the most significant linear trends in annual mean snow depth were observed in the region north of 50 °N, indicating that the increasing rate of annual mean snow depth was greater in higher latitude regions.

Changes in the maximum snow depth were similar to those in annual mean snow depth in most of Eurasian areas from 1966 to 2012, but the change rates of the maximum snow depth were greater than the values of annual mean snow depth (Fig. 8b). The significant increasing trends were observed in the same regions as those with increases in annual mean snow depth. The decreasing trends were found in generally the same locations as decreases in annual mean snow depth, with greater reductions in the south of Siberia and the Russian Far East.

In October and November, there were few stations with significant changes in snow depth (at the 95 % level) (Figs. 9a, b). The increasing trends were mainly observed in most areas across the Eurasian continent in October. But the increasing trends of snow depth only appeared in Siberia and the Russian Far East in November. The decreasing trends in monthly mean snow depth occurred in the eastern regions of European Russia, the southern areas of the West Siberian Plain, and some areas of the northeast Russian Far East.

In winter months (December, January and February), there was a gradual expansion in areas with monthly mean snow depth variation at the 95 % level (Figs. 9c–e). There were increasing trends of monthly mean snow depth in the eastern regions of European Russia, southern parts of Siberia, the northern Xinjiang Autonomous Region of China, and Northeast China. In contrast, significant decreasing trends were observed in the north and west of European Russia, scattered in Siberia, the northeast of the Russian Far East, and most areas of China.

From March to May, the number of stations with significant changes (at the 95 % level) in monthly mean snow depth decreased, especially in May because of snow melt (only 78 stations) (Figs. 9f-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 of snow depth across China; for these, monthly snow depths tended to decrease in most stations. Compared with the south of 50 °N, the changes in monthly mean snow depth were more significant to the north of 50 °N.

3.3 Variability of Snow Depth with Latitude, Elevation and Continentality

To explore the spatial variability of snow depth, we conducted a linear regression analysis of annual mean snow depth with latitude, elevation and continentality (Fig. 10). Snow depth is positively correlated with latitude, i.e., snow depth generally increases with latitude (Fig. 10a). The increase rate of snow depth was about 0.81 cm per 1 °N. We detected a closer relationship between latitude and snow depth to the north of 40 °N (Figs. 10a, d). In these regions, snow cover was relatively stable (the number of annual mean continuous snow cover days was more than 30) (Zhang and Zhong, 2014), in which snow cover was easier to accumulate by the heavy snowfall and more difficult to melt with low air temperature.

There was a negative correlation between snow depth and elevation across the Eurasian continent (Fig. 10b): 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 high elevation, the shallow snow depth in this area resulted in the generally negative correlation between snow depth and elevation across the Eurasian continent. However, we also determined that snow depth increased with elevation in most regions north of 45 °N (Fig. 10d). This result indicates that elevation is an important factor affecting snow depth in these regions.

There was a significant positive relationship between snow depth and continentality, but the correlation coefficient was not high ($r=0.1$, Fig. 10c). This indicated that the continentality is not an important driving factor of snow cover climatology over Eurasia, though it will determine the snowfall rate.

3.4 Relationships among Snow Depth, SWE, Air Temperature and Snowfall

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 USSR (Fig. 11). The period (snow cover years) spanned from 1966 through 2009 because data on air temperature and precipitation were recorded only until 2010. Snow depth significantly decreases with increasing air temperature ($P \leqslant 0.05$), but the Goodness of Fit of the relationship was only 16% (Fig. 11a). Compared with the air temperature, snowfall exhibited a better relationship with snow depth (Fig. 11b). The mean snow depth was less than 20 cm in most stations with the accumulated snowfall being <50 mm from November through March. It increased with the accumulated snowfall increased, and the thickest snow depth reached 120 cm when the maximum cumulative snowfall was 350 mm.

Comparing the long-term inter-annual trends of changes in snow depth, SWE, air temperature and snowfall, the variability of snow depth and SWE were mainly affected by the changes in snowfall. Overall, the trends in long-term air temperature, precipitation, snowfall and SWE displayed increasing trends from November to March (Fig. 12). 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 greater supply of moisture for snowfall, hence the snow accumulation still increased (Ye et al., 1998). The significant increasing snowfall can explain the sudden drop in the 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 lowed the whole density of snowpack. There were basically consistent trends of variations in snow depth, SWE and snowfall accumulation from November through March during 1966-2009 (Figs. 12b-d). The results indicated that the increasing trend in snow depth was the combined effect of the increasing air temperature and snowfall.

The partial correlation coefficients between snow cover and air temperature, as well as snow cover and snowfall were calculated to discuss the spatial relationship between them (Fig. 13). The significant negative correlation ($p \leqslant 0.05$) between snow depth and air temperature presented in most areas of European Russia and the southern Siberia (Fig 13a). The stations with negative effects of air temperature on SWE were fewer, and there were no statistically significant correlation in the northern Siberia (Fig 13b). It was because the air temperature was below 0℃ in most areas of Siberia during December through March, the increasing temperature did not have an obvious effect on snow depth.

Consistent with the interannual variation, changes in snow depth and SWE were more affected by snowfall in most areas across the former USSR from December through March. The greater partial correlation coefficients (>0.6) between snow cover and snowfall appeared in the northern European Russia, the southern Siberia, the northeast and southeast of the Russian Far East. Variations in snow depth and SWE were more sensitive to snowfall and snowfall rate in these areas.

4 Discussion

4.1 Comparison with Previous Results

Comparing our results with previous research across the Eurasian continent, we found that the climatology of mean snow depth was basically consistent with that described in the previous studies in China (Ma and Qin, 2012), but was higher than that in northern Eurasia (Kitaev et al., 2005; Bulygina et al., 2011). These discrepancies may result from differences in the time frame of data collection, number of stations, calculation methods, and data quality control. For example, Kitaev et al. (2005) reported a historical record of snow depth spanning the period from 1936 to 2000, with the onset and end of the snow year earlier than the definition used in this study. Nevertheless, the distributions of high snow depth in the two studies were located in the same regions and the regional and continental inter-annual and inter-decadal variations were consistent.

Previous research found that historical winter snow depth increased in most areas (30-140 °E, 50-70 °N), with the exception of European Russia, during 1936-1983 (Ye et al., 1998), similarly to our results. However, in the present study, we found that decreasing trends also appeared in some regions of the southern portion of western and central Siberia. The time sequence of observations may be the main reason for this difference. Compared with our study, the areas with increasing trends in snow depth reported by Ma and Qin (2012) were larger in China. Snow depth increased significantly in the northeastern TP in their results. The differences may have been caused by the different statistical methods and interpolation of nearby stations in the study of Ma and Qin.

In addition to the above reasons, these differences can be explained by the changes in climatic factors during the different study periods. The sensitivity of snow cover 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 leading to differences in snow depth at different times (Ye et al., 1998; Kitaev et al., 2005). The results of our study showed that there was significant negative relationship between snow depth and air temperature in the southern Siberia, however, it did not exist in the northern Siberia. This may explain the difference in the results of these studies.

4.2 Topographical effects in snow depth

Some important questions that are not addressed in the current research should be resolved in the future. Topography is an important factor affecting the climatology of snow depth, and is the main reason causing the inhomogeneity of data. Previous studies have analyzed the representation of snow depth for single stations to solve the issue (Grünewald and Lehning, 2011, 2013; Grünewald et al., 2014). However, in the present study, we did not discuss this question because of the complexity of spatial difference. But we still got some interesting conclusions: There was a closely relationship between snow depth and elevation at the local scale. However, compared with latitude, the correlation between them was not so significant in the whole Eurasian Continent. Moreover, the continentality did not play a great role in spatial distribution of snow depth, especially on TP. The previous studies showed that the Tibetan Plateau’s largest snow accumulation occurred in the winter, but the snowfall during winter months is the smallest of the year (Ma, 2008). This was mainly due to majority of annual precipitation occurs during the summer monsoon season on TP which cause very less snowfall during winter half year (or snow accumulated season). Furthermore, the water vapor from the east and west was blocked by the Hengduan Mountains and Nyainqentanglha Mountains, respectively, which resulted in less snowfall. Although there was more snowfall in spring, snow cover was not easy to accumulate with higher temperatures. Therefore, snow depth was shallow on TP in general. In addition to topographic factors, spatial distribution of snow depth was also affected by atmospheric circulation. We will discuss this issue in the future studies.

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 northeastern 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 southwestern TP.

There were statistically significant trends of variations in long-term snow depth over the Eurasian continent as a whole. A similar increase 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 decreasing trend, while there were increasing trends of variations of 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, the southern Siberia, the Russian Far East, northern areas of the Xinjiang Autonomous Region of China, and northeastern China. Decreasing linear trends were observed in most western areas of European Russia, some regions of southern Siberia, the northeastern Russian Far East and most areas in the southern 40 °N across China.

Compared with elevation, latitude played a more important role in the snow depth climatology. Variations of snow depth were explained by air temperature and snowfall in most areas of the European Russia and some regions of the southern Siberia, the effects of the two factors on SWE only appeared in some of these areas; however, snowfall was the main driver force of the variance of snow depth and SWE in the former USSR.

Acknowledgements. We express our gratitude to the researchers who assembled and digitized the snow depth data at meteorological stations and snow surveys across the Eurasian continent over a period of >40 years. This work was funded by the National Key Scientific Research Program of China (2013CBA01802), the Open Foundation from the State Key Laboratory of Cryospheric Sciences (SKLCS-OP-2016-12), the Project for Incubation of Specialists in Glaciology and Geocryology of the National Natural Science Foundation of China (J1210003/ J0109), and the Foundation for Excellent Youth Scholar of Cold and Arid Research Environmental and Engineering Research Institute, Chinese Academy of Sciences.

References

AMAP: Snow, Water, Ice and Permafrost in the Arctic (SWIPA), Oslo, Norway: Arctic Monitoring and Assessment Programme (AMAP), 553pp, 2011.

Armstrong, R. L.: Historical Soviet daily snow depth, version 2 (HSDSD). Boulder, Colorado: National Snow and Ice Data Center. CD-ROM. 2001.

Armstrong, R. L. and Brown, R.: Introduction, in: Snow and climate: Physical processes, surface energy exchange and modeling, edited by: R. L. Armstrong, and Brun, E., Cambridge University Press, Cambridge, UK, 1-11, 2008.

Beniston, M.: Variations of snow depth and durations in the Swiss Alps over the last 50 years: Link to changes in large-scale climatic forcings, Clim. Change, 36, 281–300, 1997.

Brasnett, B.: A global analysis of snow depth for numerical weather prediction, J. Appl. Meteorol., 38, 726-740, 1999.

Brown, R. D.: Northern Hemisphere snow cover variability and change, 1915-97, J. Climate, 13, 2339-2355, 2000.

Brown, R. D. and Braaten, R. O.: Spatial and temporal variability of Canadian monthly snow depth, 1946-1995, Atoms.-Ocean, 36, 37-45, 1998.

Brown, R. D. and Goodison, B. E.: Interannual variability in reconstructed Canadian snow cover, 1915-1992, J. Climate, 9, 1299-1318, 1996.

Bulygina O. N., Razuvaev, V. N., and Korshunova, N. N.: Changes in snow cover over Northern Eurasia in the last few decades, Environ. Res. Lett., 4, 045026, doi:10.1088/1748-9326/4/4/045026, 2009.

Bulygina, O. N., Groisman, P. Y., Razuvaev, V. N., and Korshunova,N. N.: Changes in snow cover characteristics over Northern Eurasia since 1966, Environ. Res. Lett., 6, 045204. doi:10.1088/1748-9326/6/4/045204, 2011.

Callaghan, T. V., Johansson, M., Brown, R. D., Groisman, P. Ya., Labba, N., and Radionov, V.: The changing face of Arctic snow cover: A synthesis of observed and projected changes, Arctic cryosphere—Changes and impacts, T. V. Callaghan, M. Johansson, and T. D. Prowse, Eds., Ambio, 40, 17-31. doi:10.1007/s13280-011-0212-y, 2011a.

Che, T., Dai, L., Zheng, X., Li X., and Zhao, K.: Estimation of snow depth from passive microwave brightness temperature data in forest regions of northeast China, Remote Sens.

Environ., 183, 334-349, 2016.
Cohen, J. L., Furtado, J. C., Barlow, M. A., Alexeev, V. A., and Cherry, J. E.: Arctic warming, increasing snow cover and widespread boreal winter cooling, Environ. Res. Lett., 7, 014007, 2012.
Derksen, C., Walker, A., and Goodison, B.: A comparison of 18 winter seasons of in situ and passive microwave-derived snow water equivalent estimates in Western Canada, Remote Sens. Environ., 88, 271-282, 2003.
Dickerson-Lange, S.E., Lutz, J.A., Martin, K.A., Raleigh, M.S., Gersonde, R., and Lundquist, J.D.: Evaluating observational methods to quantify snow duration under diverse forest canopies, Water Resour. Res., 51, 1203-1224, 2015.
Dressler, K.A., Leavesley, G.H., Bales, R.C., Fassnacht, S.R.: Evaluation of gridded snow water equivalent and satellite snow cover products for mountain basins in a hydrologic model. Hydrol. Process., 20, 673-688, 2006.
Dyer, J. L. and Mote, T.: Spatial variability and trends in observed snow depth over North America, Geophys. Res. Lett., 33, L16503, 2006.
Fallot, J., Barry, B. G., and Hoogstrate, D.: Variations of mean cold season temperature, precipitation and snow depths during the last 100 years in the former Soviet Union (FSU), Hydrol. Sci., 42, 301-327, 1997.
Folland, C.K. and Karl, T.R.: Observed climate variability and change. Climate Change 2001: The Scientific Basis, edited by: J. T. Houghton et al., Cambridge University Press, Cambridge, UK, 99–181, 2001.
Foster, J.L., Chang, A.T.C., and Hall, D.K.: Comparison of Snow Mass Estimates from a Prototype Passive Microwave Snow Algorithm, Remote Sens. Environ., 62, 132-142, 1997.
Ghatak, D., Frei, A., Gong, G., Stroeve, J., and Robinson, D.: On the emergence of an Arctic amplification signal in terrestrial Arctic snow extent, J. Geophys. Res., 115, D24105, 2010.
Graps, A.: An introduction to wavelets, Computational Science & Engineering, IEEE, 2, 50-61, 1995.
Grippaa, M., Mognarda, N., Le Toana, T., and Josberger E.G.: Siberia snow depth climatology derived from SSM/I data using a combined dynamic and static algorithm, Remote Sens. Environ., 93, 30-41, 2004.

Groisman, P.Y., Karl, T.R., and Knight, R.W.: Observed impact of snow cover on the heat balance and the rise of continental spring temperatures, Science, 263: 198-200, 1994.

Groisman, P., Knight, R., Razuvaev, V., Bulygina, O., and Karl, T.: State of the Ground: Climatology and Changes during the Past 69 Years over Northern Eurasia for a Rarely Used Measure of Snow Cover and Frozen Land, J. Climate, 19, 4933–4955, 2006.

Grünewald, T. and Lehning, M.: Altitudinal dependency of snow amounts in two small alpine catchments: can catchment-wide snow amounts be estimated via single snow or precipitation stations? Ann. Glaciol., 52, 153-158, 2011.

Grünewald, T. and Lehning, M.: Can a point measurement represent the snow depth in its vicinity? A comparison of areal snow depth measurements with selected index sites, Proceedings of the International Snow Science Workshop, 27 October 7 to 11, Grenoble, France, 69-72, 2013.

Grünewald, T., Bühler, Y., and Lehning, M.: Elevation dependency of mountain snow depth, The Cryosphere, 8, 2381-2394, 2014.

Integrated Global Observing Strategy (IGOS): Cryosphere Theme Report - For the monitoring of our environment from space and from earth, WMO/TD-No.1405, World Meteorological Organization, Geneva, 100 pp., 2007.

King, J. C., Pomeroy, J. W., Gray, D. M., Fierz, C., Fohn, P., Harding, R. J., Jordan, R. E., Martin, E., and Pluss, C.: Snowatmosphere energy and mass balance, in: Snow and Climate: Physical Processes, Surface Energy Exchange and Modeling, edited by: Armstrong, R. L. and Brun, E., Cambridge University Press, Cambridge, UK, 70–124, 2008.

Kitaev, L., Kislov, A., Krenke, A., Razuvaev, V., Martuganov, R., and Konstantinov, I.: The snow cover characteristics of northern Eurasia and their relationship to climatic parameters, Boreal Environ. Res., 7, 437-445, 2002.

Kitaev, L., Førland, E., Razuvaev, V., Tveito, O. E., and Krueger, O.: Distribution of snow cover over Northern Eurasia, Nord. Hydrol., 36, 311-319, 2005.

Kuusisto, E.: Snow accumulation and snowmelt in Finland, Publications of the Water Research Institute, v. 55, Valtion painatuskeskus, Helsinki, 149 pp., 1984.

Lazar, B. and Williams, M.: Climate change in western ski areas: potential changes in the timing of wet avalanches and snow quality for the Aspen ski area in the years 2030 and 2100, Cold

Reg. Sci. Technol., 51, 219–228, 2008.
Lehning, M., Grünewald, T., and Schirmer, M.: Mountain snow distribution governed by an altitudinal gradient and terrain roughness, Geophys. Res. Lett., 38, L19504, 2011.
Li, P. and Mi, D.: Distribution of snow cover in China, J. Glaciol. Geocryol., 5, 9-18, 1983 (in Chinese with English abstract).
Liston, G.E., and Hiemstra, C.A.: The changing cryosphere: Pan-Arctic snow trends (1979-2009), J. Climate, 24, 5691-5712, 2011.
Liu, J., Curry, J., Wang, H., Song, M., and Horton, R.: Impact of declining Arctic sea ice on winter snowfall, Proc. Natl. Acad. Sci. U.S.A., 109, 4074-4079, 2012.
Ma, L.: Spatiotemporal variation in snow cover and the relationship between snow cover and atmospheric circulation in the Tibetan Plateau in recent 50 years, PhD dissertation, Graduate University of Chinese Academy of Sciences, 156pp, 2008.
Ma, L. and Qin, D.: Spatial-temporal characteristics of observed key parameters for snow cover in China during 1957-2009, J. Glaciol. Geocryol., 34, 1-11, 2012 (in Chinese with English abstract).
Ministry of Environment Province of British Columbia (MEPBC): Snow survey sampling guide, Surface Water Section, Water Management Branch, Ministry of Environment Province of British Columbia, 1981.
Nayak, A., Marks, D., Chandler, D.G., and Seyfried, M.: Long-term snow, climate, and streamflow trends at the Reynolds Creek experimental watershed, Owyhee Mountains, Idaho, United States. Water Resour. Res., 46, W06519. doi: 10.1029/2008WR007525, 2010.
Park, H., Walsh, J. E., Kim, Y., Nakai, T., and Ohata, T.: The role of declining Arctic sea ice in recent decreasing terrestrial Arctic snow depths, Polar Sci., 7, 174-187, 2013.
Rawlins, M.A., Steele, M., Holland, M.M, and 27 others: Analysis of the Arctic system for freshwater cycle intensification: Observations and expectations, J. Climate, 23, 5715-5737, 2010.
Rees, A., English, M., Derksen, C., Toose, P., and Silis, A.: Observations of late winter Canadian tundra snow cover properties, Hydrol. Process., 28, 3962-3977, 2014.
Revuelto, J., López-Moreno, J.I., Azorin-Molina, C., and Vicente-Serrano, S.M.: Topographic control of snowpack distribution in a small catchment in the central Spanish Pyrenees: intra-

and inter-annual persistence, The Cryosphere, 8, 1989-2006, 2014.

Robinson, D. A., Dewey, K. F., and Heim, R. R.: Global snow cover monitoring: An update, B. Am. Meteorol. Soc., 74, 1689-1696, 1993.

Stuefer, S., Kane, D.L., and Liston, G.E.: In situ snow water equivalent observations in the US Arctic, Hydrol. Res., 44, 21-34, 2013.

Sturm, M., McFadden, J. P., Liston, G. E., Chapin III, F. S., Racine, C. H., and Holmgren, J.: Snow-shrub interactions in Arctic tundra: A hypothesis with climatic implications. J. Climate, 14, 336-344, 2001.

Terzago, S., Hardenberg, J. Palazzi, E., and Provenzale, A.: Snowpack changes in the Hindu Kush-Karakoram-Himalaya from CMIP5 global climate models, J. Hydrometeorol., 15, 2293-2313, 2014.

Veselov, V. M.: PC archives of the State Data Holding and technology of their organization, Proceedings of the RIHMI-WDC (Russian Research Institute for Hydrometeorological Information-World Data Center), 170, 16-30, 2002 (in Russian).

Ye, H. C., Cho, H. R., and Gustafson, P. E.: The changes in Russian winter snow accumulation during 1936-83 and its spatial patterns, J. Climate, 11, 856-863, 1998.

You, Q., Kang, S., Ren, G., Fraedrich, K., Pepin, N., Yan, Y., and Ma L.: Observed changes in snow depth and number of snow days in the eastern and central Tibetan Plateau, Clim. Res., 46, 171-183, 2011.

Zhang, T.: Influence of the seasonal snow cover on the ground thermal regime: An overview, Rev. Geophys., 43, RG4002, doi: 10.1029/2004RG000157, 2005.

Zhang, T. and Zhong, X.: Classification and regionalization of the seasonal snow cover across the Eurasian continent, J. Glaciol. Geocryol., 36, 481-490, 2014 (in Chinese with English abstract).

Zhong, X., Zhang, T., and Wang, K.: Snow density climatology across the former USSR, The Cryosphere, 8, 785-799, 2014.

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 course	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

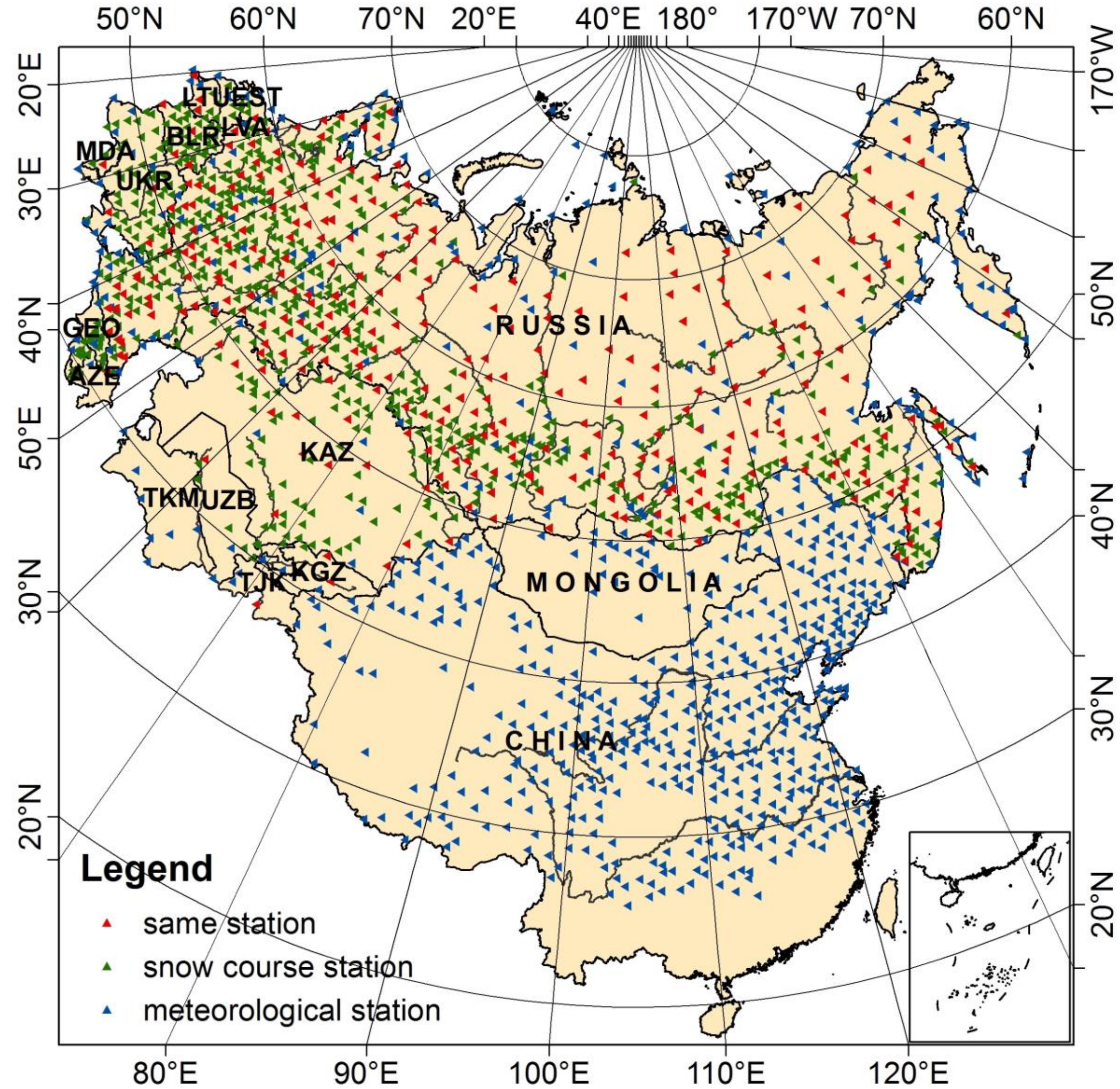


Figure 1. Geographical locations of meteorological and snow course stations across the Eurasian continent. The red triangles represent stations where snow depth was measured at both meteorological stations and snow course surveys, the green triangles show stations where snow depth was measured at snow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

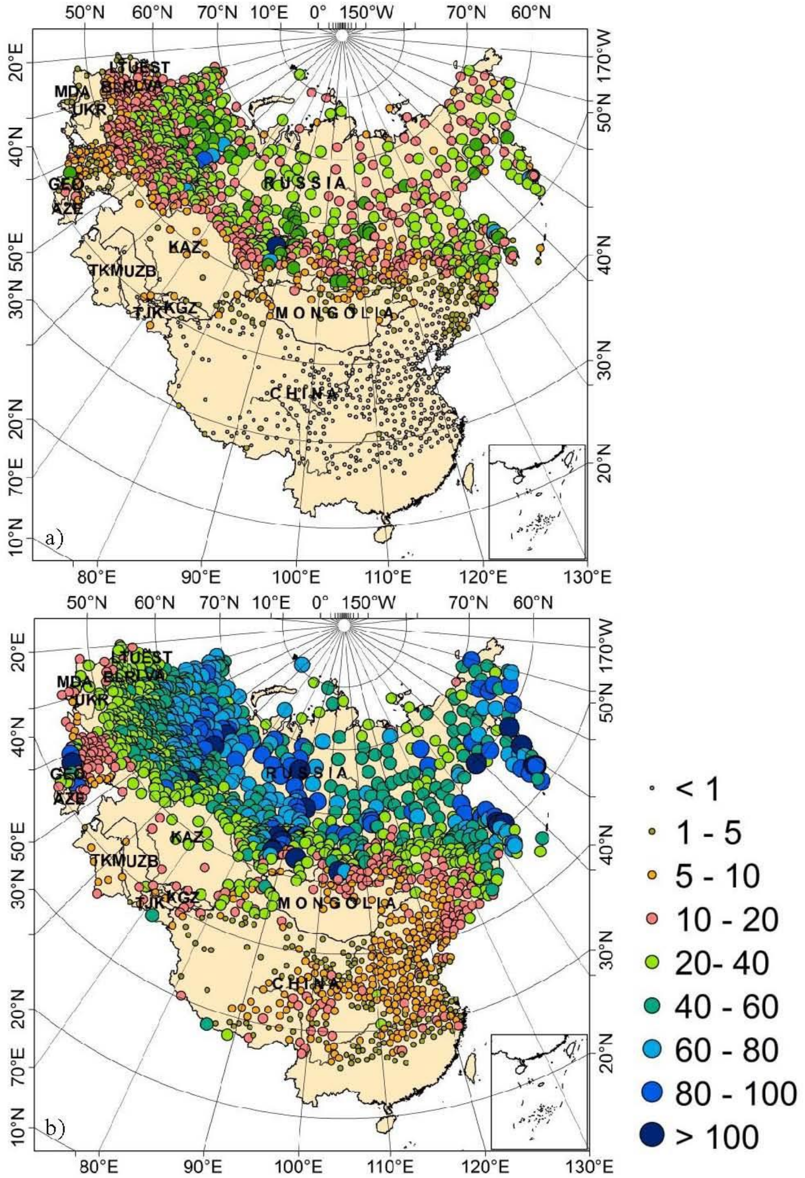
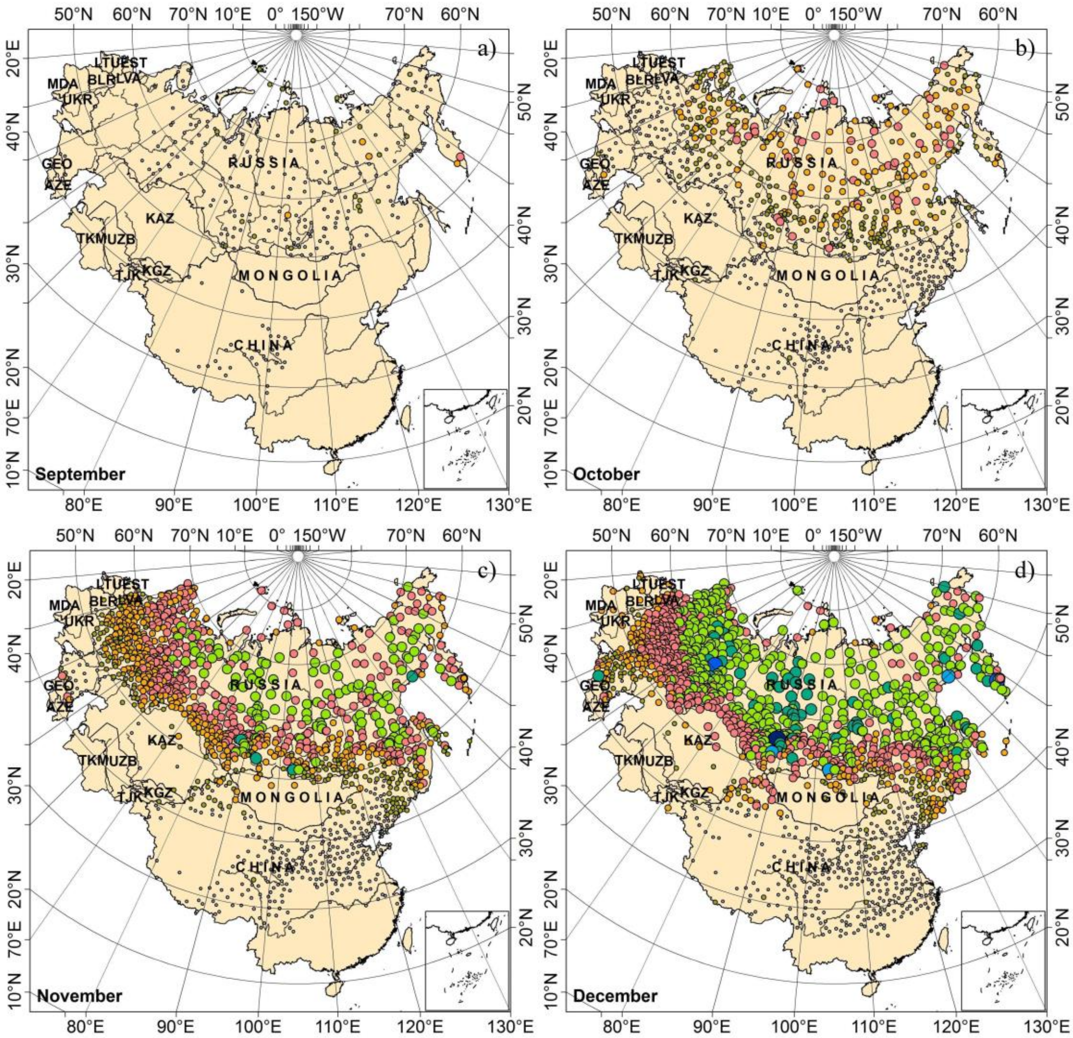


Figure 2. Annual mean snow depth (a) and maximum snow depth (b) across the Eurasian continent (cm) during 1966-2012.

1



a)
b)
c)
d)
September
October
November
December
RUSSIA
MONGOLIA
CHINA
KAZ
TKM
UZB
TJK
KGZ
GEO
AZE
MDA
UKR
BLR
LVA
LTU
EST

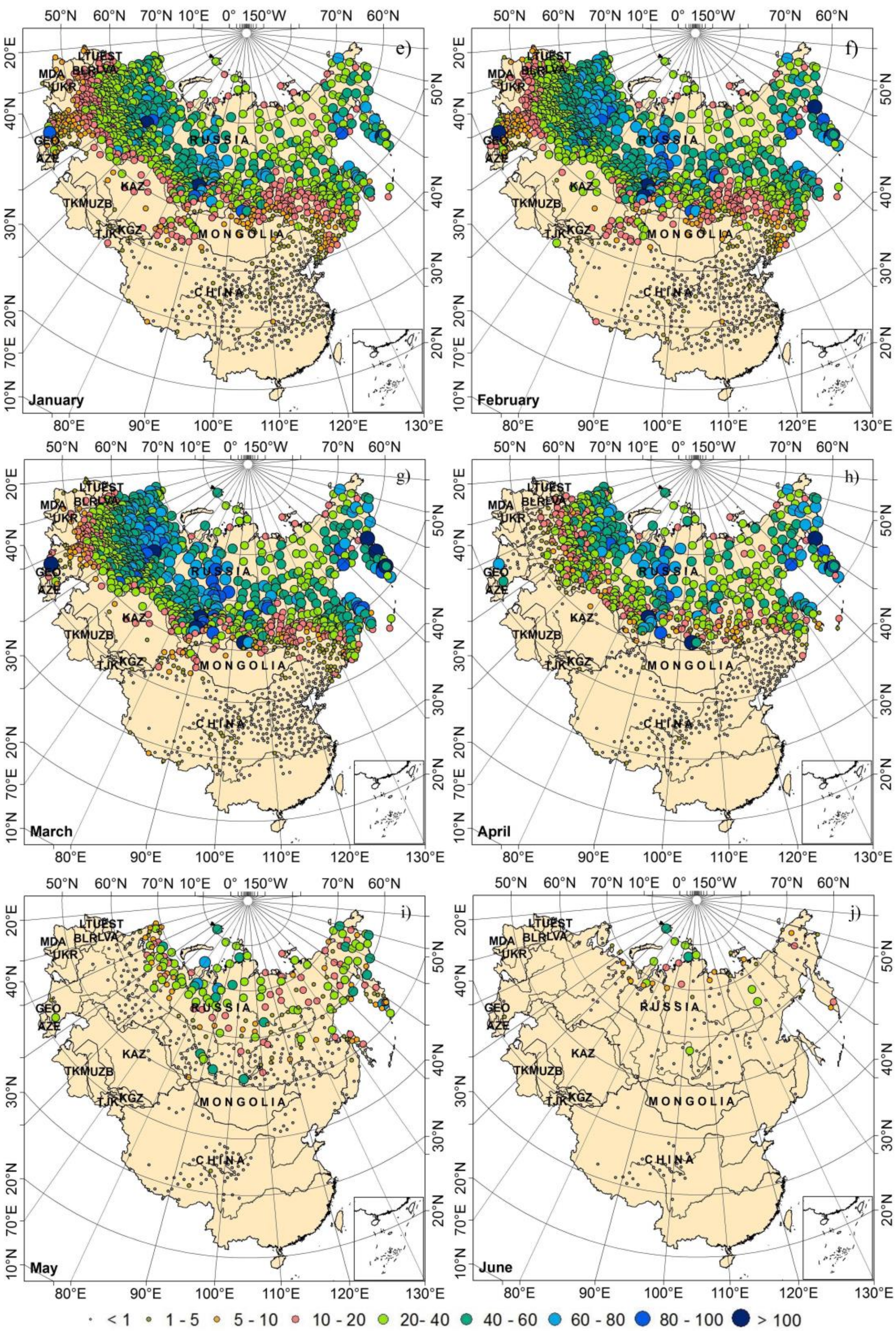


Figure 3. Monthly mean snow depth (from September to June) (cm) across the Eurasian continent (cm) during 1966-2012. (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, (i) May, (j) June.

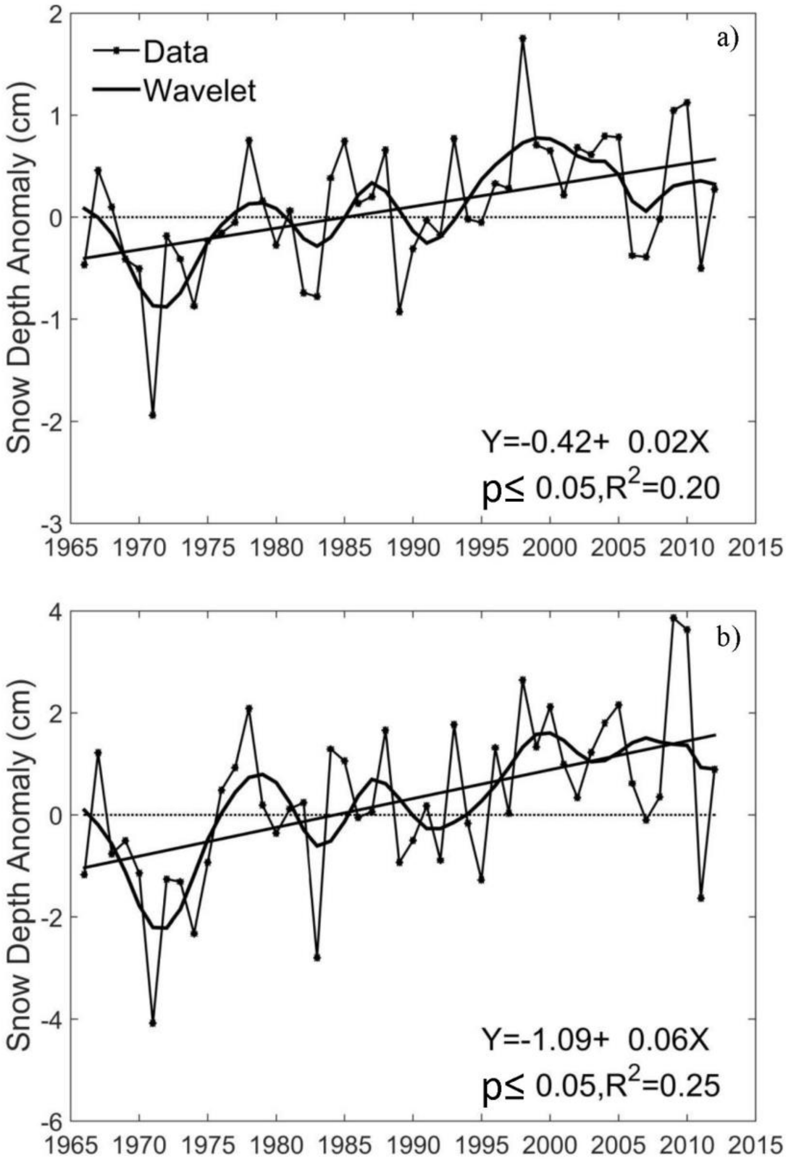


Figure 4. Composite of inter-annual variation of annual mean snow depth (a) and maximum snow depth (b) from 1966 through 2012 with respect to the 1971-2000 mean across the Eurasian continent. The line with dots is the anomaly of snow depth; the thick curve represents the smoothed curve using wavelet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

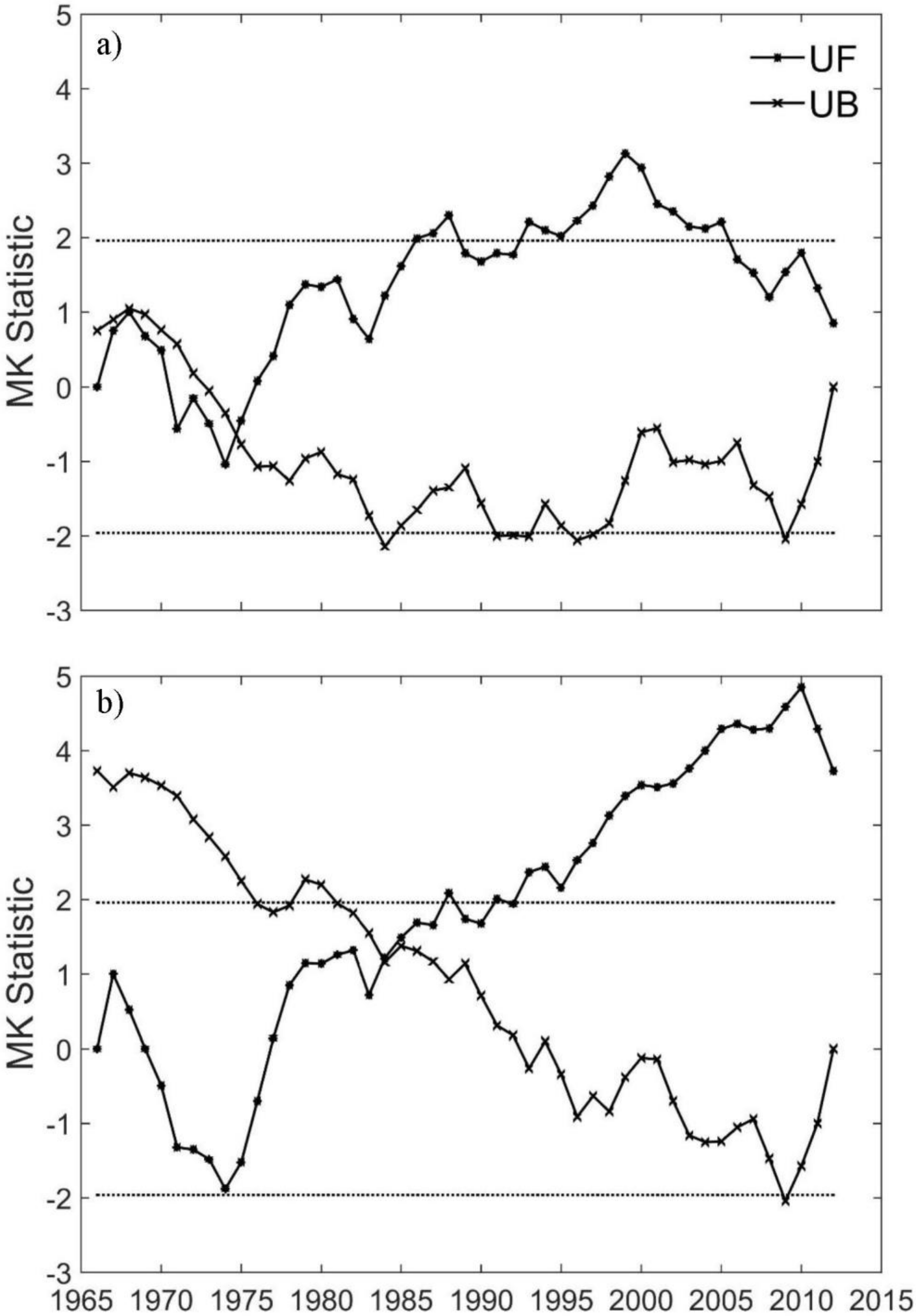


Figure 5. Mann-Kendall statistical curve of annual mean snow depth (a) and maximum snow depth (b) from 1966 through 2012 across the Eurasian continent. Straight line presents significance level at 0.05.

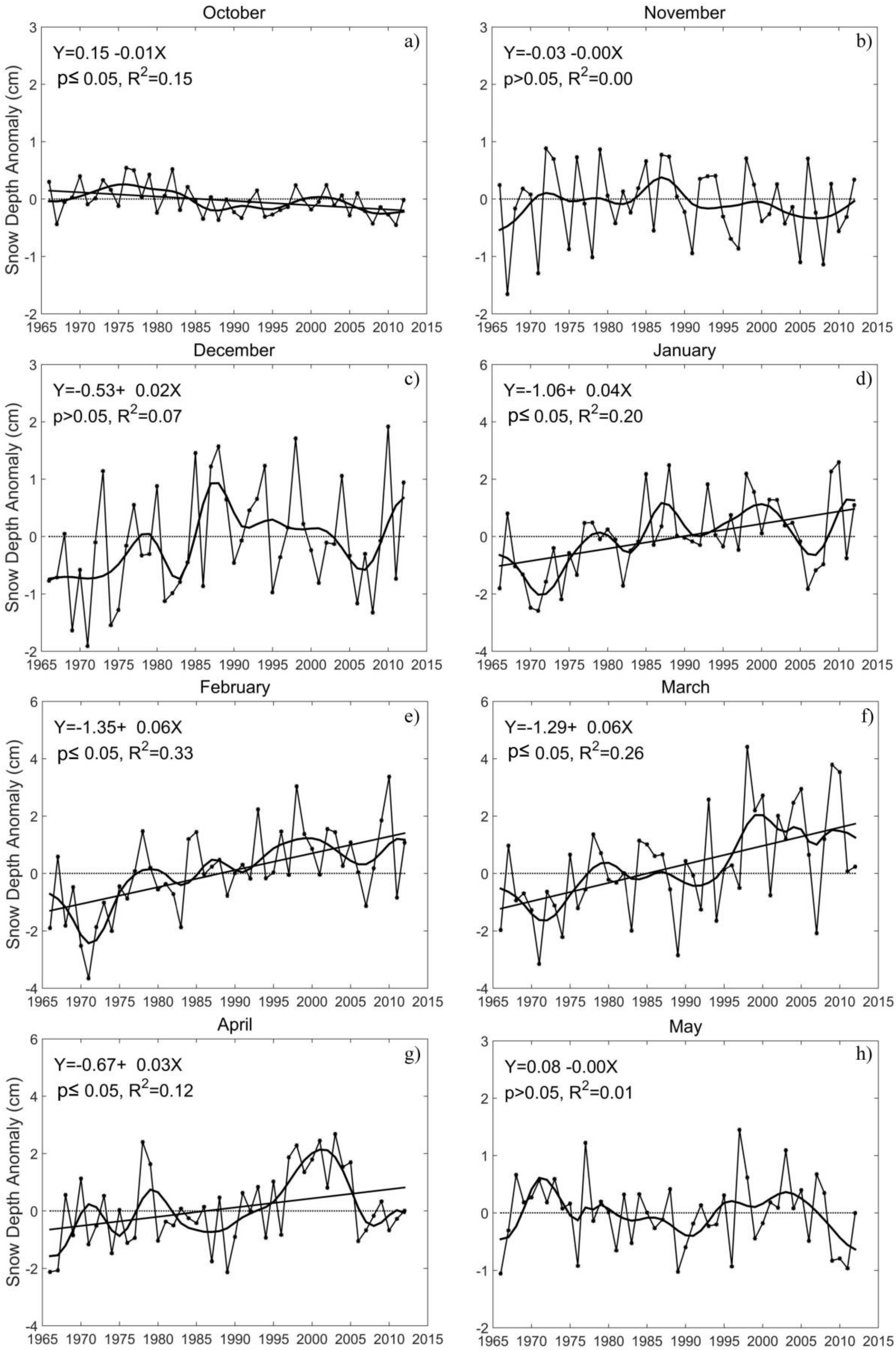


Figure 6. Composites of inter-annual variation of monthly mean snow depth (from October to May) from 1966

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.

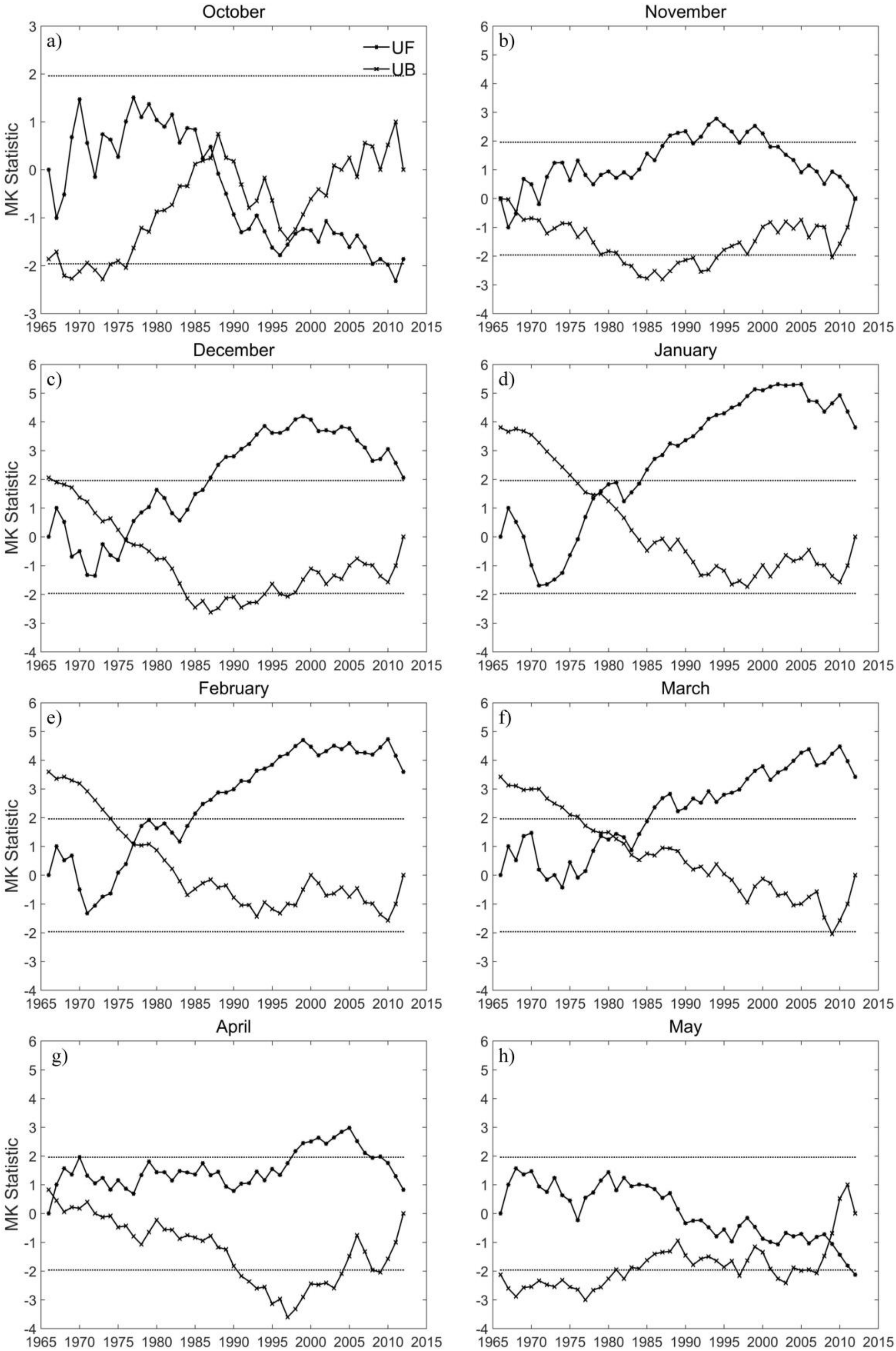


Figure 7. Mann-Kendall statistical curve of monthly mean snow depth (from October to May) from 1966 through 2012 across the Eurasian continent. (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May. Straight line presents significance level at 0.05.

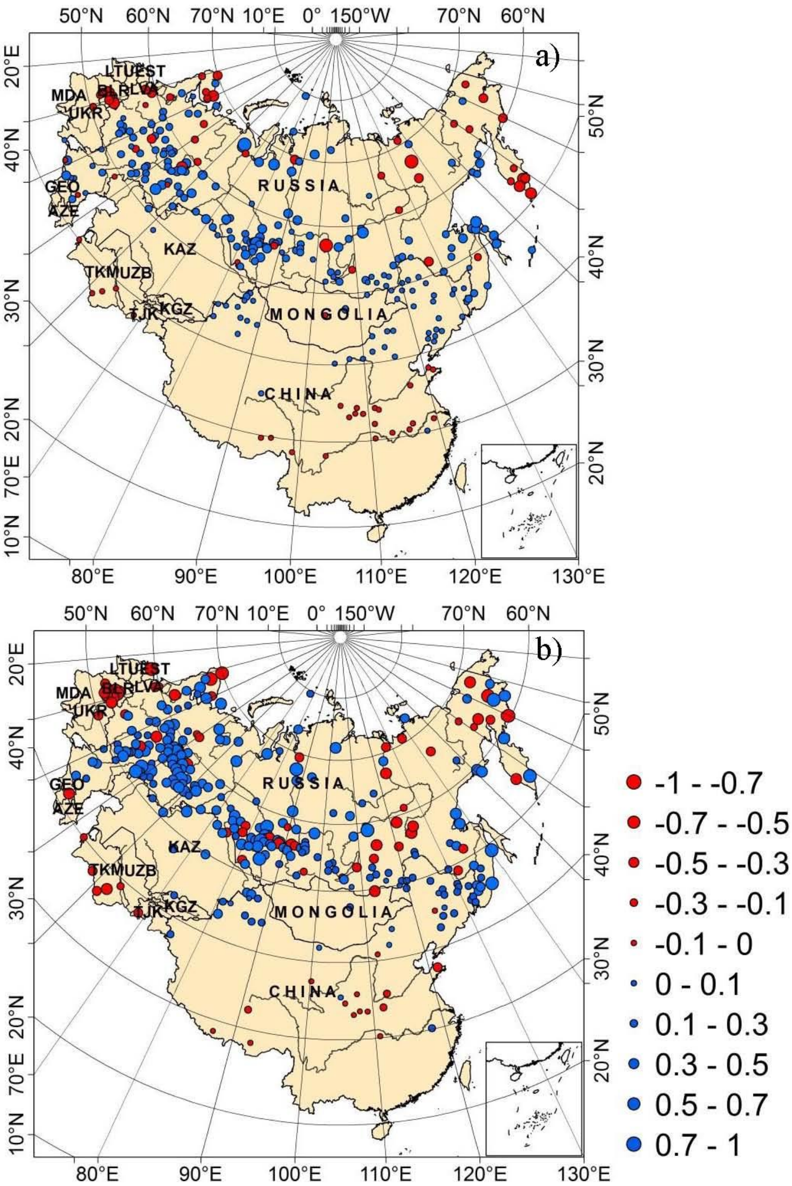


Figure 8. Spatial distribution of linear trend coefficients (cm yr^{-1}) of annual mean snow depth (a) and maximum snow depth (b) for each station in 1966-2012. The rate of change was at the 95% level. Red circles represent a decreasing trend, and blue circles represent an increasing trend.

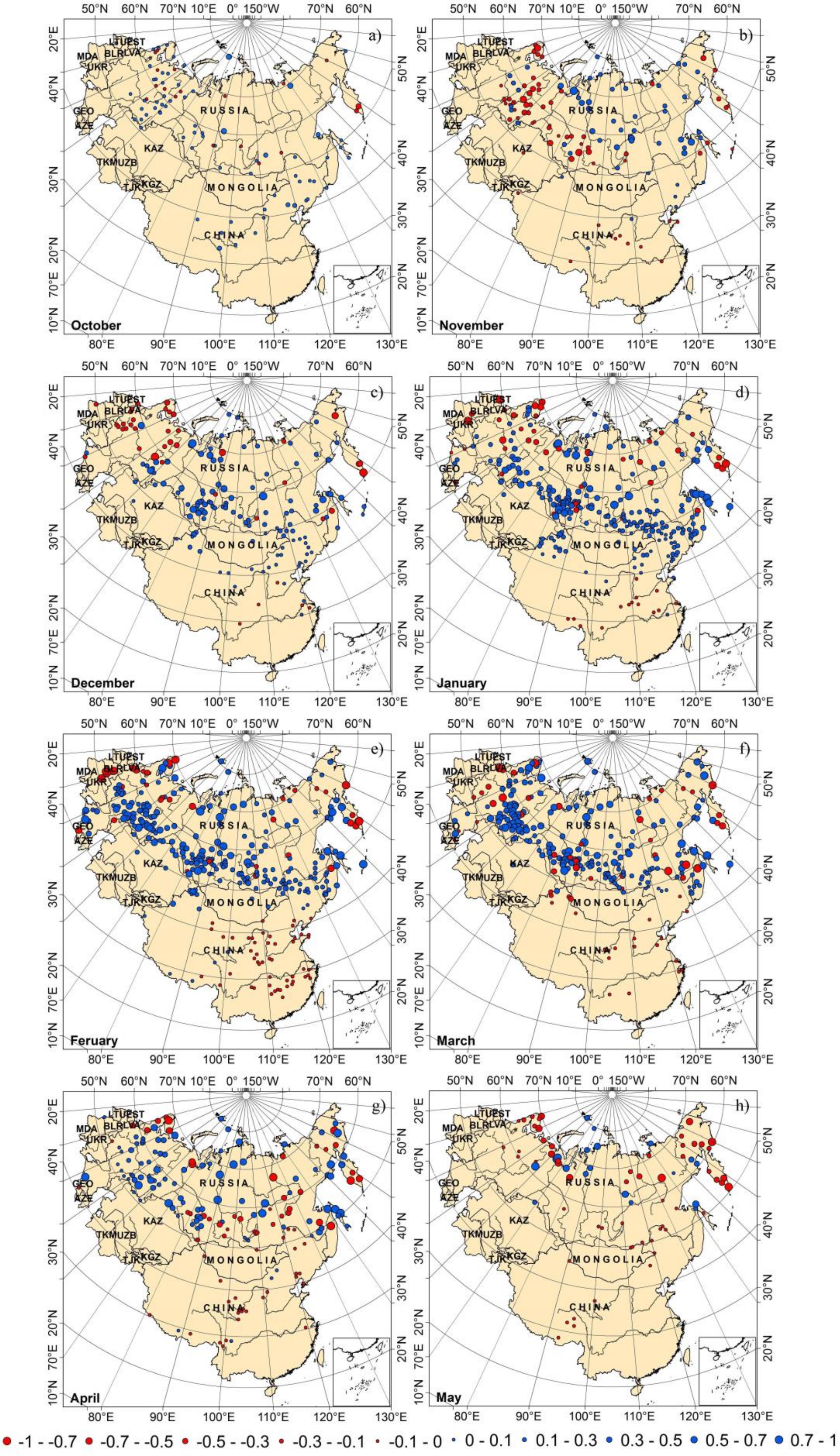

a)
October
b)
November
c)
December
d)
January
e)
Feruary
f)
March
g)
April
h)
May
RUSSIA
MONGOLIA
CHINA
KAZ
TKMUZB
TJKKGZ
GEO
AZE
MDA
UKR
BLRLVA
LTUEST
50°N 60°N 70°N 10°E 0° 150°W 70°N 60°N
80°E 90°E 100°E 110°E 120°E 130°E
● -1 - -0.7 ● -0.7 - -0.5 ● -0.5 - -0.3 ● -0.3 - -0.1 ● -0.1 - 0 ● 0 - 0.1 ● 0.1 - 0.3 ● 0.3 - 0.5 ● 0.5 - 0.7 ● 0.7 - 1

Figure 9. 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.

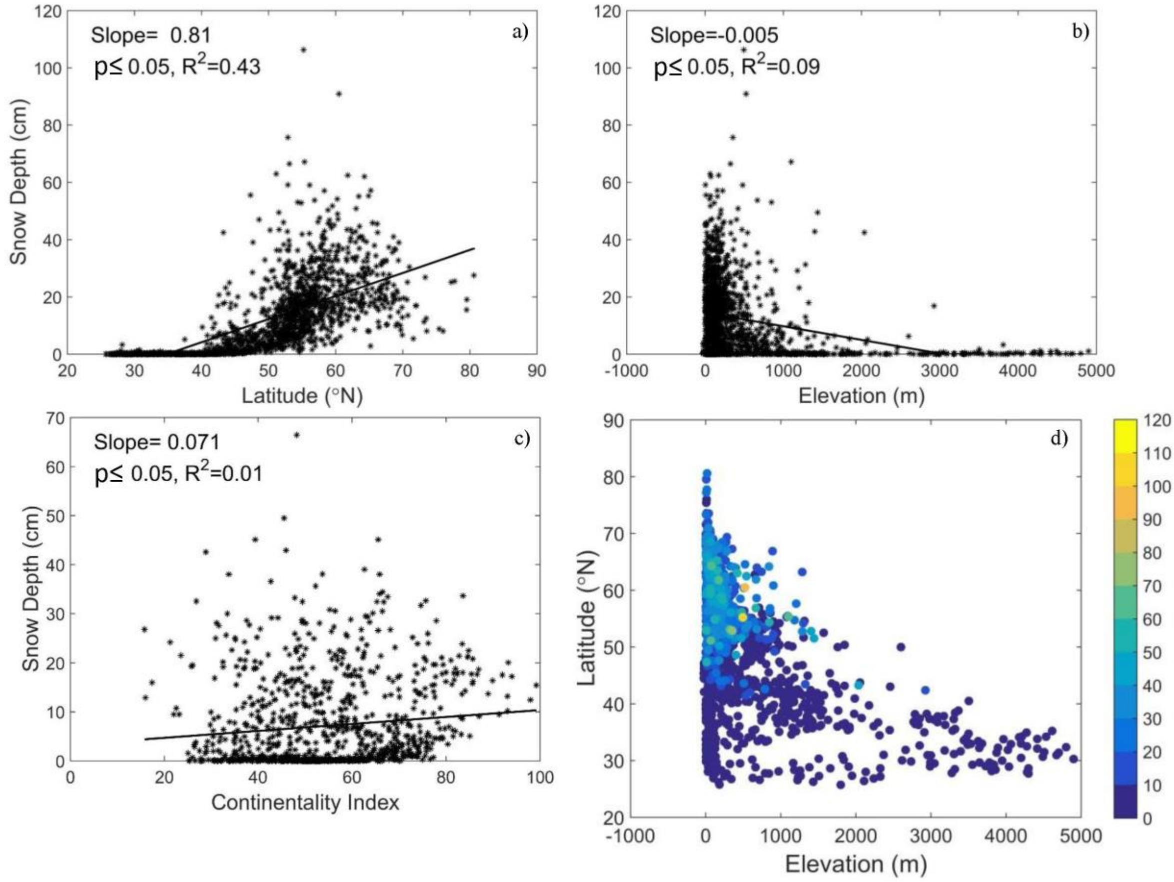


Figure 10. The relationship between annual mean snow depth and latitude (a), elevation (b) and continentality (c) for all stations across the Eurasian continent during 1966-2012. Asterisks show the mean snow depth of each station; the thick line is a linear regression trend; the different colors represent snow depth (cm) of each station (d).

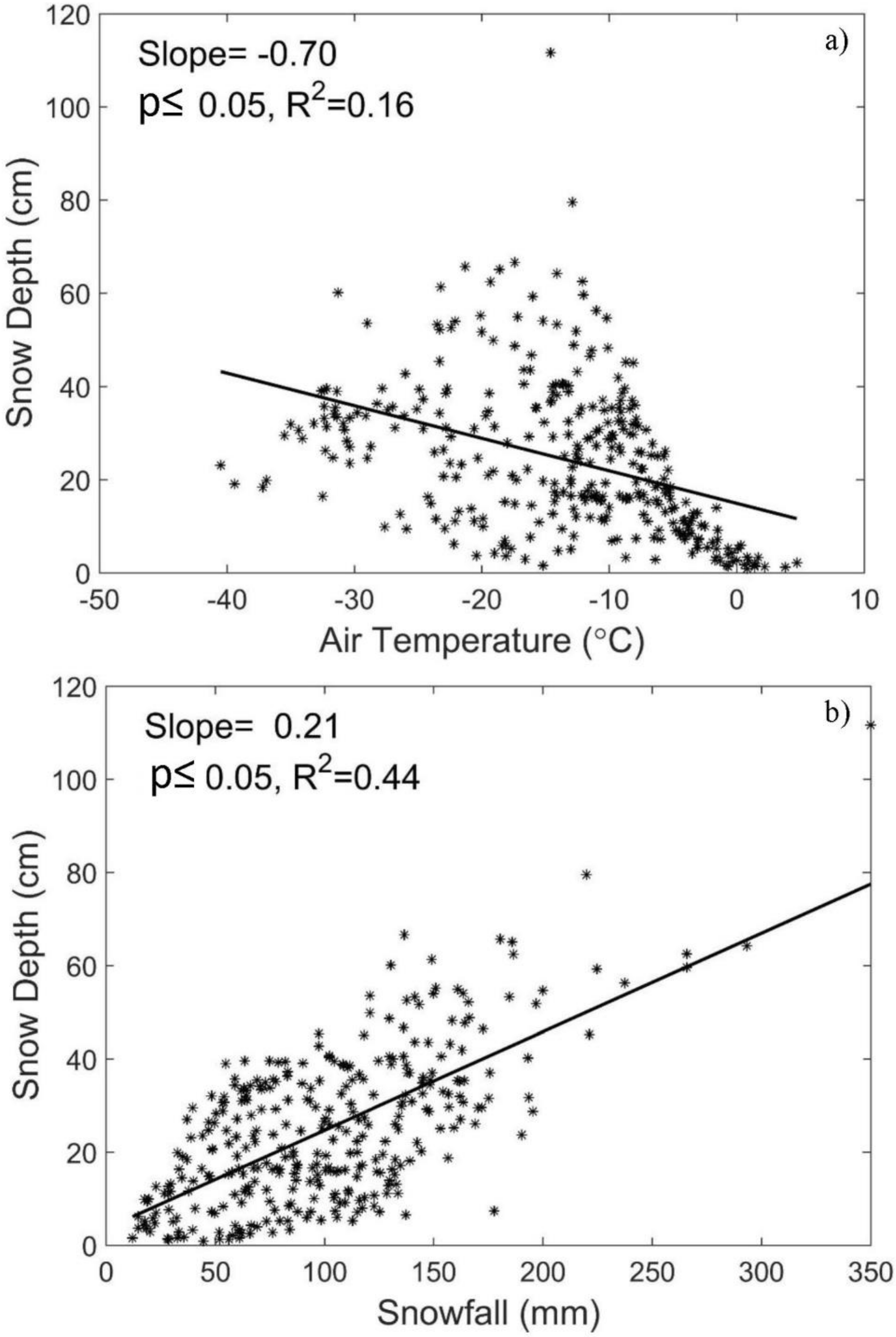


Figure 11. The relationships among annual mean snow depth, air temperature and snowfall for 386 stations from November through March during 1966-2009 over the USSR. The thick line is a linear regression trend.

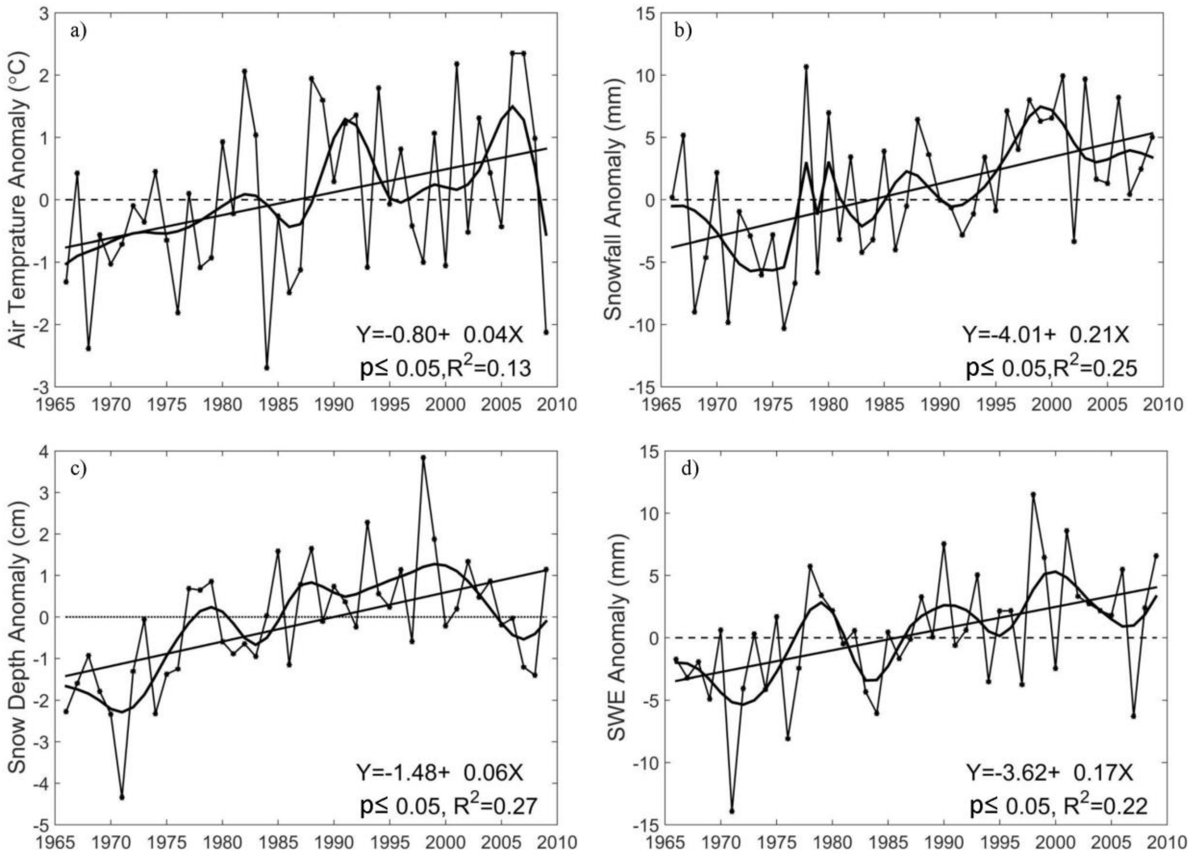


Figure 12. Composite of inter-annual variation of annual mean air temperature (a), annual snowfall (b), annual snow depth (c) and snow water equivalent (d) from November through March during 1966-2009 with respect to the 1971-2000 mean across the former USSR. The line with dots is the composite of the annual means; the thick curve represents the smoothed curve using wavelet analysis; the thick line presents a linear regression trend.

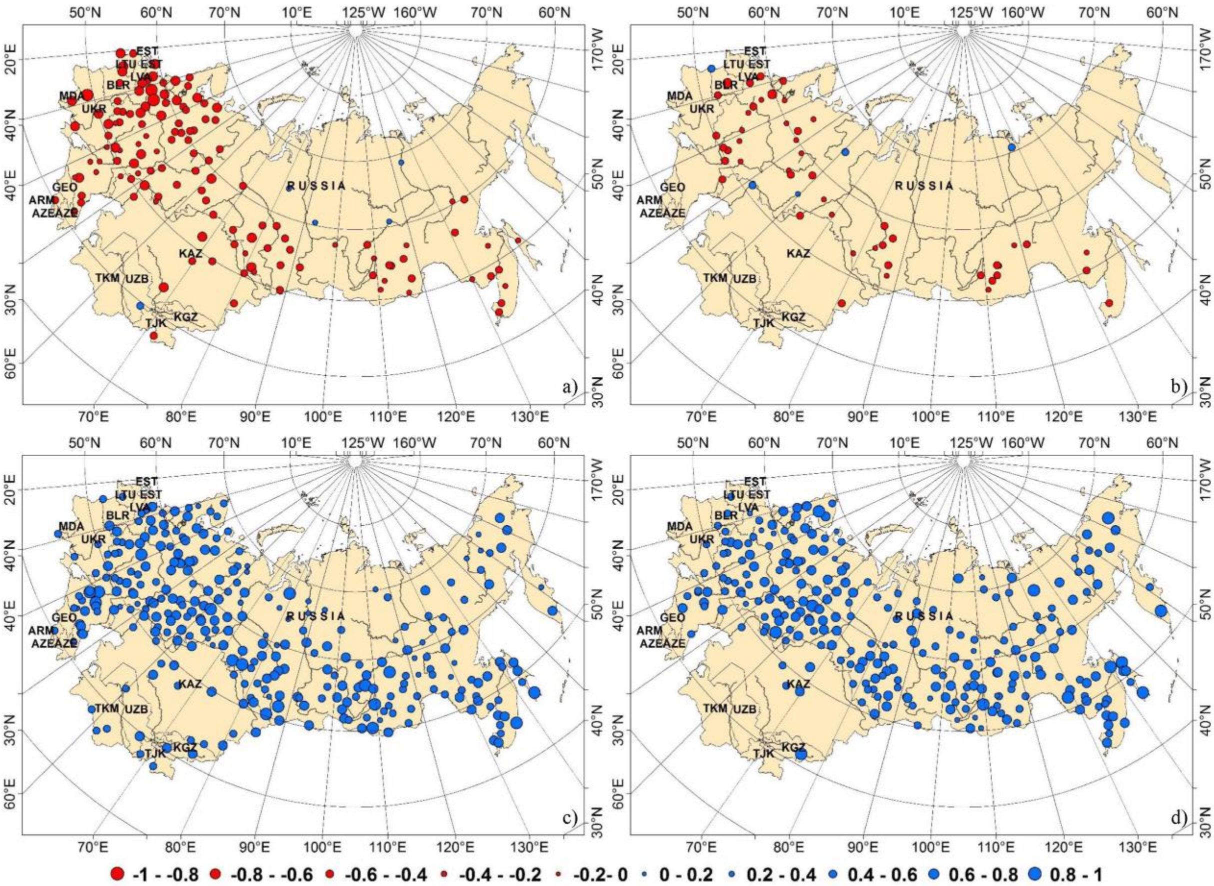


Figure 13. Spatial distributions of partial correlation coefficients of snow depth and air temperature (a), snow depth and snowfall (b), SWE and air temperature (c), SWE and snowfall from November through March during 1966-2009. The coefficients reaching to 0.05 confident level are displayed. Red circles represent a negative relationship, and blue circles indicate a positive relationship.