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

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

[1] *Key Laboratory of Remote Sensing of Gansu Province, 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] *CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China*

[5] *Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, Colorado, 80309, USA*

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

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

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. In this study, spatiotemporal change and variability of 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 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 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 are significant in climate system changes over the Eurasian continent.

1 Introduction

Snow cover is a key part of cryosphere, which is a critical component of the global climate system. Changes in snow cover, including snow depth and snow area extent, serve as an indicator of climate change because of its 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). 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 depth would have dramatic impacts on weather and climate through surface energy balance (Sturm et al., 2001), soil temperature and frozen ground (Zhang, 2005), spring runoff, water supply, and human activity (AMAP, 2011). Although snow cover extent declined with climate warming, snow depth showed an increasing trend in northern Eurasia during 1936 to 2010 (Kitaev et al., 2005; Bulygina et al., 2011). This may be explained by warmer air led to greater moisture supply for 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 local and regional evapotranspiration (Groisman et al., 1994).

Using in-situ observational data from meteorological stations and satellite remote sensing, several studies had documented changes in snow depth over the Northern Hemisphere, demonstrating that snow depth varied differently over different regions. 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) with large regional differences (Bulygina et al., 2009, 2011; Ma and Qin, 2012; Stuefer et al., 2013; Terzago et al., 2014). Changes in snow depth 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 were 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 was closely related to synoptic-scale atmospheric circulation indices, such as the North Atlantic Oscillation /Arctic Oscillation (NAO/AO). For example, Beniston (1997) found that NAO played a crucial role in fluctuations in the amount of snowfall and snow depth in Swiss Alps from 1945 to 1994. Kitaev et al. (2002) reported that NAO index was positively related to snow depth in northern part of the East European Plain of Russia and over western Siberia during the period from1966 to 1990; however, NAO 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 winter AO/NAO index and between snow depth and Niño-3 region sea surface temperature (SST) on the eastern and central Tibetan Plateau (TP) from 1961 through 2005.

To increase the spatial coverage of snow depth, researchers 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 in-situ snow depth observations, they have low spatial resolution (25×25 km) and the accuracy is always affected by clouds, underlying surface conditions, and perfect algorithms. Using ground-based snow depth measurements across Eurasian continent against snow depth obtained from passive microwave satellite remote sensing, Zheng et al. (2015) found that the mean percentage error is greater than 50% and can be up to about 200%. Utilization of snow depth obtained from satellite remote sensing has large uncertainties and impractical. In addition, data acquisition from large airborne equipment or aerial systems are costly and strict data use limitation applies. Ground-based measurement provides currently available accurate snow depth with long time-series, which are critical data and information for investigating snow depth climatology and variability.

During winter, the average maximum terrestrial snow cover is approximately 47 × 10^6 km^2 over Northern Hemisphere lands (Robinson et al., 1993; IGOS, 2007). A large fraction of Eurasian continent is covered by snow during 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 were 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 TP (Li and Mi, 1983; Ma and Qin, 2012). 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 climatology and variability of snow depth over the Eurasian continent from 1966 to 2012. We will further analyze spatial and temporal changes of snow depth with topography and climate factors over the study area. 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

Data used in this study includes daily snow depth, snow water equivalent (SWE), air temperature and precipitation. Measurements of daily snow depth were conducted at 1103 meteorological stations over 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 Eurasian continent since the meteorological observation standard was established by the former USSR and followed by all the former USSR republics, Mongolia and China. Snow depth is one of the standard elements to be measured on 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 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 of that is often used in water resource evaluation and hydroclimate studies. SWE was measured by 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 by thermometer which was placed at a height of 1.5 m above the ground surface in an instrument shelter at meteorological station (WMO, 1996). Air temperature measurement should be accurate to 0.1℃. Air temperature was measured four times a day at 0200, 0800, 1400, and 2000 at local time. Daily mean air temperature was calculated by simple arithmetic average of the four measurements, while monthly mean was based on daily mean and annual mean was based on monthly mean. Precipitation was gathered and measured by a precipitation gauge and was reported with a 0.1-mm precision (Groisman and Rankova, 2001). 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:

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

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

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 meteorological data was automatically undertaken prior to 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 is deleted. (2) Stations with sudden step changes of snow depth are eliminated from the list. (3) Stations with less than 20 years of data during the 1971-2000 period were excluded from the analysis. (4) At each station, we eliminated data points which exceed 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 climatology and variability of snow depth over 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 in order 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 have inhomogeneities in the time series over the period of record. Fortunately, there was no change in procedure and technique of snow depth measurements since 1965 in Russia and the other countries in this study (Bulygina et al., 2009). In this study, therefore, 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 way for deriving monthly mean snow depth by World Meteorological Organization (WMO) climatological products (Ma and Qin, 2012). According to 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 ground within each month.

(2) Annual mean snow depth: an annual mean snow depth was calculated as an arithmetic sum of 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 than20 snow years during 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 annual maximum snow depth from stations with more than 20 years of data during 1966-2012 period.

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

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. The linear trend analysis is also a useful approximation when systematic low-frequency variations emerged 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 T test was used to assess statistical significant of the slope in linear regression analysis and the partial correlation coefficients, and the confidence level above 95% was considered in our study. The Durbin-Watson test was used to detect serial correlation of data in 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 time series of 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. Snow depth generally increased with latitude northward across 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. Snow 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. 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 (Fig. 2b) showed a similar spatial distribution pattern as compared to annual mean snow depth pattern. The maximum value was about 201.8 cm in 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 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 decreased to 6–10 cm as moving the central and eastern Mongolia. Maximum snow depths were higher over the northern part of the Xinjiang Autonomous Region of China, Northeast China, and the eastern and southwestern TP, mostly greater than 10 cm, even greater than 20 cm in some areas. For the remaining regions of China, maximum snow depth were relatively small, mostly less than 10 cm.

In autumn months (September to November), 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). As moving southward, monthly mean snow depth was less than 5 cm in north of Mongolia and across China. From December to February, snow depth increased and 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 part of China, but except the northern Xinjiang Autonomous Region of China, Northeast China, and southwestern 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) mainly because of snow disappearance in the majority part of China. However, 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 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 about 0.2 cm decade^{-1}, while annual mean maximum snow depth increased at a rate of about 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 (about ± 2 cm) was much larger than that of mean snow depth anomaly (about ±1 cm). From the mid-1960s to the early 1970s, 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 about 3 to 4 cm in the maximum snow depth during the 1970s, then with large fluctuation without 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 Eurasian continent from 1966 through 2012 (Fig. 5). Snow depth decreased in October at a rate of about -0.1 cm decade^{-1} (Fig. 5a), there were no significant trend in November and December with large inter-annual variations (Fig. 5b-c). From January through April, snow depth showed statistically increased trends with rates between 0.3 cm decade^{-1} and 0.6 cm decade^{-1} (Fig. 5d-g). Overall, snow depth decreased or 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 $p \leqslant 0.05$. The significant increasing trends (blue circles) of annual mean snow depth occurred in European Russia, south of Siberia and the Russian Far East, 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 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, indicating that the increasing rate of annual mean snow depth was greater in higher latitude regions.

Changes in maximum snow depth were similar to those in annual mean snow depth in most of Eurasia from 1966 to 2012, but the magnitude of changing rates in maximum snow depth were greater than the values of annual mean snow depth (Fig. 6b). The significant increasing trends were observed in the same regions as those with increases in annual mean snow depth. The decreasing trends were found generally in the same regions where annual mean snow depth decreased, with greater reductions in southern Siberia and the Far East.

In October and November, there were few stations with significant increasing trends in snow depth (P≤0.05) (Figs. 7a, 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 of snow depth only appeared in Siberia and the Russian Far East while decreasing trends in monthly mean snow depth occurred over eastern European Russia, southern West Siberian Plain, and 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) , mainly in eastern European Russia, southern Siberia, northern Xinjiang Autonomous Region of China, and Northeast China. In contrast, significant decreasing trends were observed in northern and western European Russia, scattered in Siberia, 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 of snow depth across China; for these, monthly snow depths tended to decrease in most stations. Compared with regions south of 50°N, changes in monthly mean snow depth were more significant over regions north of 50°N.

3.3 Variability of Snow Depth with Latitude, Elevation and Continentality

Topography is an important factor affecting 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 spatial variability of snow depth, we conducted a linear regression analysis of annual mean snow depth with latitude, elevation and continentality (Fig. 8). Snow depth is positively correlated with latitude, i.e., snow depth generally increases with latitude (Fig. 8a). The increase rate of snow depth was about 0.81 cm per 1°N across Eurasian continent. A closer relationship between latitude and snow depth was found in regions north of 40°N (Figs. 8a, d), where snow cover was relatively stable with number of annual mean continuous snow cover days of 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 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 found that snow depth increased with elevation in most regions north of 45°N (Fig. 8d)..

There was a statistically significant positive relationship between snow depth and continentality over Eurasian continent ($r=0.1$, $P \leqslant 0.05$, Fig. 8c). This indicated that the continentality may be not an important driving factor of snow depth distribution over Eurasia, especially on TP. Although the previous studies showed that the Tibetan Plateau's largest snow accumulation occurred in the winter, but the precipitation during winter months was the smallest of the year (Ma, 2008). This was mainly due to the majority of annual precipitation occurs during the summer monsoon season on TP which cause much less precipitation during winter half year (or snow accumulated season).

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 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 ($P \leqslant 0.05$), 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 the accumulated snowfall of <50 mm from November through March. Snow depth increased with increased accumulated snowfall increased, and the thickest snow depth of about 120 cm had the maximum cumulative snowfall of about 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. 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 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 lowered 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. 10b-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. 11). The significant negative correlation ($p \leqslant 0.05$) between snow depth and air temperature presented 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 correlation in northern Siberia (Fig 11b). It was because there was no obvious effect of increasing temperature on snow depth when the air temperature was below 0℃ in most areas of Siberia during December through March.

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, 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

Comparing our results with previous research across the Eurasian continent, we found that climatology of 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 on 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 (2012).

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 southern Siberia, however, it did not exist in northern Siberia. This may explain the difference in the results of these studies.

According with modeling studies of snow across Eurasia, the distribution patterns of snow cover were basically similar. Both observations in our research and simulations with the SnowModel (Liston and Hiemstra, 2011) presented the peak snow depth and SWE were more in the west of northern Eurasia than the west of the Russian Far East. However, compared with our results, the snow accumulations were overestimated on TP from phase 5 of the Coupled Model Intercomparsion Project (CMIP5) (Terzago et al., 2014, Wei and Dong, 2015) and underestimated in the northeast of China with the Reginal Climate Model version 4.0 (RegCM4) (Ji and Kang, 2013). It implied that large uncertainties still exist in the projection of snow cover changes in present days. The snow cover models should be improved, especially over the high elevation and forest areas in the future.

Snow depth is an important factor of controlling the ground thermal regime (Goodrich, 1982; Zhang et al., 1996; Zhang, 2005; Ling and Zhang, 2005). The research showed that thin snow cover resulted in cooler soil surface, while 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 significant influence on active layer depth in the following summer. In our results, snow depth significantly decreased on TP and increased in Siberia, which would inevitably accelerate the influence on permafrost freezing and thawing. We hope our research can provide an important reference for estimating the thermal regime of soil in these regions.

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 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 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, 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 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, Atmos.-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, Ambio, 40, 17-31. doi:10.1007/s13280-011-0212-y, 2011.

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. J., 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.

Goodrich, L.E.: The influence of snow cover on the ground thermal regime, Can. Geotech. J., 19, 421-432, 1982.

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.Y. and Rankova, E.Y.: Precipitation trends over the Russian permafrost-free zone: removing the artifacts of pre-processing, Int. J. Climatol., 21, 657-678, 2001.

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.

Ji, Z., and Kang, S.: Projection of snow cover changes over China under RCP scenarios, Clim. Dyn., 41: 589-600, 2013.

King, J. C., Pomeroy, J. W., Gray, D. M., Fierz, C., Fohn, P., Harding, R. J., Jordan, R. E., Martin, E., and Pluss, C.: Snow-atmosphere 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).
Ling, F. and Zhang, T.: Modeling the effect of variations in snowpack-disappearence date on suiface-energy balance on the Alaskan north slope, Arct. Antarct. Alp. Res., 37, 483-489, 2005.
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).

Wei, Z. and Dong, W.: Assessment of Simulations of Snow Depth in the Qinghai-Tibetan Plateau Using CMIP5 Multi-Models, Arct. Antarc. Alp. Res., 47, 611-625, 2015.

WMO: Guide to meteorological instruments and methods of observation, WMO-No.8, Geneva, Switzerland, 1996.

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., Osterkamp, T. E., and Stamnes, K.: Influence of the depth hoar layer of the seasonal snow cover on the ground thermal regime, Water Resour. Res., 32, 2075-2086, 1996.
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).
Zheng, L., Zhang, T., Che, T., Zhong, X., and Wang, K.: Evaluation of snow depth products derived from passive microwave satellite remote sensing data using ground-based snow measurements, Remote Sensing Technology and Application, 30, 413-423, 2015 (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 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

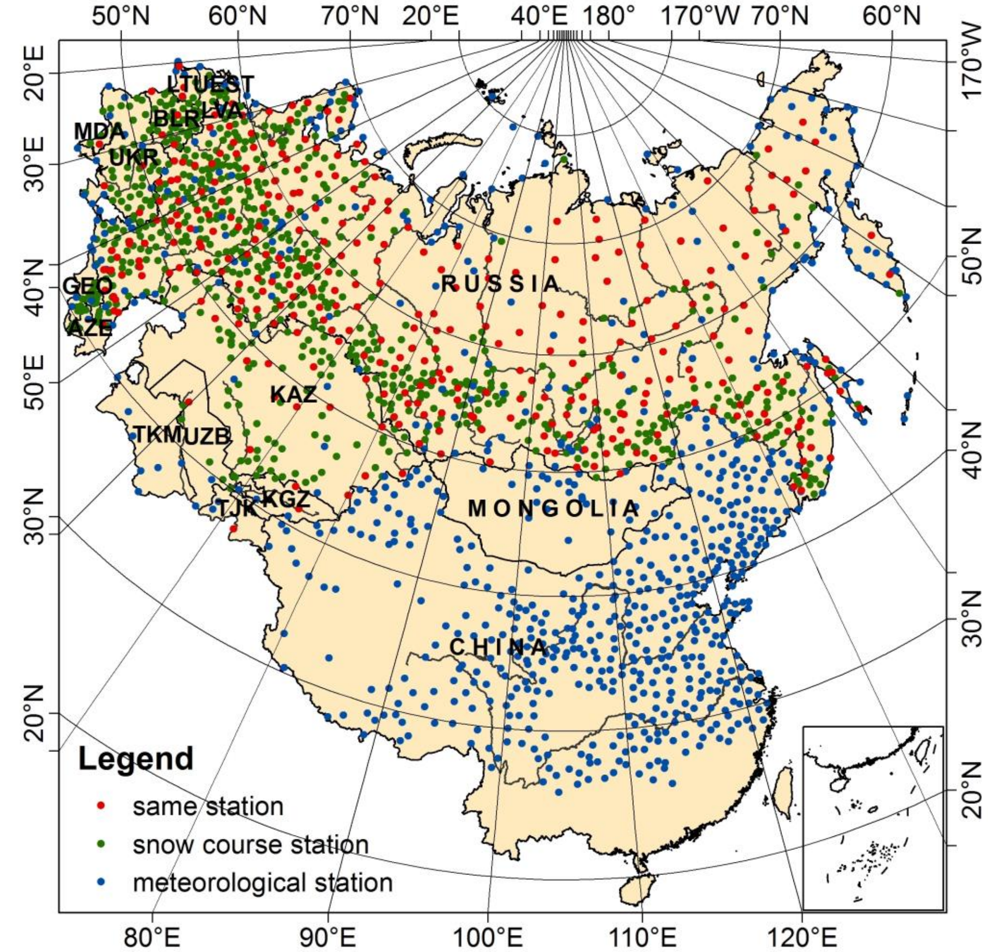


Figure 1. Geographical locations of meteorological and snow course stations across the Eurasian continent. The red triangles represent stations where snow depth was measured at both meteorological stations and snow course surveys, the green triangles show stations where snow depth was measured at snow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

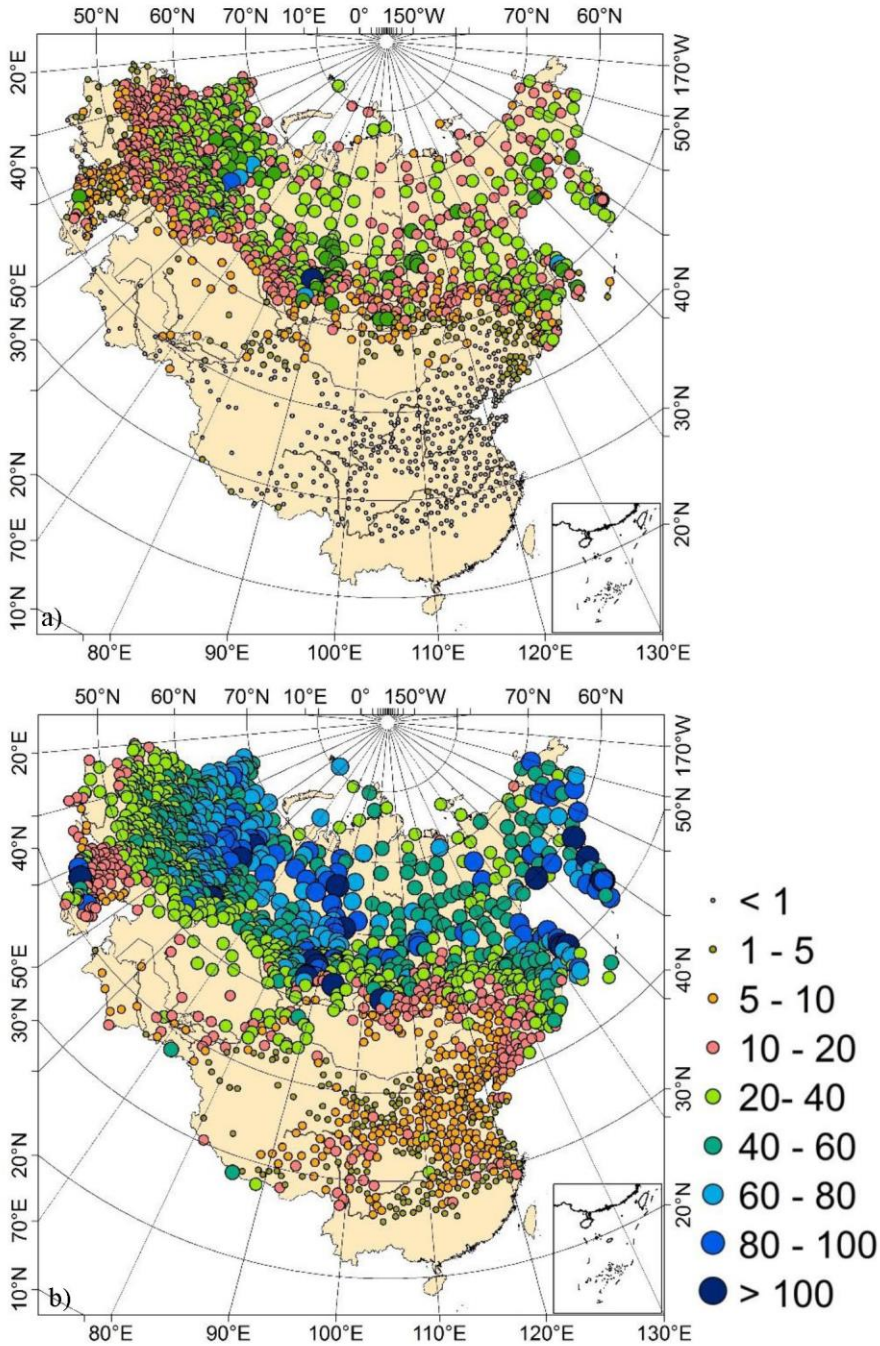
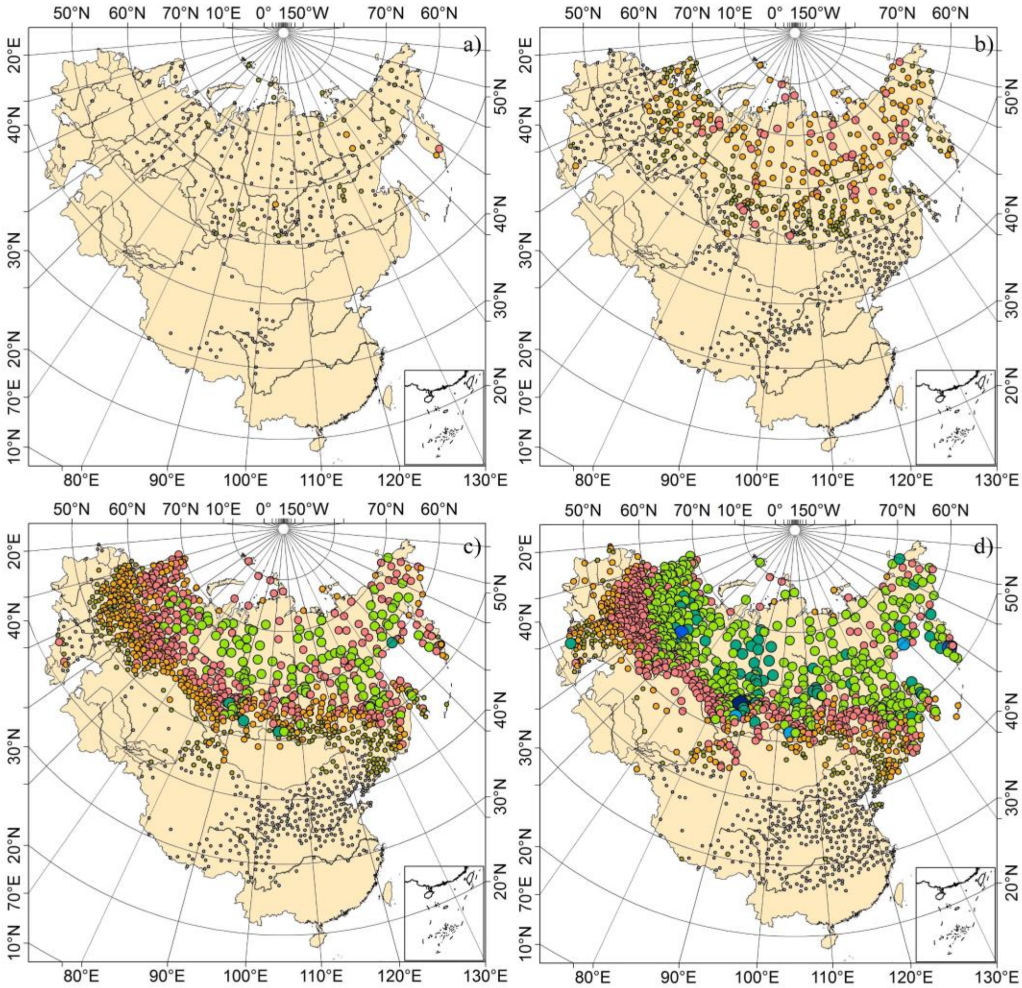


Figure 2. Annual mean snow depth (a) and maximum snow depth (b) across the Eurasian continent (cm) during 1966-2012.


a)
b)
c)
d)
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
20°E 40°N 30°N 20°N 70°E 10°N
50°N 40°N 30°N 20°N

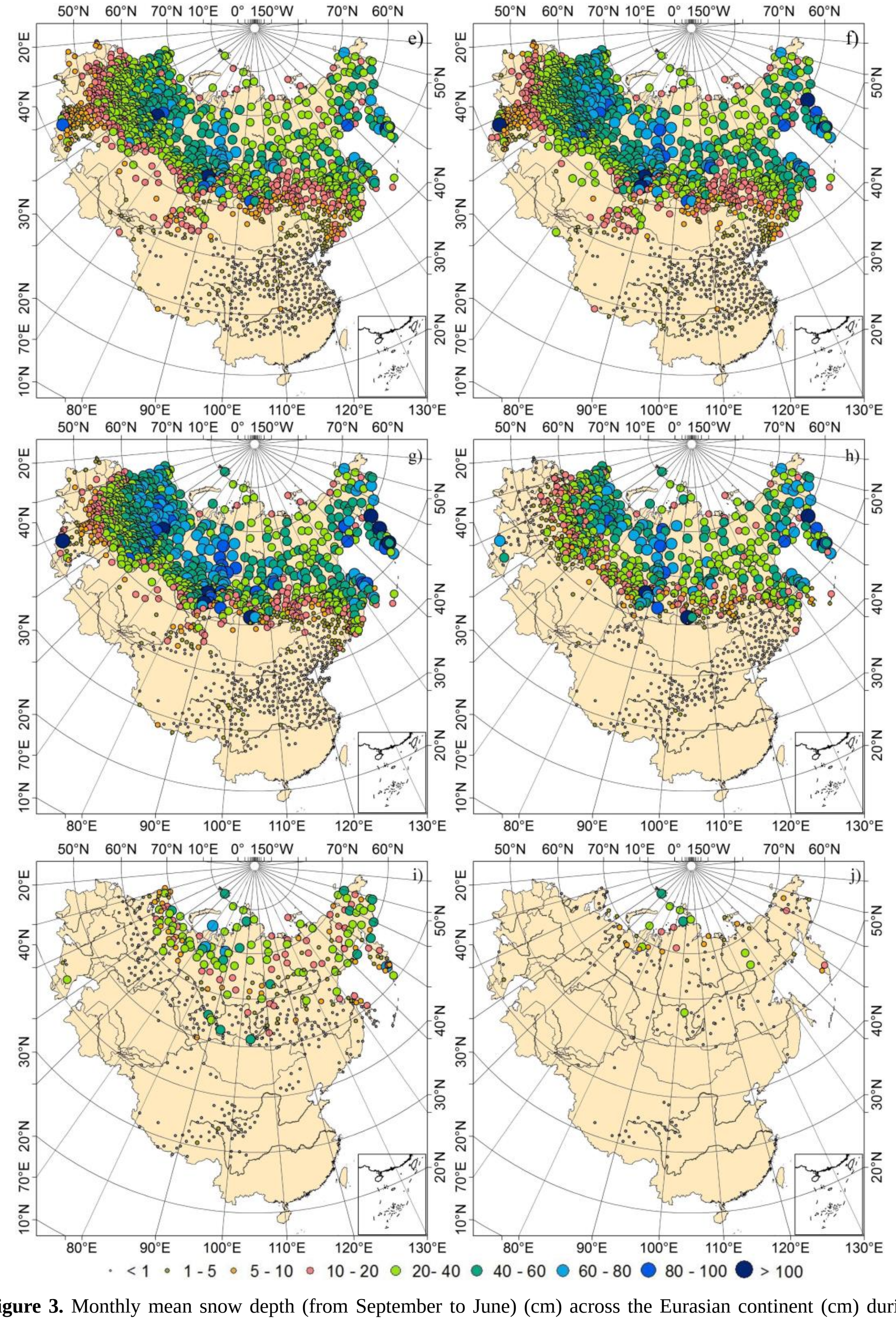


Figure 3. Monthly mean snow depth (from September to June) (cm) across the Eurasian continent (cm) during 1966-2012. (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, (i) May, (j) June.

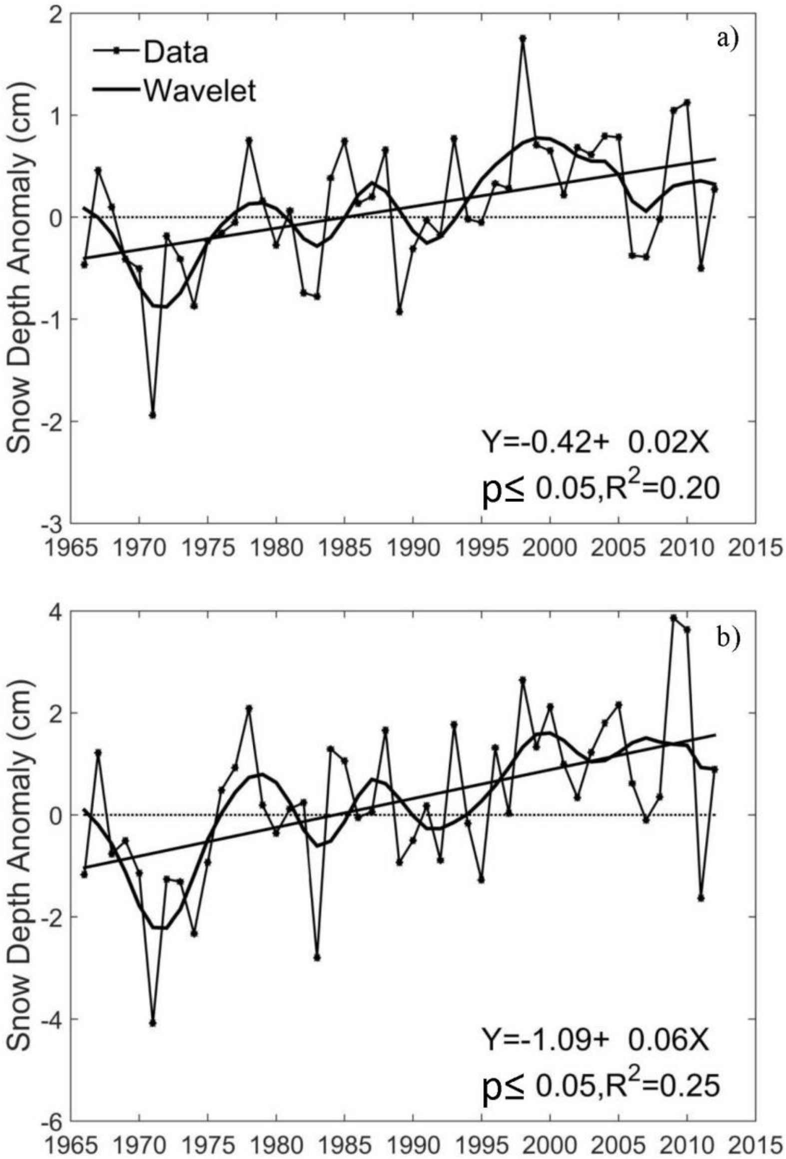


Figure 4. Composite of inter-annual variation of annual mean snow depth (a) and maximum snow depth (b) from 1966 through 2012 with respect to the 1971-2000 mean across the Eurasian continent. The line with dots is the anomaly of snow depth; the thick curve represents the smoothed curve using wavelet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

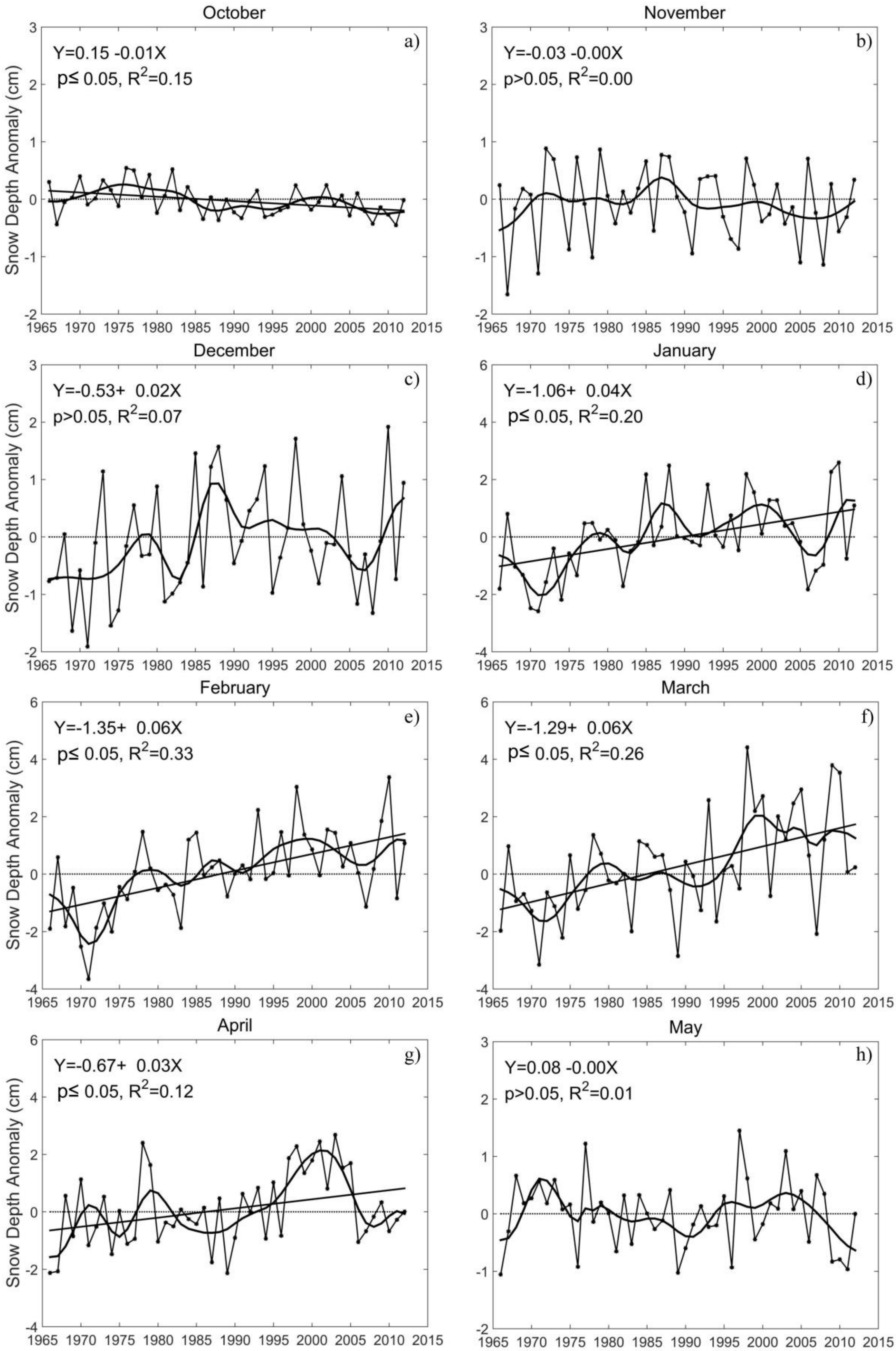


Figure 5. Composites of inter-annual variation of monthly mean snow depth (from October to May) from 1966

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.

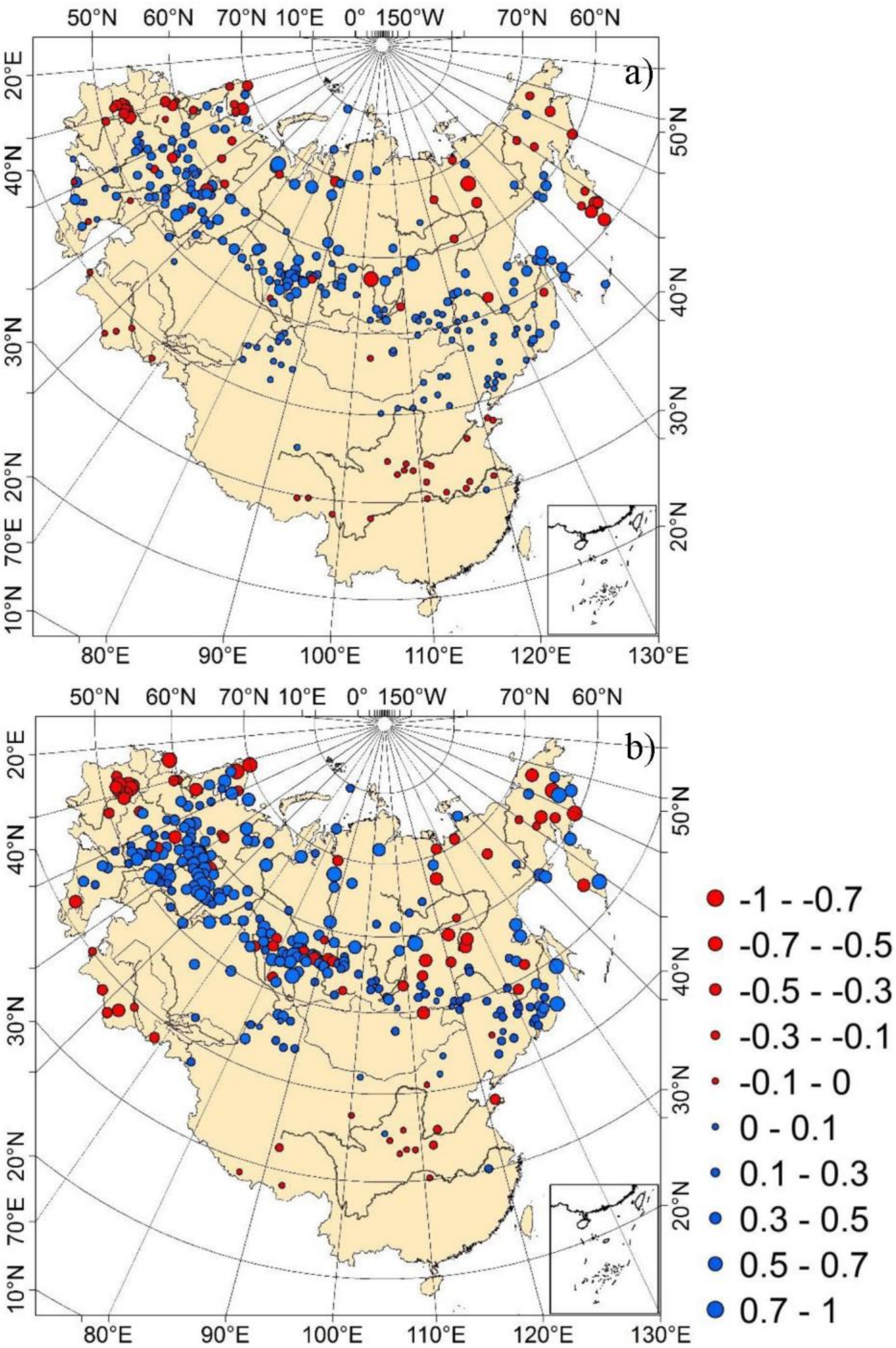
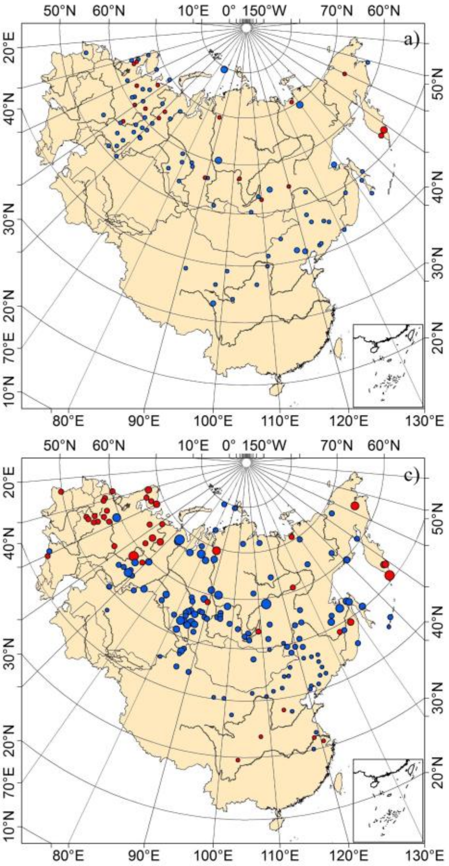


Figure 6. Spatial distribution of linear trend coefficients (cm yr^{-1}) of annual mean snow depth (a) and maximum snow depth (b) for each station in 1966-2012. The rate of change was at the 95% level. Red circles represent a decreasing trend, and blue circles represent an increasing trend.


a)
b)
c)
d)

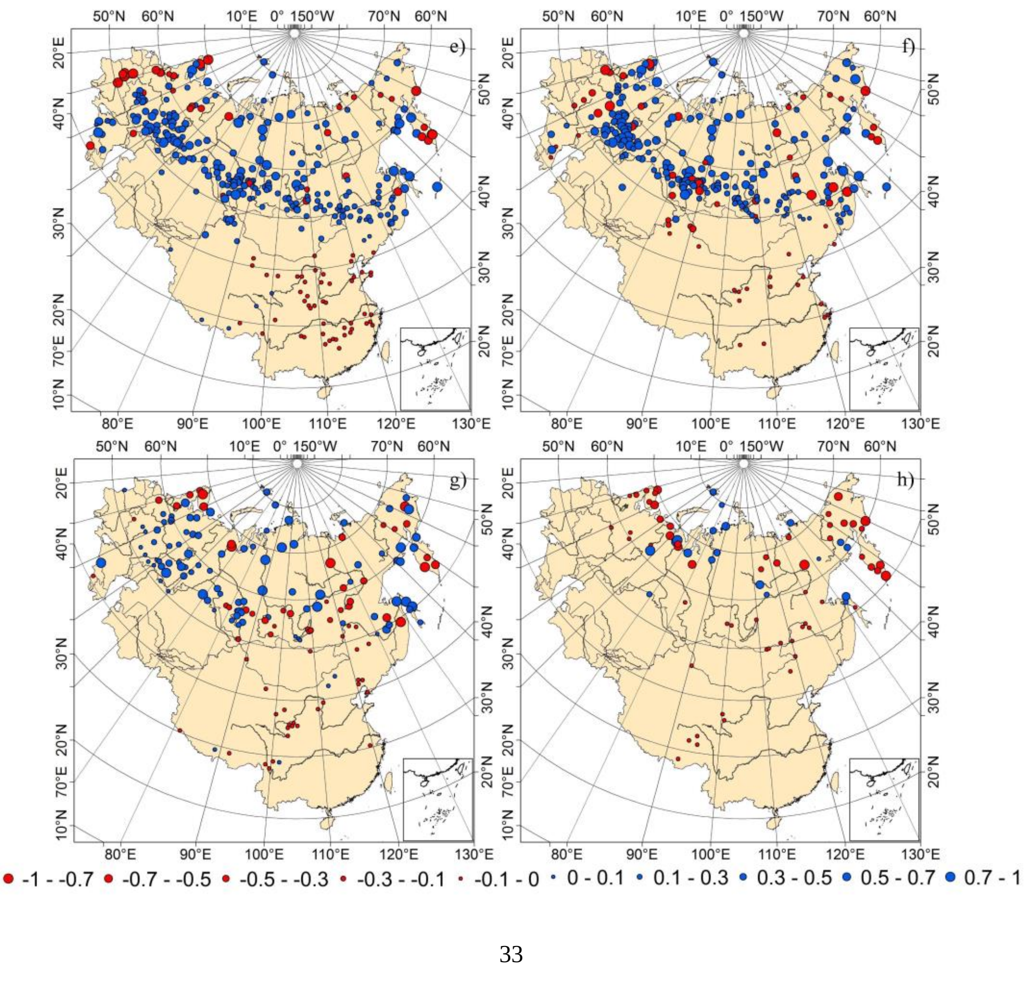

e)
f)
g)
h)
-1 - -0.7 -0.7 - -0.5 -0.5 - -0.3 -0.3 - -0.1 -0.1 - 0 0 - 0.1 0.1 - 0.3 0.3 - 0.5 0.5 - 0.7 0.7 - 1

Figure 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.

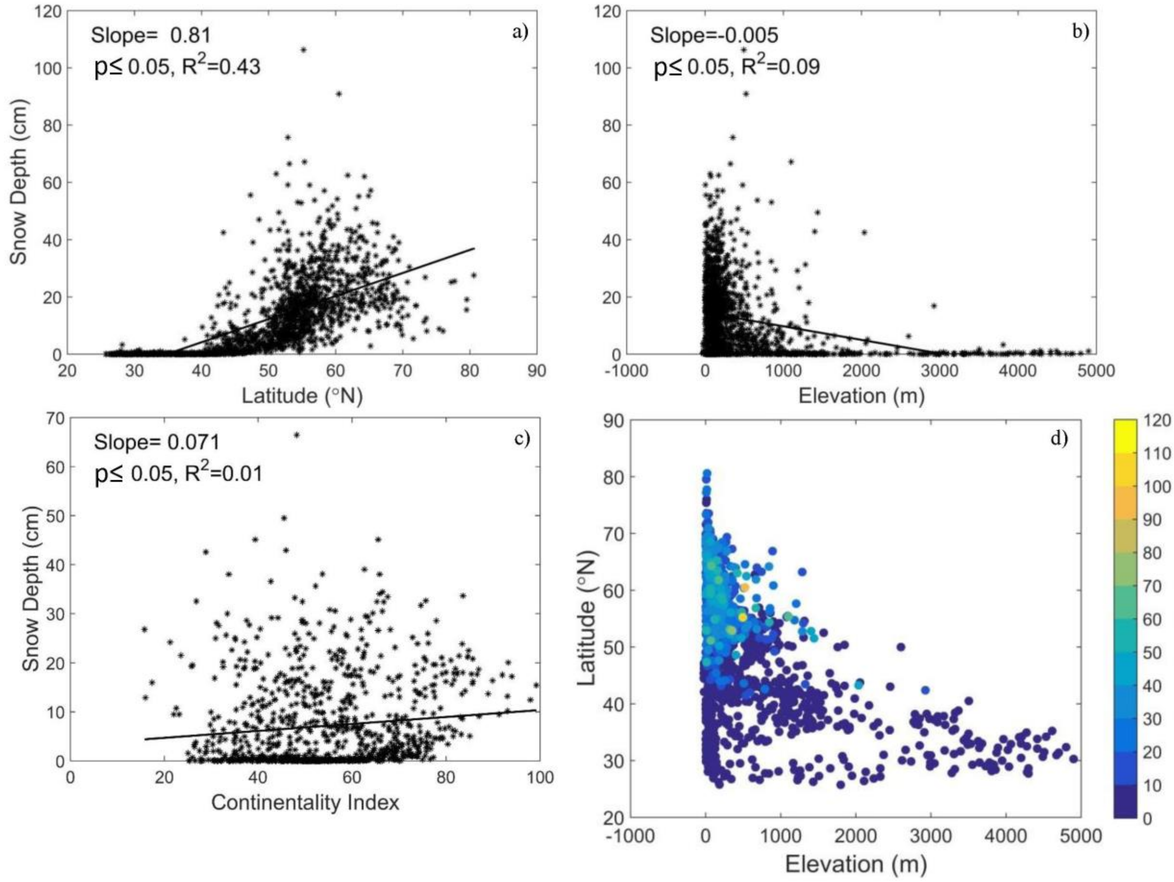


Figure 8. The relationship between annual mean snow depth and latitude (a), elevation (b) and continentality (c) for all stations across the Eurasian continent during 1966-2012. Asterisks show the mean snow depth of each station; the thick line is a linear regression trend; the different colors represent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

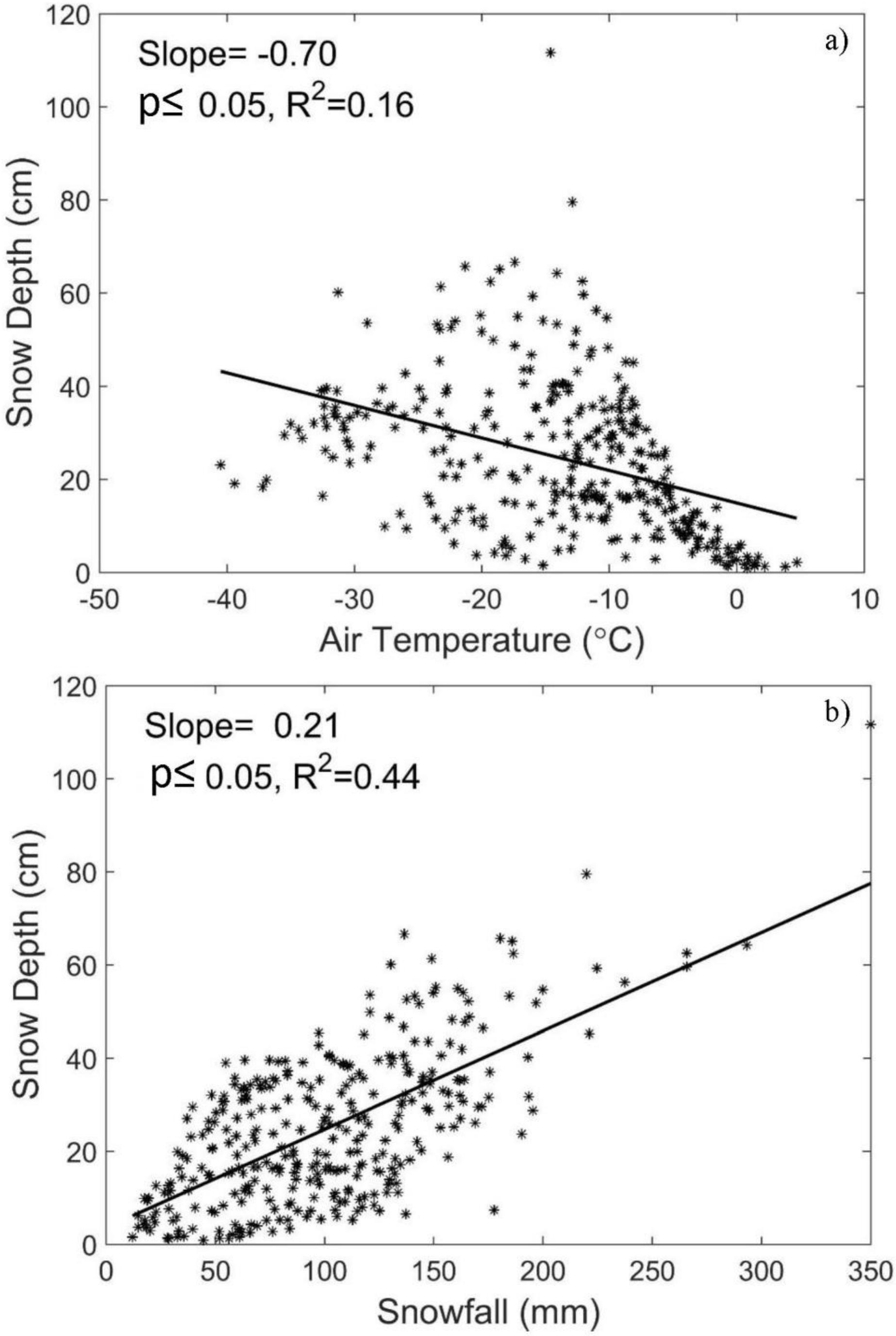


Figure 9. The relationships among annual mean snow depth, air temperature and snowfall for 386 stations from November through March during 1966-2009 over the USSR. The thick line is a linear regression trend.

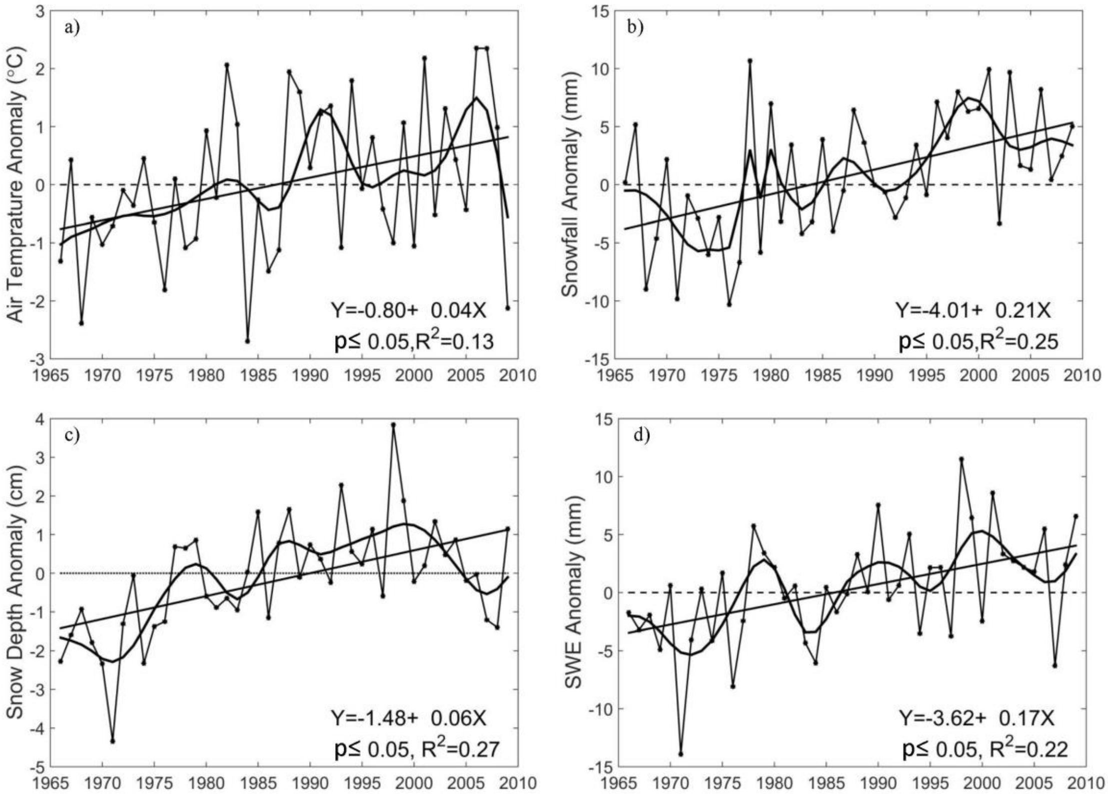


Figure 10. Composite of inter-annual variation of annual mean air temperature (a), annual snowfall (b), annual snow depth (c) and snow water equivalent (d) from November through March during 1966-2009 with respect to the 1971-2000 mean across the former USSR. The line with dots is the composite of the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

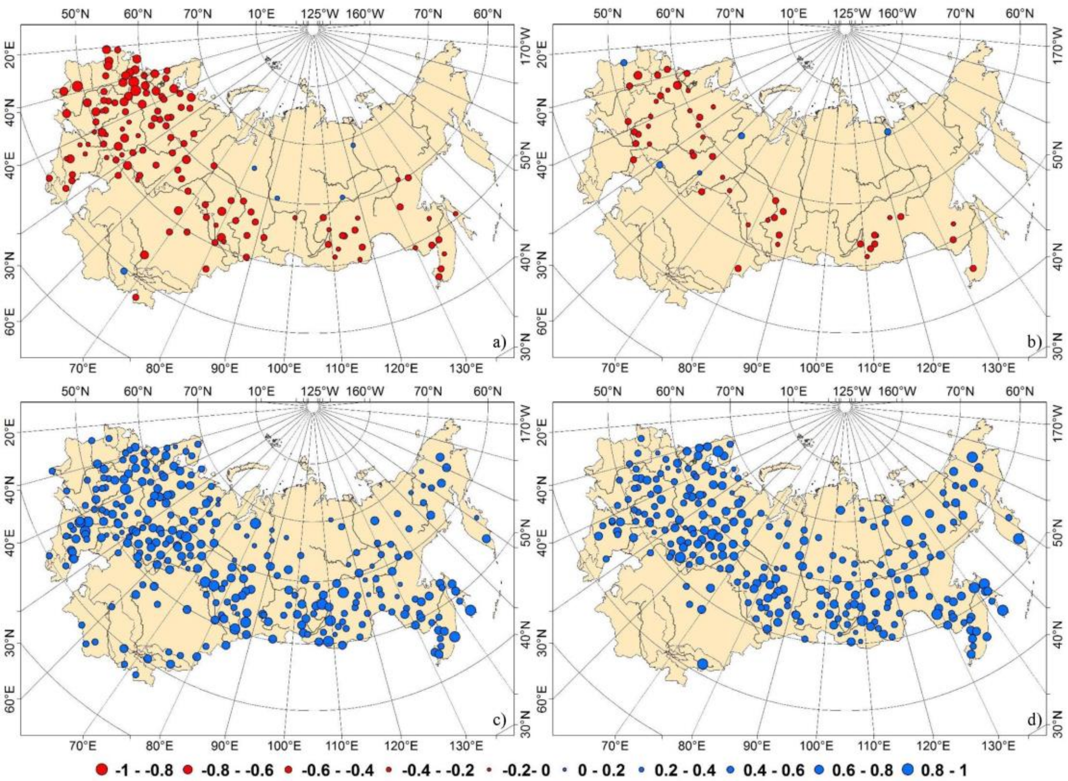


Figure 11. Spatial distributions of partial correlation coefficients of snow depth and air temperature (a), snow depth and snowfall (b), SWE and air temperature (c), SWE and snowfall from November through March during 1966-2009. The coefficients reaching to 0.05 confidence level are displayed. Red circles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