Review of “Snow density climatology across the former USSR”   tcd-7-3379-2013
By X. Zhong, T. Zhang, and K. Wang

Reviewer: M. Sturm

This paper uses station data from 1259 stations in Russia to look at snow density between 1969 and 2008. Density is a fundamental property of a snow cover. It is used to infer snow water equivalent (SWE), thermal conductivity, trafficability and so on. So this topic is important, and I would like to see the paper published. However it has three problems that are going to require effort on the part of the authors to correct before it is acceptable for publication. The good news is I think these problems can be corrected.

The first is that the authors have missed some good but old references in on snow density. A paper like this, which is fundamentally a retrospective paper, needs to be exhaustive in citing the prior literature. There is strong tendency today for researchers to look at the last published paper on a subject and use the references therein as the starting point for their work. The references are:

> Bilello, M. A. 1969. Relationships between climate and regional variations in snow-cover density in North America. CRREL Res. Rep. 267.
>
> Keeler, C. 1967. Some observations on the densification of alpine snow covers. CRREL Tech. Rep. 197.
>
> McKay, G. A., and B. F. Findlay, 1971: Variation of snow resources with climate and vegetation in Canada. Proc. 39th Western Snow Conf., Billings, MT, Western Snow Conference, 17–26.
>
> McKay, G. A. and D. M. Gray, 1981: The distribution of snowcover. In Handbook of Snow, 1st ed. D. M. Gray and E. D. H. Male, Eds., Pergamon Press, 153–190.

The second problem is that the text is basically a verbal description of the figures….so much so that eventually the reader (or at least this reader) gets numb and confused reading all the numbers and the trend values and so on in the text. The figures are really very good and a reader can glean most that information directly from them. What is utterly missing in the text is what I call the “discerning eye and mind of the scientist.” There is no such thing as data without errors and flaws, particularly data collected across a continent by a legion of unnamed, and probably grossly underpaid, technicians who patiently collected the data through such a turbulent period of Russian history. The text of this (or any paper) has to do more than just describe the results. It has to discuss and interpret them. The current “Discussion-Conclusion” section is nothing more than another Abstract. This data set really demands more. The authors need to think about what the results show and *why*.

Which leads to the final and most serious flaw: the densities presented overall are disturbing low…far lower than the general range of the 25,000 data we used in our recent study of bulk densities from the U.S. (Sturm, M., Taras, B., Liston, G. E., Derksen, C., Jonas, T., and Lea, J.: Estimating snow water equivalent using snow depth data and climate classes, J. Hydrometeorol., 11, 1380–1394,

2010) and lower than the approx. 200,000 data Brown used in his work in Canada. The density-time curves are also significantly lower than those from the classic work by MacKay and Findley (1971). Why? Is this real or an artifact of the way the data were collected and reduced? The authors need to think about this issue and discuss it, as everything else hinges on it. I think after introducing the data, there should be a discussion of the data accuracy today and stretching back through 1968. I realize that the authors did not collect the data, but from the current text I cannot even tell how the bulk density values were derived. I think for each measurement the authors had access to depth (h_s) and SWE (SWE). They then computed density from:

$$\rho_s = \frac{SWE \cdot \rho_i}{h_s}$$

where ρ is density and i indicates ice and s indicates snow. The point is that there is no discussion of the quality check/assurance for the data, nor how recent snowfalls can skew these bulk density computations. As a general rule, we tend to measure snow depth reasonably well, but there has been traditionally considerable problems with coring for SWE. In Sturm et al. (2010) there is a brief discussion of these issues. How were the Russian SWE values measured that are used in this study? A case in point is Figure 7 and there is a peculiar drop in density by almost 10% in 2000. I have difficulty even conceiving how the winter weather a cross a continent would have to change in order to manifest this way. On the other hand, I could well imagine that the Russians changed the core tubes their field people were using in 2000.

In spite of the three problems detasiled above, this is a paper that deserves to be published (once it is improved). For example, Figure 4 is fabulous. It should be turned into a movie so that we can watch how a continental scale snow cover densifies through the winter. Even if in revision, the densities need to be adjusted upward, the patterns shown here will still hold because they are relative. Likewise, Figures 7 and 8, if they can be shown to be reliable, suggest that something is changing in the snow cover over a vast continent. That is truly noteworthy finding.

So in conclusion, my recommendations to the editor and authors are:

1. Describe how the data were collected in more detail, do a serious analysis of how accurate and trustworthy the data are, and tell the readers what is found. Be a little skeptical of the data set.
2. Use the text to explore the data, explain what you see in it, not just the numbers. There are fascinating patterns in the data, potentially errors and false trends, possibly startling changes in hemispheric snow cover. Dig in and see if you believe your own data, then tell us (the readers) why we should or should not believe it as well.
3. Carefully compare the Russian data with past Russian data and comparable data from similar snow domains. Are they consistent or not? If not, why? Suggest adjustments if you think they are needed, otherwise some modeler will take what you publish and use it without ever knowing that it is possible too low. They will then prorogate the error forward.
4. Stick with it. A solid density climatology of Russia would be extremely useful and a paper on that topic would be a useful addition to the literature.

I have made more detailed comments in the pdf.

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Snow density climatology across the former USSR

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Abstract

Snow density is one of the basic properties used to describe snow cover characteristics, and it is a key factor for retrieving snow depth and snow water equivalent, which are critical for water resources assessment and modeling inputs. In this study, we used long-term data from ground-based measurements to investigate snow density climatology and its spatiotemporal variations across the former Soviet Union (USSR) from 1966 to 2008. The results showed that the long-term monthly mean snow density was approximately $0.194 \pm 0.046\,\mathrm{g\,cm^{-3}}$ over the study area. The maximum and minimum monthly mean snow density was $\sim 0.295\,\mathrm{g\,cm^{-3}}$ in June, and $0.135\,\mathrm{g\,cm^{-3}}$ in October, respectively. Maritime snow had the highest monthly mean snow density, while taiga snow had the lowest. The higher values of monthly snow density were mainly located in the European regions of the former USSR, in Arctic Russia, and in some regions of the Russian Far East, and the lower snow density occurred in central Siberia. Significant increasing trends of snow density from September through June of the next year were observed, however, the rate of the increase varied with different snow classes. The long-term (1966–2008) monthly and annual mean snow densities had significant decreasing trends, especially during the autumn months. Spatially, significant positive trends in monthly mean snow density lay in the southwestern areas of the former USSR in November and December and gradually expanded in Russia from February through April. Significant negative trends mainly lay in the European Russia and the southern Russia. Snow density decreased with elevation, at about $0.004\,\mathrm{g\,cm^{-3}}$ per 100 m increase in elevation. This same relationship existed for all snow classes except for maritime and ephemeral snow.

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 fluxes, moisture fluxes, hydrological processes, and atmospheric and oceanic circulations (Brown and Goodison, 1996; Armstrong and Brown, 2008; King et al., 2008). There are three basic properties used to describe snow cover: snow depth, snow density, and snow water equivalent (SWE). Snow density is a key factor for retrieving the other two factors (Armstrong and Brown, 2008). It is also one of the fundamental parameters for studying the hydrological cycle and for estimating snowmelt runoff, forecasting avalanches, using models, and assessing water resources (Margreth, 2007; Lazar and Williams, 2008).

Every winter, the average maximum terrestrial snow cover equals nearly 50×10^6 km^2, almost half of the land surface area in the Northern Hemisphere (Robinson et al., 1993; IGOS, 2007). Snow cover in Russia and Europe accounts for ~ 60 % of the total snow cover in the Northern Hemisphere (Barry et al., 1993). The former Soviet Union (USSR) is a critical region for snow investigations. Generally, most areas of the former USSR are covered by snow up to 4 or 5 months every year. Over the high Arctic Russia, snow cover starts from the early September and persists to the following June; up to 10 months each year. There are long-term and large-scale snow cover measurements and observations across the former USSR, with the first snow cover record dating back to 1881 in Latvia. These measurements are valuable data for snow cover studies.

Across the former USSR, snow cover characteristics, including snow density, are controlled by various environmental conditions. There have been many studies of snow cover extent, snow depth, snow cover duration, and SWE in the area (Robinson and Dewey, 1990; Gutzler and Rosen, 1992; Brown, 1997; Ye et al., 1998; Kitaev et al., 2005; Groisman et al., 2006; Bulygina et al., 2009), and of the relationship between snow cover and climatic change (Foster et al., 1983; Groisman et al., 1994; Clark et al., 1999; Robock et al., 2003; Matsumura and Yamazaki, 2012; Cohen et al., 2012; Peng et al., 2013). Mean SWE has also been estimated ~~by~~ the monthly mean snow depth, snow cover extent, and an assumed monthly mean snow density over much of southern Canada for the period from 1964 to1993 (Brown and Goodison, 1996).

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Kershaw (2001) analyzed the variation in snow density in Canada and the relationship between an altered wind regime and snow depth and SWE. Roebber et al. (2003) found that snowfall could be forecasted by determining snow density. Sturm et al. (2010) presented a method of obtaining SWE from snow depth by estimating the bulk density of snow.

There have been few studies, however, on climatology and the variability of snow density on a regional basis. Williams and Gold (1958) presented the variation of snow density across Canada, and the relationship between snow density and meteorological variables, particularly wind velocity and air temperature. Yang et al. (1992) analyzed the spatiotemporal distribution of snow density at the source area of the Urumqi river (China), and identified the relationship between snow density and snow depth. Observations indicate that there was a significant positive correlation between snow density and precipitation, snow depth, and wind velocity in Xinjiang, China (Huang et al., 2007). Dai and Che (2011) analyzed the temporal and spatial distribution of snow density across China in 1999–2008, and showed that snow depth was the primary influence on snow density. Ma and Qin (2012) presented the spatiotemporal changes in snow density across China.

Snow density can be calculated using measured snow depth and SWE. Snow depth and SWE can be obtained from ground meteorological stations or snow course sites, and can be estimated from Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave/Imager (SSM/I) data. Although satellite data enrich the snow data that cannot be monitored by ground stations at high altitudes, the accuracy of these data is affected by clouds, underlying surface conditions, and the inversion algorithm. In contrast, ground-station snow data could provide for more accurate and longer time-series generation. Therefore, ground station data are key to analyzing climatology and the variability of snow density.

The objective of this study is to provide a detailed description of snow density and to investigate the variability in snow density on a regional basis across the former USSR from 1966 to 2008. Our aim is to improve the understanding of snow density climatology and its variation over the former USSR, to analyze the probability distribution function (PDF) of snow density, and to discuss the relationships between snow density and elevation.

2 Data and methodology

2.1 Snow density

Our analyses are based on monthly mean snow density. Daily snow density is computed using the measured daily snow depth and SWE at snow course stations, and then daily snow density is used to create an average monthly mean snow density for each station.

We used two snow density datasets from 1259 snow stations in the former USSR (Table 1). One is from the Russian Research Institute for Hydrometeorological Information-World Data Center (RIHMI-WDC, http://meteo.ru/), which has a total of 517 meteorological stations of Russia. In this dataset, measurements were performed throughout the entire period from 1966 to 2009. The other dataset used in this study is from the National Snow and Ice Data Center (NSIDC, http://nsidc.org/), University of Colorado at Boulder. This dataset includes 1319 snow course sites in the former Soviet Union, and the historical records span the period from 1966 to 2000. Both of the datasets include routine snow surveys that ran throughout the cold season (every 10 days) and during snowmelt (every 5 days). Routine snow surveys contain snow depth, snow density, ice crust thickness, thickness of saturated snow and the water layer, snow water equivalent, total water storage, snow cover features, and snow structure. Snow surveys ran across all environmental types of sites for 1 to 2 km in fields (open terrain) and forest. Snow depth was measured each 10 m in the forest and each 20 m in open areas; a more comprehensive measurement of all attributes such as snow depth, snow water equivalent, snow density, fractional snow covered area, etc. was made every 100 m in the forest and every 200 m in fields.

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We computed the probability distribution function (PDF) of snow density, which is the ratio between the sample data and the total snow density data. All snow densities are arranged in ascending order, and then divided equally into 30 brackets. The sample is the number of data point within a given density bracket, and the total data is the total number of data for all ground stations.

We define the period from 1 September to 31 August of the following year as a snow cover year. From September to November, new and/or fresh snow appears across the former USSR; we define this as the snow cover formation period. There is a steady and slow increase in snow density from December to February, so these months are defined as the stable period (Huang et al., 2007). March to June show obvious fluctuations in snow density, and these months are known as the unstable period of snow cover (Huang et al., 2007). Over the whole of the former USSR, the longest snow cover duration was recorded on the coast of north Russia, where snow cover first appears in early September and ends in late June of the following year. Based on this, we used snow density data from September to June in our research. We collected data from 1259 unique snow course stations across the former USSR, including geographical attributes such as longitude, latitude, and elevation, during the period from 1966 through 2008. Figure 1 shows the locations of stations used in the study.

2.2 Snow classes

Sturm et al. (1995) categorized the world's seasonal snow cover into six classes (tundra, taiga, alpine, maritime, prairie, and ephemeral snow) based on their physical properties, and then empirically related these to climate using three variables (precipitation, wind, and air temperature). A vegetation proxy was used for wind data: tall vegetation equaled low wind, and short vegetation equaled high wind.

In our study, we investigated changes in snow density over each snow class. Based on the seasonal snow cover classification system proposed by Sturm et al., the Global Seasonal Snow Classification System dataset is established. Figure 1 shows the distribution of snow classes over the former USSR with the dataset (Sturm et al., 1995) (data

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provided by the National Center for Atmospheric Research-Earth Observing Laboratory (NCAR/EOL), http://data.eol.ucar.edu/). The snow classification data are formatted into an array of integers, each value representing a 0.5° latitude by 0.5° longitude cell. The total snow cover extent in the former USSR is approximately $21.34 \times 10^6\,\mathrm{km}^2$, of which tundra, taiga, and prairie snow account for ~ 87 % (Fig. 2).

3 Results

3.1 Climatology of snow density

Figure 3 shows daily mean snow density at all stations from September through June. The maximum daily mean snow density was ~ $0.46\,\mathrm{g\,cm^{-3}}$, and the minimum value was $0.08\,\mathrm{g\,cm^{-3}}$. Overall, daily snow density increased across the former USSR, at a rate of ~ $0.0004\,\mathrm{g\,cm^{-3}\,day^{-1}}$. In early September, there was higher snow density on some days due to fresh snow melting with the high air temperature. Daily mean snow density gradually increased with time until late February. There was a significant fluctuation of snow density between March and April: increasing on some days, while decreasing on others (affected by snow melt and new snowfall). From May to June, daily snow density increased sharply.

There is obvious monthly characteristic in snow density across the former USSR (Fig. 4). The highest values of monthly snow density were mainly located in the European part of the former USSR, in Arctic Russia, and some regions of the Russian Far East. In contrast, the lowest snow density was found in central Siberia. There were few ground stations with snow in September, and sites were mainly located in Russia and some regions of Kazakhstan. Most of the monthly snow density values were less than $0.20\,\mathrm{g\,cm^{-3}}$, but the sites with values ranging from 0.20 to $0.40\,\mathrm{g\,cm^{-3}}$ were located in the northeast of the Russian Far East, the south of western Siberia, and the central areas of European Russia. From October to November, the number of stations with snow gradually increased, and monthly snow density became higher. Most snow

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density mainly ranged from 0.10 $g\,cm^{-3}$ to 0.20 $g\,cm^{-3}$. The stations with snow density greater than 0.2 $g\,cm^{-3}$ appeared in the European areas of the former USSR in October, and on the coast of northern Russia and in the Russian Far East in November.

In the stable period of snow cover, snow density was greater than in autumn months. Most monthly snow density measurements ranged between 0.15 $g\,cm^{-3}$ and 0.30 $g\,cm^{-3}$; they were higher in the northeast of the Russian Far East and on the coast of Arctic Russia (> 0.30 $g\,cm^{-3}$). The highest snow density was 0.44 $g\,cm^{-3}$ in January in Uzbekistan. However, the range of extremes of monthly snow density decreased in February, from < 0.10 $g\,cm^{-3}$ to 0.38 $g\,cm^{-3}$, which was due to new snow with low density in some stations at the end of February.

High temperature led to snow melt, which increased the snow density during the unstable period. Monthly snow density ranged between 0.20 $g\,cm^{-3}$ and 0.35 $g\,cm^{-3}$ in March, with values above 0.35 $g\,cm^{-3}$ in most areas of European Russia and on the coast of northern Russia, while snow density values were low in central Siberia and in some regions of the Russian Far East (0.01–0.20 $g\,cm^{-3}$). In April, monthly snow density continued to increase, with most values ranging from 0.25 $g\,cm^{-3}$ to 0.40 $g\,cm^{-3}$. Compared with March, the number of sites with snow density > 0.40 $g\,cm^{-3}$ increased, with a range was 0.20 to 0.30 $g\,cm^{-3}$ in Central Siberia. In May, there were significantly less sites with snow, and these were mainly located in Russia. There were obviously increasing trends in monthly snow density in Russia. The highest snow density was 0.54 $g\,cm^{-3}$ in central European Russia. However, snow density decreased in some areas of the southwestern portion of the former USSR. This was due to old snow melting, new snow appearing, and the proportion of new snow being larger than old snow. A few stations located in the northern areas of Russia, the south of central Siberia, the northeast of the Russian Far East reported data in June. The maximum monthly snow density value across the 10 month study period ranged between 0.30 $g\,cm^{-3}$ and 0.50 $g\,cm^{-3}$.

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3.2 Variability of snow density

Figure 5 and Table 2 show monthly mean snow density during the period from 1966 to 2008 across the entire former USSR. There were significant monthly and seasonal changes in snow density. The average snow density was approximately $0.194 \pm 0.046\,\mathrm{g\,cm^{-3}\,month^{-1}}$. The maximum long-term monthly mean snow density of $\sim 0.295\,\mathrm{g\,cm^{-3}}$ occurred in June during snowmelt season, while the minimum was $\sim 0.135\,\mathrm{g\,cm^{-3}}$ in October, with mostly fresh snow. The largest standard deviation of snow density from its long-term monthly mean was $\sim 0.066\,\mathrm{g\,cm^{-3}}$ in May, with a mixture of new and old snow across the entire study area. The minimum standard deviation of $\sim 0.035\,\mathrm{g\,cm^{-3}}$ occurred in September, indicating relatively uniform fresh snow across the region. There is a general trend of increasing monthly mean snow density from September through June of the next year (Fig. 5) with an average rate of $\sim 0.015\,\mathrm{g\,cm^{-3}}$, which is basically consistent with the daily increase rate as shown in Fig. 3. Monthly mean snow density increases with time demonstrate that as snow becomes mature and old, snow density becomes higher due to the complicated snow densification processes. From September through November, monthly mean snow density was lower than $0.15\,\mathrm{g\,cm^{-3}}$, indicating new and/or fresh snow across the region. From December to February, monthly snow density increased gradually from $\sim 0.170\,\mathrm{g\,cm^{-3}}$ in December to $\sim 0.201\,\mathrm{g\,cm^{-3}}$ in February. Snow density was influenced by cold temperature and wind, which compacted the snow layer and caused high snow density. In the spring months (the unstable period), snow density fluctuated. From March to April, monthly snow density decreased to $\sim 0.204\,\mathrm{g\,cm^{-3}}$, probably due to more new spring snow over the old snow cover. Monthly mean snow density increased rapidly in May and June to $0.295\,\mathrm{g\,cm^{-3}}$. This is mainly because snow began to melt with increasing air temperature, and the meltwater infiltration led to a sharp increase in monthly snow density in May and June.

For the six snow classes, the maximum long-term monthly mean snow density was observed in maritime snow, $\sim 0.241 \pm 0.032\,\mathrm{g\,cm^{-3}}$, and the minimum value of

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$0.173 \pm 0.043\,\mathrm{g\,cm^{-3}}$ per month was seen in taiga snow. The long-term monthly mean snow density of the six snow classes also changed significantly with the seasons (Fig. 6). The variation in monthly snow density for tundra snow and taiga snow were consistent with the trend across all data. This was mainly because the areas of tundra snow and taiga snow accounted for more than 60 % of the total area across the former USSR, and the sample data points of the two snow classes accounted for $\sim 40\,\%$ of all data points. During the initial snow cover period (September–November), monthly snow density of the two snow classes were lower compared with other months, due to new snow with low snow density. The minimum long-term monthly snow density appeared in October for tundra snow ($0.129\,\mathrm{g\,cm^{-3}}$) and taiga snow ($0.117\,\mathrm{g\,cm^{-3}}$). With the increase in the amount of snow cover and snow depth, and weak solar radiation, in the winter months, snow layers were gradually compacted by overlying snow and strong winds, and thus snow density increased. From autumn to winter, the monthly mean snow density of tundra snow and taiga snow increased by $\sim 0.107\,\mathrm{g\,cm^{-3}}$ and $0.076\,\mathrm{g\,cm^{-3}}$, respectively. Monthly snow density declined from March to May. This may be attributed to the emergence of new snow with the increase in precipitation in the unstable period of snow cover, which resulted in a decrease in snow density. However, the higher air temperatures during this period caused snowmelt, and sharply increased the monthly average snow density in June. Therefore, the maximum long-term monthly mean snow density, $0.286\,\mathrm{g\,cm^{-3}}$ for tundra snow and $0.248\,\mathrm{g\,cm^{-3}}$ for taiga snow, appeared in June. The maximum standard deviation of snow density from its long-term monthly mean occurred in April for tundra snow ($0.066\,\mathrm{g\,cm^{-3}}$), and in June for taiga snow ($0.075\,\mathrm{g\,cm^{-3}}$). There was a large fluctuation in the snow density of new and old snow in these months for the two snow classes. In contrast, the minimum ($0.035\,\mathrm{g\,cm^{-3}}$ and $0.027\,\mathrm{g\,cm^{-3}}$) snow density was in September and December for tundra snow and in January and February for taiga snow, indicating that snow density of fresh or mature snow was relatively steady in these sites.

The trends of monthly mean snow density for maritime, ephemeral, prairie, and alpine snow had similar variability: there was a significant increase in monthly snow density as the season progressed from September to June. The maximum long-term monthly snow density was observed in June, and the minimum value occurred in autumn, except for ephemeral snow. There were no snow density records for ephemeral snow in September and June; its maximum was $\sim 0.435\,\mathrm{g\,cm^{-3}}$ in May, with a minimum of $0.130\,\mathrm{g\,cm^{-3}}$ in October and December. The largest standard deviation of snow density was found in prairie snow, $0.058\,\mathrm{g\,cm^{-3}}$, which meant there was significant variation in monthly snow density for this snow class. From September to November, there was a lower monthly snow density for the four snow classes due to fresh snow across the regions. In the stable period of snow cover, monthly snow density increased slowly because of snow densification processes. However, there was a sharp increase in snow density from March to June: monthly snow density increased by $0.212\,\mathrm{g\,cm^{-3}}$ for maritime snow, $0.242\,\mathrm{g\,cm^{-3}}$ for ephemeral snow, $0.118\,\mathrm{g\,cm^{-3}}$ for prairie snow, and $0.074\,\mathrm{g\,cm^{-3}}$ for alpine snow. These increases were caused by snowmelt penetrating to the bottom of the snow layer and by less new snow.

The long-term maximum annual mean snow density across the former USSR from 1966 through 2008 was $\sim 0.236\,\mathrm{g\,cm^{-3}}$ in 1975 and the minimum was $0.198\,\mathrm{g\,cm^{-3}}$ in 2000 (Fig. 7). From the mid-1960s to the late 1990s, there was a slow decrease in annual mean snow density; decreasing by $\sim 0.014\,\mathrm{g\,cm^{-3}}$ at a rate of about $-0.0004\,\mathrm{g\,cm^{-3}}$ per year. From the late 1990s to the early 2000s, the mean decreased sharply by $\sim 0.02\,\mathrm{g\,cm^{-3}}$, at a rate of $\sim 0.0054\,\mathrm{g\,cm^{-3}\,yr^{-1}}$, which was more than 13 times greater than the rate from the mid-1960s to the late 1990s. After the early 2000s, annual mean snow density increased, at a rate of $0.0013\,\mathrm{g\,cm^{-3}\,yr^{-1}}$, but it was far less than its long-term mean value.

The long-term annual variation of monthly snow density is presented in Fig. 8. There were annual decreasing trends of monthly snow density from September to May, and the trends were statistically significant at $> 95\,\%$. In September, the maximum annual mean snow density was $\sim 0.293\,\mathrm{g\,cm^{-3}}$ in 1974, and the minimum was $0.093\,\mathrm{g\,cm^{-3}}$ in 2007. There was a decreasing trend over time, with a rate of $0.0009\,\mathrm{g\,cm^{-3}\,yr^{-1}}$. For the period from the late 1960s to the mid-1970s, annual mean snow density was generally above its long-term average. An obvious increasing trend occurred during this period, with a rate of 0.0091 $g\,cm^{-3}\,yr^{-1}$. Thereafter, there was a rapid decrease until the early 1980s. Monthly snow density was mostly below its long-term mean from the late 1970s to the late 2000s.

Similar variation in annual mean snow density appeared in October and November. The annual mean maximum was ~ 0.214 $g\,cm^{-3}$ in 1971 for October, and 0.202 $g\,cm^{-3}$ in 1970 for November. The minimum value was 0.104 $g\,cm^{-3}$ in 2001 and 0.132 $g\,cm^{-3}$ in 2003, respectively. For the period from 1966 to the early 1970s, annual mean snow density increased slightly, and the value was above the long-term mean snow density. However, it sharply decreased from the late 1970s to the late 2000s. The rate of decrease was ~ 0.0013 $g\,cm^{-3}\,yr^{-1}$ and 0.0012 $g\,cm^{-3}\,yr^{-1}$, respectively.

Compared with the autumn months, the interannual variability of snow density significantly decreased from December to May, and was lower than 0.001 $g\,cm^{-3}\,yr^{-1}$. In December and January, the annual mean maximum of snow density was 0.213 $g\,cm^{-3}$ and 0.225 $g\,cm^{-3}$ in 1973, and the minimum was 0.157 $g\,cm^{-3}$ in 2001and 0.166 $g\,cm^{-3}$ in 2008, respectively. For the period from the mid-1960s to the late 1980s, the annual mean snow density was generally above its long-term mean value, and there was a stable trend in December and January. However, for the period from 1990s to the late 2000s, annual mean snow density was below its long-term mean value, showing an obvious decreasing trend, with a rate of about −0.0009 $g\,cm^{-3}\,yr^{-1}$ in December and −0.0008 $g\,cm^{-3}\,yr^{-1}$ in January. The annual mean maximum of snow density occurred in February in 1973 (0.243 $g\,cm^{-3}$), but it was 0.259 $g\,cm^{-3}$ in March in 1994. The minimum value in these two months recorded in 2005 was 0.199 $g\,cm^{-3}$ and 0.189 $g\,cm^{-3}$, respectively. From 1966 to the mid-1990s, the annual mean snow density in these two months fluctuated, while after the late 1990s, it showed a significant decrease, with a rate of 0.0014 $g\,cm^{-3}\,yr^{-1}$ and 0.0008 $g\,cm^{-3}\,yr^{-1}$, respectively. However, it increased from the early 2000s to the late 2000s in March. The interannual variability of snow density was smaller in April and May, ~ 0.0002 $g\,cm^{-3}\,yr^{-1}$. In April, the trend of change in annual mean snow density was stable over the period from the mid-1960s to the mid-1980s, and then it presented a fluctuant trend. There was a stable trend in May from 1966 to the mid-1970s, while then it fluctuated.

Figure 9 shows the spatial distributions of linear trend coefficients of monthly mean snow density for each station during 1966 through 2008. In November, the positive trends were mainly presented in the southwestern areas of the former USSR. The decreasing trends in changes of monthly mean snow density lay in most regions of the European Russia, the south of western and central Siberia. The maximum values of increasing and decreasing linear trends were $\sim 0.008\,\mathrm{g\,cm^{-3}\,yr^{-1}}$ and $-0.010\,\mathrm{g\,cm^{-3}\,yr^{-1}}$, respectively.

From December through February, the positive trends gradually reduced in the southwest of the former USSR, but they were found in some regions of the European Russia, and the southern areas of Russia. The significant increases were found on the coast of the Arctic Russia. In contrast, the negative trends in monthly mean snow density decreased slightly in the European Russia and in the south of western Siberia and the significant decreases lay in the northwest of the former USSR. The extreme linear trend coefficients were $\sim 0.01\,\mathrm{g\,cm^{-3}\,yr^{-1}}$ in February and $-0.01\,\mathrm{g\,cm^{-3}\,yr^{-1}}$ in December.

In the spring months (March and April), there were significant increasing trends in monthly snow density, and they were found in most areas of Russia. The decreasing trends mainly lay in the southwest of the European Russia and the east of Kazakhstan in March, and some regions of the southern Russia in April. The stations with rates of changes in monthly mean snow density were at greater than 95 % significant level decreased obviously in April, and most located in Russia.

3.3 Probability distribution function of snow density

The probability distribution function (PDF) can be used to indicate the distribution of snow density occurrence and changes in distribution of snow density with time. We calculated the PDF of snow density from 0.01 to $0.60\,\mathrm{g\,cm^{-3}}$, and the result showed that snow density exhibited a nearly symmetrical distribution. Then, in order to verify the density distribution was a normal distribution, we simulated the normal distribution

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of snow density with an approximate statistical method: all snow density data values were ranged by ascending order and were divided into 30 brackets, then specific data points were selected from observations to fit the probability distribution, such as the midpoint and the computed mean of each interval, and the approximate solutions were obtained. The fitting result showed that the PDF of snow density fit with the normal distribution. PDFs of snow density for all data and each snow class across the former USSR are shown in Figs. 10 and 11.

It can be seen from Fig. 10 that the mean snow density from all data was 0.23 $g\,cm^{-3}$, with a standard deviation of ~ 0.07 $g\,cm^{-3}$. The peak PDF was 0.12, which accounted for ~ 12 % of the total number of snow density measurements from all snow course stations. The corresponding snow density ranged from 0.18 to 0.20 $g\,cm^{-3}$. The credibility intervals indicated that 95 % of all snow density values lay between 0.11 $g\,cm^{-3}$ and 0.38 $g\,cm^{-3}$.

There were significant similarities in the spectrum distribution, mean value, peak PDF, and credibility intervals of snow density for tundra and taiga snow (Fig. 11). The mean snow densities of the two snow classes was ~ 0.22 $g\,cm^{-3}$ and 0.21 $g\,cm^{-3}$, respectively, which were smaller than the value of all snow densities, and they had the same standard deviation of 0.06 $g\,cm^{-3}$. The range was ~ 0.18 to 0.20 $g\,cm^{-3}$ at the maximum frequency distribution of snow density, the same as the result for all data, accounted for 14 %. The range (2.5–97.5 % of snow density) was 0.11 $g\,cm^{-3}$ to 0.36 $g\,cm^{-3}$ for tundra snow, and 0.10 $g\,cm^{-3}$ to 0.35 $g\,cm^{-3}$ for taiga snow. Compared with tundra and taiga snow, maritime, prairie, and alpine snow had a wider range of the snow density distribution, and the parameter values were greater. These snow types had the same mean of 0.24 $g\,cm^{-3}$ and standard deviation was 0.07 $g\,cm^{-3}$. Due to the distribution range of snow density, the proportion of snow density at the peak PDF declined, which accounted for 12 %, 11 %, and 13 %, respectively, of these three snow types. But the corresponding density spectrum increased slightly. At the 95 % confidence interval, there was no change in snow density at the 2.5 % percentile. In contrast, significant differences were present at the 97.5 % percentile, and snow

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density increased by ~ 0.03–0.05 g cm^{-3} compared with taiga snow. The widest range of snow density appeared in ephemeral snow, and the frequency distribution was not concentrated, with a small range of snow densities at the peak PDF, 0.15–0.16 g cm^{-3}. Although we found the lowest mean snow density (0.20 g cm^{-3}) in ephemeral snow, the standard deviation (0.09) was greatest among the six snow classes. This was because of the large difference in snow density at each station for ephemeral snow. Accordingly, the 95 % range of snow density was wider, falling between 0.02 and 0.42 g cm^{-3}.

Figure 12 represents the frequency distribution of monthly snow density across the former USSR. There were significant normal distributions of snow density in months except September and June, and the distribution of snow density gradually widened with months. We found an increasing trend in the mean snow density from September to June, which increased by approximately 0.20 g cm^{-3}. The standard deviation increased gradually from April to June, and snow density distribution widened in these months. The largest proportion of snow density in the distribution was 17–18 % from September to October, and the corresponding snow density range was 0.09–0.11 g cm^{-3} and 0.10–0.12 g cm^{-3}, respectively. The proportion was maintained at the range of 15–16 % in winter months, and snow density at the peak PDF increased to between 0.18 and 0.22 g cm^{-3}, almost double the range in autumn, which was caused by low temperatures and strong winds. After March, with snow melt, snow density increased significantly and the density distribution was more dispersed (density brackets were wider). The value of the largest percentage of snow density only accounted for 10 % of all density in June, but ranged from 0.35 to 0.37 g cm^{-3}. The 95 % confidence interval was also expanded with the increase in snow density. The range (2.5–97.5 %) was ~ 0.06 to 0.30 g cm^{-3} in September; however, 95 % of the data lay between 0.10 and 0.51 g cm^{-3} in June, an increase of approximately 70 %. Furthermore, the mainly spectrum distributions of monthly snow density were similar to the most ranges of monthly snow density in spatial distributions.

3.4 Changes in snow density with elevation

We prepared a linear regression analysis of snow density and elevation for all stations (Fig. 13), with a slope of −0.004 in $\mathrm{g\,cm^{-3}}$ per 100 m, and found that the trend was statistically significant at greater than the 95 % significance level. The asterisk in Fig. 13 represents the annual average snow density of each station with elevation. The long-term annual mean maximum was ~ 0.36 $\mathrm{g\,cm^{-3}}$ and the minimum was 0.11 $\mathrm{g\,cm^{-3}}$. The elevation of the study sites ranged between −24 m and 2077 m. The goodness of fit between snow density and elevation across the former USSR was not meaningful, only 11 %. However, it should be noted that even though snow density was not a strong function of elevation, there was an anti-correlation between them; a trend of declining snow density with increasing elevation. The rate of decrease in snow density was 0.004 $\mathrm{g\,cm^{-3}}$ with each 100 m increase in elevation.

The same correlations between snow density and elevation existed in tundra, taiga, prairie, and alpine snow (Fig. 14). However, the patterns at each of the snow classes were distinct. The long-term annual mean snow density and elevation for taiga snow and alpine snow had small ranges. Snow density at the two snow classes ranged from 0.11 to 0.30 $\mathrm{g\,cm^{-3}}$, and elevation was between 0 and 2000 m. With every 100 m rise in elevation, snow density declined by 0.005 $\mathrm{g\,cm^{-3}}$ for taiga and 0.003 $\mathrm{g\,cm^{-3}}$ for alpine snow. The R^2 value of 17 % for taiga snow and 13 % for alpine snow were greater than the value for all data. Tundra snow had wider snow density range than the other snow classes, which changed from 0.12 to 0.36 $\mathrm{g\,cm^{-3}}$, but the elevation was no more than 1800 m. However, tundra snow sites had the largest slope and R^2, and snow density decreased by ~ 0.006 $\mathrm{g\,cm^{-3}}$ with each 100 m rise in elevation. Prairie snow had the widest range of elevation. Annual mean snow density ranged from 0.11 $\mathrm{g\,cm^{-3}}$ to 0.32 $\mathrm{g\,cm^{-3}}$, and elevation varied between −24 m and 2077 m. Although there were 401 sites for prairie snow, these sites had the lowest correlation of snow density and elevation among the four snow classes. Snow density decreased at a rate of approximately 0.003 $\mathrm{g\,cm^{-3}}$ per 100 m increase in elevation, and the goodness of fit was only 6 %.

This indicates that snow density for prairie snow may be more subject to the influence of climatic factors than to elevation. The relationships of snow density and elevation for maritime snow and ephemeral snow were not analyzed, because there were not enough data from the two snow classes.

4 Discussion and conclusions

This research analyzed snow density across the former USSR from 1966 to 2008, using data for six snow classes from 1259 stations. We investigated the climatology and variation in monthly mean snow density and the PDF of monthly snow density for each snow class, and researched the connection between snow density and elevation.

The results show the stations with larger monthly mean snow density were mainly located in the European regions of the former USSR, in Arctic Russia, and some areas of the Russian Far East, while the smaller values were found in central Siberia. There was little snow accumulation in September and June, and most stations with snow were mainly located in Russia.

There were significant monthly and seasonal changes in snow density across the study area. The maximum and minimum long-term monthly mean snow density was $\sim 0.295\,\mathrm{g\,cm^{-3}}$ in June and $0.135\,\mathrm{g\,cm^{-3}}$ in October, respectively. Monthly snow density was lower in the snow-cover formation period, which was effected by low-density new snow. During the stable period, monthly snow density increased gradually with cold temperatures and wind, which compacted the snow layer. From March to April, monthly snow density decreased due to the presence of more new spring snow over the old snow cover. Monthly snow density increased sharply in May and June as snow began to melt with increasing air temperatures. For the six snow classes, the maximum long-term monthly mean snow density was $0.241 \pm 0.032\,\mathrm{g\,cm^{-3}}$ for maritime snow, and the minimum value was $0.173 \pm 0.043\,\mathrm{g\,cm^{-3}}$ in taiga snow. Monthly mean snow density also exhibited significant seasonal changes across the six snow classes. We observed

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an increasing trend in monthly mean snow density from September through June of the next year, but the rate of increase varied with different snow classes.

The long-term annual mean maximum of monthly snow density mainly appeared in 1970s, and the minimum values were mostly during 2000s. Sharp changes in annual mean snow density mainly occurred during the autumn months, while the decreasing trend slowed in the winter and spring months.

From November to January, there were significant decreasing trends in monthly mean snow density and mainly lay in most regions of the European Russia, the south of western and central Siberia. However, the positive trends increased gradually from February to April, which were found in most areas of Russia.

PDFs of snow density for all data and all six snow classes were fit with normal distribution. We found that there were similarities in the distribution and the parameter values of snow density for tundra snow and taiga snow, as well as maritime, prairie, and alpine snow. As the snow density distribution for ephemeral snow was more dispersed in all snow classes, there was a larger range of snow densities at the 95 % confidence interval. From September to June, monthly snow density showed a dispersed distribution trend. The proportion of snow density at the largest PDF declined, but the corresponding density increased with months.

Snow density in general decreased with elevation for all sites, at a rate of about $-0.004\,\mathrm{g\,cm^{-3}}$ per 100 m elevation increase. This same relationship existed in all snow classes except for maritime and ephemeral snow. The best correlation of snow density and elevation existed in tundra snow, and the worst in prairie snow. Snow density declined by $\sim 0.006\,\mathrm{g\,cm^{-3}}$ and $0.003\,\mathrm{g\,cm^{-3}}$ with each 100 m rise in elevation for tundra and prairie snow, respectively. There were no obvious linear relationships in maritime and ephemeral snow.

The trends of snow density variation for all data were basically consistent with tundra and taiga snow, because the areas of tundra snow and taiga snow accounts for more than 60 % of the total area across the former USSR, and the sample data points of the two snow classes accounted for ~ 40 % of all data points. Therefore, tundra snow and taiga snow played important roles in the variability of snow density across the former USSR.

Snow density is one of the most fundamental and important characteristics for estimating and researching snow depth and SWE. In this study, we analyzed the spatiotemporal variability of snow density and the changes of snow density with elevation across the former USSR. In future research, we intend to use snow density to investigate SWE, and water resources assessment, in Eurasia.

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References

Armstrong, R. L. and Brown, R.: Introduction, In: Snow and Climate: Physical Processes, Surface Energy Exchange and Modeling, edited by: Armstrong, R. L. and Brun, E., Cambridge University Press, Cambridge, UK, 1–11, 2008.

Barry, R. G., Armstrong, R. L., and Krenke, A. N.: An approach to assessing changes in snow cover, an example for the former Soviet Union, Proc. Eastern Snow Conf., 50th Annual Meeting, Montreal, PQ, Canada, 25–33, 1993.

Brown, R. D.: Historical variability in Northern Hemisphere spring snow-covered area, in: Ann. Glaciol., International Glaciological Society, 1997.

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.

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, doi:10.1088/1748-9326/7/1/014007, 2012.

Clark, M. P., Serreze, M. C., and Robinson, D. A.: Atmospheric controls on Eurasian snow extent, Int. J. Climatol., 19, 27–40, 1999.

Dai, L. and Che, T.: Spatiotemporal distributions and influences on snow density in China from 1999–2008, Sciences in cold and arid regions, 3, 325–331, 2011.

Foster, J., Owe, M., and Rango, A.: Snow cover and temperature relationships in North America and Eurasia. J. Climate Appl. Meteorol., 22, 460–469, 1983.

Groisman, P. Y., Karl, T. R., Knight, R. W., and Stenchikov, G. L.: Changes of snow cover, temperature, and radiative heat balance over the northen hemisphere, J. Climate, 7, 1633–1656, 1994.

Groisman, P. Y., Knight, R. W., Razuvaev, V. N., Bulygina, O. N., and Karl, T. R.: 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.

Gutzler, D. S. and Rosen, R. D.: Interannual variability of wintertime snow cover across the Northern Hemisphere, J. Climate, 5, 1441–1447, 1992.

Huang, W., Huang, Z., Cui, C., Feng, Z., Li, Q., and Wang, L.: Temporal and spatial distribution of Xinjiang snow density and its consequence, J. Glaciol. Geocryol., 29, 66–72, 2007.

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

Kershaw, G. P.: Snowpack characteristics following wildfire on a simulated transport corridor and adjacent subarctic forest, Tulita, NWT, Canada, Arct. Antarct. Alp. Res., 33, 131–139, 2001.

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

Lazar, B. and Williams, M.: Climate change in western ski areas: potential changes in the timing of wet avalanches and snow quality for the Aspenski area in the years 2030 and 2100, Cold Reg. Sci. Technol., 51, 219–228, 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.
Margreth, S.: Snow pressure on cableway masts: analysis of damages and design approach, Cold Reg. Sci. Technol., 47, 4–15, 2007.
Matsumura, S. and Yamazaki, K.: Eurasian subarctic summer climate in response to anomalous snow cover, J. Climate, 25, 1305–1317, 2012.
Peng, S., Piao, S., Ciais, P., Friedlingstein, P., Zhou, L., and Wang, T.: Changes in snow phenology and its potential feedback to temperature in the Northern Hemisphere over the last three decades, Environ. Res. Lett., 8, 014008, doi:10.1088/1748-9326/8/1/014008, 2013.
Robinson, D. A. and Dewey, K. F.: Recent secular variations in the extent of Northern Hemisphere snow cover, Geophys. Res. Lett., 17, 1557–1560, 1990.
Robinson, D. A., Dewey, K. F., and Heim, R. R.: Global snow cover monitoring: an update, B. Am. Meteorol. Soc., 74, 1689–1696, 1993.
Robock, A., Mu, M., Vinnikov, K., and Robinson, D.: Land surface conditions over Eurasia and Indian summer monsoon rainfall, J. Geophys. Res., 108, 4131, doi:10.1029/2002JD002286, 2003.
Roebber, P. J., Bruening, S. L., Schultz, D. M., and Cortinas, J. V.: Improving snowfall forecasting by diagnosing snow density, Weather Forecast., 18, 264–287, 2003.
Sturm, M., Holmgren, J., and Liston, G. E.: A seasonal snow cover classification system for local to global applications, J. Climate, 8, 1261–1283, 1995.
Sturm, M., Taras, B., Liston, G. E., Derksen, C., Jonas, T., and Lea, J.: Estimating snow water equivalent using snow depth data and climate classes, J. Hydrometeorol., 11, 1380–1394, 2010.
Williams, G. P. and Gold, L. W.: Snow density and climate, Transactions, Engineering Institute of Canada, 2, 91–94, 1958.
Yang, D., Wang, C., Zhang, Y., and Zhang, Z.: Distribution of seasonal snowcover and variation of snow density on the headwaters of Urumqi river basin, Geogr. Res., 11, 86–96, 1992.
Ye, H., Cho, H., and Gustafson, P. E.: The changes in Russian winter snow accumulation during 1936–83 and its spatial patterns, J. Climate, 11, 856–863, 1998.

Table 1. Sources of snow density data.

Data source	Number of Sites	Source
Snow course – Russia (1)	517	RIHMI-WDC, http://meteo.ru/
Snow course – USSR (2)	1319	NSIDC, http://nsidc.org/
Unique Total	1259	

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Table 2. Monthly mean snow density of each snow class ($g\,cm^{-3}$).

	Tundra	Taiga	Maritime	Ephemeral	Prairie	Alpine	All
Sep	0.145 ± 0.035	0.136 ± 0.040	0.165 ± 0.025	NaN	0.119 ± 0.032	0.136 ± 0.044	0.140 ± 0.035
Oct	0.129 ± 0.050	0.117 ± 0.040	0.155 ± 0.046	0.130 ± 0.038	0.155 ± 0.035	0.126 ± 0.029	0.135 ± 0.040
Nov	0.145 ± 0.045	0.125 ± 0.031	0.132 ± 0.021	0.164 ± 0.051	0.153 ± 0.050	0.143 ± 0.045	0.150 ± 0.041
Dec	0.221 ± 0.035	0.178 ± 0.028	0.182 ± 0.023	0.130 ± 0.041	0.163 ± 0.059	0.156 ± 0.022	0.170 ± 0.037
Jan	0.221 ± 0.043	0.190 ± 0.027	0.193 ± 0.024	0.143 ± 0.034	0.163 ± 0.059	0.165 ± 0.034	0.183 ± 0.037
Feb	0.252 ± 0.044	0.201 ± 0.027	0.205 ± 0.042	0.170 ± 0.038	0.198 ± 0.055	0.193 ± 0.051	0.201 ± 0.043
Mar	0.254 ± 0.053	0.183 ± 0.045	0.243 ± 0.020	0.193 ± 0.047	0.209 ± 0.066	0.186 ± 0.052	0.224 ± 0.047
Apr	0.217 ± 0.066	0.173 ± 0.058	0.299 ± 0.048	0.265 ± 0.056	0.224 ± 0.049	0.216 ± 0.031	0.204 ± 0.051
May	0.213 ± 0.054	0.177 ± 0.056	0.380 ± 0.066	0.435 ± 0.073	0.267 ± 0.101	0.225 ± 0.044	0.235 ± 0.066
Jun	0.286 ± 0.050	0.248 ± 0.075	0.455 ± 0.009	NaN	0.327 ± 0.079	0.260 ± 0	0.295 ± 0.059
Mean	0.208 ± 0.047	0.173 ± 0.043	0.241 ± 0.032	0.204 ± 0.047	0.198 ± 0.058	0.181 ± 0.035	0.194 ± 0.046

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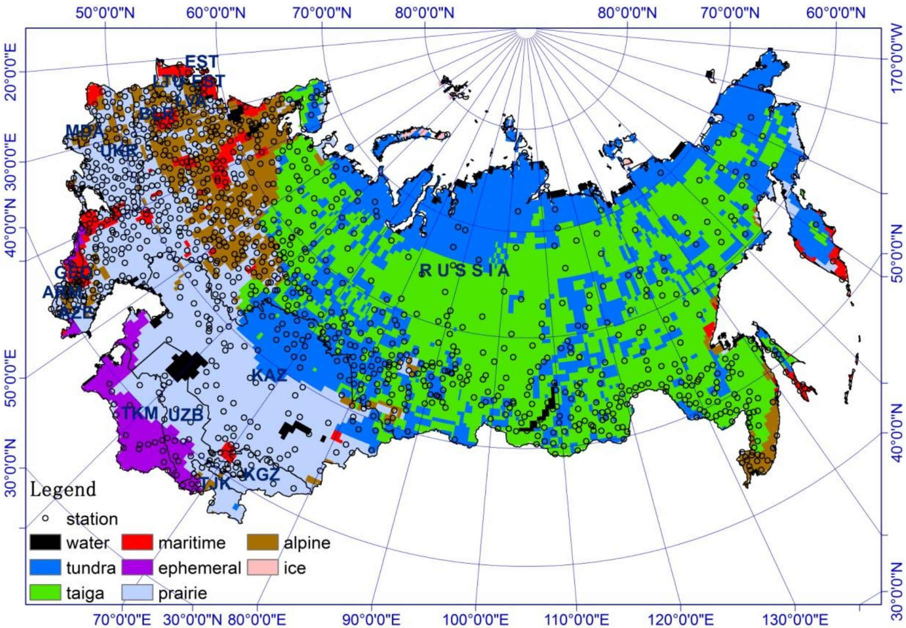

Fig. 1. Geographical locations and distribution of snow course stations and snow classes.

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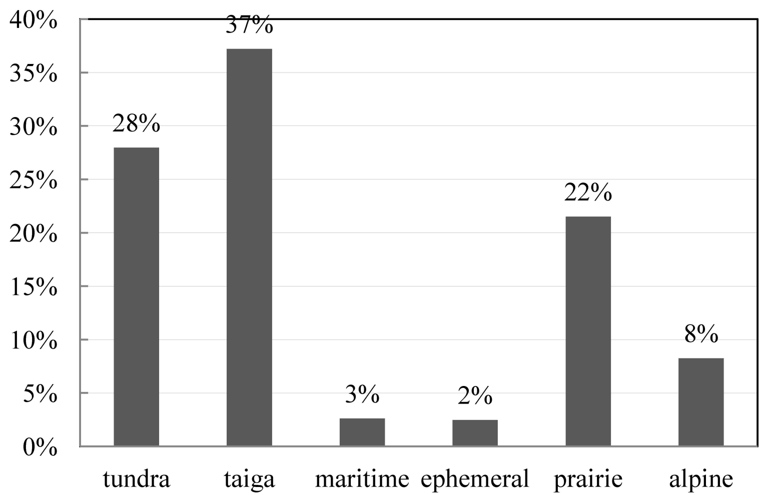

Fig. 2. The percentage of snow cover area for six snow classes across the former USSR.

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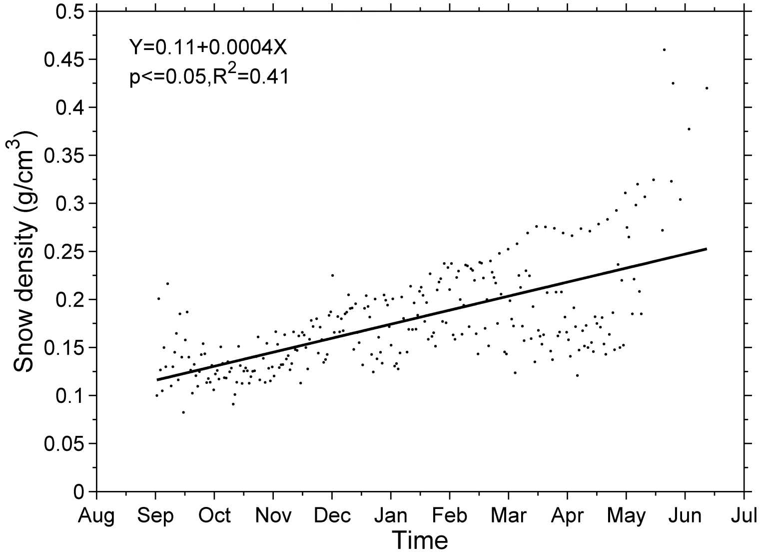

Fig. 3. Daily mean snow density at all stations across the former USSR from September to June. The dot is the computed daily mean snow density of all stations. The thick line represents a linear regression trend. Y-axis stands for snow density in $\mathrm{g\,cm^{-3}}$, and x-axis for date; p is the confidence interval for the coefficient estimates, and R^2 is the sum of residual squares. We defined 1 September as the first day in a snow cover year, therefore, X ranged from 1 (1 September) to 304 (30 June) in the simulation of daily snow density.

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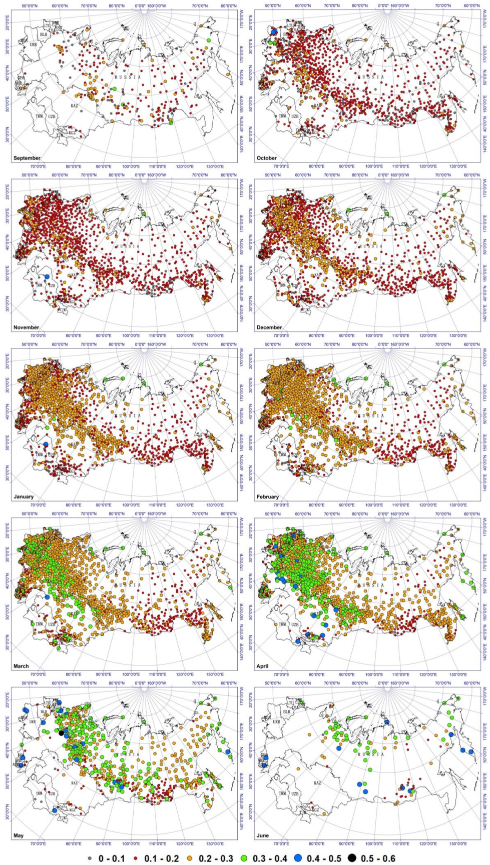

Fig. 4. Spatial distribution of monthly mean snow density for each station during 1966 to 2008 across the former USSR. Dot represents the value of the monthly mean snow density ($\mathrm{g\,cm^{-3}}$) of each station.

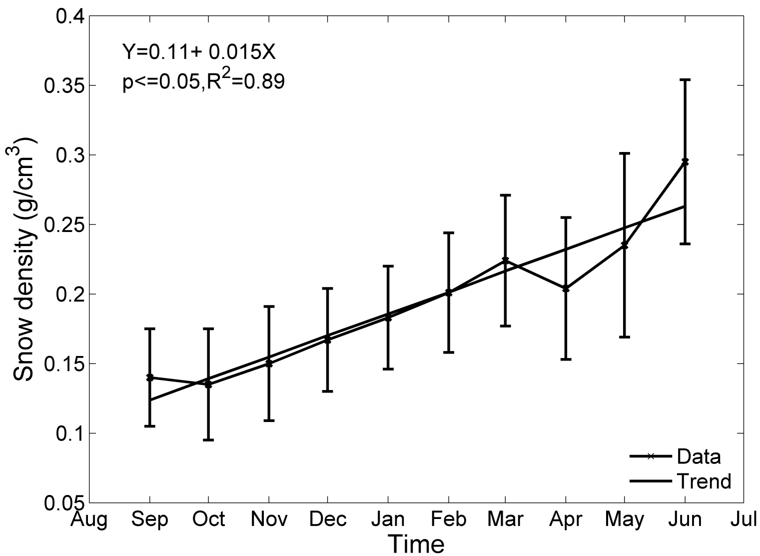

Fig. 5. Monthly mean snow density at 1259 stations across the former USSR from 1966 to 2008. The asterisk is the computed monthly mean snow density; the error bar represents one standard deviation from the mean. The thick line is a linear regression trend. Y-axis stands for snow density in $\mathrm{g\,cm^{-3}}$, and x-axis for time in months (from September to June), p is the confidence interval for the coefficient estimates, and R^2 is the sum of residual squares. September was the first month in a snow cover year, therefore, X ranged from 1 (September) to 10 (June) in the simulation of monthly snow density.

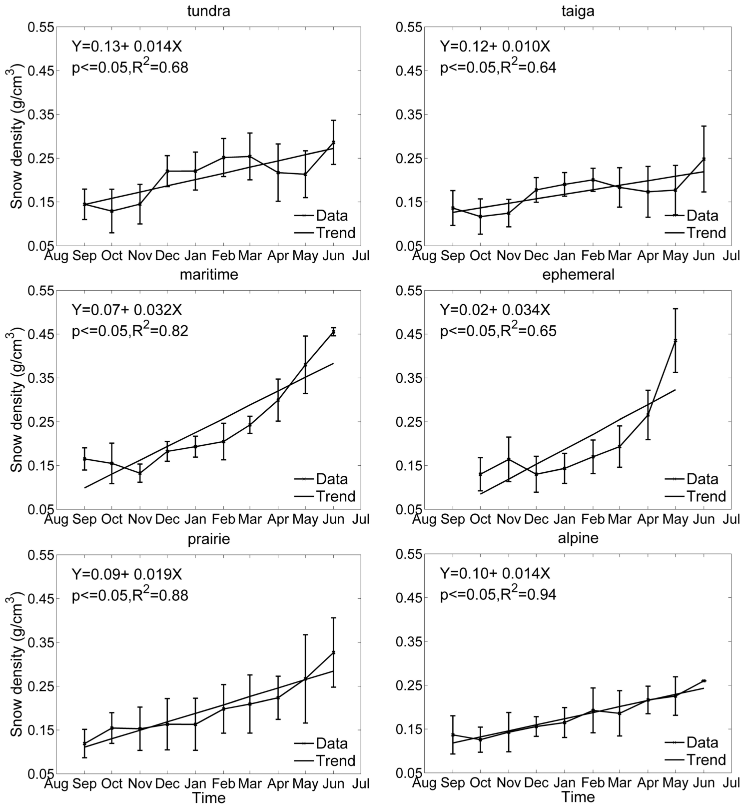

Fig. 6. Monthly mean snow density for tundra, taiga, maritime, ephemeral, prairie, and alpine snow. The attributions were the same as Fig. 5.

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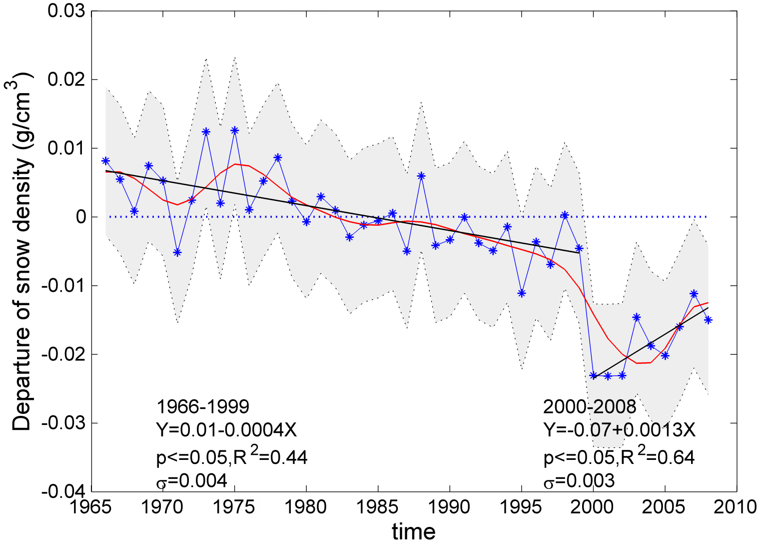

Fig. 7. Variation of annual mean snow density across the former USSR from 1966 through 2008, with respect to the 1971–2000 mean. The thin solid line with asterisk is the computed annual mean of snow density; the solid curve represents the trend of wavelet analysis; the gray area presents the interval of Y in a linear regression; the thick solid line is a linear regression with the parameters shown in the lower corner, where Y represents snow density in $g\,cm^{-3}$ and X represents time in snow cover years, p is the confidence intervals for the coefficient estimates, R^2 is the sum of residual squares, and σ is the standard deviation.

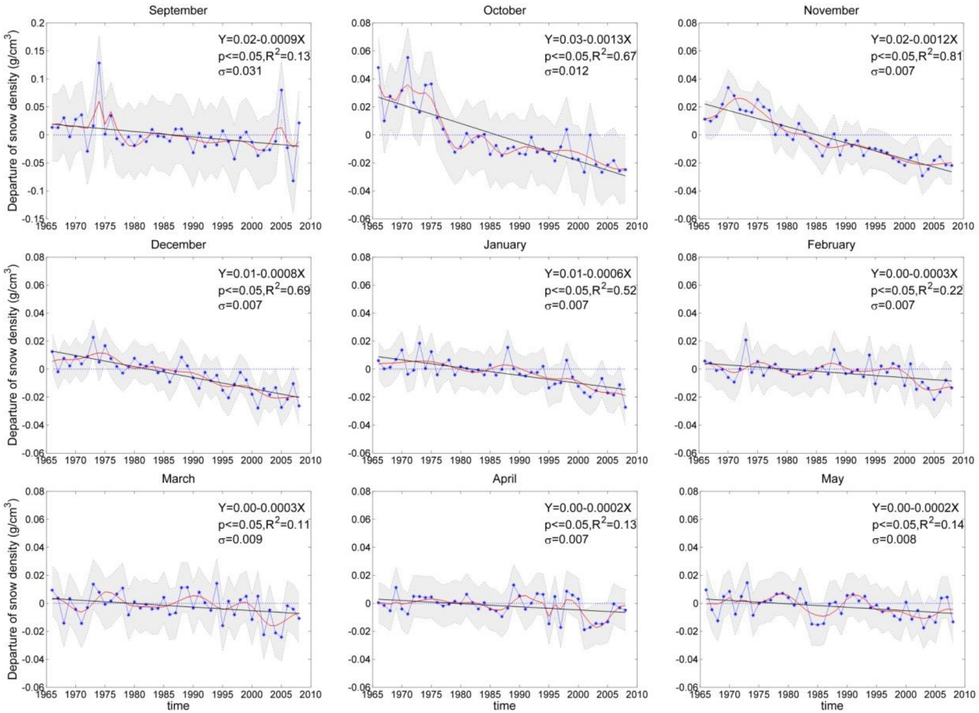

Fig. 8. The annual variation of monthly snow density across the former USSR from 1966 through 2008, with respect to the 1971–2000 mean. The attributions were the same as Fig. 7.

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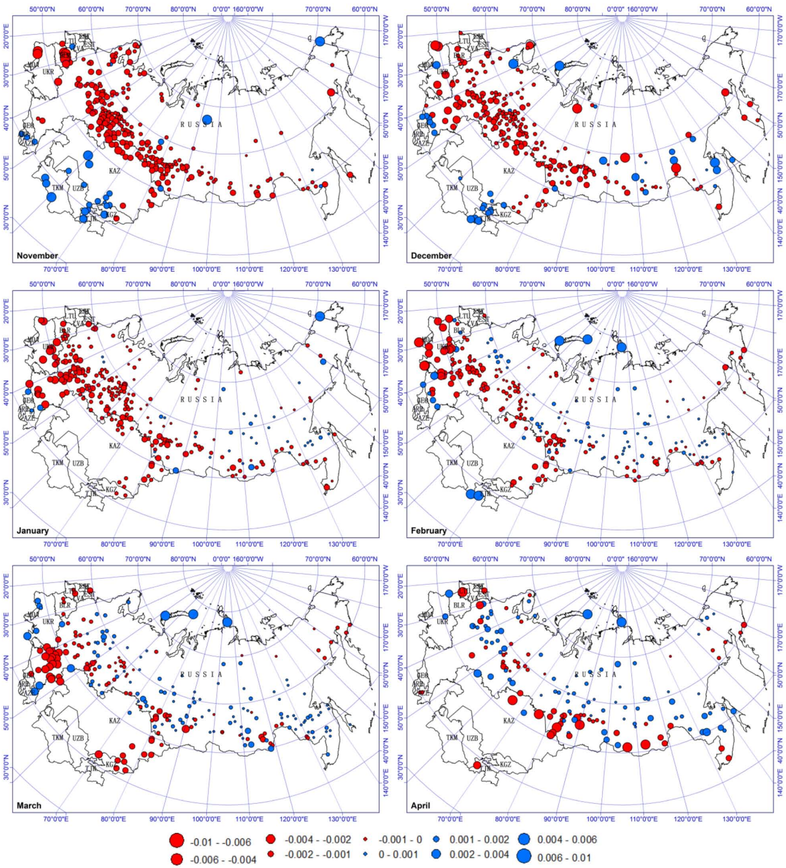

Fig. 9. Spatial distributions of linear trend coefficients ($g\,cm^{-3}\,yr^{-1}$) of monthly mean snow density (from November to April) for each station during 1966–2008. The rates of changes in monthly mean snow depth were statistically significant at > 95 % significant level. Red circle represents decreasing trend, and blue one is increasing trend.

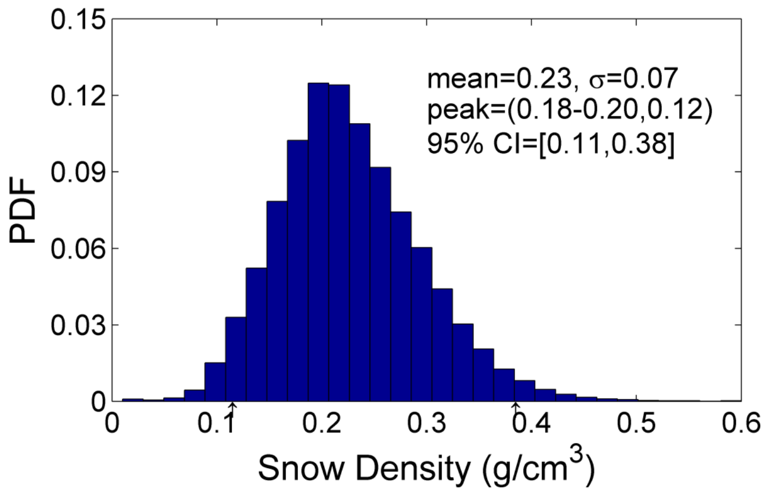

Fig. 10. Probability distribution function (PDF) of snow density for all data. The bar is PDF of snow density; the arrows bracket 2.5 % and 97.5 % spectrum distribution of snow density. Mean and σ represent the calculated mean and standard deviation of all snow density, respectively. Peak stands for the peak PDF of snow density (right) and the corresponding snow density (left). 95 % CI is 95 % credibility intervals of snow density that lie between 0.11 and 0.38 $\mathrm{g\,cm^{-3}}$.

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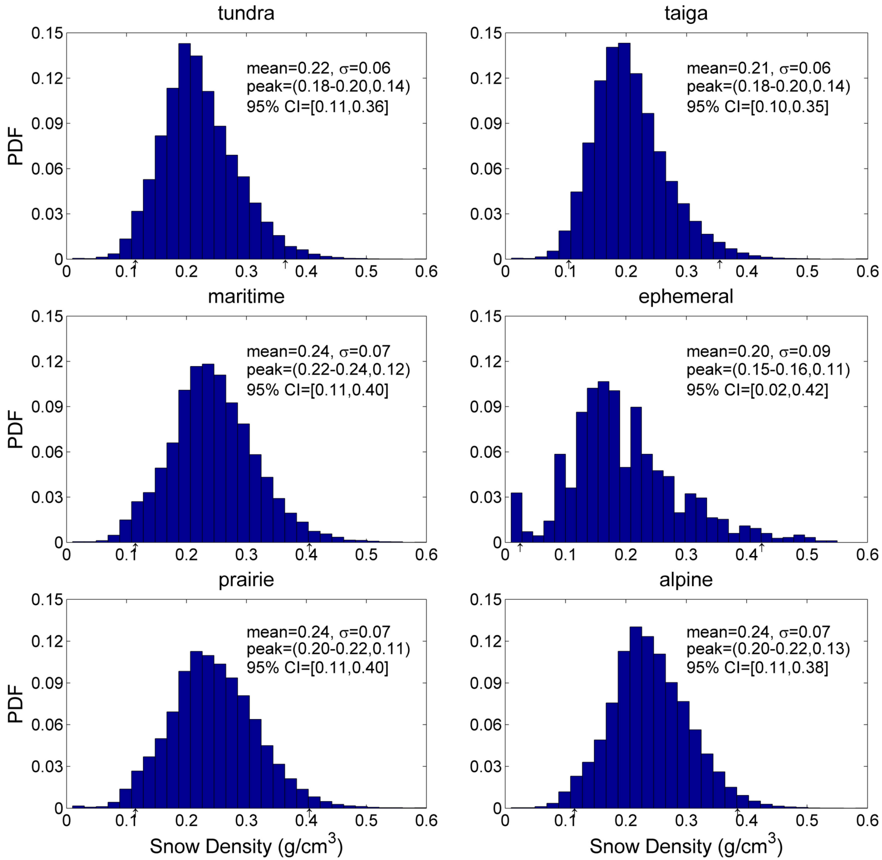

Fig. 11. PDF of snow density for tundra, taiga, maritime, ephemeral, prairie, and alpine snow. The attributions were the same as Fig. 10.

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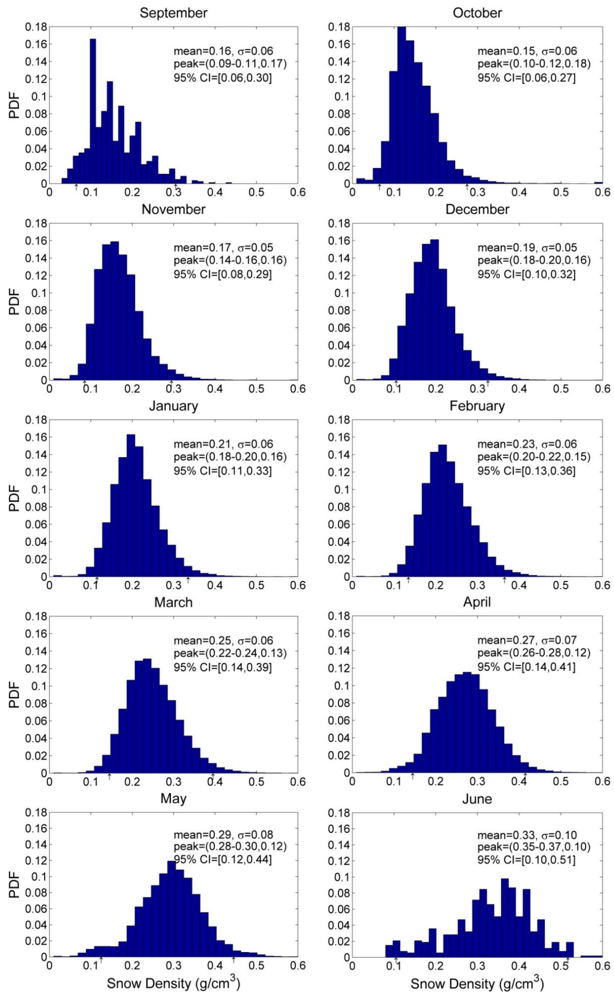

Fig. 12. PDF of monthly snow density. The attributions were the same as Fig. 10.

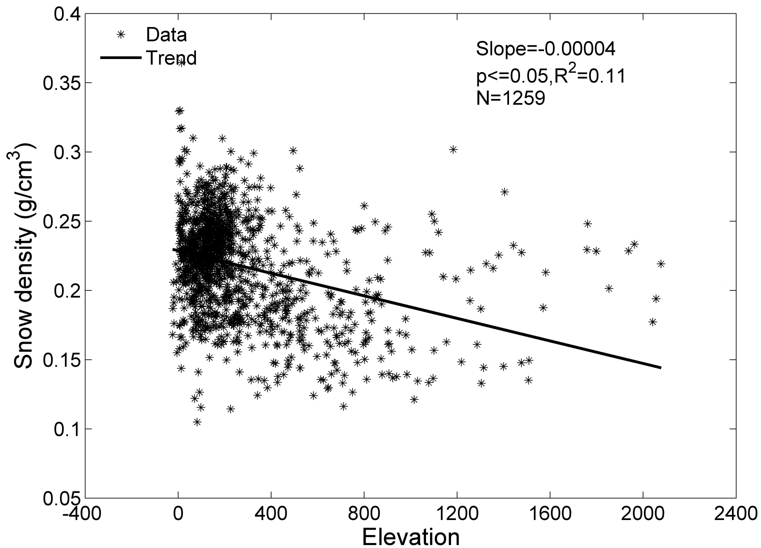

Fig. 13. Snow density changes with elevation for all stations across the former USSR during 1966–2008. Asterisk shows the mean snow density of each site; the thick line is a linear regression with the parameters shown on the upper-right corner, where slope was −0.004 in $\mathrm{g\,cm^{-3}}$ −100 m, p is the 95 % confidence intervals for the coefficient estimates, R^2 is the sum of residual squares, and N is the number of stations.

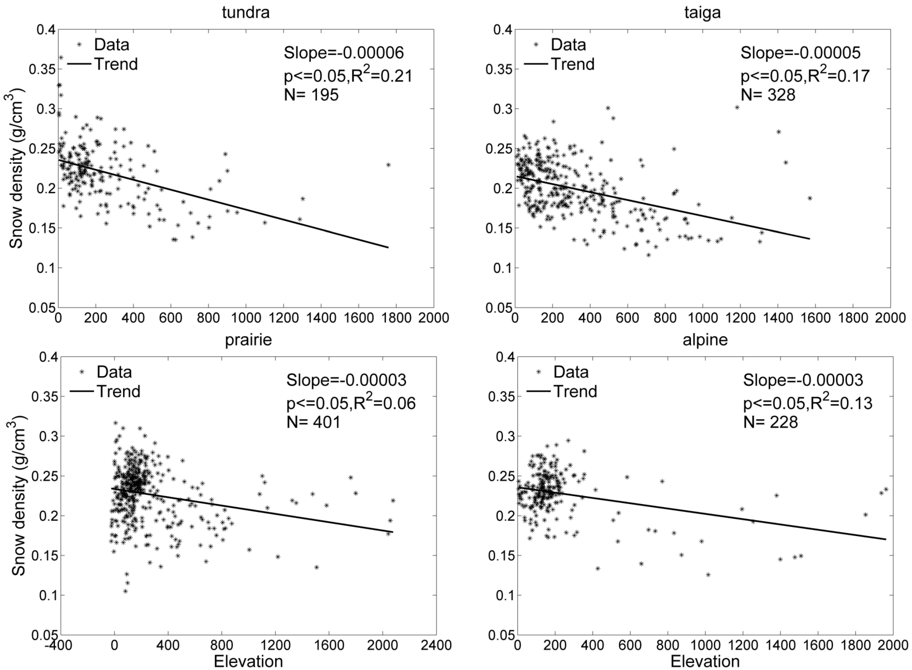

Fig. 14. Same as Fig. 13, but for tundra, taiga, prairie, and alpine snow.