Dear Dr. Guillaume Chambon,

Thank you very much for your comments on this manuscript. Your help and guidance during this long review process is much appreciated. We have followed your instructions and made necessary changes. Please see details for our reply for each item. Please let us know if you have further concerns.

Best wishes,

Tingjun Zhang

Response to Editor

1. P. 1, lines 24-26: unclear sentence.

Reply: We have modified the sentences:

"Previous studies by using in-situ measurements were mostly site-specific (Bulygina et al., 2009, 2011; Ma and Qin, 2012); data from satellite remote sensing may cover a large area or in global scale, but uncertainties remain large, even misleading (Zheng et al., 2015). In this study, we obtained snow depth data of ground-based measurements from 1814 stations across Eurasian continent from 1966 to 2012. The main objective of this study is to investigate the spatial and temporal changes and variabilities in snow depth over the Eurasian continent in this study.

2. P. 2, lines 6-7: unclear sentence.

Reply: We have modified the sentences:

"This study provides a baseline for snow depth climatology and snow depth changes, using in-situ measured snow depth data for investigating climate system changes over the Eurasian continent."

3. P. 3, line 9: replace "could" by "can".

Done.

4. P. 3, line 22: delete "on".

Done.

5. P. 3, line 23: replace “which” by “and”.

Done.

6. P. 3, lines 23-24: not very clear: try to be more specific. Is this sentence connected to the previous one? Is so, make it more evident.

Reply: we have modified the sentences:

“Previous studies on snow depth have focused at local and regional scales over Russia (Ye et al., 1998; Kitaev et al., 2005; Bulygina et al., 2009, 2011; Brasnett, 1999) and the Tibetan Plateau (TP) (Li and Mi, 1983; Ma and Qin, 2012). These studies demonstrated that that annual mean snow depth has increased in northern Eurasia and the Arctic during the last 70 years (Ye et al., 1998; Kitaev et al., 2005; Callaghan et al., 2011a; Liston and Hiemstra, 2011). However, there are large regional differences at various scales (Bulygina et al., 2009, 2011; Ma and Qin, 2012; Stuefer et al., 2013; Terzago et al., 2014).”

7. P. 4, line 4: insert “In addition,”.

Done.

8. P. 4, line 14: Why? Explain more clearly why this information is required.

Reply: We have deleted the sentence.

9. P. 4, line 26: delete “approximately”

Reply: Has been deleted.

10. P. 4, line 26: insert “Therefore,” before “utilization”.

Reply: We have deleted the sentence.

11. P. 4, line 27: This statement appears a bit strong. Consider toning down.

Reply: We have deleted the sentence.

12. P. 4, line 28: delete “accurate and”.

Reply: Has been deleted.

13. P. 4, line 30-P. 5, line 2: unclear sentence.

Reply: We have modified the sentences:

“However, low-resolution satellite remote sensing data is used as input parameter, which can affect simulation accuracy and does not provide a sufficient time series length.”

14. P. 5 line 7: insert “Hence,” before “ground-based”, delete “and”

Reply: Has been modified.

15. P. 5, line 8: insert “most” before “accurate”, replace “depth” by “depths”.

Reply: Has been modified.

16. P. 5, line 10: replace “simulation” by “simulations”.

Reply: Has been replaced.

17. P. 5, lines 11-12: To connect with what is said above, you should already briefly describe here the type of data considered in the study.

Reply: We have modified the paragraph:

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

18. P. 6, lines 7-9: This sentence is not useful here. Consider moving it - if not too redundant - in the introduction. Only very few results concerning SWE are presented in the sequel. Why?

Reply: We have deleted the analysis of the relation between SWE and climate factors in the sequel because there are similar results in snow depth.

19. P. 6, lines 18-19: Explain briefly why.

Reply: We have deleted the sentence.

20. P. 6, lines 24-25: This should probably be said earlier, after lines 5-6.

Reply: We have moved the sentence after lines 5-6:

"…Snow depth was measured every 10 m in the forest and every 20 m in open terrain. The final snow depth at each station was determined as the average of all measurements in each snow course survey (Bulygina et al., 2011)."

21. P. 7, lines 17-18: Seems contradictory with what is said at the beginning of the section: please be more precise here and there.

Reply: We have deleted the contradictory sentence at the beginning of the section and added the period here:

"Procedures and techniques for measuring snow depth may have changed over the course of station history before the 1950s."

22. P. 8, lines 2-5: Note very clear. Is the annual mean snow depth a data computed for each year, or a single value averaged over the whole 1966-2012 period?

Reply: We have modified the definition:

"(3) Annual mean snow depth: annual mean snow depth was calculated as an arithmetic sum of monthly mean snow depth divided by the number of available snow months for each snow year.
(6) Long-term mean annual snow depth: it was averaged from annual mean snow depths over the 1971-2000 period. "

23. P. 8, lines 6-9: Idem. It is not very clear here whether this annual mean max snow depth is an average value over the 1966-2012 period or a data available for each year (and averaged over what in this case?). In fact, both quantities are used in the sequel, so you should be more precise here (and use different denominations?).

Reply: We have modified the definition:

"(4) Annual maximum snow depth: the annual maximum snow depth is defined as the maximum daily snow depth within each snow year.
(7) Long-term mean maximum snow depth: it was averaged from annual maximum snow depth over the 1971-2000 period."

24. P. 8, lines 15-16: Unnecessary sentence.

Reply: We have deleted the sentence.

25. P. 8, lines 23-24: Was it calculated on the low-pass filtered signal or the raw data?

Reply: We have modified the sentence:

“The linear trend coefficient of the raw snow depth was calculated to represent the rate of change at each station.”

26. P. 8, line 26: Which partial correlation coefficients? They have not yet been introduced at this stage.

Reply: We have added as following:

“The Student’s t-test was used to assess statistical significance of the slope in the linear regression analysis and the partial correlation coefficients of snow depth, air temperature and snowfall,…”

27. P. 8, line 30: consider replacing by: "...trends in the time series of the corrected data were recalculated"

Reply: Has been replaced.

28. P. 9, line 1: replace “were” by “are”

Reply: Has been replaced.

29. P. 9, line 7: Unclear terminology: could be confused with the "annual maximum mean snow depth" defined earlier.

Reply: We have modified it as “The maximum value of 109.3”

30. P. 9, line 11: Why do you use past tense in all this description? Consider using present tense instead in the whole "Results" section.

Reply: We have used present tense in the whole “Results” section.

31. P. 9, line 29: replace “however,” by “in contrast”.

Reply: Has been replaced.

32. P. 10, line 3: higher than what?

Reply: We have replaced “higher” by “high”.

33. P. 10, line 5: insert “in” and “they”.

Reply: Has been inserted.

34. P. 10, line 19: replace by "due mainly to snow disappearance..."

Reply: Has been replaced.

35. P. 11, line 25: replace by “some regions south of...”.

Reply: Has been replaced.

36. P. 12, line 8: replaced by “p”

Reply: Has been replaced.

37. P. 12, line 21: Consider adding here a brief summary of the more significant trends observed in the data.

Reply: We have added:

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

38. P. 12, line 28: replace by “the present”.

Reply: Has been replaced.

39. P. 12, line 29: suppress “that”.

Reply: Has been deleted.

40. P. 13, line 4: replace by "the present" or "our"

Reply: Has been replaced.

41. P. 13, line 20: replace by “the present”.

Reply: Has been replaced.

42. P. 13, line 21: missing words here?

Reply: We have added:

“…however, we found winter monthly mean snow depth increased at a rate of 0.42 cm yr^{-1} in southern Siberia during the period from 1966 to 2012.”

43. P. 13, line 29: No data of SWE have been presented up to now. Hence, focus only on snow depth?

Reply: Yes, we focus only on snow depth, and have deleted the analysis of SWE.

44. P. 13, line 30: not clear: try using similar geographic references as those used in the description of results.

Reply: We have deleted the second “the western portion of”.

45. P. 13, line 30: What is "this" here?

Reply: We have replaced “This” by “The similar result”.

46. P. 14, line 22: Not clear. Where is this calculation procedure described before?

Reply: We described the calculation procedure in the definition of daily snow depth:

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

47. P. 14, lines 25-27: Unclear sentence, should be rephrased.

Reply: We have modified the sentence:

“Snow depths were averaged at each 200 m elevation band.”

48. P. 14, line 30-P.15 line1: unclear formulation.

Reply: We have modified the sentence:

“Annual mean snow depths increase with elevation and reach to the peak at 1600 m.”

49. P. 15, line 4: This whole paragraph is unclear and would need to be rephrased.

Reply: We have modified the paragraph:

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

50. P. 15, line 9: You should define continentality here.

Reply: We have added the definition of continentality:

“Continentality is a measure of the difference between continental and marine climates. It is roughly a measure of distance from oceans. Continentality affects precipitation, thus determines snowfall rate and snow depth.”

51. P. 15, line 10: Appears contradictory with the previous sentence and the significant positive correlation.

Reply: We have modified the sentences:

“Although there is a statistically significant positive relationship between annual mean snow depth and continentality over the Eurasian continent, the Goodness of Fit is only 1% (Fig. 8d). This indicates that the continentality may not be an important driving factor of annual mean snow depth distribution compared with latitude and elevation over Eurasia, especially on the TP.”

52. P. 15, lines 11-16: What is the relation between these last 2 sentences and the influence of continentality? Shouldn't these sentences be rather moved to section 4.3 about climate factors?

Reply: We have deleted the sentences.

53. P. 16, line 1: remove "snow depth" here, since you cannot compare snow depth to snow depth!

Reply: Has been deleted.

54. P. 16, line 1: Where is this evident?

Reply: We have deleted the sentence.

55. P. 16, line 11: unclear statement: what is the "entire density"?

Reply: We have replaced “entire” by “bulk”.

56. P. 16, line 12: How is "heavy snowfall" defined?

Reply: We have added the definition of heavy snowfall:

“In addition, there are similar inter-annual variations in snowfall and heavy snowfall (daily snowfall amount is between 5-10 mm).”

57. P. 16, line 18: This is the first time that data concerning SWE are presented. You should at least also present, and comment, SWE data in Fig. 9 and 10.

Reply: We have deleted the analysis of the relation between SWE and climate factors in the sequel because there are similar results in snow depth.

58. P. 16, line 19: between what and what?

Reply: We have modified the sentences:

“A significant negative correlation ($p \leqslant 0.05$) between annual mean snow depth and air temperature is present in most areas of European Russia and southern Siberia (Fig 11a). However, there is no statistically significant correlation among them in northern Siberia.”

59. P. 17, line 6: Where is this demonstrated? This conclusion does not seem to by fully supported by the presented results. Hence, consider either expanding the argument or toning down.

Reply: We have modified the sentences:

“The present study shows that there are similar inter-annual variations in annual mean snow depth and heavy snowfall, which implies that extreme snowfall may be the main reason for snow thickening.”

59. P. 17, line 6: Idem: none of the presented results directly concern atmospheric circulation.

Reply: We have deleted.

60. P. 17, line 17: replace by "the present".

Reply: Has been replaced.

61. P. 43, line 5: was referred to as the "95% confidence level" in previous figures: be consistent.

Reply: Has been replaced.

List of relevant changes

According to editor's comments, we have made relevant changes in this manuscript. The main changes are followed:

1. We have reorganized the objective of our study:

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

2. All of the snow depth variable have been redefined and have replaced all the words in the manuscript:

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

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

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

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

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

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

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

3. The data of long-term mean annual snow depth, long-term mean maximum snow depth and long-term mean monthly snow depth from 1971 through 2000 are used to reanalyze the climatology of snow depth. This is because the analysis of the anomalies of annual mean snow depth, annual maximum snow depth and monthly

mean snow depth from 1966 through 2012 with respect to the 1971-2000 mean across the Eurasian continent.

4. We focus only on snow depth in this manuscript, therefore, we have deleted the analysis of the relation between SWE and climate factors in the sequel because there are similar results in snow depth.

5. We have added a brief summary of the more significant trends observed in the “3.2 Variability of Snow Depth” section:

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

6. We have added definition of continentality:

“Continentality is a measure of the difference between continental and marine climates. It is roughly a measure of distance from oceans. Continentality affects precipitation, thus determines snowfall rate and snow depth.”

7. All the unclear sentences have been modified.

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

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ABSTRACT

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

1 Introduction

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

During winter, the average maximum terrestrial snow cover is approximately 47 × 10^6 km^2 over the Northern Hemisphere land surfaces (Robinson et al., 1993; IGOS, 2007). A large fraction of the Eurasian continent is covered by snow during the winter season, and some areas are covered by snow for more than half a year. There are long-term snow measurements and observations across the Eurasian continent with the first snow depth record dating back to 1881 in Latvia (Armstrong, 2001). These measurements provide valuable data and information for snow cover phenology and snow cover change detection. Many studies on snow depth have focused on local and regional scales over Russia (Ye et al., 1998; Kitaev et al., 2005; Bulygina et al., 2009, 2011; Brasnett, 1999) and ~~on~~ the Tibetan Plateau (TP) (Li and Mi, 1983; Ma and Qin, 2012), ~~which~~ and have revealed ~~the~~ significant regional ~~characteristics in the~~ changes. ~~in snow depth:~~.~~.~~ It has been reported that a~~A~~nnual mean snow depth has increased in northern Eurasia and the Arctic during the last 70 years (Ye et al., 1998; Kitaev et al., 2005; Callaghan et al., 2011a; Liston and Hiemstra, 2011) ~~and showed~~with large regional differences (Bulygina et al., 2009, 2011; Ma and Qin, 2012; Stuefer et al., 2013; Terzago et al., 2014). Changes in snow depth are primarily affected by air temperature and precipitation. Ye et al. (1998) and Kitaev et al. (2005) showed that higher air temperatures caused an increase in snowfall in winter from 1936 through

1995, and thus, greater snow depth was observed in northern Eurasia~~ in response to global warming~~. ~~Furthermore, the s~~Snow depth distribution and variation are controlled by terrain (i.e., elevation, slope, aspect, and roughness) and vegetation (Lehning et al., 2011; Grünewald et al., 2014; Revuelto et al., 2014; Rees et al., 2014; Dickerson-Lange et al., 2015). Snow depth is closely related to synoptic-scale atmospheric circulation indices such as the North Atlantic Oscillation/Arctic Oscillation (NAO/AO). ~~For example, ~~Kitaev et al. (2002) reported that the NAO index was positively related to snow depth in the northern part of ~~the ~~East European Plain of Russia and over western Siberia from 1966 to 1990~~; ~~, ~~however, the NAO index was~~but negatively correlated with snow depth in most southern regions of northern Eurasia. You et al. (2011) demonstrated that there was a positive relationship between snow depth and the winter AO/NAO index and between snow depth and Niño-3 region sea surface temperature (SST) on the eastern and central TP from 1961 through 2005. ~~However, most snow depth studies are at regional scale, information of snow depth at continental scale is required over the Eurasian continent.~~

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

The objective of this study is to (i) ~~develop a~~establish snow depth climatology (1971-2000), ~~and~~ (ii) investigate ~~the~~ snow depth variability at various scales ~~of snow depth over the Eurasian continent~~ from 1966 to 2012, and (iii) analyze factors controlling snow depth distribution and changes over Eurasian continent. Snow depth data used in this study are daily or 10-day interval ground-based measurements from 1814 stations. Detailed description of in-situ measurements ~~In addition, we analyse the effects of topography and climate factors (i.e., air temperature and snowfall) on the changes in snow depth over the study area. This study is unique in snow cover analysis using the most comprehensive daily snow depth observational network at continental scale over Eurasia. The dataset~~ and methodology are described in Section 2 with major ~~the~~ results, discussions, and conclusions presented in Sections 3, 4, and 5, respectively.

2 Data and Methodology

~~The~~ Snow depth data used in this study include daily ~~snow depth~~measurements from national meteorological stations and 10-day interval measurements from snow course.~~,~~ ~~snow water equivalent (SWE),~~ ~~air temperature and precipitation.~~

Measurements of daily snow depth were conducted at 1103 meteorological stations over the Eurasian continent from 1881 to 2013 (Table 1). Snow depth was measured once a day ~~at meteorological stations~~ using a graduated stake installed at a fixed point location within the station or by a wooden ruler. Snow depth was measured using the same method across the Eurasian continent, which ~~since the meteorological observation standard was established by the former Union of Soviet Socialist Republics (USSR) and followed by all of the former USSR republics, Mongolia and China~~. ~~Snow depth~~ is also one of the standard elements to be measured on a daily basis (WMO, 1996). Historical snow course data were obtained from ~~over~~ the former Union of Soviet Socialist Republics (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~~ 10-day interval~~s~~) and during ~~the~~ snowmelt period (~~every five~~ 5-day interval~~s~~) 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)~~. Then final snow depth at each station was determined as the average ~~value~~ of all ~~series of~~ measurements in each snow course survey (Bulygina et al., 2011).

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

Daily air temperature and precipitation data were obtained from 386 meteorological stations across the former USSR from 1966 to 2010 (Table 1). Snowfall data were derived from daily precipitation and air temperature. ~~was measured using a thermometer, which was placed at a height of 1.5 m above the ground surface in an instrument shelter at the meteorological station (WMO, 1996). The air temperature measurement was accurate to 0.1 °C. Air temperature was measured four times a day at 0200, 0800, 1400, and 2000 local time. The daily mean air temperature was calculated by a simple arithmetic average of the four measurements, whereas the monthly mean was based on the daily mean and the~~

~~annual mean was based on the monthly mean. Precipitation was gathered and measured by a precipitation gauge and was reported with a 0.1-mm precision (Groisman and Rankova, 2001). The original precipitation data were not corrected by considering the gauge undercatch .~~ Daily precipitation was partitioned into a solid and liquid fraction based on daily mean temperature (Brown, 2000). The solid fraction of precipitation, S_{rat}, was estimated by

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

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

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

~~Snow depth and SWE at each station were determined as the average value of a series of measurements in each snow course survey (Bulygina et al., 2011).~~ In individual measurements, both random and systematic errors inevitably occur (Kuusisto, 1984). To minimize these errors, a quality control of meteorological data was automatically undertaken prior to the datasets being stored at the Russian Research Institute for Hydrometeorological Information-World Data Center (RIHMI-WDC) (Veselov, 2002) and the National Meteorological Information Center (NMIC) of China Meteorological Administration (Ma and Qin, 2012). We implemented additional quality control using the following requirements: (1) To ensure snow depth stability, at a given location, a month with less than 15 days of snow depth measurements was deleted. (2) Stations with sudden and steep changes in snow depth were eliminated from the list. (3) The World Meteorological Organization common approach to calculate anomalies is based on a 30-years climate normal period (IPCC, 2013). In ~~our~~ this study, we use 1971-2000 ~~was used~~ as the normal period. To ensure data continuity, stations with less than 20-years data during the 1971-2000 period were excluded. (4) At each station, we eliminated data points that exceeded two standard deviations from their long-term (1971-2000) mean. After these four steps of snow depth quality control, we used data from 1814 stations to investigate the climatology and variability of snow depth over the Eurasian continent (Fig. 1 and

Table 1).

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

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

(~~1~~2) Monthly mean snow depth: ~~in this study, we defined a snow cover day with snow depth equal to or greater than 0 cm according to the standard method for deriving monthly mean snow depth based on the World Meteorological Organization (WMO) climatological products (Ma and Qin, 2012). According to the quality control, months having more than 15 days with snow data were used. The~~ monthly mean snow depth was computed as an arithmetic sum of daily snow depth divided by the number of days with snow on the ground within each month.~~;~~

(~~2~~3) Annual mean snow depth: ~~an~~ annual mean snow depth was calculated as an arithmetic sum of ~~the~~ monthly mean snow depth divided by the number of available snow months ~~within~~ for each snow year. ~~The annual mean snow depth was averaged for stations with more than 20 snow years during the 1966-2012 period;~~

(~~3~~4) Annual ~~mean~~ maximum snow depth: ~~an~~ the annual ~~mean~~ maximum snow depth was defined as the maximum daily snow depth within each snow year.~~determined from the maximum daily snow depth in each snow year. It was calculated using the average value of the annual maximum snow depth from stations~~

~~with more than 20 years of data during the 1966-2012 period.~~

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

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

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

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

Wavelet analysis was performed to reveal the long-term low-frequency variations in snow depth over the entire study area. ~~A wavelet is a wave-like oscillation with an amplitude that begins at 0, increases, and then decreases back to 0 (Graps, 1995).~~ We applied a discrete wavelet transform, excluded the high-frequency components and then used the inverse transform to reconstruct the lower frequency signal. Any trend analysis is an approximate and simple approach to obtain what has occurred on average during the study period. A linear trend analysis provides an average rate of this change. The linear trend analysis is also a useful approximation when systematic low-frequency variations emerge even though there is a nonlinearity (Folland and Karl, 2001; Groisman et al., 2006). The linear trend coefficient of the raw snow depth was calculated to represent the rate of change at each station. The Student's t-test was used to assess statistical significance of the slope in the linear regression analysis and the partial correlation coefficients of snow depth, air temperature and snowfall, and a confidence level above 95% was considered significant in our study. The Durbin-Watson test was used to detect serial correlation of data in the time series, and the Cochrane-Orcutt test was used to correct the serial correlation. Then, the serial correlations of the new data were rechecked and ~~recalculated~~ trends in the time series of the ~~new~~ corrected data were recalculated. The methods and test results ~~were~~ are described in the appendix.

3 Results

3.1 Climatology of Snow Depth

Distributions of long-term mean annual snow depth indicate~~d~~ a strong latitudinal zonality. Generally, long-term mean annual snow depth ~~increased~~ increases with latitude northward across the Eurasian continent (Fig. 2). ~~A~~ The maximum ~~annual mean snow depth~~value of ~~106~~109.3 cm ~~was~~ is observed over west of the Yenisey River (dark blue circle) (Fig. 2a). In contrast, the minimum values (~0.01 cm) ~~were~~ are observed in some areas south of the Yangtze River in China (small grey circles).

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

Long-term ~~Annual~~ mean maximum snow depth (Fig. 2b) shows~~ed~~ a similar spatial distribution pattern compared to the long-term ~~annual~~ mean snow depth pattern. The maximum value ~~was~~ is approximately ~~201.8~~200.2 cm in snow depth. For the majority of Russia, the long-term mean maximum snow depth ~~was~~ is >40 cm. The regions with the long-term mean maximum snow depths of ~~(~~exceeding 80 cm~~)~~ ~~were~~ are in the north-eastern regions of European Russia, the northern part of the West

Siberian Plain, the Yenisey River basin, the Kamchatka Peninsula, and Sakhalin; ~~however~~in contrast, along the coast of the Caspian Sea, the long-term mean maximum snow depth ~~was~~ is <10 cm. Most of the rest of the former USSR ~~had~~ has a long-term mean maximum depth of >10 cm, except for some regions of the Ukraine and Uzbekistan. The long-term mean ~~Maximum~~ maximum snow depth ~~was~~ is >10 cm in northern Mongolia and decreases~~d~~ to 6–10 cm when moving south to central and eastern Mongolia. The long-term mean m~~M~~aximum snow depths ~~were~~ are high~~er~~ over the northern part of the Xinjiang Autonomous Region of China, Northeast China, and eastern and southwestern TP, in which they ~~were~~ are mostly greater than 10 cm and even greater than 20 cm in some areas. For the remaining regions of China, the long-term mean maximum snow depths ~~were~~ are relatively small and mostly less than 10 cm.

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

~~was~~ is observed only in Russia and in the TP in June (Fig. 3j).

3.2 Variability of Snow Depth

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

Monthly snow depth changes~~d~~ significantly across the Eurasian continent from 1966 through 2012 (Fig. 5). ~~Snow depth~~It ~~decreased~~ decreases in October at a rate of approximately -0.1 cm decade^{-1} (Fig. 5a), and there ~~were~~ are no significant trends in November and December with large inter-annual variations (Fig. 5b-c). From January through April, ~~snow depth~~it ~~showed~~ shows statistically increasing trends with rates between 0.3 cm decade^{-1} and 0.6 cm decade^{-1} (Fig. 5d-g). Overall, monthly mean snow depth shows decrease~~d~~ in October, ~~or there was~~ no trends with large inter-annual variability in November and December, and increasing trend from January to April.~~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 annual maximum snow depth for each station during 1966-2012 with $p \leqslant 0.05$. The significant increasing trends (blue circles) of annual mean snow depth occur~~red~~ in European Russia, south of Siberia and the Russian Far East, the northern Xinjiang Autonomous Region of China, and Northeast China (Fig. 6a). In contrast, decreasing trends (red circles) ~~were~~ are detected in western European Russia, some regions of Siberia, north of the Russian Far East, and ~~some~~ the 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~~ are observed in regions north of 50°N, ~~which indicated~~ indicating that the increasing rate ~~of annual mean snow depth was~~ is greater in higher latitude regions.

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

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

From March to May, the number of stations with significant changes (~~P~~$p \leqslant 0.05$) in monthly mean snow depth decreases~~d~~, especially in May because of snow melt (only 78 stations) (Figs. 7f-h). Changes in monthly mean snow depth ~~were~~ are consistent with the trends in winter over the former USSR, but more stations with decreasing trends ~~were~~ are found in southern Siberia. There ~~were~~ are few stations with statistically significant trends ~~in snow depth~~ across China; for these stations, monthly mean snow depths tend~~ed~~ to decrease at most stations. ~~Compared with regions south of 50°N, changes in monthly mean snow depth were more significant over regions north of 50°N.~~

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

4 Discussion

4.1 Comparisons with previous results

Studies on changes in snow depth have received much attention over different regions across Eurasian continent. ~~This~~ The present study, for the first time, investigated changes in snow depth using ground-based data and information over the ~~region~~ Eurasian continent as a whole. ~~Ma and Qin (2012) investigated changes in snow depth across China over period from 1957 to 2009.~~ We found that ~~the~~ climatology ~~(1966-2012)~~ of long-term mean annual snow depth (1971-2000) ~~from this study~~ was basically consistent with ~~that~~ the results from Ma and Qin (2012) over China. In terms of changes in annual mean snow depth, both studies showed increase in annual mean snow depth but with slight difference in magnitude. This may be caused by using a different number of stations and covering different study periods. ~~Over northern Eurasia, Kitaev et al. (2005) and Bulygina et al. (2011) investigated snow depth and its change.~~ The long-term (~~1966~~1971-~~2012~~2000) mean annual snow depth from ~~this~~ the present study was approximately 5-10 cm higher than the results from Kitaev et al. (2005) and Bulygina et al. (2011) over northern Eurasia. These discrepancies may result from differences in the time frame of data collection, the number of stations, calculation methods, and data quality control. For example, Kitaev et al. (2005) investigated historical changes in annual mean snow depth spanning 65 years from 1936 to 2000, while ~~this~~ the present study covered 47 years from 1966 through ~~2010~~2012. ~~In this study, w~~We intentionally did not use the earlier (1936-1965) data due primarily to data quality. The earlier Russian snow depth data were discontinuous and did not meet the data quality control requirements used ~~in this study~~. Historical changes ~~of~~ in the hydrometeorological station locations ~~were~~ are also a critical reason for deleting many stations from the study. Based on results from ~~this~~ the present study, we believe that snow depth data in the early years (prior to 1965) may be questionable and changes in snow depth prior to 1965 over Russia need further in-depth investigation.

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

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

4.2 Impact of Topography on Snow Depth

Topography is an important factor affecting ~~the~~ climatology of snow depth and ~~is~~

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

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

Continentality is a measure of the difference between continental and marine climates. It is roughly a measure of distance from oceans. Continentality affects precipitation, thus determines snowfall rate and snow depth. Although t~~T~~here ~~was~~ is a statistically significant positive relationship between annual mean snow depth and continentality over the Eurasian continent, the Goodness of Fit is only 1% (~~r=0.1, P≤ 0.05,~~ Fig. 8d). This indicates~~d~~ that the continentality may not be ~~not~~ an important driving factor of annual mean snow depth distribution compared with latitude and elevation over Eurasia, especially on the TP. ~~Although previous studies showed that the TP's largest snow accumulation occurred in winter, precipitation during winter months was the smallest of the year (Ma, 2008). This was mainly due to the majority of annual precipitation that occurs during the summer monsoon season on the TP, which causes much less precipitation during the winter half year (or the snow accumulation season).~~

4.3 Impact of Climate Factors on Snow ~~Accumulation~~Depth

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

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

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

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

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

4.4 Potential Effects of ~~the~~ Variations in Snow Depth

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

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

5 Conclusions

In this study, daily snow depth and snow course data from 1814 stations were used to investigate spatial and temporal changes in annual mean snow depth and annual maximum snow depth over the Eurasian continent for the period from 1966 to 2012. Our results demonstrate that greater long-term ~~average~~ annual mean snow depth was observed in north-eastern European Russia, the Yenisey River basin, the Kamchatka Peninsula, and Sakhalin. In contrast, the shallowest long-term annual mean snow depths were recorded in China, except for the northern Xinjiang Autonomous Region of China, Northeast China, and in some regions of the southwestern TP.

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

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

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

Appendix A: Analysis of serial correlation

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

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

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

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

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

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

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

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

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

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

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.

Barnett, T.P., Adam, J.C., and Letternmaier, D.P.: Potential impact of a warming climate on water availability in snow-dominated regions, Nature, 438, 303-309, 2005.

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

Brown, R. D. and Robinson, D. A.: Northern Hemisphere spring snow cover variability and change over 1922-2010 including an assessment of uncertainty, The Cryosphere, 5, 219-229, 2011.

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.: Eurasian snow cover variability and links with stratosphere-troposphere coupling and their potential use in seasonal to decadal climate predictions, US National Oceanic and Atmospheric Administration, Climate test bed joint seminar series, NCEP, Camp Springs, Maryland, 6pp, 2011.

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.

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. 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.

Hedstrom, N.R. and Pimeroy, J.W.: Measurement and modelling of snow interception in the boreal forest, Hydrol. Process., 12, 1611-1625, 1998.

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.

IPCC: Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, edited by: T.F. Stocker et al., Cambridge University Press, Cambridge, UK, and New York, USA, 1535 pp, 2013.

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

Khaliq, M.N., Ouarda, T.B.M.J., Gachon, P., Sushama, L., and St-Hilaire, A.: Indentification of hydrological trends in the presence of serial and cross correlations: A review of selected methods and their application to annual flow regimes of Canadian rivers, J. Hydrol., 368, 117-130, 2009.

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 surface-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.

Neter, J., Wasserman, W., and Kutner, M.H.: Applied linear regression model, Boston, IRWIN, 1989.

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.

Park, H., Fedorov, A.N., Zheleznyak, M.N., Konstantinov, P.Y., and Walsh, J.E.: Effect of snow cover on pan-Arctic permafrost thermal regimes, Clim. Dyn., 44, 2873-2895, 2015.

Peng, S., Piao, S., Ciais, P., Fang, J., and Wang, X.: Change in winter snow depth and its impacts on vegetation in China, Global Change Biol., 16, 3004-3013, 2010.

Pomeroy, J.W., Bewley, D.S., Essery, R.L.H., Hedstrom, N.R., Link, T., Granger, R.J., Sicart, J.-E., Ellis, C.R., and Janowicz, J.R.: Shrub tundra snowmelt, Hydrol. Process., 20, 923–941, 2006.

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.

Storch, H.V.: Misuses of Statistical Analysis in Climate Research, in: Analysis of Climate Variability, edited by: Storch, H.V. and Navarra, A.: Springer Press, Berlin Heidelberg, Germany, 11–26, 1999.

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.

Tao, J., Zhang, X., Tao, J., and Shen, Q.: The checking and removing of the autocorrelation in climatic time series, Journal of Applied Meteorological Science, 19, 47-52, 2008.

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).

Weatherhead, E.C., Reinsel, G.C., Tiao, G.C., Meng, X., Choi, D., Cheang, W., Keller, T., DeLuisi, J., Wuebbles, D.J., Kerr, J.B., Miller, A.J., Oltmans, S.J., and Frederick, J.E.: Factors affecting the detection of trends: Statistical considerations and applications to environmental data, J. Geophys. Res., 103(D14), 17149-17161, 1998.

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.

Xu, W., Ma, L., Ma, M., Zhang, H., and Yuan, W.: Spatial-temporal variability of snow cover and depth in the Qinghai-Tibetan Plateau, J. Climate, 30, 1521-1533, 2017.

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.

Ye, K., Wu, R., and Liu Y.: Interdecadal change of Eurasian snow, surface temperature, and atmospheric circulation in the late 1980s, J. Geophys. Res. Atmos., 120, 2738-2753, 2015.

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.: Progress in global permafrost and climate change studies, Quaternary Sciences, 32, 27-38, 2012 (in Chinese with English abstract).

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., Barry, R.G., Gilichinsky, D., Bykhovets, S.S., Sorokovikov, V.A., and Ye, J.: An amplified signal of climatic change in soil temperatures during the last century at Irkutsk, Russia, Clim. Change, 49, 41-76, 2001.

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).

Zhao, H., Higuchi, K., Waller, J., Auld, H., and Mote, T.: The impacts of the PNA and NAO on annual maximum snowpack over southern Canada during 1979-2009, Int. J. Climatol., 33, 388-395, 2013.

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
Daily air temperature and precipitation~~Snow water equivalent (SWE)~~	the former USSR~~the former USSR~~	386~~386~~	RIHMI-WDC~~RIHMI-WDC~~
~~Daily air temperature and precipitation~~	~~the former USSR~~	~~386~~	~~RIHMI-WDC~~

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

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

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

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

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

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

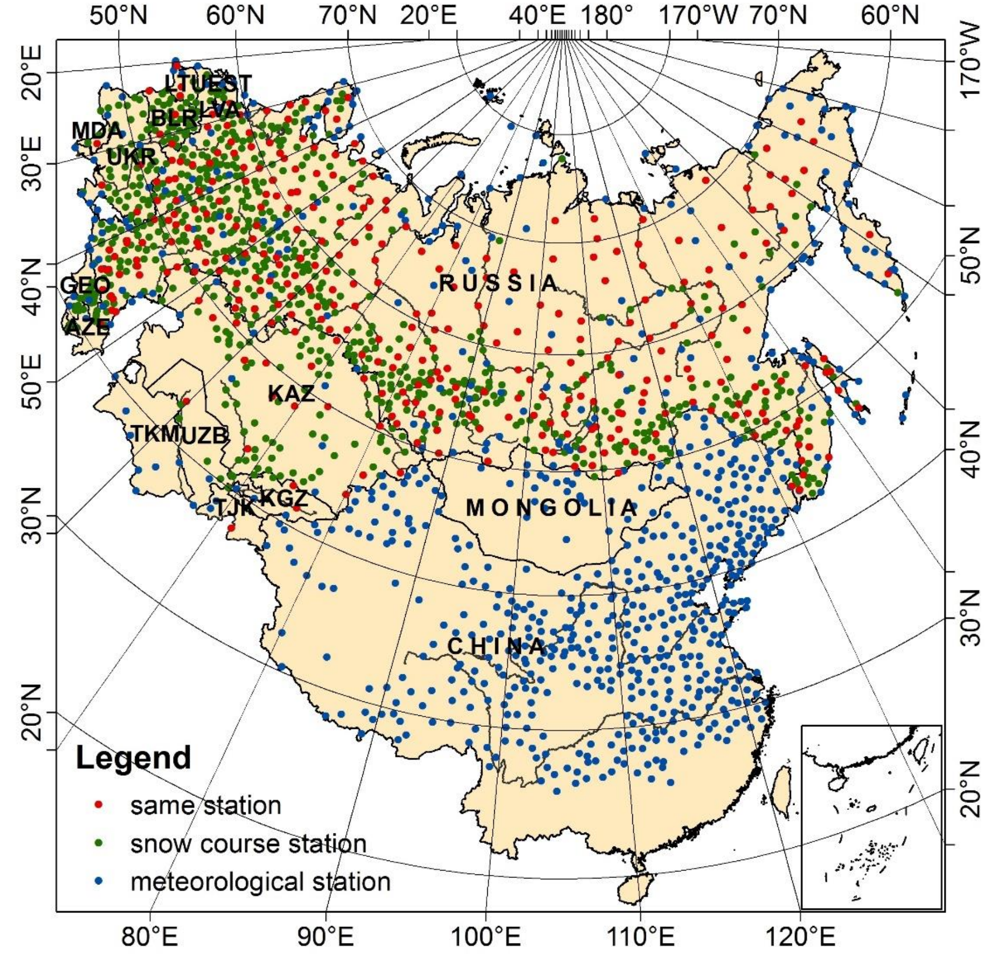
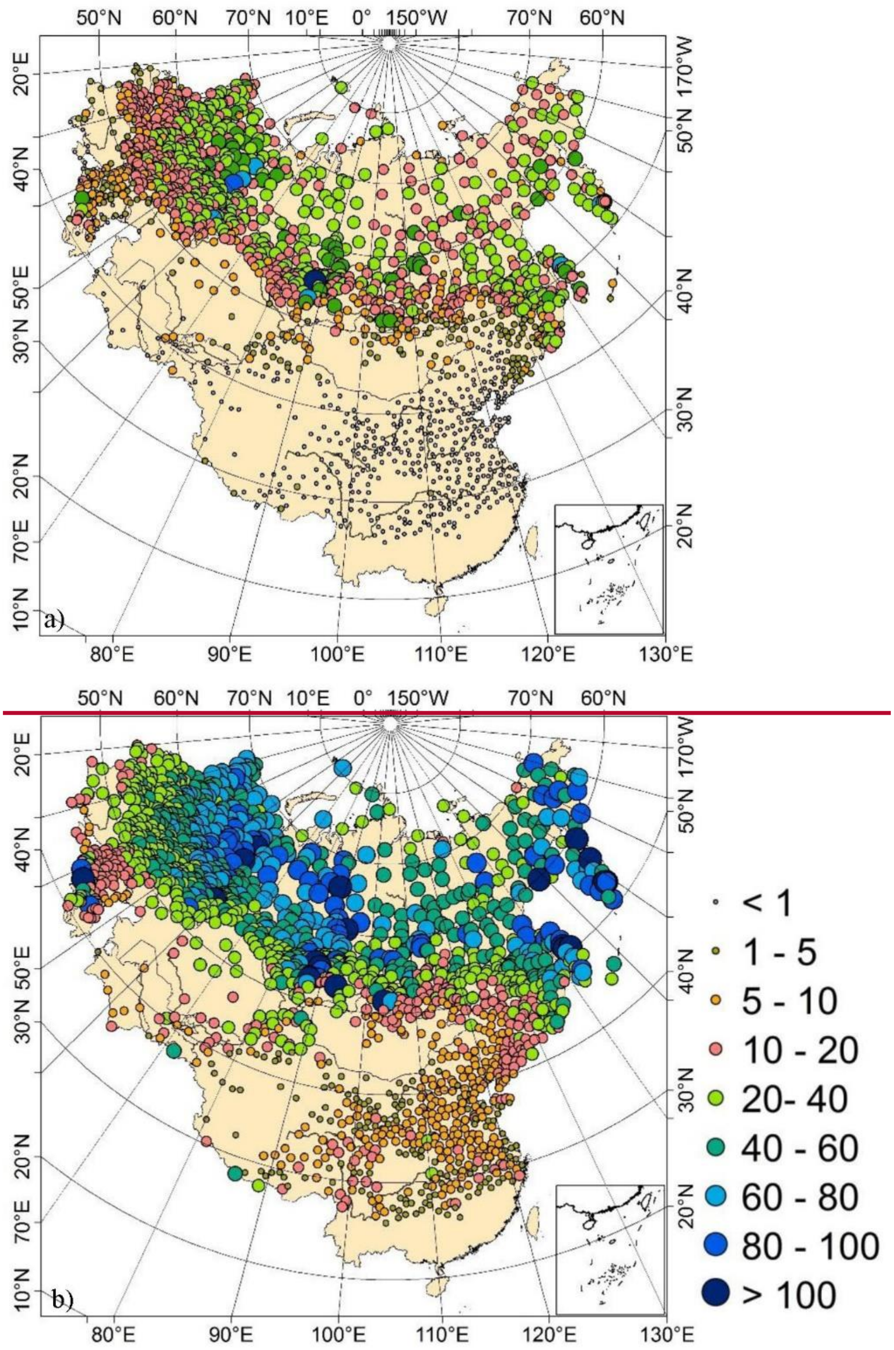


Figure 1. Geographical locations of meteorological stations and snow course ~~stations~~ survey across the Eurasian continent. The red circles represent stations where snow depth was measured at both meteorological stations and snow course surveys, the green circles show stations where snow depth was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


a)
b)
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20°N
70°E
10°N
170°W
50°N
40°N
30°N
20°N
80°E
90°E
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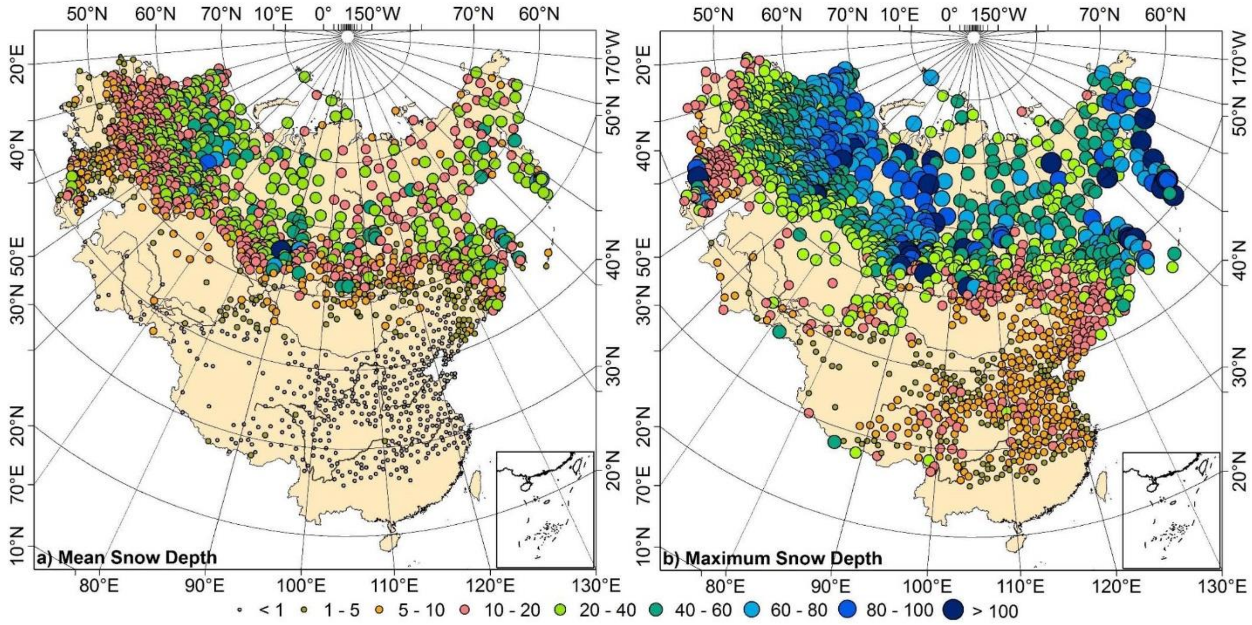
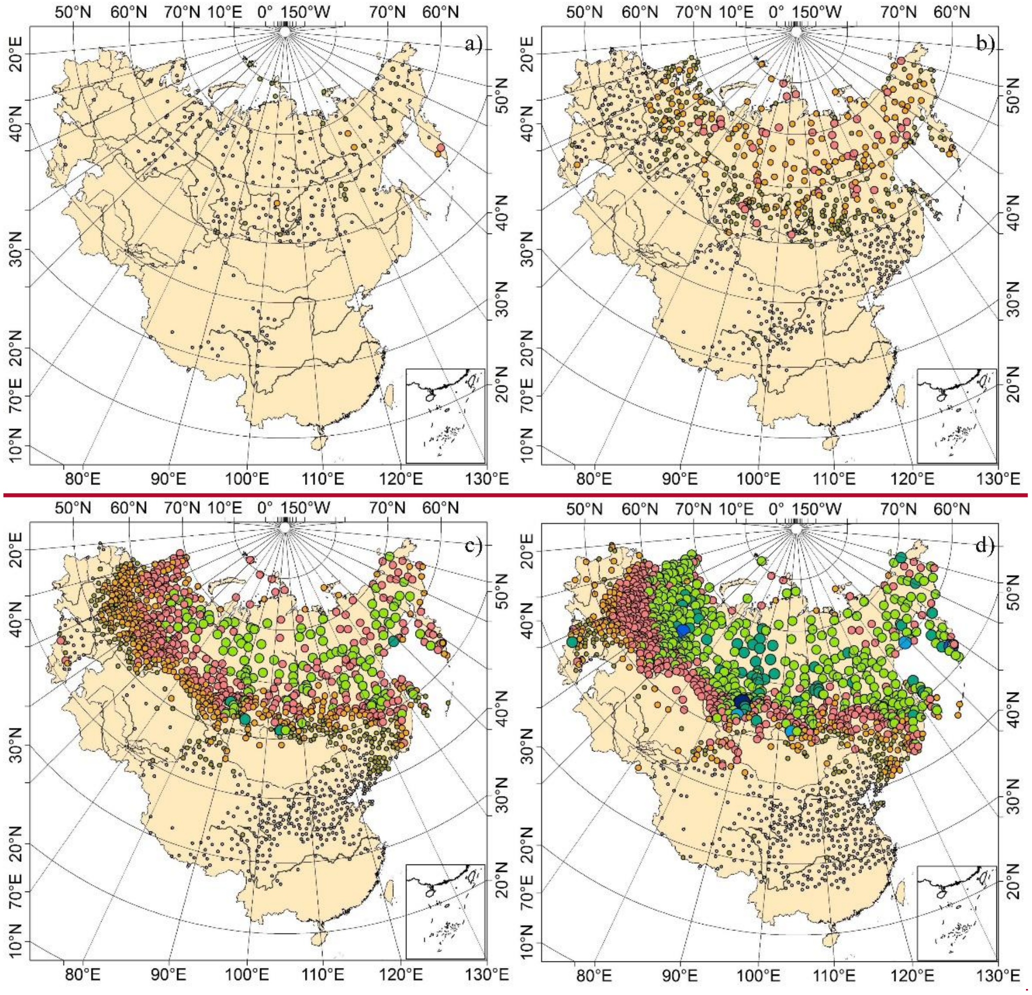
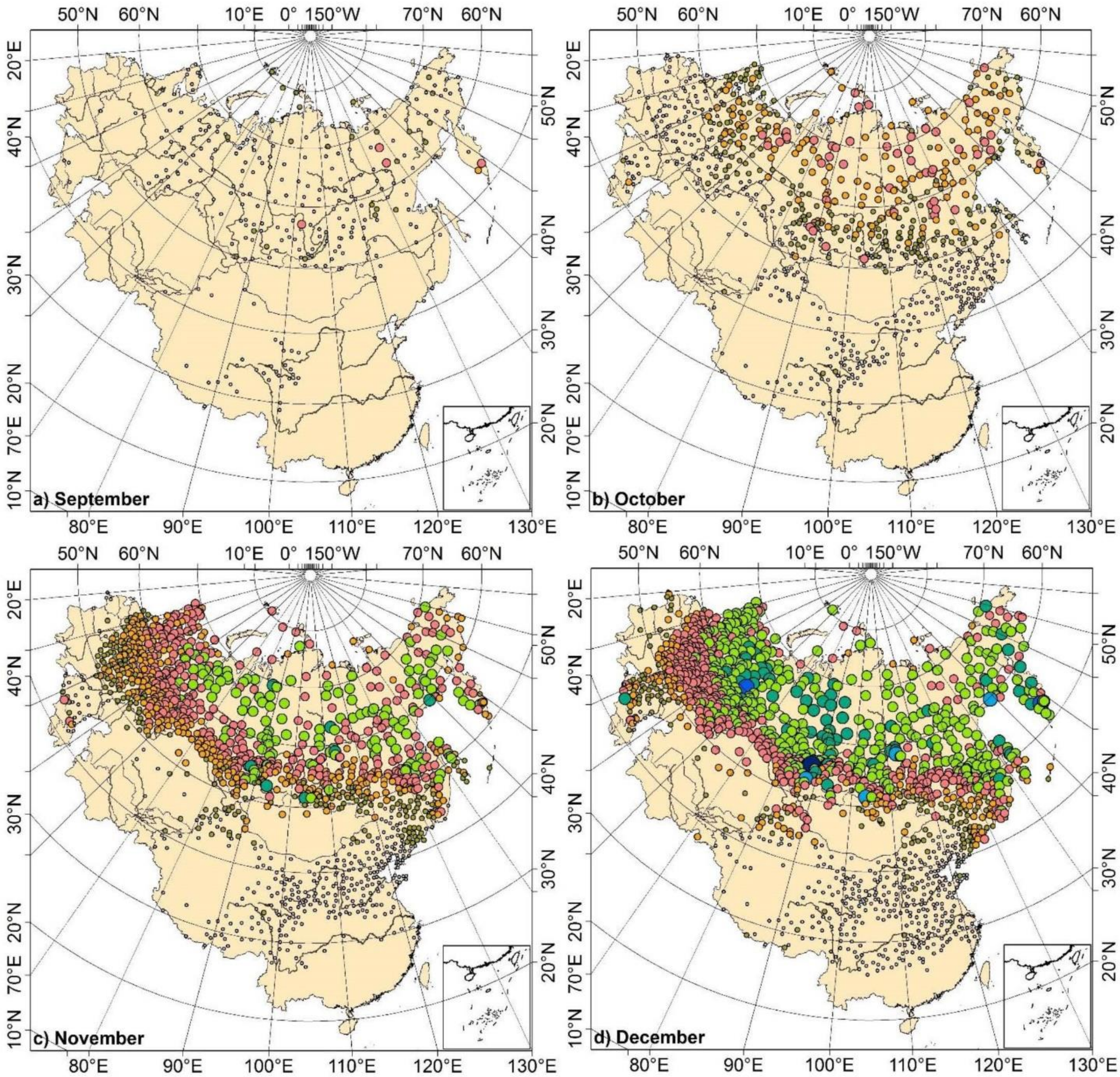


Figure 2. Long-term mean a~~A~~nnual ~~mean~~ snow depth (a) and long-term mean maximum snow depth (b) across the Eurasian continent (cm) during the ~~1966~~1971-~~2012~~2000 period.




a) September
b) October
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20°N
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90°E
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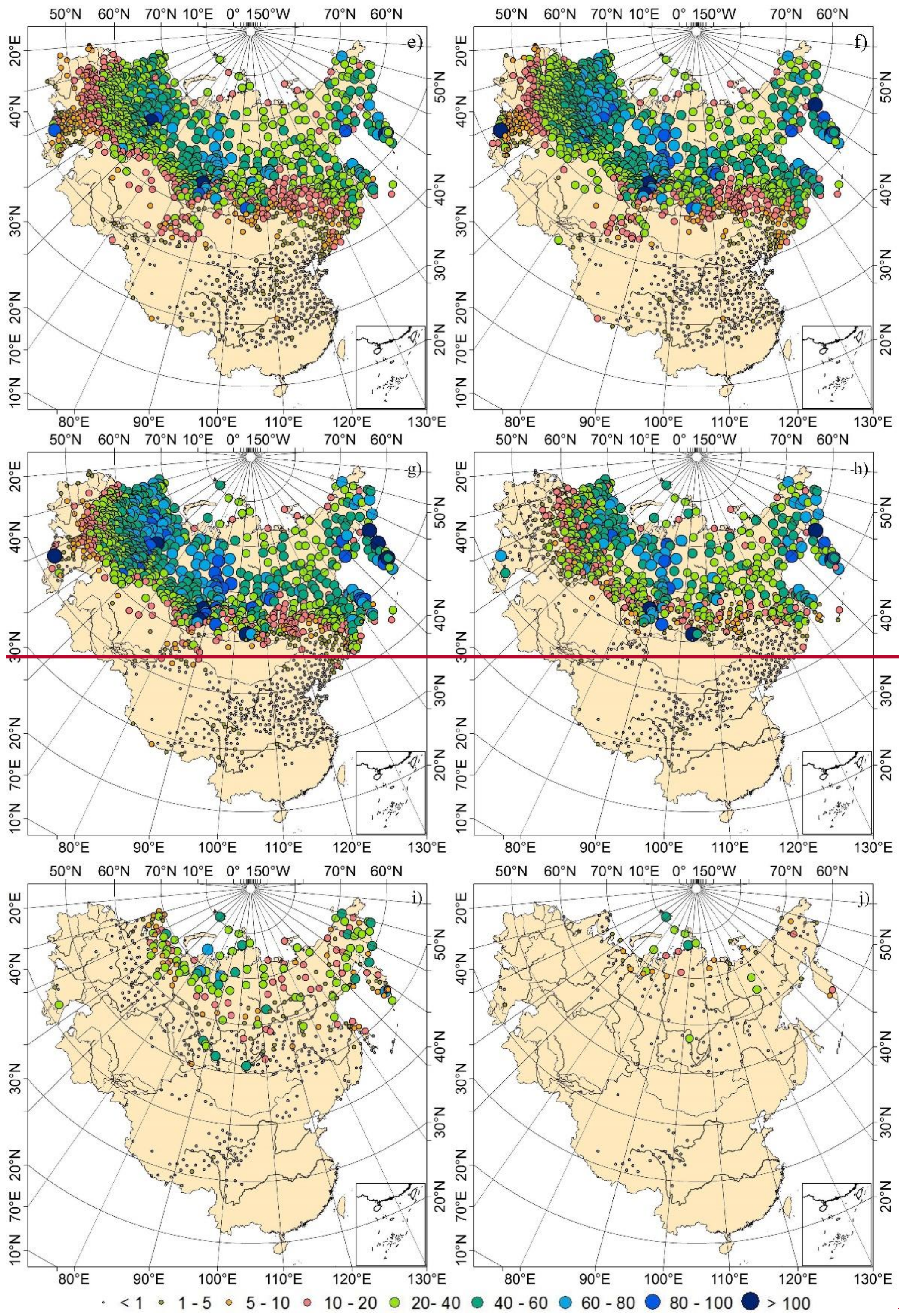
110°E
120°E
130°E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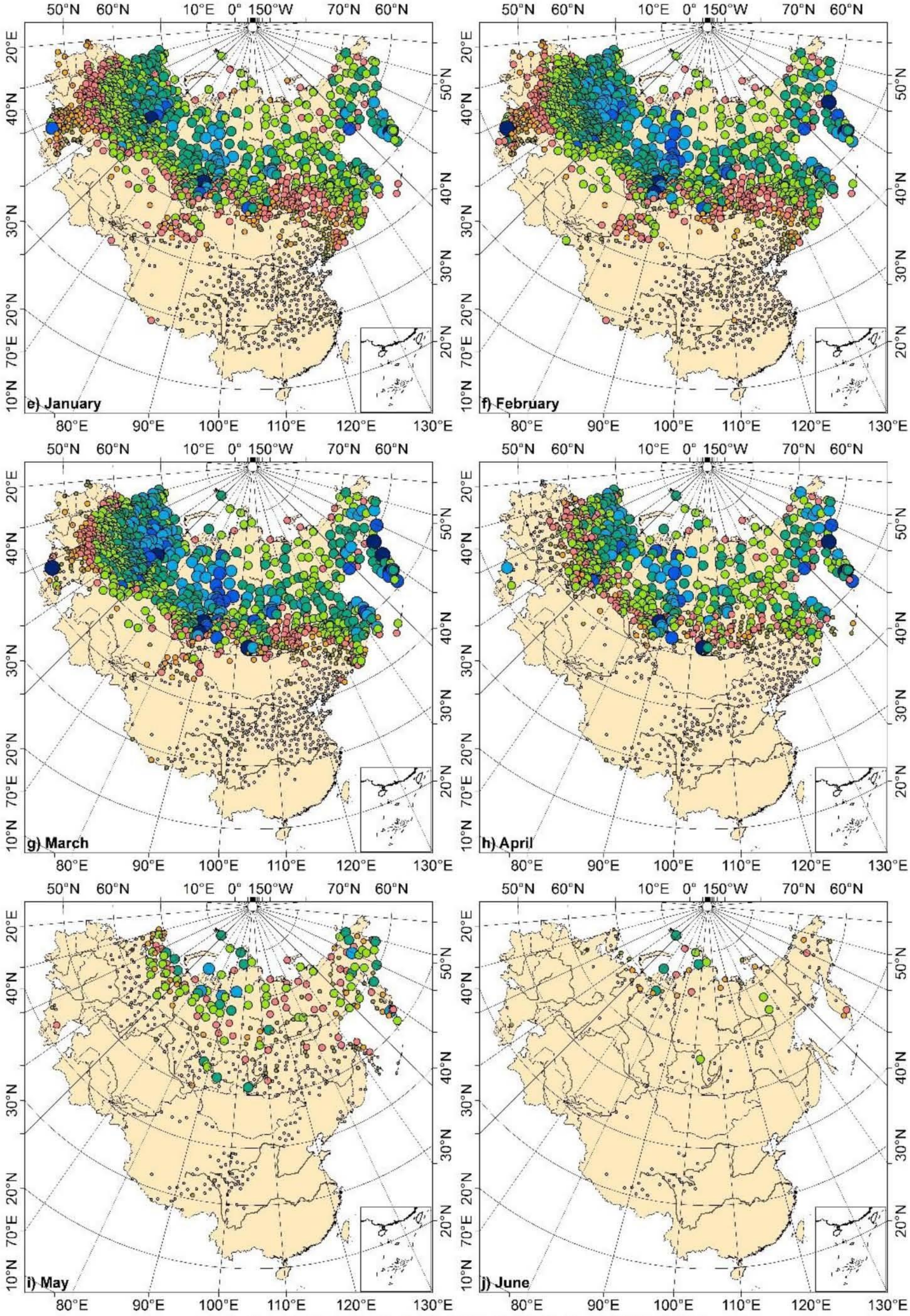
e) January
f) February
g) March
h) April
i) May
j) June
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20°N
70°E
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80°E
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110°E
120°E
130°E
< 1
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5 - 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100

Figure 3. Long-term mean ~~Monthly~~ monthly ~~mean~~ snow depth (from September to June) (cm) across the Eurasian continent (cm) during the ~~1966~~1971-~~2012~~2000 period. (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, (i) May, (j) June.

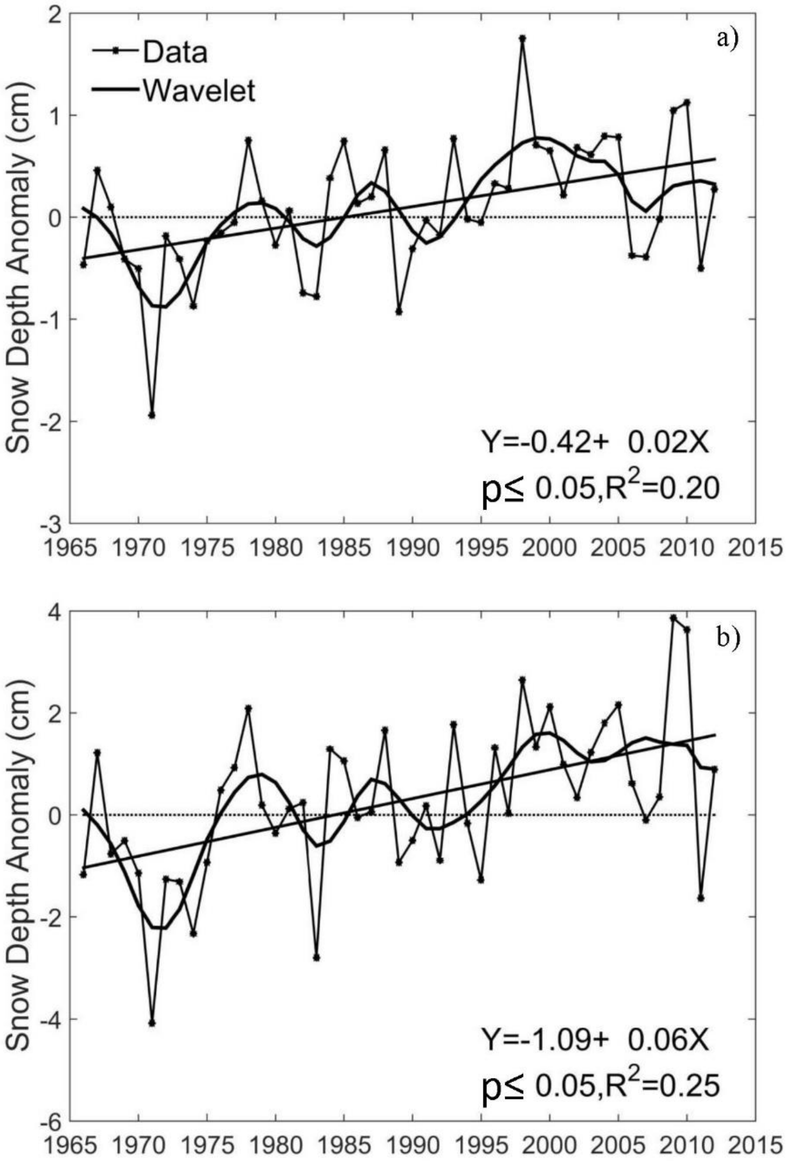


Figure 4. Composite of the anomalies ~~inter-annual variation~~ of annual mean snow depth (a) and annual maximum snow depth (b) from 1966 through 2012 with respect to the 1971-2000 mean across the Eurasian continent. The composite anomaly was calculated by the sum of anomalies from all stations divided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

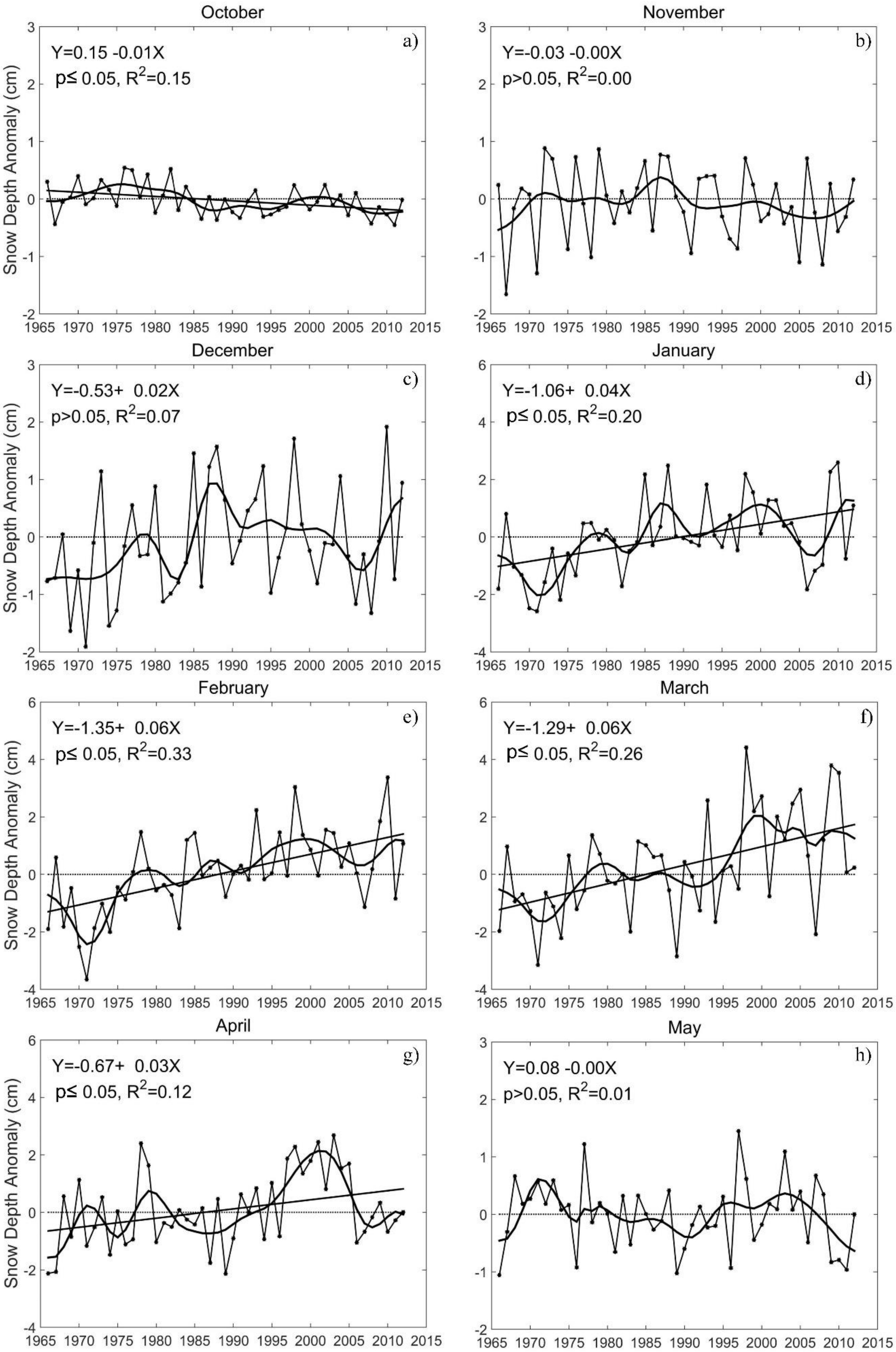


Figure 5. Composites of <ins>the anomalies</ins> ~~inter-annual variation~~ of monthly mean snow depth (from

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

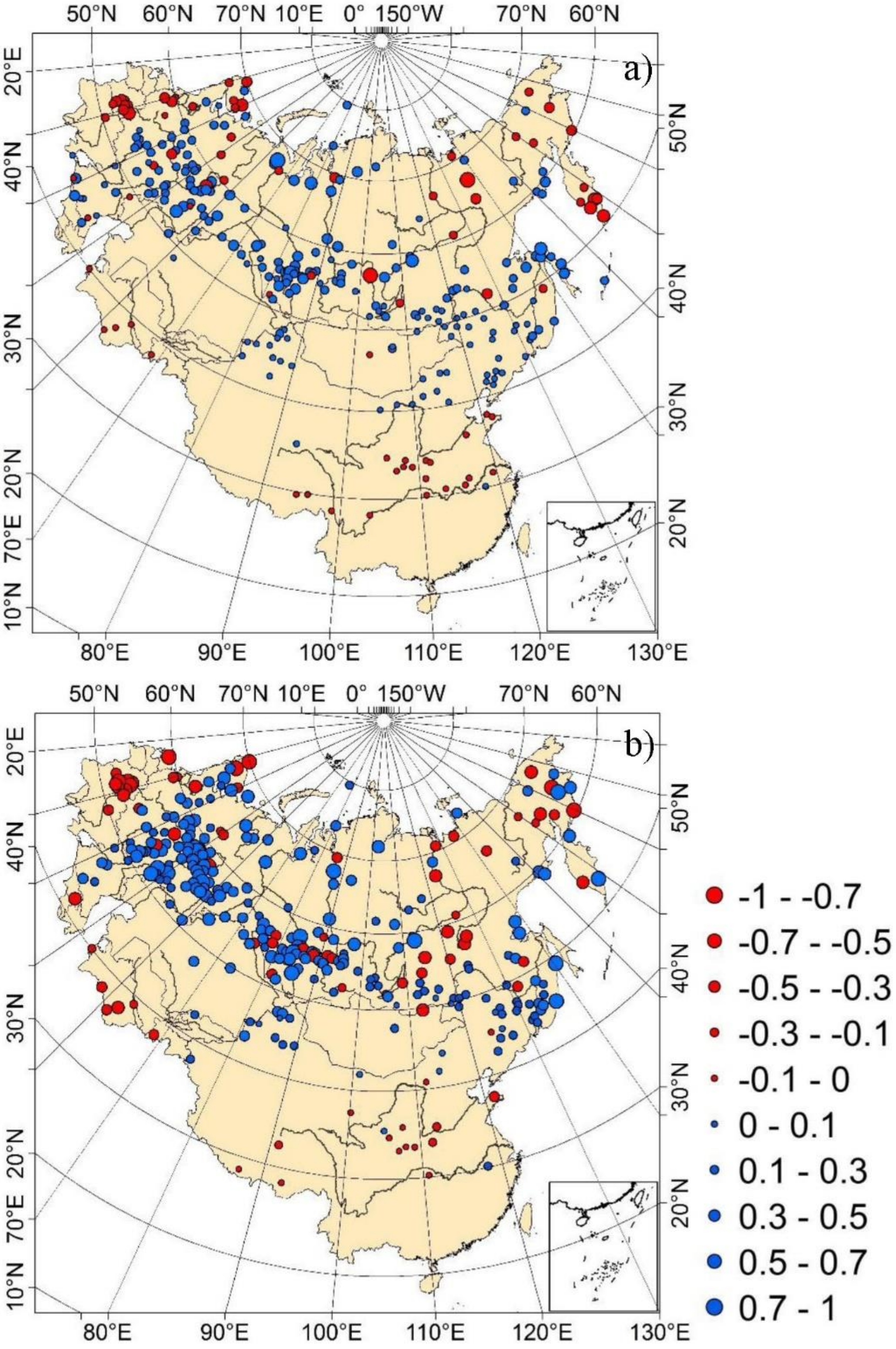
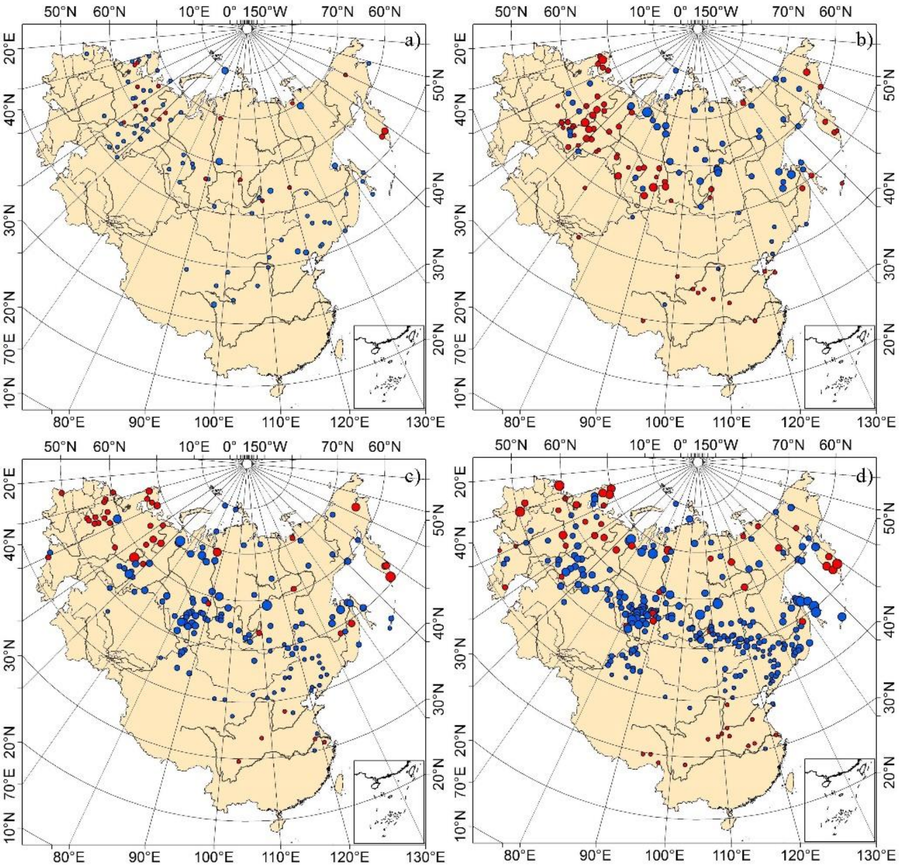


Figure 6. Spatial distribution of linear trend coefficients (cm yr^{-1}) of annual mean snow depth (a)

and annual maximum snow depth (b) for each station in 1966-2012. The rate of change ~~was~~ at the 95% level is displayed. Red circles represent a decreasing trend, and blue circles represent an increasing trend.



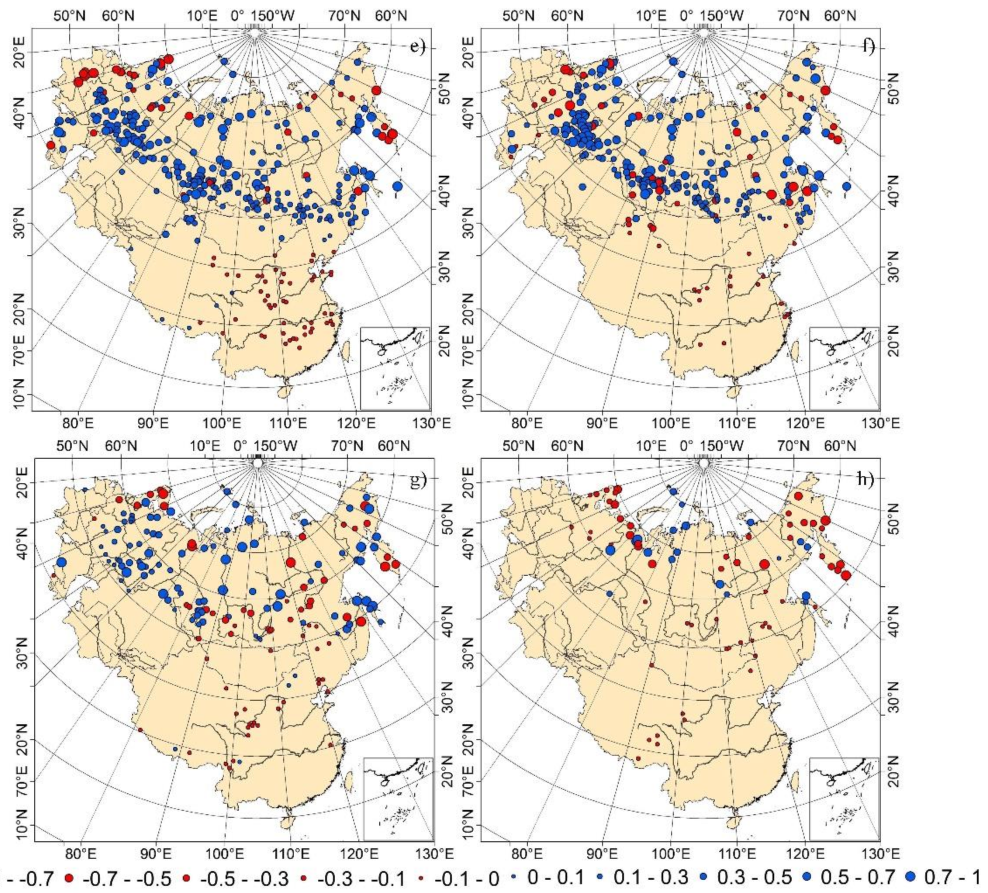


Figure 7. Spatial distributions of linear trend coefficients (cm yr^{-1}) of monthly mean snow depth (from October to May) during 1966 to 2012. (a)October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May. The rate of change ~~was~~ at the 95% level is displayed. Red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

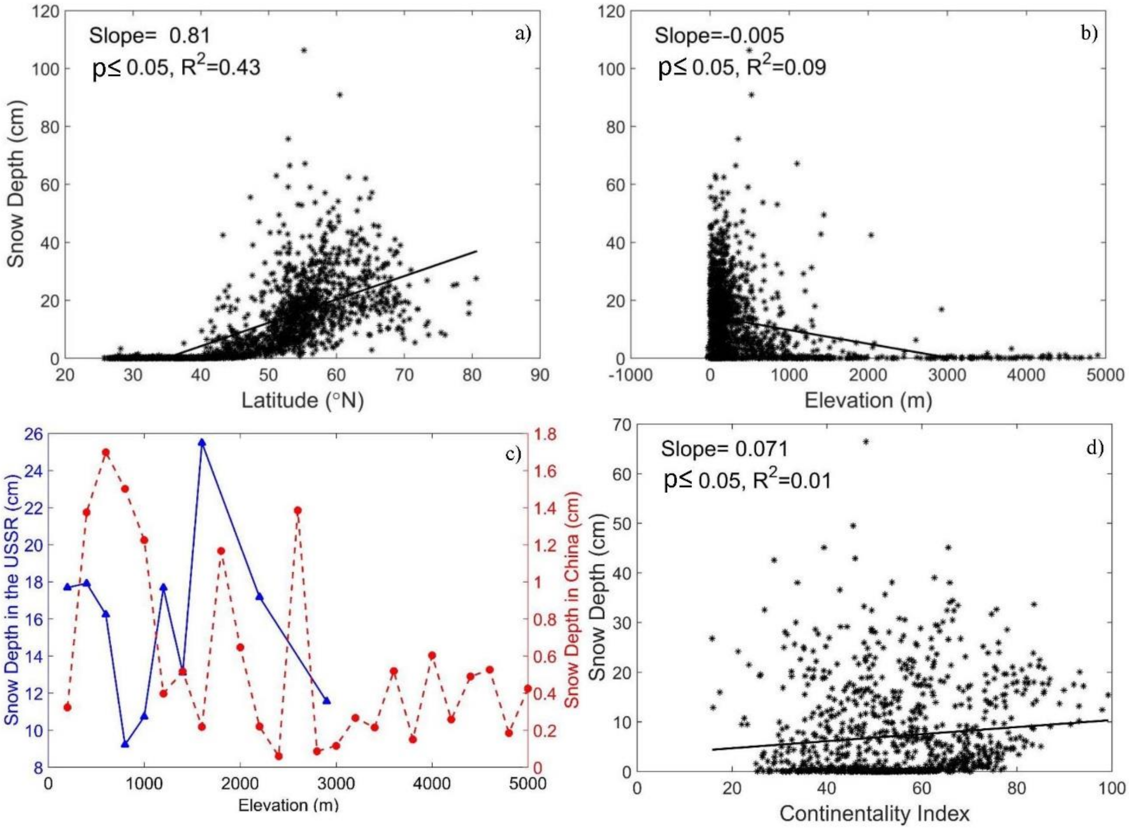


Figure 8. ~~The r~~Relationship between annual mean snow depth and latitude (a), elevation (b and c) and continentality (d) for all stations across the Eurasian continent during 1966-2012. Asterisks show the annual mean snow depth ~~of~~ at each station; the thick line is a linear regression trend.

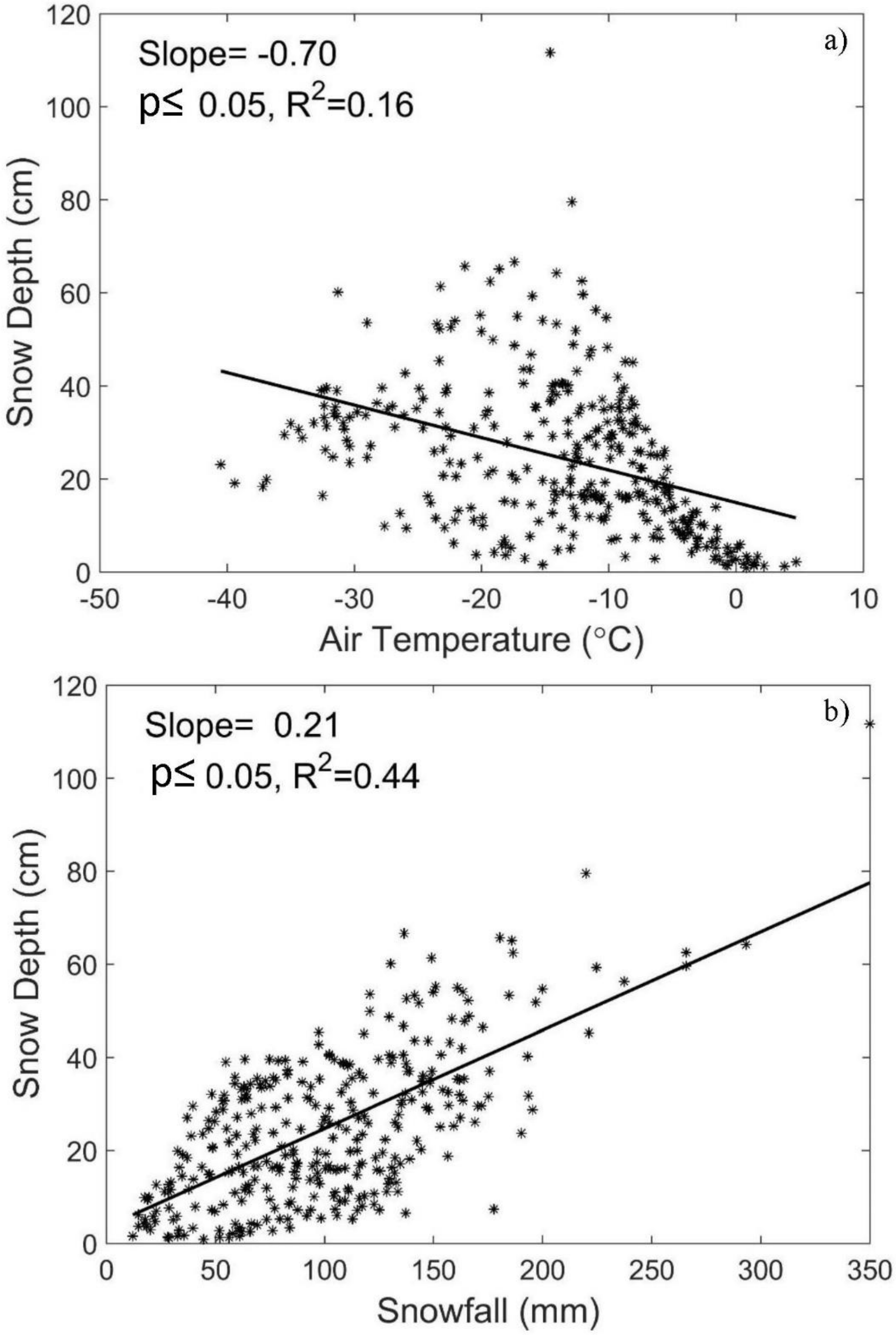


Figure 9. ~~The r~~Relationship~~s among~~ between annual mean snow depth~~,~~ and air temperature (a) and between annual snow depth and snowfall (b) from~~for~~ 386 stations from November through March during 1966-2009 over the USSR. The thick line is a linear regression trend.

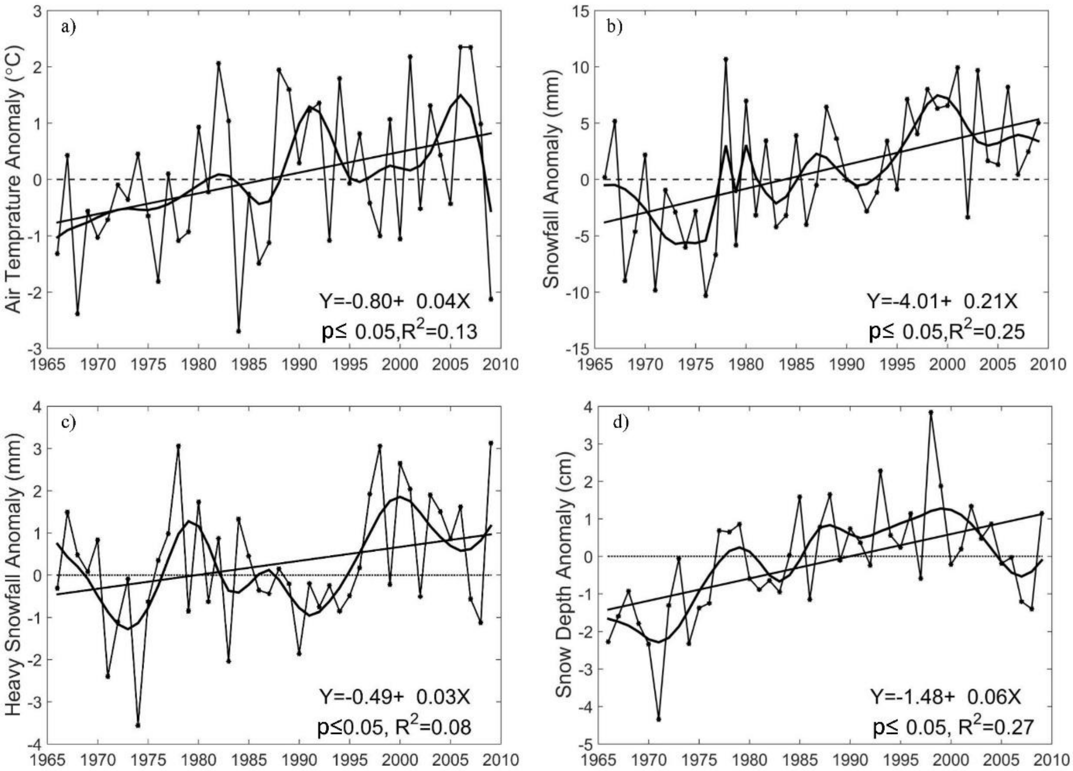
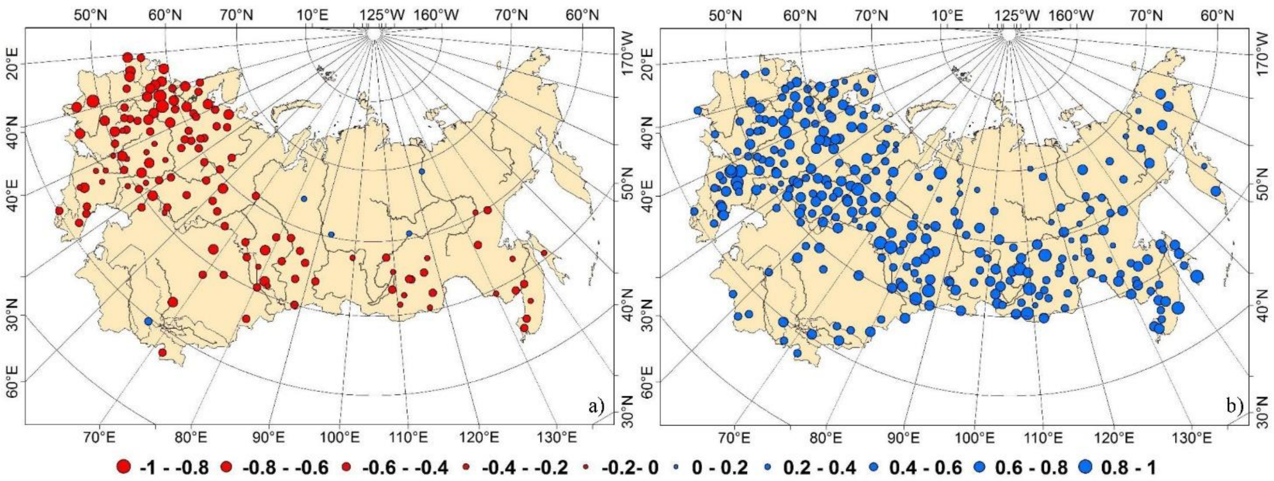


Figure 10. Composite of the anomalies~~inter-annual variation~~ of annual mean air temperature (a), annual snowfall (b), annual heavy snowfall (c) and annual mean snow depth (d) from November through March during 1966-2009 with respect to the 1971-2000 mean across the former USSR. The composite anomaly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



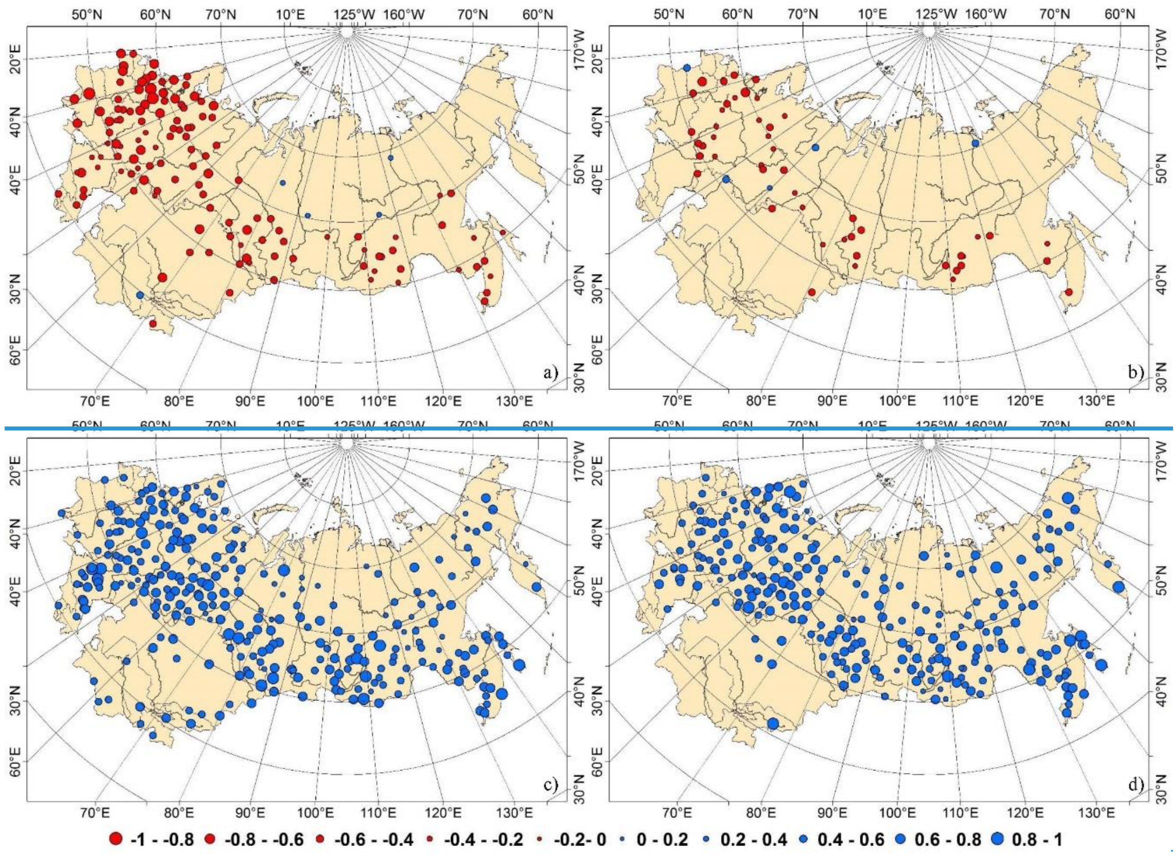


Figure 11. Spatial distributions of partial correlation coefficients ~~of~~ between mean snow depth and air temperature (a)~~,~~ and between mean snow depth and snowfall (b)~~, SWE and air temperature (c), SWE and snowfall~~ from November through March during 1966-2009 across the former USSR. The coefficients reaching to the 95%~~ 0.05~~ confidence level are displayed. Red circles represent a negative relationship, and blue circles indicate a positive relationship.

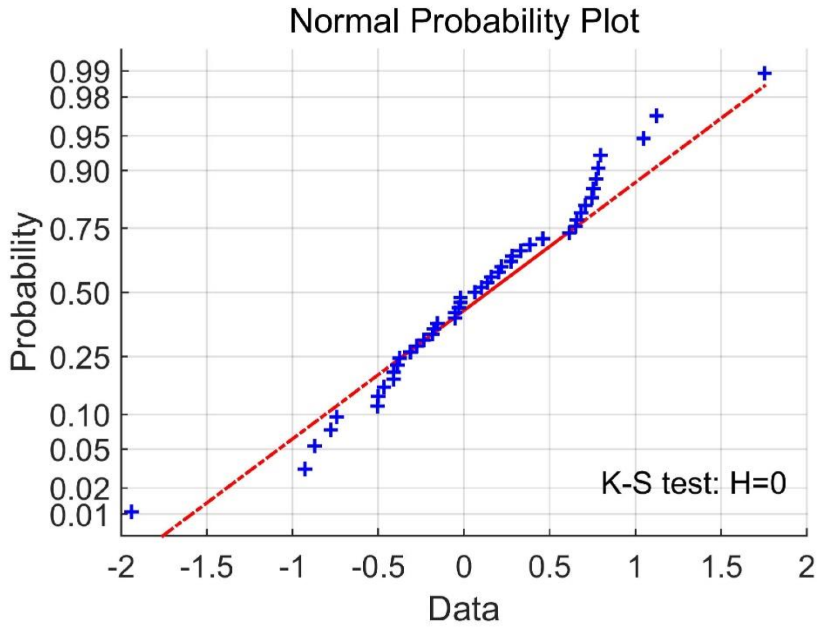


Figure A1. Normal distribution test of annual mean snow depth for all station by K-S test.