Response to Referee #1

General Comments:

1) This study examines the characteristics and trends across the Eurasian continent from 1966 to 2012. To do so, the authors assemble snow depth data from 1103 stations across the study area. How representative are the station (point) snow depth data of the overall regional landscapes of interest? For instance, are snow depth data in forested areas collected at airports or other open areas, that may not represent the regional snow characteristics?

Reply：Thank you for your comments and concerns. The spatial representativeness of stations is always a key and difficult problem in snow depth research or any ground-based studies at various regional scales. In fact, we did not do spatial interpolation of snow depth using these in-situ data across the study area just because the uneven distribution of stations spatially and among different landscapes. The passive microwave remote sensing snow depth products may mitigate the regional coverage problem, their low spatial resolution (25×25 km) and high uncertainties (up to 200%) provide no better help to the issue. The combination of in-situ snow depth data with satellite remote sensing snow depth will be a better approach but it is out of the scope of this study. Here for the first time, we present all data we can possibly collect from various countries over the continent and show snow depth spatial variations and temporal changes. We are fully aware the shortcomings of station distribution but this in-situ dataset and its coverage is unprecedented. We may read a lot of published literatures regarding snow cover extent in regional or hemispheric scales, but not snow depth. In this study, we present spatial and temporal changes in snow depth using available in-situ data.

2) Further to this, snow course data from the former USSR are also employed in establishing the snow depth climatology (see Section 2). Is it therefore a fair comparison to present the station (point) data with those from local (spatially averaged) data?

Reply: In our study, 440 stations have both snow course and station data. We compared the snow course averaged data and the station point data and found that they were statistically significantly correlated, and the goodness of fit reached to 94% (Fig. 1). Therefore, we are confident that it was a fair practice to combine the snow course average data and the station point data together in this study.

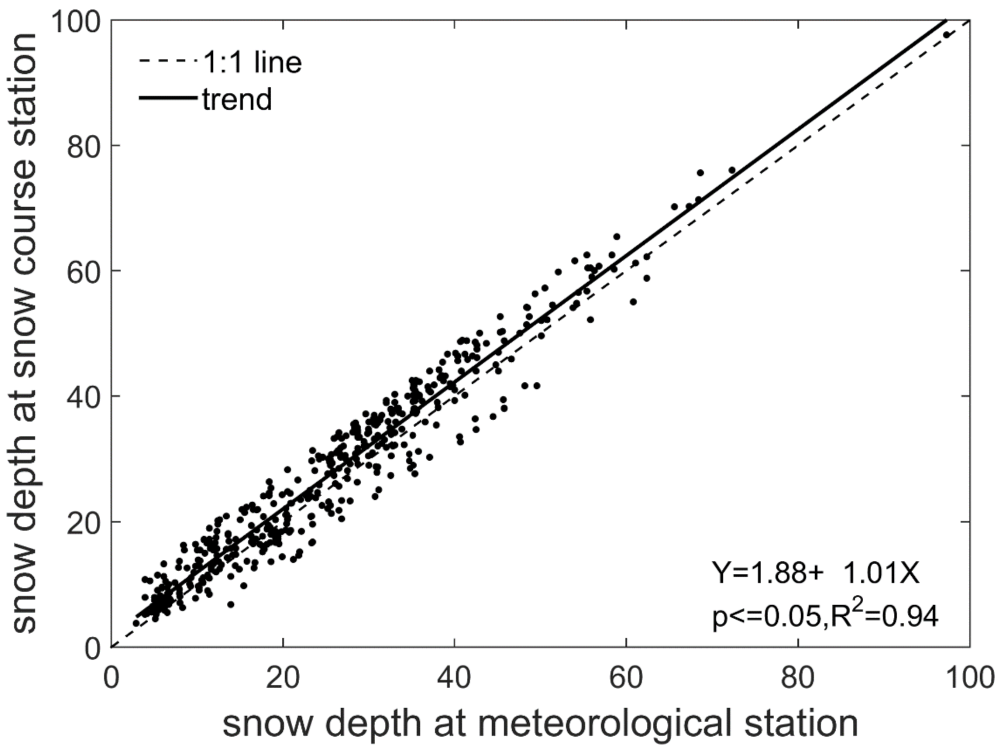


Figure1. The relationship between snow depth of meteorological station and snow course at 440 stations.

3) The Introduction section is quite lengthy and could be abbreviated by focusing on past studies that report climatologies and trends in snow depth across Eurasia only and the gap being filled by the present study. Further to this, the Introduction should emphasize the novelty of this research compared to previous studies cited in the text.

Reply: We have abbreviated the introduction, and focused on the report of climatologies and trends in snow depth, the existing problems of the previous studies, as well as the characteristics of our study.

4) The authors should consider the Mann-Kendall test to assess linear trends or other non-parametric trend analysis rather than linear regressions.

Reply: Any trend analysis is an approximate and simple approach to obtain what has happened on average during the study period. Linear trend analysis provides an average rate of this change. Despite there is a nonlinearity, the linear trend analysis is also a useful approximation when a systematic low-frequency variations emerged. Meanwhile, to overcome the strong assumption in ordinary least squares (independent and normal distribution), we added a Mann-Kendall (MK) test to identify the monotonic trend in snow depth. These two test methods could provide more robust and comprehensive information of the trend analysis. We have added the method introduction in the “data and methodology” section and discussed the similarities and differences of the two kind of trend analysis results in the “results” section.

“Any trend analysis is an approximate and simple approach to get what has happened on average during the study period. Linear trend analysis provides an average rate of this change. Despite there is a nonlinearity, the linear trend analysis is also an useful approximation when a systematic low-frequency variations emerged. (Folland and Karl, 2001; Groisman et al., 2006). The linear trend coefficient of snow depth was calculated to represent the rate of change at each station. The Student T test was used to assess the statistical significant of the slope in the linear regression analysis and the partial correlation coefficients, and the confidence level above 95% was considered in our study. Meanwhile, to overcome the strong assumption in ordinary least squares (independent and normal distribution), we applied a Mann-Kendall (MK) test to identify the monotonic trend in snow depth. Confidence level above 95% was used to determine the statistically significant increase or decrease in snow depth. These two test methods could provide more robust and comprehensive information of the trend analysis.”

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

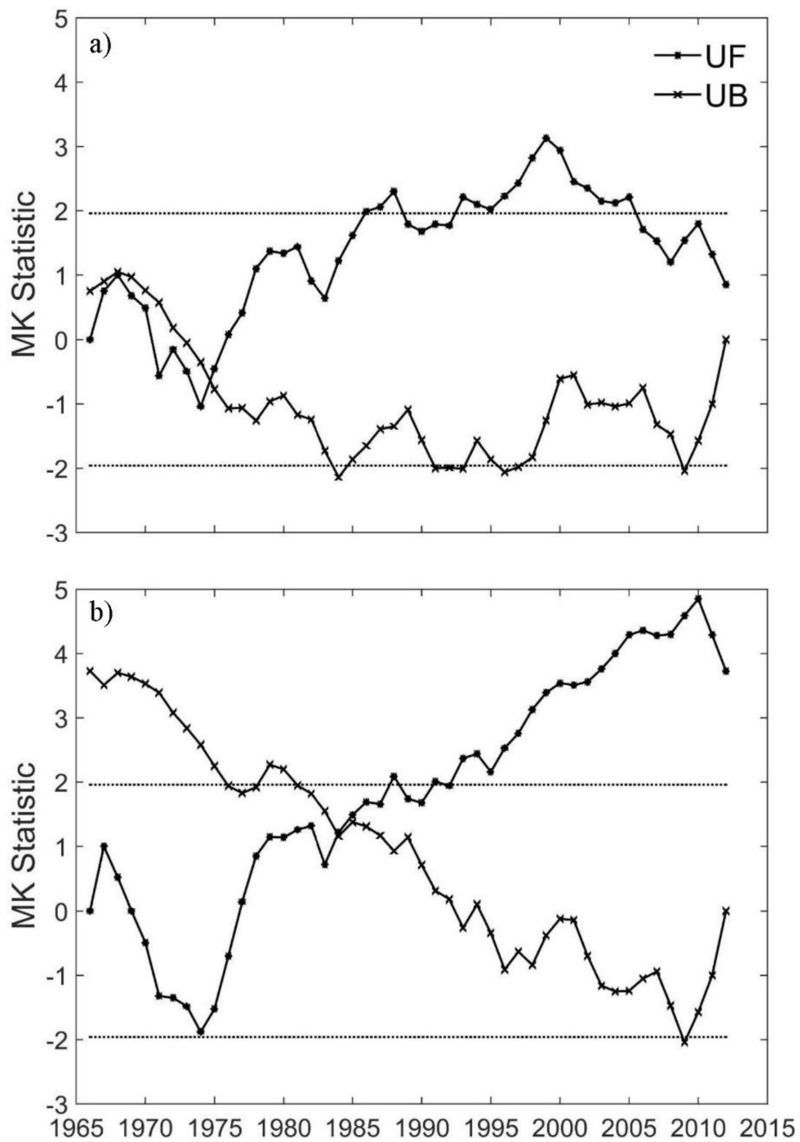


Figure 5. Mann-Kendall statistical curve of annual mean snow depth (a) and maximum snow depth (b) from 1966 through 2012 across the Eurasian continent. Straight line presents significance level at 0.05.

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

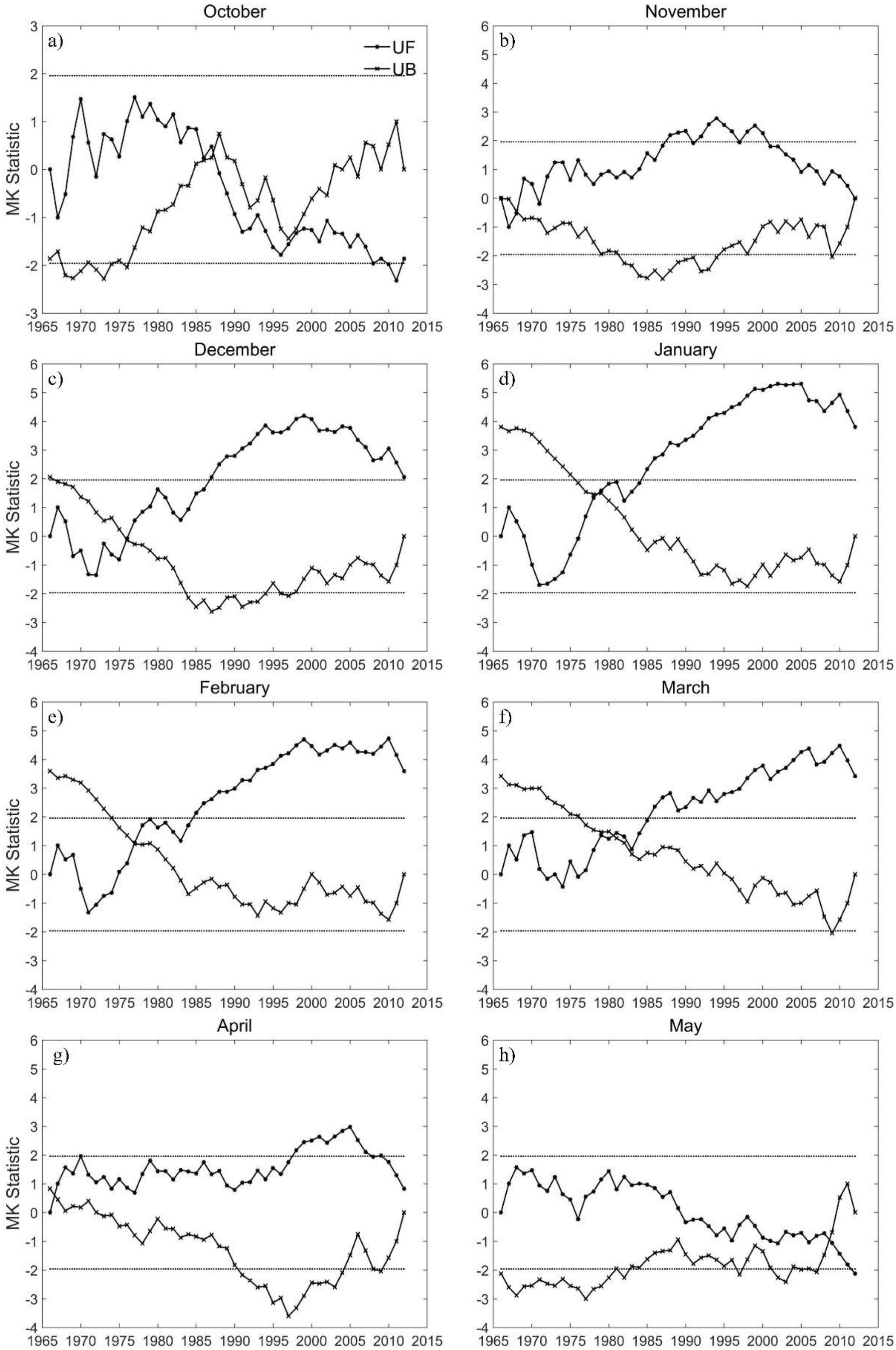


Figure 7. Mann-Kendall statistical curve of monthly mean snow depth (from October to May) from 1966 through 2012 across the Eurasian continent. (a) October, (b) November, (c) December, (d) January, (e) February, (f) March,

(g) April, (h) May. Straight line presents significance level at 0.05.

5) Do the linear trends reported in Section 3.2 exceed the variability in the snow depth data? In other words, are there “detectable” trends in snow depth, i.e. with the signal greater than the noise in the system?

Reply: The Student T test was used to assess the statistical significant of the slope in the linear regression analysis, and the confidence level above 95% was considered in our study. We have tested the results of the linear trends in Section 3.2, and the results show that all of the “detectable” trends in snow depth were greater than the noise in the system.

6) All figures are rather small and difficult to interpret when printed on paper.

Reply: Thank you for pointing this out. We have expanded all figures.

Specific Comments:

1) P. 1, line 21: Insert “a” before “snow depth”. Then insert “its” before “spatiotemporal”.

Reply: Has been done.

2) P. 1, line 27: Consider a word other than “dramatically” here. Are these statistically significant trends?

Reply: We replaced it with “significantly”. In our study, the trends with the confidence level above 95% were only considered.

3) P. 3, lines 10-20: Note that the tense for verbs changes throughout this paragraph.

Reply: We replaced “is” with “was” in line 15, and replaced “promotes” with “prompted” in line 19.

4) P. 3, lines 22-24: Are the soil thermal conditions reported here for winter only?

Reply: Yes, the soil thermal conditions are in winter.

5) P. 4, line 8: Delete “the” before “ecological”.

Reply: Has been deleted.

6) P. 5, line 8: Delete “In order” and begin the sentence with “To obtain…”

Reply: Thank you for your suggestions. We revised it.

7) P. 6, lines 4-8: Delete “Using data from ground-based measurements” as this repeats text from the previous sentence. Also, please rephrase the statement “a detailed description of snow depth”, as this suggests the paper goes at length in describing how snow depth is defined, which is not the case. This entire sentence is awkward and quite long, so should be rephrased and perhaps divided into two sentences.

Reply: Thank you for your suggestions. We rephrased the sentence: “The objective of this study is to investigate the climatology and variability of snow depth, and analyze snow depth relationships with the topography and climate factors over the Eurasian continent from 1966 to 2012.”

8) P. 6, line 14: Snow depth data from 17 countries are apparently used in the present study; yet Table 1 lists only three countries (former USSR, Mongolia and China) as sources for the snow depth data.

Reply: Seventeen countries includes China, Mongolia and 15 countries previously belonged to the former USSR. In order to avoid the readers’ confusion, we deleted “in 17 countries”.

9) P. 6, line 15: Insert “a” before “daily”.

Reply: We inserted it.

10) P. 6, line 18: Replace “5” with “five”.

Reply: We revised it.

11) P. 6, line 22: “SWE” has not yet been defined.

Reply: We have defined SWE at P. 3, line 7.

12) P. 8, line 2: Delete “In order” and start the sentence with “To reflect…”

Reply: We revised it.

13) P. 9, line 8: What is a “scale gram”?

Reply: We deleted “gram”.

14) P. 9, line 15: Delete extra spaces before “from”.

Reply: We deleted it.

15) P. 10, line 11: “TP” is not defined.

Reply: We have defined TP at P. 5, line 7.

16) P. 11, line 4: Delete extra space before “northern”.

Reply: We deleted it.

17) P. 12, line 2: Insert “it” before “fluctuated”.

Reply: Thank you very much for your suggestion. We inserted it.

18) P. 12, line 7: Change to “decreasing trend”.

Reply: We revised it.

19) P. 12, line 25: Rephrase “fluctuant trend”.

Reply: We inserted “increasing” before “trend”.

20) P. 13, line 7: Delete “variability” before “trends”.

Reply: We deleted it.

21) P. 13, line 25: Delete the space in “95%”.

Reply: We deleted it.

22) P. 14, line 23: Delete the extra space before “snow”.

Reply: We deleted it.

23) P. 15, line 2: Variations in hydrometeorological quantities such as snow depth are due to climate variability, not climate change.

Reply: Thank you very much for your suggestion. We replaced “climate change” with “climate variability”.

24) P. 15, line 7: Here reports of significant declines in snow depth are provided, while the abstract (line 27) suggests the opposite pattern is being observed – which is correct?

Reply: Here the result showed the relationship between snow depth and air temperature. There was a negative correlation between them. Increasing air temperature result in the snow depth decreased. However, in the abstract, the increasing trend represented the interannual variation in snow depth. They are different.

25) P. 15, line 18: Change to “increased”.

Reply: We revised it.

26) P. 15, line 27: Insert “is” before “not”.

Reply: We inserted it.

27) P. 16, lines 7-8: “differences” is used twice in succession.

Reply: We replaced the first “differences” with “discrepancies”

28) P. 17, line 5: Delete the extra space before “is the”.

Reply: We deleted it.

29) P. 22, line 20: This should read “Liston”.

Reply: Thank you for your suggestions. We revised it.

30) P. 26, Figure 1: The colors highlighting three regions (Sakhalin, Kamchatka Peninsula, and northern Xinjiang Autonomous region) are nearly indistinguishable. Please consider using colors of greater contrast. Why are these regions highlighted in the first place? A number of abbreviations are used on the map that are not defined in the figure caption (this is an issue in other figures as well).

Reply: We highlighted the three regions due to snow depths were greater in these areas. We wanted to indicate the accurately locations for readers who are not familiar with the geography of Eurasia. We have canceled the highlight because it may cause confusion for the reader. The country abbreviations were used because the space is limited and cannot be spelled out. We have spelled out the names of countries as an annex.

Abbreviation Description

Country	Abbreviation
Kazakhstan	KAZ
Ukraine	UKR
Turkmenistan	TKM
Uzbekistan	UZB
Tajikistan	TJK
Belarus	BLR
Estonia	EST
Georgia	GEO
Latvia	LVA
Lithuania	LTU

Azerbaijan	AZE
Kyrgyzstan	KGZ
Moldova	MDA

31) P. 27, Figure 2: Given the high number of sites with high average snow depth values in the northern reaches of the Eurasian continent, would the results be better depicted using contour lines instead? Consider adding the latitudinal averages of the snow data as secondary diagrams to these figures.

Reply: We tried to use the contour lines instead of the point values. But we found that there was a problem of the accuracy of interpolation with Kriging interpolation in AcrGIS, in which there was snow cover in some no snow areas. Therefore, the results cannot be depicted using contour lines instead. Snow depth distributions are affected by the topographic factors over the Eurasia. Snow depth is also affected by elevation, slope, aspect in the same latitude. The latitudinal average of snow data cannot fully reflect the snow depth distribution.

32) P. 30, Figure 4: Does the number of stations used in the composite snow depth anomalies vary over time? The statistical significance of the trends should use the symbol "⩽" rather than "<=". Why does the last sentence in the figure caption mention "simulation" of snow depth?

Reply: Thank you for your suggestions. The number of stations used in the composite snow depth anomalies vary over time. First, we calculated the snow depth anomaly at each site, and then took the average of the anomalies as the general anomaly. We replaced "<=" with "⩽". In the figure, X means the value of the linear regression trend, which is calculated by the snow depth anomaly with linear regression. Therefore, it is a calculation of snow depth.

33) P. 31, Figure 5: See comments for Figure 4.

Reply: We replaced "<=" with "⩽".

34) P. 34, Figure 8: The statistical significance of the linear regressions should use the symbol "⩽" rather than "<=". Are any of the stations below sea level? If not, panels (b) and (c) should have their x-axes begin at 0 m in elevation. The caption should also state that these are relationships between snow depth and latitude and elevation, not changes.

Reply: Thank you for your suggestions. We replaced "<=" with "⩽". There are 9 stations below sea level in the former USSR. We revised the caption: "The relationships among annual mean snow depth, air temperature and snowfall for 386 stations from November through March during 1966-2009 over the USSR. The thick line is a linear regression trend."

35) P. 35, Figure 9: See comments for Figure 8.

Reply: We replaced "<=" with "⩽".

36) P. 36, Figure 10: See comments for Figure 8.

Reply: We replaced “<=” with “≤”.

Response to Referee #2

General Comments:

1) Methods to measure snow depth. The authors describe the snow course data, how is snow depth/snowfall measured at other stations? Is the method similar in the different countries?

Reply: All measurements at the meteorological stations across the Eurasian continent was set at the same standard by the former USSR after the World War II, including China in the 1950s. All snow depth measurements at these meteorological stations were conducted with the same kind of instruments, the same standard, and the same local time. Therefore, snow depth at all meteorological stations are all consistent. Snow courses were established and operated the same way as the snow depth measurements.

Choice of time window for analysis. The snow year was defined from July 1st to June 30th. Why this choice of period? Figure 3 shows that snow seems to begin accumulating in September but snow remains in June in northern Russia and the Tibetan Plateau. So the chosen analysis window may not be optimal and should probably begin, and end, later so as to capture the complete seasonal cycle over the studied area.

Reply: We checked that the snow cover extent is the smallest in July and August. We also conducted analysis about snow depth in July and snow was essentially gone based on the data we have. Snowfall can happen anytime of the year on the Qinghai-Tibetan Plateau but it only lasts from a few hours to a few days during summer months such as June through August. We believe it is safe to say that a snow-year from June 30 through July 1 would capture the entire seasonal snow cycle.

Trend detection. Trend detection in environmental time-series is a delicate topic and this is a big concern for this study, as the 'significant' trends reported could be cited in future works. The authors seem to have used ordinary linear regression (OLS) with classical hypothesis tests (Fisher or 'F-test' on the variance explained, and/or Student T test on regression coefficients). These parametric tests make the assumption that the data is normally and independently distributed. The authors have not reported on checking these assumptions, and I doubt that the time series presented in the figures are free of autocorrelation. As a result I question the validity of much of the 'significant' linear trends reported in this study and suggest the author should apply a statistical test which account for the serial correlation of time-series. A suggestion is given below.
If the data are normally distributed, OLS can be used but the degree of freedom for the significance test must be adjusted for the reduction in the degree of freedom caused by the auto- ('serial) correlation. If the data is not normally distributed, transformation or a non-parametric test is necessary. The Mann-Kendall trend test is commonly used on

non-normal data. Here again serial correlation must accounted for. The authors could quickly apply a normality test and the Durbin-Watson statistic to the residuals of their regression to diagnose these problems. One possible approach to take the autocorrelation into account using OLS is outlined in Weatherhead et al. (1998):

Weatherhead, E. C., et al. (1998), Factors affecting the detection of trends: Statistical considerations and applications to environmental data, J. Geophys. Res., 103(D14), 17149–17161, doi:10.1029/98JD00995.

Another possibility is to apply pre-whitening to the time series. A pertinent paper is:

Yue, S., Pilon, P., Phinney, B. and Cavadias, G. (2002), The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrol. Process., 16: 1807–1829. doi:10.1002/hyp.1095 ï´C ˘g Wavelet analysis (P8, L26-30 and P9, L1-20)

Reply: Thank you very much for your comments and suggestions. Any trend analysis is an approximate and simple approach to obtain what has happened on average during the study period. Linear trend analysis provides an average rate of this change. Despite there is a nonlinearity, the linear trend analysis is also a useful approximation when a systematic low-frequency variations emerged (Folland and Karl, 2001; Groisman et al., 2006). The linear trend coefficient of snow depth was calculated to represent the rate of change at each station. We checked and found that the data were normally distributed. The Student T test was used to assess the statistical significant of the slope in the linear regression analysis and the partial correlation coefficients, and the confidence level above 95% was considered in our study. Meanwhile, to overcome the strong assumption in ordinary least squares (independent and normal distribution), we also added the Mann-Kendall (MK) test to identify the monotonic trend in snow depth. Confidence level above 95% was used to determine the statistically significant increase or decrease in snow depth. These two test methods could provide more robust and comprehensive information of the trend analysis.

Folland, C.K. and Karl, T.R. (2001), 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.

Groisman, P. et al. (2006), 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.

The description of the wavelet analysis is very confusing and seems unnecessarily complicated, due to their limited role in the paper. It does not allow the reader to understand what was done to the data and to replicate the analysis. This section really cuts the flow of reading and should be reworked altogether in order to bring out the essential, with proper supporting references. Which wavelet transform was used in the end, a continuous or discrete? Which wavelet family/filter? From my understanding of this paragraph you applied a discrete wavelet transform, excluded the high-frequency components and then used the inverse transform to reconstruct the lower frequency signal. Or is it that you applied an averaging filter on the wavelet coefficient before reconstructing the signal with the inverse wavelet transform?

Reply: We have revised the description of the wavelet analysis. As your comments, we applied a discrete wavelet transform, excluded the high-frequency components and then used the inverse transform to reconstruct the lower frequency signal. The new description as following:

"Wavelet analysis was performed to reveal the long-term low-frequency variations of snow depth over the study area as a whole. A wavelet is a wave-like oscillation with an amplitude that begins at 0, increases, and then decreases back to 0 (Graps, 1995). We applied a discrete wavelet transform, excluded the high-frequency components and then used the inverse transform to reconstruct the lower frequency signal."

2) Results and discussion

Physiographic and climatic control on spatial variability of snow depths. The analysis of the factors controlling the spatial variability of snow depths is somewhat limited in breadth. The authors show a general increase in snow depth with latitude and a general decrease in snow depth with increasing altitude. Large-scale control on snow depth will be mainly dependent on the interplay between latitude and altitude but also distance to moisture sources (continentality) and position relative to orographic barriers. Together these will determine the snowfall rate. For such a large and topographically contrasted region as the Eurasian continent, ignoring these last two effects does not allow a clear understanding of large-scale snow depth spatial variability in the region. The negative (but poor) relationship between snow depth and altitude shown by the authors is largely explained by the continentality and rain shadow effect of the high Tibetan Plateau, while at higher latitude snow depth does seem to increase with altitude in response to orographic enhancement of snowfall. The authors should try to incorporate quantitatively the effects of continentality and barrier effect into their analysis, or at least provide a more in depth discussion of their results in the light of known large-scale physiographic control on the snow cover, with proper supporting references.

Reply: Thank you very much for your comments and suggestions. We indeed conducted analysis on impact of continentality on snow depth over the study area. To our surprise, the correlation between the two are not significant. However, we strongly agree with the reviewer that at local and regional (less than continental) scales, topography can play key roles. In Section 4.2, we added more discussions about topographical effects on snow depth, especially on Tibetan Plateau (TP). The Tibetan Plateau's largest snow accumulation occurred in the winter, but the snowfall during winter months is the smallest of the year. This was mainly due to the terrain factors: the water vapor from the east and west was blocked by the Hengduan Mountains and Nyainqentanglha Mountains, respectively, which resulted in less snowfall. Although there was more snowfall in spring, snow cover was not easy to accumulate with higher temperatures. Therefore, snow depth was shallow on TP in general. In addition to topographic factors, spatial distribution of snow depth was also affected by atmospheric circulation. We will discuss this issue in the future studies.

Relationships between mean (Eurasian) climate and snow depth over time.
The authors revealed interesting increases in snow depth, SWE, temperature and snowfall rates over the study period. However the analysis and interpretation of these tendencies remains somewhat superficial. This section could be enhanced by quantitative analysis, i.e. by performing correlation analysis, and/or multiple correlation/regression analysis to highlight the respective influence of temperature and snowfall changes on mean Eurasian snow depth and SWE. Even more interesting would be to see this analysis done spatially, perhaps in a future study. This would probably highlight the effect of continentality and position relative to orographic barriers on the response of the snow cover to climate.

Reply: We have added the quantitative analysis by the partial correlation analysis between snow depth, SWE, air temperature and snowfall. The results showed that the significant negative correlation ($p \leqslant 0.05$) between snow depth and air temperature presented in most areas of European Russia and the southern Siberia (Fig 13a). The stations with negative effects of air temperature on SWE were fewer, and there were no statistically significant correlation in the northern Siberia (Fig 13b). It was because the air temperature was below 0℃ in most areas of Siberia during December through March, the increasing temperature did not have an obvious effect on snow depth. Consistent with the interannual variation, changes in snow depth and SWE were more affected by snowfall in most areas across the former USSR from December through March. The greater partial correlation coefficients (>0.6) between snow cover and snowfall appeared in the northern European Russia, the southern Siberia, the northeast and southeast of the Russian Far East. Variations in snow depth and SWE were more sensitive to snowfall and snowfall rate in these areas.

Specific comments and editorial changes:

1) P3, L13. Although snow cover extent reduced with climate warming, snow depth still increased in northern Eurasia (Kitaev et al., 2005; Bulygina, 2011). Over which period?

Reply: The sentence is revised as “Although snow cover extent reduced with climate warming, snow depth still increased in the northern Eurasia during 1936 to 1995 (Kitaev et al., 2005) and 1966-2010 (Bulygina et al., 2011).”

2) P3 L23, ’a’ thin snow cover results...

Reply: We deleted the third paragraph in P.3 and the second paragraph in P.4 according to the suggestion of referee #1.

3) P3 L24. Frauenfeld et al. (2004) indicated that in permafrost areas the maximum snow depth by the end of winter has a significant influence on the active layer depth during the following summer.

Reply: We deleted the third paragraph in P.3 and the second paragraph in P.4 according to the suggestion of referee #1.

4) P3, L28. The numerical modeling results showed that the rate of mean annual ground surface temperature increase with the increasing maximum snow depth was about 0.1℃ cm-1 for the maximum snow depth at 15 cm. This sentence is convoluted and hard to understand, please rephrase more clearly. Maybe: The numerical modeling results showed that the mean annual ground surface temperature increases with increasing snow depth at a rate of 0.1 _C cm-1 until up to a snow depth of 15 cm...?

Reply: We deleted the third paragraph in P.3 and the second paragraph in P.4 according to the suggestion of referee #1.

5) P4, L2, ...also increased with snow depth.

Reply: We deleted the third paragraph in P.3 and the second paragraph in P.4 according to the suggestion of referee #1.

6) P4, L5: Furthermore, snow accumulation an important freshwater resources and has direct impacts on the hydrological cycle.

Reply: We deleted the third paragraph in P.3 and the second paragraph in P.4 according to the suggestion of referee #1.

7) P4, L11. Adam et al. (2009) suggested that the variations in snow depth will significantly affect the hydrological regime of the Arctic in the future.

Reply: We deleted the third paragraph in P.3 and the second paragraph in P.4 according to the suggestion of referee #1.

8) P4, L14-26: here you describe trends in snow cover and other variables. Please mention the period over which these changes were observed for respective studies

Reply: Thank you very much for your suggestion. We added the period over these changes for respective studies:

“overall, the annual mean snow depth decreased in most areas over North America during 1946 to 2000 (Brown and Braaten, 1998; Dyer and Mote, 2006), and increased in Eurasia and the Arctic during the recent 70 years (Ye et al., 1998; Kitaev et al., 2005; Callaghan et al., 2011a; Liston and Hiemstra, 2011) but there was regional differences (Bulygina et al., 2009, 2011; Ma and Qin, 2012; Stuefer et al., 2013; Terzago et al., 2014). Changes in snow depth were primarily affected by air temperature and precipitation. Ye et al. (1998) and Kitaev et al. (2005) showed that higher air temperatures caused an increase in snowfall in winter from

1936 through 1995, thus greater snow depth was observed in northern Eurasia in response to global warming. Furthermore, snow depth distribution and variation are also controlled by terrain (i.e., elevation, slope, aspect, and roughness) and vegetation (Lehning et al., 2011; Grünewald et al., 2014; Revuelto et al., 2014; Rees et al., 2014; Dickerson-Lange et al., 2015). Snow depth is also closely related to other large-scale atmospheric circulation indices, such as the North Atlantic Oscillation /Arctic Oscillation (NAO/AO) indices. For example, Beniston (1997) found that the NAO played a crucial role in fluctuations in the amount of snowfall and snow depth in the Swiss Alps from 1945 to 1994. Kitaev et al. (2002) reported that the NAO index is positively related to snow depth in the northern part of the East European Plain and over western Siberia during the period 1966-1990;"

9) P4, L28. Snow depth is also closely related to other large-scale atmospheric circulation indices, such as the North Atlantic Oscillation /Arctic Oscillation (NAO/AO) indices. For example, Beniston (1997) found that the NAO....

Reply: We have revised the sentence.

10) P5, L8. In order to obtain a wider range of snow depth...Wider range is imprecise. In order to increase the spatial coverage? and/or spatial resolution?

Reply: We revised it with "increase the spatial coverage"

11) P5, L18. Ground-based snow measurement remains the basis for verification of remote sensing and instrumental data...

Reply: We replace "is" with "remains"

12) P6, L1. 'TP' = Tibetan Plateau I presume, but I don't think it was defined before.

Reply: We have defined it in P.5, line7.

13) P6, L15. on a daily basis.

Reply: We inserted it.

14) P6, L15. Suggested change: Historical snow course data over the former USSR from 1966 to 2011 were also used in this study

Reply: We revised it.

15) P6, L17 snow surveys performed throughout the accumulation season

Reply: We revised it.

16) P6, L19. Snow surveys were conducted over 1–2 km-long transects.

Reply: We revised it.

17) P6, L20. Snow depth was measured every 10 m in the forest, and every 20 m in open terrain.

Reply: We replace “each” with “every”

18) P6, L22. SWE: define once

Reply: We have defined it in P.3, line7.

19) P6. L25 ... over the former USSR. Why only over USSR? Maybe complete sentence with ... ’where SWE data are available...’

Reply: We added it.

20) P6 L25. SWE was measured every 100 m along the 0.5-1.0 km courses and every 200m along the 2 km course.

Reply: We replace “each” with “every”

21) P6, L27. Precipitation data were divided proportionally into daily solid and liquid data, and the solid-to-liquid fraction was determined according to daily mean temperature (Brown,2000). I suggest replacing by: Daily precipitation was partitioned into a solid and liquid fraction, based on daily mean temperature (Brown,2000). You then describe the partitioning equation in the following sentence. S_{rat} : whatdoesratstandsfor…?

Reply: Thank you very much for your suggestion. We replaced this sentence.

22) P7, L9. Quality control steps. (1) daily snow depth observations (equal to or greater than 0 cm, not including missing data) for <15 days in one month were omitted; This is confusing. Do you mean that months having less than 15 days with snow depth data were omitted from the analyse? If that so rephrase in that sense. (2) snow data from stations with <20 years of measurements during 1971-2000 were excluded; I suggest replacing by: Stations with less than 20 years of data during the 1971-2000 period were excluded from the analysis. 3) data exceeding two standard deviations compared with the annual average value during 1966-2012 were omitted. Add: ’At each station,’ before the sentence.

Reply: We rephrased this sentence as “Months having less than 15 days with snow depth data were omitted from the analysis”

23) P7, L16. We defined a snow year as the period from July 1st of a current year to June

30th of the following year. Why this choice of period..? maybe add short complement to the sentence: '... so as to insure that the complete seasonal snow cycle is captured across the study region...' Also, I note in Figure 3 that snow remains in June in some areas, and seems to begin accumulating in September. So the chosen analysis window may not be optimal and should probably begin and end later.

Reply: Thank you very much for your suggestion. The snow cover extent is smallest during July to August, in order to capture the beginning of snow cover, we defined a snow year as the period from July 1st of a current year to June 30th of the following year. We have added the explanation of the choice of time window before we defined the snow year.

24) P7, L17. Because the procedures for taking snow observations have changed over the course of the studied period, there were some inhomogeneities in the data.

Reply: We revised it.

25) P7, L25....World Meteorological Organization (WMO) climatological products. A reference would be needed here.

Reply: We added the reference "World Meteorological Organization (WMO) climatological products (Ma and Qin, 2012)"

26) P7, L25. A threshold of 15 days was selected because the snow cover duration in some areas of China was less than one month, and the data for 15 days' snow depth in a month were relatively stable. Do you refer to the previously defined quality control step 1? If this is the case this sentence should go in the quality control paragraph. You can here recall it in short sentence.

Reply: Thank you very much for your suggestion. We moved this sentence to the quality control paragraph.

27) P8. L2. In order to capture the primary...

Reply: We revised it.

28) P8, (4) Linear trend coefficient of snow depth: the linear trend coefficient of snow depth for each station was obtained by linear regression analysis with respect to time, and thus represents the rate of change in snow depth for a period of time. Replace 'for a period of time' by 'over time'? Or by: 'for a >20 year time period'. Statistical test on linear trend: see main comments...

Reply: We replaced it. And the analysis of the statistical test on linear trend is answered in the main comments.

29) P8. L23. ...each station and averaged the anomalies for all stations to the anomalies for the whole Eurasian continent. : 'averaged the anomalies for all stations to obtain mean anomalies for the whole Eurasian continent'.

Reply: We revised it.

30) P8, L26 -. Description of wavelet analysis. See main comment on this. You need to include at least once key reference.

Reply: Thank you very much for your suggestion. We have revised the description of the wavelet analysis. As your understanding, we applied a discrete wavelet transform, excluded the high-frequency components and then used the inverse transform to reconstruct the lower frequency signal. The new description as following:

"Wavelet analysis was performed to reveal the long-term low-frequency variations of snow depth over the study area as a whole. A wavelet is a wave-like oscillation with an amplitude that begins at 0, increases, and then decreases back to 0 (Graps, 1995). We applied a discrete wavelet transform, excluded the high-frequency components and then used the inverse transform to reconstruct the lower frequency signal."

31) P9, L12. We used an averaging filter for wavelets analysis. Using this method, values that are too small or too large may be excluded; This description is really unclear. Please simplify and add proper references so that the interested reader can fin further explanations on the technique used, if wanted.

Reply: We deleted this sentence.

32) P9, L15. obtained from filtering. Remove extra space.

Reply: We deleted the space.

33) P9, L26. increased with the latitude... A maximum annual mean snow depth... in the west of the Yenisey River

Reply: We replace "the" with "A"

34) P9, L28. ...were observed in some areas of China. 'some areas' is rather vague, can you be more descriptive? ....due to wind speed, topography, underlying ground surface, and climatic conditions (refs). This is a rather very general statement which does not bring any insights. Of course snow depth will vary everywhere due to these factors... if you do analyse in a later section how these factord affect the spatial variability, mention it. 'The relation between these factors and spatial snow depth variability is further investigated in section xxx'...

Reply: We added more description L28: "in some areas of the south of Yangtze River in China". We deleted "due to wind speed, topography, underlying ground surface, and climatic conditions (Gray and Male, 1981; Sturm et al., 1995, 2001; Callaghan et al., 2011b)."

35) P10, L5. The regions with the smallest annual mean snow depth (<5 cm) were located in most areas of the Caucasus Mountains. This is a bit surprising given the high elevations. Is there an elevation bias here? (snow stations are at low elevations?)

Reply: The stations with the smallest annual mean snow depth are located in the eastern and western areas of the Caucasus Mountains, close to the coast of the Caspian Sea and the Black Sea, where the elevations are below 2000 m. We have added the specific location in the text: "were located in the eastern and western areas of the Caucasus Mountains"

36) P10, L13. varied with the latitude

Reply: We deleted "also"

37) P10, L15. . (201.8 cm) :here as elsewhere in the text you can should round the snow depth to the nearest centimeter, as this is the probably accuracy of the measurements.

Reply: The maximum value is calculated using the average values of annual maximum snow depth. The average is kept one decimal place, so it is an approximation.

38) P11, L4.... in northern Siberia. Remove extra space between in and northern

Reply: We removed the extra space.

39) P11, L21. ...the increasing rate of snow depth. increasing rates of snow depth

Reply: We replaced "rate" with "rates"

40) P11. L19-22: linear trends and results plotted on Figure 4: were trends computed on annual anomalies or on the wavelet filtered series? You must provide a trend test that accounts for the autocorrelation of time-series (see main comment).

Reply: The trends were computed on the annual anomalies. Any trend analysis is an approximate and simple approach to get what has happened on average during the study period. Linear trend analysis provides an average rate of this change. Despite there is a nonlinearity, the linear trend analysis is also a useful approximation when a systematic low-frequency variations emerged. The linear trend coefficient of snow depth was calculated to represent the rate of change at each station. The Student T test was used to assess the statistical significant of the slope in the linear regression analysis and the partial correlation coefficients, and the confidence level above 95% was considered in our study. Meanwhile, to overcome the strong assumption in ordinary least squares (independent and normal distribution), we also added the Mann-Kendall (MK) test to identify the monotonic trend in snow depth. Confidence level above 95% was used to determine the statistically significant increase or decrease in snow depth. These two test methods could provide more robust and comprehensive information of the trend analysis. We have added the MK test and compare the results of the two methods:

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

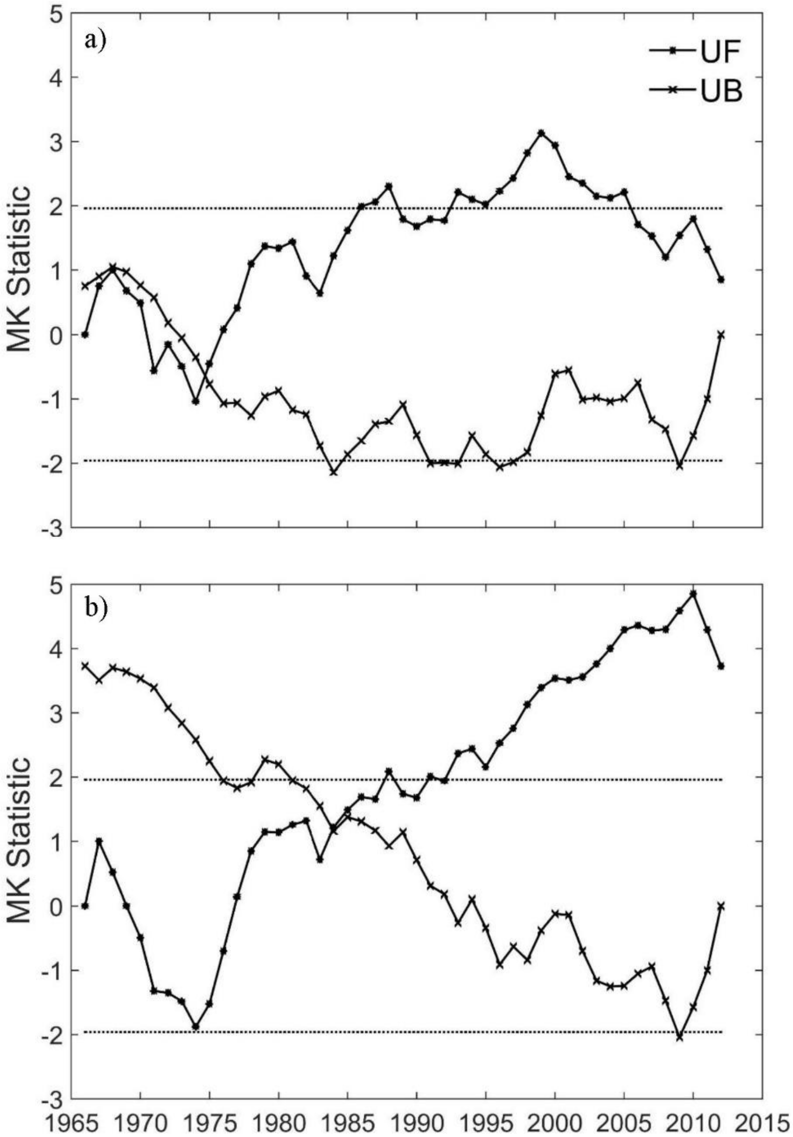


Figure 5. Mann-Kendall statistical curve of annual mean snow depth (a) and maximum snow depth (b) from 1966 through 2012 across the Eurasian continent. Straight line presents significance level at 0.05.

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

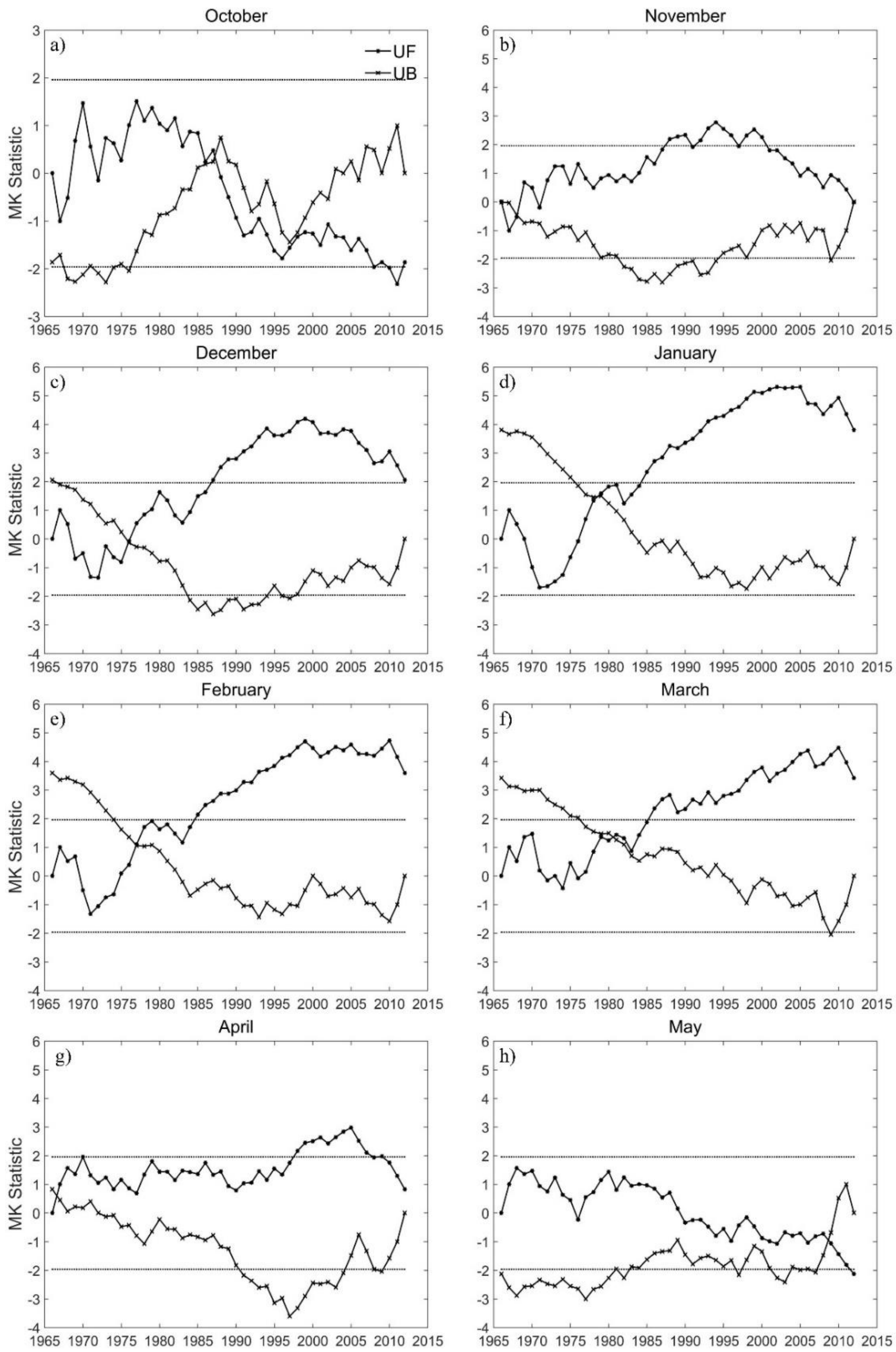


Figure 7. Mann-Kendall statistical curve of monthly mean snow depth (from October to May) from 1966 through 2012 across the Eurasian continent. (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May. Straight line presents significance level at 0.05.

41) P12, L1. There was a sharp increase of 3.5 cm in the maximum snow depth during the 1970s, then fluctuated from the late 1970s to the early 1990s. : then fluctuations from... Perhaps be more precise: what type of fluctuation?

Reply: There is no significant increase or decrease trend in fluctuation. We revised it as "then it fluctuating changed from the early 1990s through the early 2010s."

42) P12, L20. the rate of increase being about 0.6 cm decade

Reply: We replaced "was" with "being".

43) P14, L2. in monthly mean snow depth decreased,

Reply: We replaced "fell" with "decreased".

44) P14, L3. Changes in monthly mean snow depth were consistent with the trends in winter over the former USSR but more stations with the decreasing trends in the southern Siberia. Do you mean: 'but more stations with decreasing trends were found in southern Siberia'?

Reply: We revised it with "but more stations with decreasing trends were found in southern Siberia"

45) P14, L5. There were few stations with statistically significant trends of snow depth across China; for these, monthly snow depths tended to decrease at most stations.

Reply: We added "; for these,"

46) P14, L11. To explore the spatial variability of snow depth,

Reply: We replaced "features" with "variability".

47) P14, L15. snow depth to the north of 40° N

Reply: We deleted "mean".

48) P14, L23. because a snow depth. remove extra space between 'a' and 'snow'

Reply: We deleted the extra space.

49) P14. This result indicates that elevation is an important factor affecting snow depth in these regions. I find this statement and the preceding analysis a bit over simplistic. At large scales the snow cover can be tought to depend on latitude, altitude and distance to moisture source (continentality). I feel you are missing the third factor in our analysis. The poor, and generally negative relationship between elevation and snow depth is interesting because it is contrary to what would be expected from orographic effects on precipitation amounts and phase. What you show is that the high elevation of the TP does not cause larger snow depth compared to surrounding lower lands. Continentality seems to be the main driving factor here: the TP is in the rain shadow of the Himalaya and as

such is moisture-deprived. This should be better discussed, and analysed in the paper. This effect could be investigated, perhaps using a simple continentality index (e.g. http://glossary.ametsoc.org/wiki/Continentality). These indices rely on temperature annual ranges. You could use the closest distance to coast as another simple index.

Reply: We indeed conducted analysis on impact of continentality on snow depth over the study area. To our surprise, the correlation between the two are not significant. However, we strongly agree with the reviewer that at local and regional (less than continental) scales, topography can play key roles. In Section 4.2, we added more discussions about topographical effects on snow depth, especially on Tibetan Plateau (TP). The Tibetan Plateau's largest snow accumulation occurred in the winter, but the snowfall during winter months is the smallest of the year. This was mainly due to the terrain factors: the water vapor from the east and west was blocked by the Hengduan Mountains and Nyainqentanglha Mountains, respectively, which resulted in less snowfall. Although there was more snowfall in spring, snow cover was not easy to accumulate with higher temperatures. Therefore, snow depth was shallow on TP in general. In addition to topographic factors, spatial distribution of snow depth was also affected by atmospheric circulation. We will discuss this issue in the future studies.

50) P15: section 3.4.
You begin the section by stating that ' Variations in snow depth are closely related to climate change'. But what is investigated is the influence of spatially variable climate factors (mean temperature and mean snowfall) on snow depth, and NOT the effect of time-varying climate on snow depth. To do so you would have to test the influence of changing temperatures and snowfall/precipitation on snow depth over time. Rephrase the introduction of the section to clearly explain that you investigate spatial relationships between mean temperature and snowfall on mean snow depths. The spatial relationship between air temperature and snow depth will be undoubtedly complex when considered an area as big and topographically diverse as the Eurasian continent. Your analysis is till interesting as it shows that snowfall is the main factor driving spatial variability in snow depth, at this spatial scale. However snowfall rates and air temperature must also be somewhat correlated, as snowfall depends on precipitation and temperature (precipitation phase). I suggest that you also calculate and report the partial correlation coefficients, i.e. to show the influence one variable while removing effect of the other, on snow depth. You do examine the effect of changing climate on snow depth and mass in Figure 10 for the composite Eurasian and Russian records. This analysis is qualitative and hile interesting and valuable, it could be enriched by calculating and presenting the correlation coefficients between series. Especially for the SWE series, how much of the variance can be respectively explained by air temperature and snowfall? Even more constructive would be to perform this analysis on a station basis and map the results. We would then learn about the spatially variable climate control on snow.

Reply: Thank you very much for your suggestion. We have added the quantitative analysis by the partial correlation analysis between snow depth, SWE, air temperature and snowfall. The results showed that the significant negative correlation ($p \leqslant 0.05$) between snow depth and air temperature presented in most areas of European Russia and the southern Siberia (Fig 13a). The stations with negative effects of air temperature on SWE were less, and there were no statistically significant correlation in the northern Siberia (Fig 13b). It was because the air temperature was below 0℃ in most areas of Siberia during December through March, the increasing temperature did not have an obvious effect on snow depth. Consistent with the interannual variation, changes in snow depth and SWE were more affected by snowfall in most areas across the former USSR from December through March. The greater partial correlation coefficients (>0.6) between snow cover and snowfall appeared in the northern European Russia, the southern Siberia, the northeast and southeast of the Russian Far East. Variations in snow depth and SWE were more sensitive to snowfall and snowfall rate in these areas. Variations of snow depth were explained by air temperature and snowfall in most areas of the European Russia and some regions of the southern Siberia, the effects of the two factors on SWE only appeared in some of these areas; however, snowfall was the main driver force of the variance of snow depth and SWE in the former USSR.

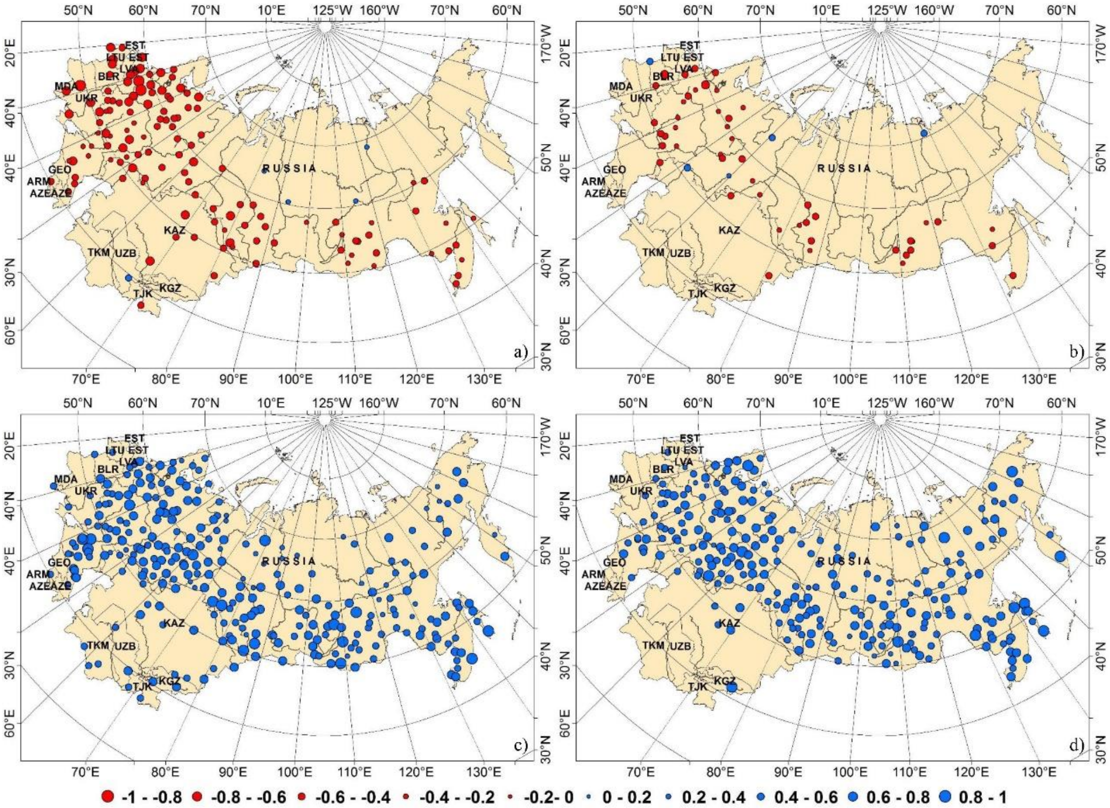


Figure 13. Spatial distributions of partial correlation coefficients of snow depth and air temperature (a), snow depth and snowfall (b), SWE and air temperature (c), SWE and snowfall from November through March during 1966-2009. The coefficients reaching to 0.05 confident level are displayed. Red circles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

51) P15, L7. Snow depth significantly decreases with increasing air temperature (P≤0.05),

Reply: We replaced “decreased” with “decreases”

52) P15, L17. Increases

Reply: We replaced “increases” with “increasing trends”

53) P15, L21. The significant increasing snowfall can explain the sudden drop in snow density observed from the mid-1990s through the early 2000s (Zhong et al., 2014): fresh snow with low snow density. Explain the last statement better in a separate statement. Why does increasing snowfall decreases snow density? Is it the mean density of the snowpack? Increasing snowfall in response to warmer temperature should increase the density, both of fresh snow, and perhaps of the whole snowpack due to faster metamorphism and increased compaction...

Reply: The snow density means the bulk snow density of the snow profile. Increasing snow fall should decrease the density of the surface snowpack, which lowed the whole density of snowpack.

54) P15, L26. increasing trend of changes in snow depth. trend in snow depth? or trend in the rate of change?

Reply: It means the trend in snow depth. We deleted “of changes”.

55) P15, L27. In fact, the climatology of snow depth not only influenced by air temperature and precipitation, but also with other climatic factors and atmospheric circulation. Poor formulation, rephrase.

Reply: We have deleted the sentences and added the analysis of the partial correlation coefficients between snow cover and air temperature, as well as snow cover and snowfall.

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

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

56) P16. L7. These discrepancies may result from differences in the time frame

Reply: We replaced the first “differences” with “discrepancies”.

57) P16. L26. during the different study periods.

Reply: We revised it.

58) P16. L.26-28. The sensitivity of snow cover to air temperature and precipitation for each station showed regional differences (Fallot et al., 1997; Park et al., 2013). The amount of snowfall can be affected by climate change, and leading to differences in snow depth at different times (Ye et al., 1998; Kitaev et al., 2005). This is why simple spatial relationship between air temperature and snow depth do not exist...

Reply: We added a sentence after it.

“The results of our study showed that there was significant negative relationship between snow depth and air temperature in the southern Siberia, however, it did not exist in the northern Siberia. This may explain the difference in the results of these studies.”

59) P17, L5. and is the main reason. Extra space between ’and’ and ’is’

Reply: We deleted the extra space.

60) P17, L10. Therefore, we will select a typical climate zone to research the climatology and variations of snow cover. This rather vague... your study looks at large scale control on snow cover and this is what this dataset allows. Studying small scale (topography, vegetation) effects on the snow cover requires other kind of data, sampled at a higher spatial resolution. I would remove this sentence.

Reply: Thank you very much for your suggestion. We removed the sentence.

61) You should better discuss your results in the light of what is known about large-scale control on snow cover: latitude, altitude and continentality are the main geographical factor which drive snowfall rates and hence snow depths. I find your analysis and the discussion on page 17 somewhat incomplete in this respect.

Reply: We have analyzed the relationship between snow depth and continentality. But the correlation coefficient was not high (r=0.1). This indicated that the continentality is not an important driving factor of snow cover climatology over Eurasia. However, we strongly agree with the reviewer that at local and regional (less than continental) scales, topography can play key roles. In Section 4.2, we added more discussions about topographical effects on snow depth, especially on Tibetan Plateau (TP):

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

List of all relevant changes

(1) P1, L.4-5: advanced the sixth co-author to the third, interchanged “2” and “3” in superscript.
(2) P1, L.8-11: interchanged the second and third affiliations.
(3) P1, L21: inserted “a” before “snow”, inserted “its” before “spatiotemporal”.
(4) P1, L27: inserted “significantly” after “depth”, deleted “dramatically”.
(5) P2, L2: replaced “cover” with “depth”.
(6) P3, L7: replaced “also” with “all”.
(7) P3, L14: inserted “the” before “northern”, inserted “during 1936 to 2010” after “Eurasia”.
(8) P3, L15: replaced “is” with “was”.
(9) P3, L19: replaced “promotes” with “promoted”.
(10) P3, L21-P4, L13: deleted the two paragraphs.
(11) P4, L17: inserted “during 1946 to 2000” after “America”.
(12) P4, L18: inserted “during the recent 70 years” after “Arctic”.
(13) P4, L23: inserted “from 1936 through 1995” after “winter”.
(14) P4, L28: inserted “also” after “is”, inserted “large-scale atmospheric circulation indices,” after “other”, deleted “climatic variables”.
(15) P4, L29: replaced “index” with “indices”, inserted “For example,” before “Beniston”.
(16) P5, L3: inserted “during the period from 1966 to 1990”.
(17) P5, L8: replaced “In order to obtain a wider rang” with “To increase the spatial coverage”.
(18) P5, L18: replaced “is” with “remains”.
(19) P6, L.4-6: deleted “Using data from ground based measurements,”, replaced “the” with “The”, deleted “provide a detailed description of snow depth and to”, replaced “as well as its” with “and analyze snow depth”.
(20) P6, L7: replaced “other” with “the”.

(21) P6, L14: deleted "in 17 countries", inserted "over" before "on".

(22) P6, L15: inserted "a" after "on", inserted "Historical" before "snow".

(23) P6, L16: inserted "from 1966 to 2011" after "USSR", deleted "from historical records from 1966 to 2011"

(24) P6, L17: replaced "that run" with "performed".

(25) P6, L18: replaced "10" with "ten", replaced "5" with "five".

(26) P6, L19: replaced "for" with "over", inserted "-long transects" after "km".

(27) P6, L20: replaced both "each" with "every".

(28) P6, L.25-26: inserted "where SWE data are available" after "USSR", replaced both "at" with "along".

(29) P6, L.27-29: replaced the sentence by "Daily precipitation was divided partitioned into a solid and liquid fraction, based on daily mean temperature (Brown, 2000)".

(30) P7, L. 9-12: replaced the sentences by "(1) A threshold of 15 days was selected because the snow cover duration in some areas of China was less than one month, and the data for 15 days' snow depth in a month were relatively stable. Months having less than 15 days with snow depth data were omitted from the analysis. (2) Stations with less than 20 years of data during the 1971-2000 period were excluded from the analysis."

(31) P7, L12: deleted "and", inserted "At each station," before "data".

(32) P7, L16: inserted "The snow cover extent is the smallest in July and August, in order to capture the entire seasonal snow cycle," before "we".

(33) P7, L17: replaced "had" with "have".

(34) P7, L18: replaced "in the past" with "over the course of the studies period".

(35) P7, L25: inserted "(Ma and Qin, 2012)" after "products".

(36) P7, L.25-27: deleted the sentence "A threshold of 15 … were relatively stable", and added a sentence "According to the quality control, months having more than 15 days with snow data were used."

(37) P8, L2: replaced "In order to reflect" with "To capture".

(38) P8, L.13-16: deleted the sentence "(4) Linear trend…at the 95% level."

(39) P8, L.23: deleted the last "the", inserted "obtain mean" after "stations to".

(40) P8, L.24-25: deleted the last sentence.

(41) P8, L.26: replaced “analyze” with “reveal”, inserted “low-frequency” before “variations”.

(42) P8, L.27: inserted “over the study area as a whole” after “depth”.

(43) P8, L26 - P9, L20: replaced the paragraph with “Wavelet analysis was performed to reveal the long-term low-frequency variations of snow depth over the study area as a whole. A wavelet is a wave-like oscillation with an amplitude that begins at 0, increases, and then decreases back to 0 (Graps, 1995). We applied a discrete wavelet transform, excluded the high-frequency components and then used the inverse transform to reconstruct the lower frequency signal. Any trend analysis is an approximate and simple approach to obtain what has happened on average during the study period. Linear trend analysis provides an average rate of this change. Despite there is a nonlinearity, the linear trend analysis is also a useful approximation when a systematic low-frequency variations emerged. (Folland and Karl, 2001; Groisman et al., 2006). The linear trend coefficient of snow depth was calculated to represent the rate of change at each station. The Student T test was used to assess the statistical significant of the slope in the linear regression analysis and the partial correlation coefficients, and the confidence level above 95% was considered in our study. Meanwhile, to overcome the strong assumption in ordinary least squares (independent and normal distribution), we applied a Mann-Kendall (MK) test to identify the monotonic trend in snow depth. Confidence level above 95% was used to determine the statistically significant increase or decrease in snow depth. These two test methods could provide more robust and comprehensive information of the trend analysis. In order to evaluate the influence of single climatic factor on snow cover, the partial correlation coefficients were calculated and reported the relationships between snow depth, SWE, air temperature and snowfall. The way to do significant test of the correlation coefficient is same to the trend analysis, which includes T-test and MK-test.”

(44) P9, L26: replaced “The” with “A”.

(45) P9, L28: inserted “the south of Yangtze River in” after “of”.

(46) P9, L29 – P10, L1: deleted “due to wind speed…Callaghan et al.,2011b)”

(47) P10, L5: replaced “most” with “the eastern and western”.

(48) P10, L13: deleted “also”.

(49) P11, L26: inserted “it” after “then”.

(50) P11, L.26-28: deleted “late 1970s…early 1990s through the”.

(51) P11, L29: inserted “and” before “then”, inserted “(Fig. 4a)” after “2012”

(52) P12, L2: replaced “fluctuated” with “it fluctuating changed”.

(53) P12, L4: inserted a new paragraph “The Mann-Kendall statistical curves of annual and maximum snow depth were consistent with the linear trend analysis (Fig. 5). The increasing trend of annual snow depth reached to the 0.05 confident level in the late 1980s and from the early 1990s to the mid-1990s; it reached to the 0.01 confident level in the late 1990s. The decreasing trend reached to the 0.05 confident level from the early 2000s through the mid-2000s. The intersection of the UF curve and UB curve appeared in the mid-1970s, it indicated that the rising trend was an abrupt change during this period. The abrupt change point of the maximum snow depth was in the mid-1980s, then it increased significantly ($p \leqslant 0.05$) from the early 1990s through the mid-1990s, and it reached to the 0.01 confident level from the late 1990s to the early 2010s.” before the second paragraph.

(54) P12, L5: replaces “Fig. 5” with “Fig. 6”.

(55) P12, L7: replaces “Figs. 5a-b” with “Fig. 6a-b”, replaced “decrease” with “decreasing”.

(56) P12, L8: replaced “Fig. 5a” with “Fig. 6a”.

(57) P12, L11: replaced “Fig. 5c-e” with “Fig. 6c-e”.

(58) P12, L15: replaced “Fig. 5d, e” with “Fig. 6d, e”.

(59) P12, L20: replaced “was” with “being”.

(60) P12, L21: replaced “Fig. 5f-g” with “Fig. 6f-g”.

(61) P12, L23: replaced “Fig. 5f” with “Fig. 6f”.

(62) P12, L25: inserted “increasing” after “fluctuant”, replaced “Fig. 5g” with “Fig. 6g”.

(63) P12, L26: replaced “increased dramatically” with “sharply increased”.

(64) P12, L28: inserted a new paragraph “In order to identify the monotonic trend in

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

(65) P12, L28: replaced "Fig. 6" with "Fig. 8".

(66) P13, L3: replaced "Fig. 6a" with "Fig. 8a".

(67) P13, L7: deleted "variability".

(68) P13, L12: replaced "Fig. 6b" with "Fig. 8b".

(69) P13, L18: replaced "Figs. 7a, b" with "Figs. 9a, b".

(70) P13, L26: replaced "7c-e" with "9c-e".

(71) P14, L2: replaced "fell" with "decreased".

(72) P14, L3: replaced "Figs. 7f-h" with "Figs. 9f-h".

(73) P14, L4: deleted "the" after "with".

(74) P14, L5: inserted "were found" after "trends", deleted "the".

(75) P14, L6: replaced "and" with "; for these,"

(76) P14, L10: replaced "and" with a comma, inserted "and Continentality" after "Elevation".

(77) P14, L11: replaced "features" with "variability"

(78) P14, L12: replaced "and elevation (Fig. 8)" with ", elevation and continentality

(Fig. 10)”.

(79) P14, L14: replaced “Fig. 8a” with “Fig. 10a”.

(80) P14, L15: deleted “mean”.

(81) P14, L16: replaced “8a, c” with “10a, d”.

(82) P14, L21: replaced “Fig. 8b” with “Fig. 10b”.

(83) P14, L28: replaced “Fig. 8c” with “Fig. 10d”.

(84) P14, L30: inserted a new paragraph “There was a significant positive relationship between snow depth and continentality, but the correlation coefficient was not high (r=0.1, Fig. 10c). This indicated that the continentality is not an important driving factor of snow cover climatology over Eurasia, though it will determine the snowfall rate.”

(85) P15, L2: replaced “Variations” with “In addition to the terrain factors, variations”, replaced “change” with “variability”

(86) P15, L5: replaced “Fig. 9” with “Fig. 11”.

(87) P15, L7: replaced “decreased” with “decreases”.

(88) P15, L9: replaced “9a” with “11a”.

(89) P15, L10: replaced “Fig. 9b” with “Fig. 11b”.

(90) P15, L17: replaced “increases” with “increasing trends”.

(91) P15, L18: replaced “10” with “12”, replaced “increase” with “increased”.

(92) P15, L22: inserted “the bulk” after “in”.

(93) P15, L23: replaced “fresh snow with low snow density” with “increasing snowfall should decrease the density of the surface snowpack, which lowed the whole density of snowpack”.

(94) P15, L25: replaced “Figs. 10b-d” with “Figs. 12b-d”.

(95) P15, L26: deleted “of changes”.

(96) P15, L.27-30: deleted the two sentences “In fact,…in the future.”

(97) P15, L30: inserted two new paragraphs “The partial correlation coefficients between snow cover and air temperature, as well as snow cover and snowfall were calculated to discuss the spatial relationship between them (Fig. 13). The significant

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

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

(98) P16, L7: replaced "differences" with "discrepancies".

(99) P16, L26: inserted "the" after "during", inserted "study" after "different".

(100) P16, L30: inserted two new sentences "The results of our study showed that there was significant negative relationship between snow depth and air temperature in the southern Siberia, however, it did not exist in the northern Siberia. This may explain the difference in the results of these studies." after "(Ye et al., 1998; Kitaev et al., 2005)."

(101) P17, L.9-14: deleted the sentences "This issue should…field measurements is required."

(102) P17, L14: inserted new sentences "But we still got some interesting conclusions: There was a closely relationship between snow depth and elevation at the local scale. However, compared with latitude, the correlation between them was not so significant in the whole Eurasian Continent. Moreover, the continentality did not play a great role in spatial distribution of snow depth, especially on TP. The previous studies showed that the Tibetan Plateau's largest snow accumulation occurred in the winter, but the snowfall is the smallest of the year (Ma, 2008). This

was mainly due to majority of annual precipitation occurs during the summer monsoon season on TP which cause very less snowfall during winter half year (or snow accumulated season). Furthermore, the water vapor from the east and west was blocked by the Hengduan Mountains and Nyainqentanglha Mountains, respectively, which resulted in less snowfall. Although there was more snowfall in spring, snow cover was not easy to accumulate with higher temperatures. Therefore, snow depth was shallow on TP in general. In addition to topographic factors, spatial distribution of snow depth was also affected by atmospheric circulation. We will discuss this issue in the future studies."

(103) P18, L1: inserted ", especially during the period of the mid-1980s through the 2000s" after "spring".

(104) P18, L.9-12: deleted the sentences "The variations in snow depth…in future stuies."

(105) P18, L12: inserted new sentences "Variations of snow depth were explained by air temperature and snowfall in most areas of the European Russia and some regions of the southern Siberia, the effects of the two factors on SWE only appeared in some of these areas; however, snowfall was the main driver force of the variance of snow depth and SWE in the former USSR."

(106) P19, L.2-3: deleted the reference.

(107) P19, L.27-30: deleted the reference.

(108) P20, L23: inserted a new reference "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."

(109) P20, L.26-27: deleted the reference.

(110) P20, L30 - P21, L1: deleted the reference.

(111) P21, L8: inserted a new reference "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."

(112) P21, L30 - P22, L3: deleted the reference.

(113) P22, L.10-11: deleted the reference.

(114) P22, L.14-19: deleted the two references.

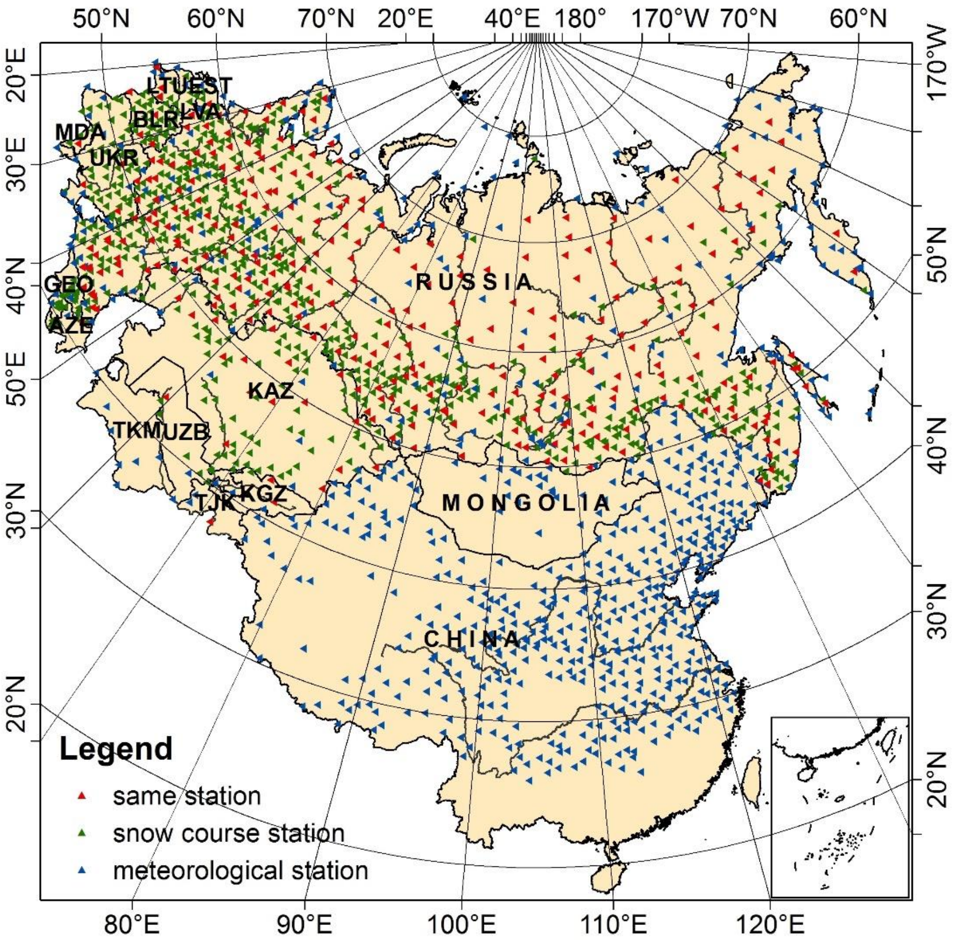
(115) P22, L20: replaced “Listion” with “Liston”.

(116) P22, L23: inserted a new reference “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.”

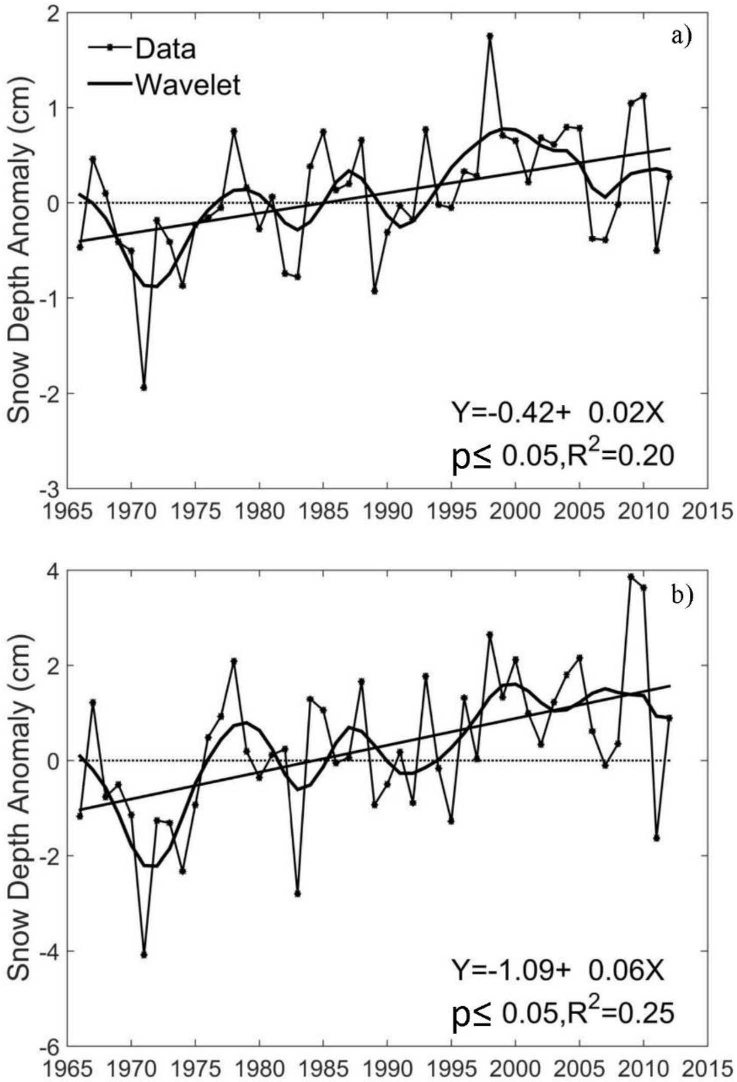
(117) P23, L.17-18: deleted the reference.

(118) P24, L.5-8: deleted the two references.

(119) P26: replaced figure 1 with a new figure



(120) P30: replaced figure 4 with a new figure



(121) P30, L.5-7: deleted the last sentence "Y represents…annual mean snow depth".

(122) P31: added a new figure as figure 5

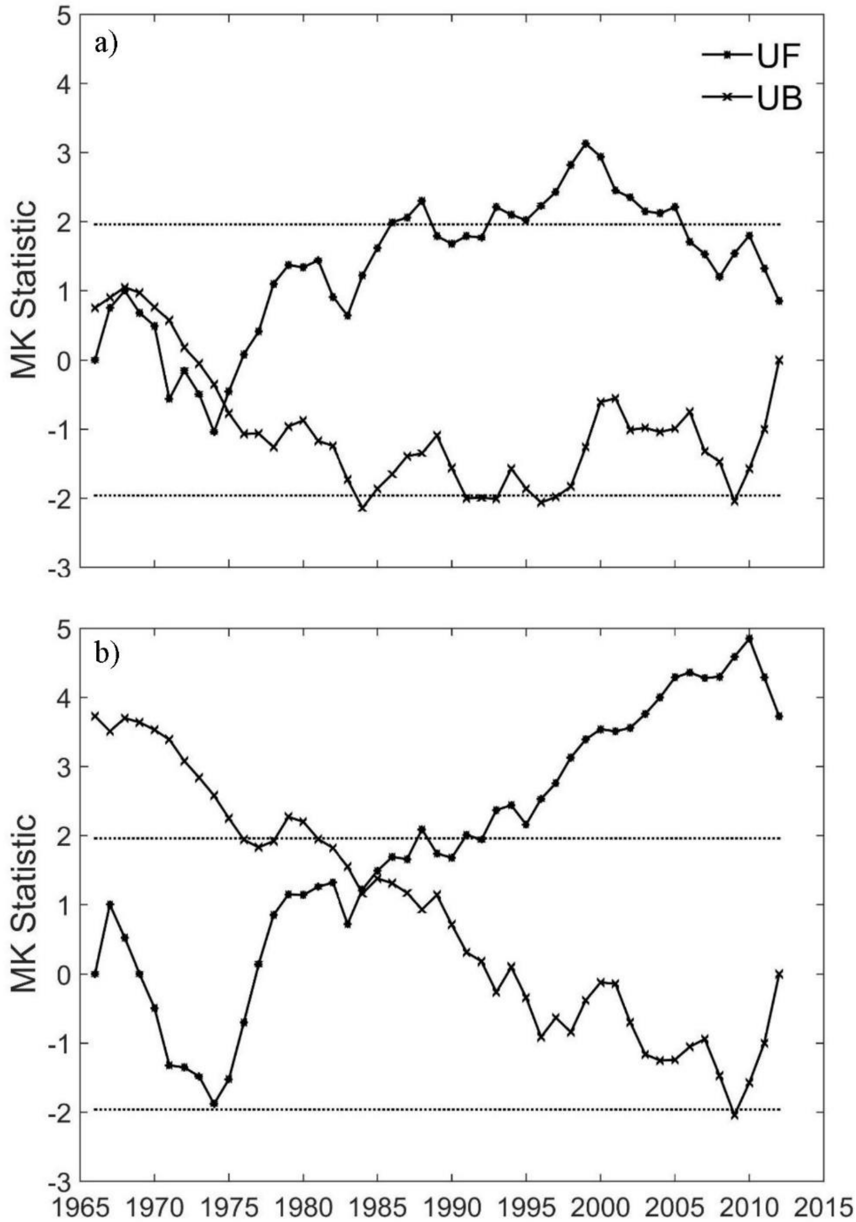
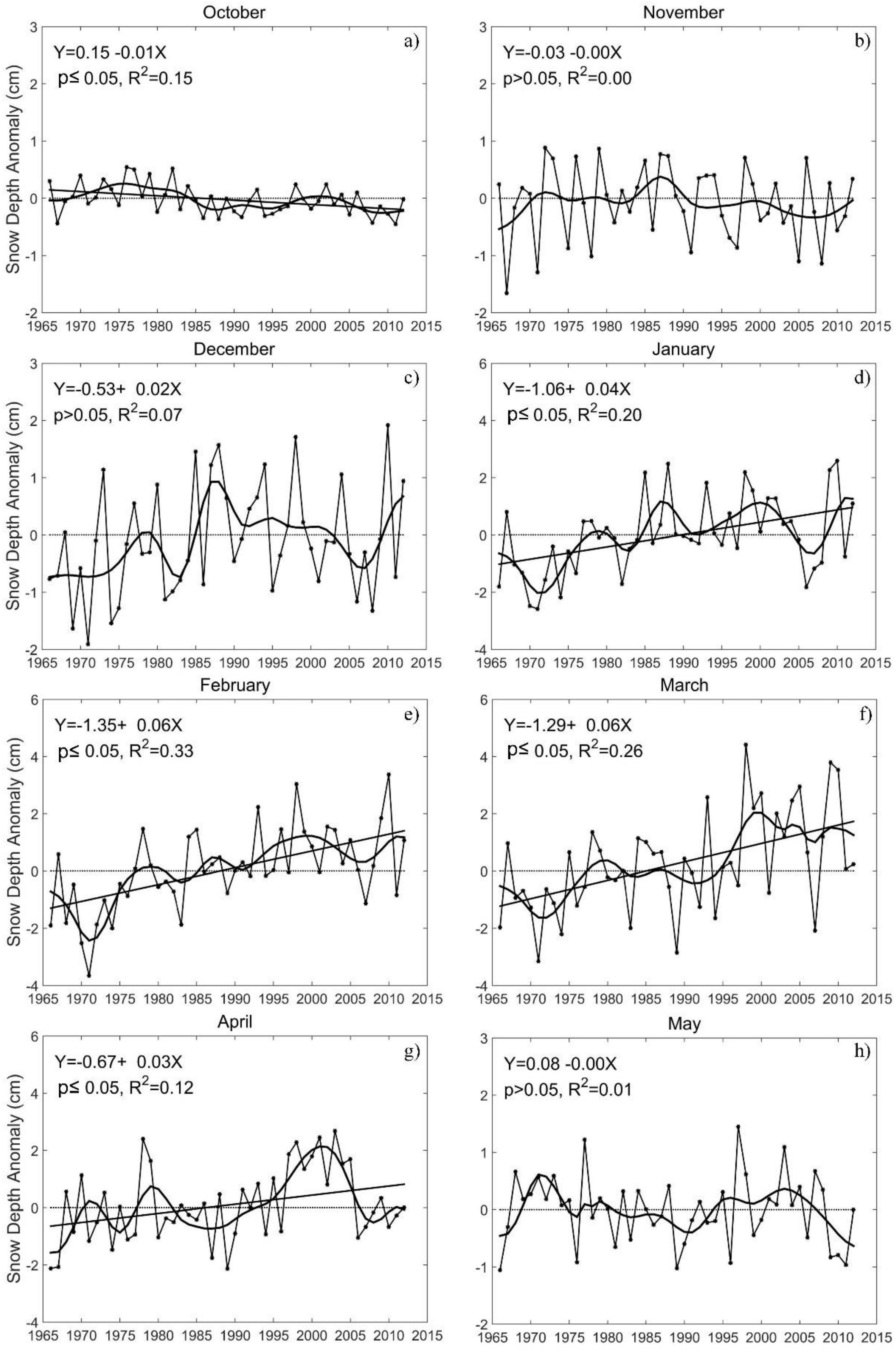


Figure 5. Mann-Kendall statistical curve of annual mean snow depth (a) and maximum snow depth (b) from 1966 through 2012 across the Eurasian continent. Straight line presents significance level at 0.05.

(123) P31, L1: replaced “Figure 5” with “Figure 6”.

(124) P31: replaced figure 6 with a new figure



(125) P32: added a new figure as figure 7

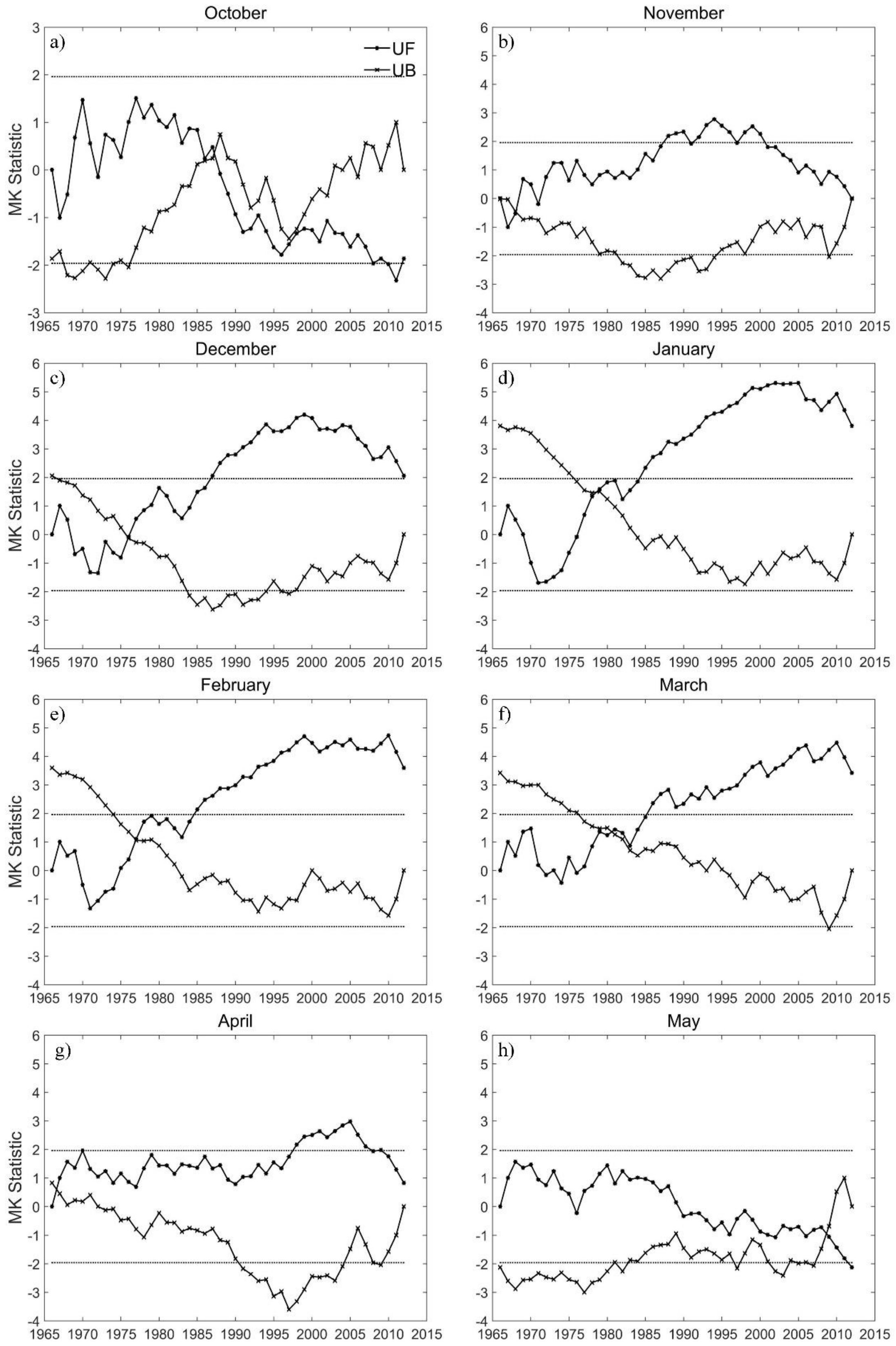


Figure 7. Mann-Kendall statistical curve of monthly mean snow depth (from October to May) from 1966 through 2012 across the Eurasian continent. (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May. Straight line presents significance level at 0.05.

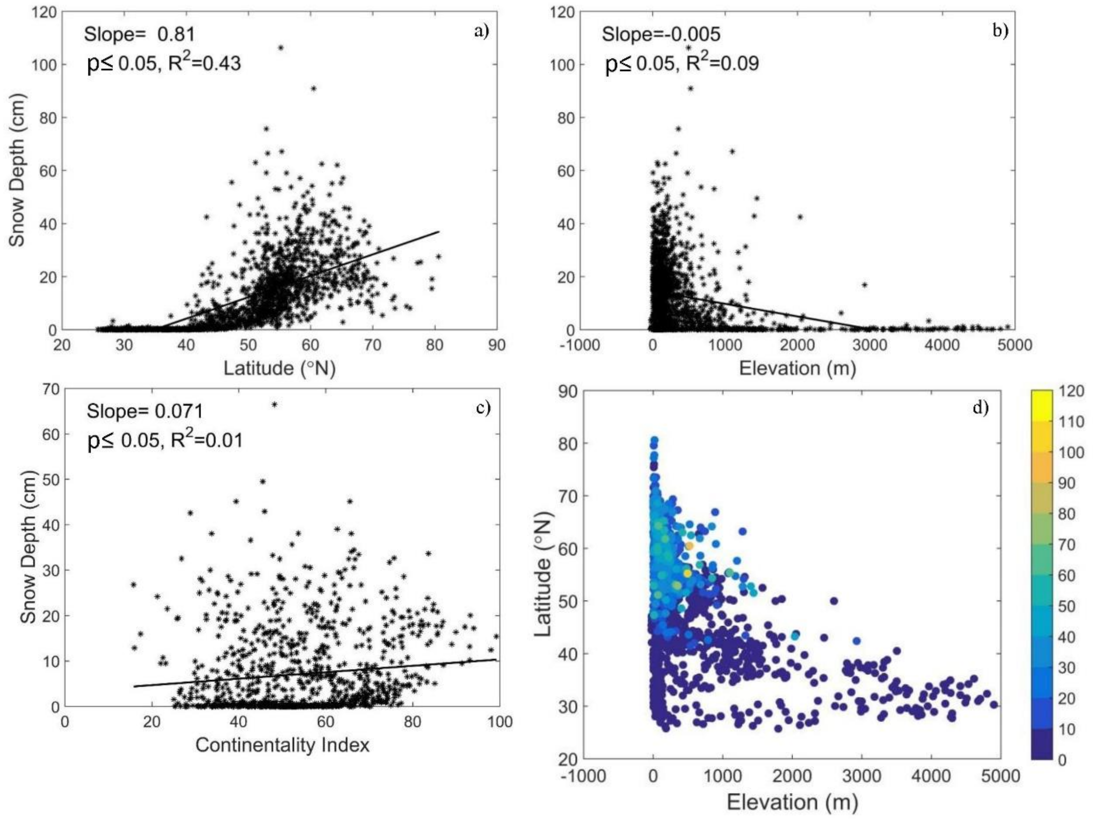
(126) P32, L2: replaced “Figure 6” with “Figure 8”.

(127) P34, L1: replaced “Figure 7” with “Figure 9”.

(128) P34, L8: replaced “Figure 8” with “Figure 10”.

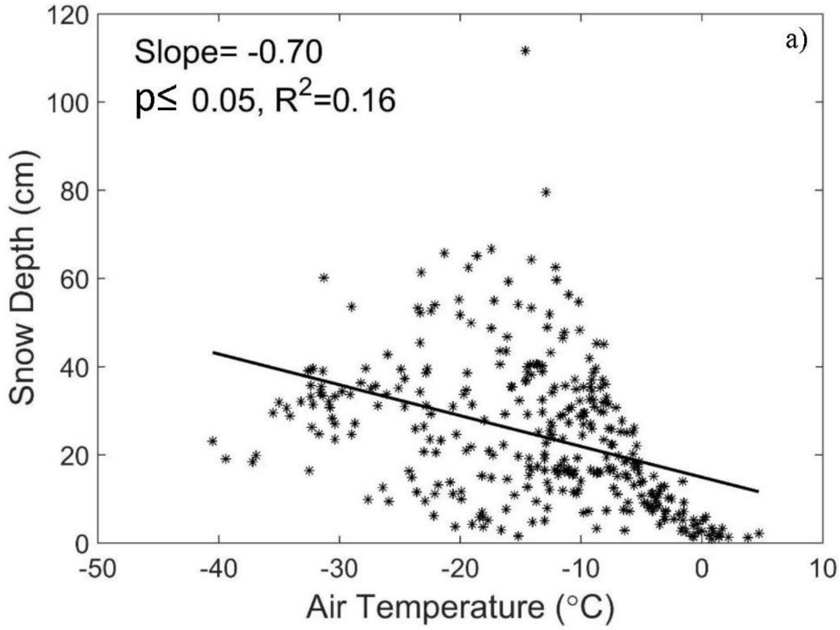
(129) P34, L.8-10: replace the explanation of Figure 10 with “Figure 10. The relationship between annual mean snow depth and latitude (a), elevation (b) and continentality (c) for all stations across the Eurasian continent during 1966-2012. Asterisks show the mean snow depth of each station; the thick line is a linear regression trend; the different colors represent snow depth (cm) of each station (d).”

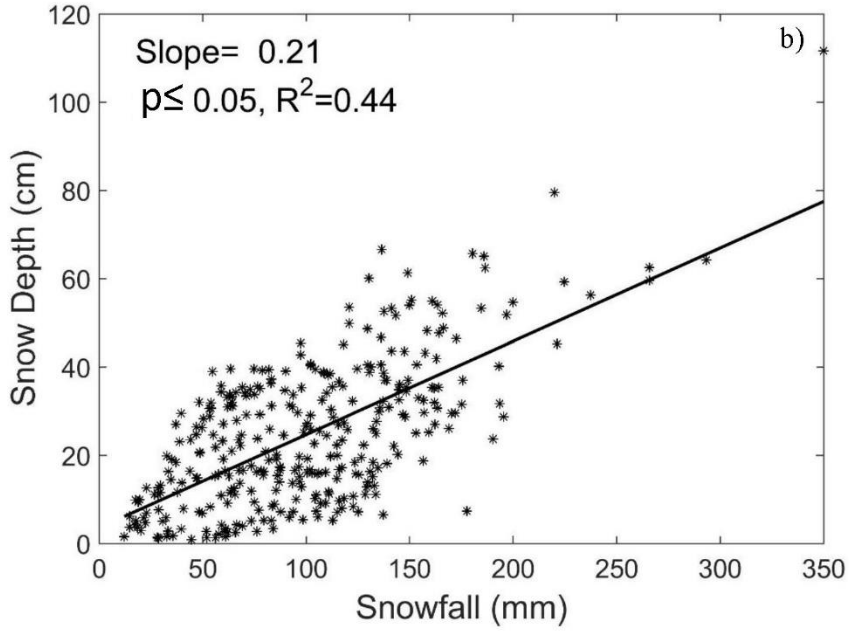
(130) P34: replaced figure 10 with a new figure



(131) P35, L2: replaced “Figure 9” with “Figure 11”.

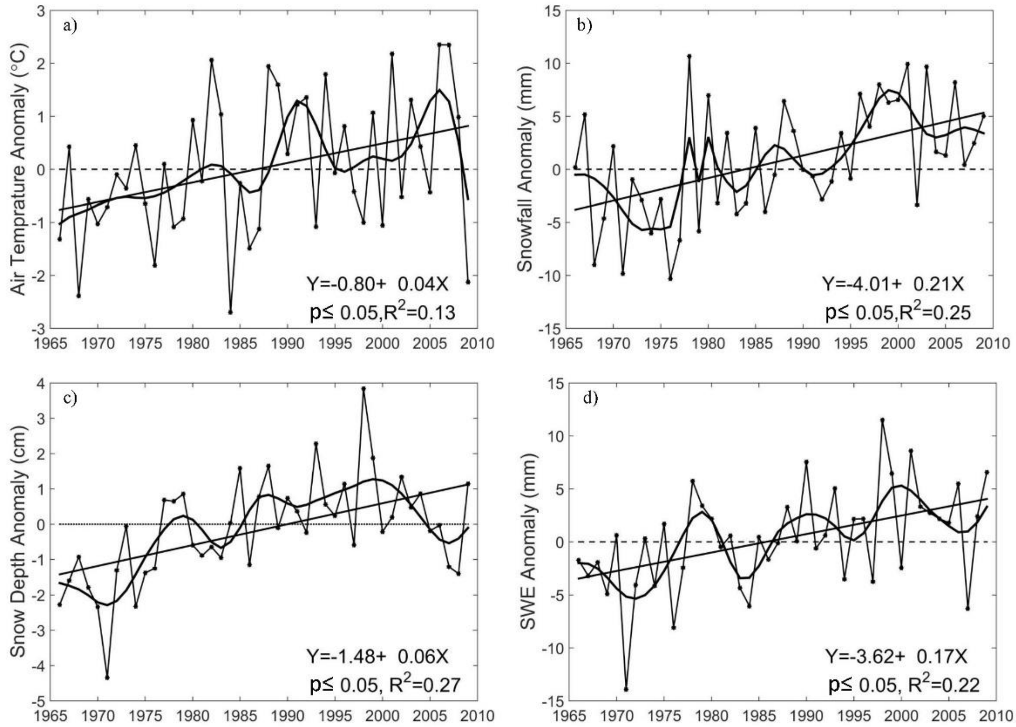
(132) P35: replaced figure 11 with a new figure





(133) P36, L2: replaced “Figure 10” with “Figure 12”.

(134) P36: replaced figure 12 with a new figure



(135) P36: added a new figure as Figure 13

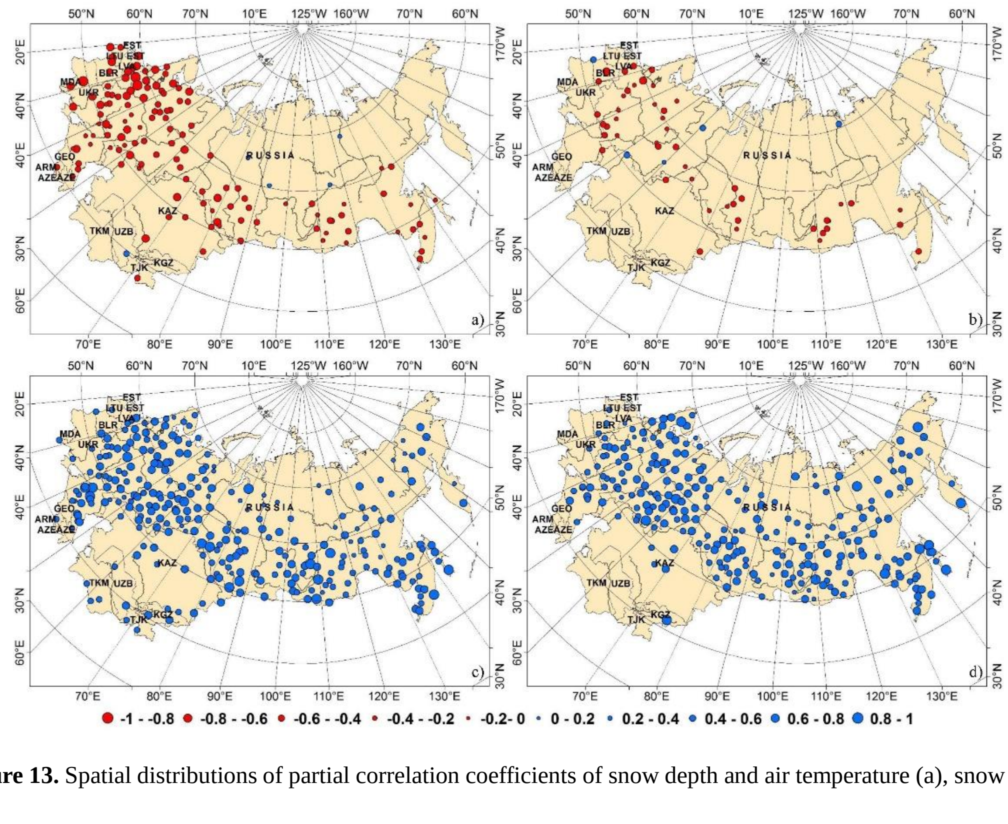


Figure 13. Spatial distributions of partial correlation coefficients of snow depth and air temperature (a), snow depth and snowfall (b), SWE and air temperature (c), SWE and snowfall from November through March during 1966-2009. The coefficients reaching to 0.05 confident level are displayed. Red circles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

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

time. Regionally, snow depth significantly increased ~~dramatically~~ in the areas north of 50 °N. Compared with air temperature, snowfall had more influence on snow depth and snow water equivalent during November through March across the former Soviet Union. This study provides a baseline for changes in snow ~~cover~~depth, which are significant in climate system changes over the Eurasian continent.

1 Introduction

Snow cover is a key part of the cryosphere, which is a critical component of the global climate system. Changes in snow cover serve as indicators of climate change because of its interactions and feedbacks with surface energy and moisture fluxes, hydrological processes, and atmospheric and oceanic circulation (Brown and Goodison, 1996; Armstrong and Brown, 2008; King et al., 2008). Snow depth, snow water equivalent (SWE) and snow density are ~~also~~ all important parameters for water resource assessment, hydrological and climate model inputs and validation (Dressler et al., 2006; Lazar and Williams, 2008; Nayak et al., 2010).

Snow depth is a basic and important parameter of snow cover, which can provide additional information related to climate, surface energy balance, soil temperature, moisture budgets, spring runoff, water supply, and human activity (Sturm et al., 2001; Zhang, 2005; AMAP, 2011). Although snow cover extent reduced with climate warming, snow depth still increased in the northern Eurasia during 1936 to 2010~~1995~~ (Kitaev et al., 2005; Bulygina et al., 2011). This ~~is~~ was due to changes in the atmospheric moisture budget altering the atmospheric circulation, the warmer air led to greater moisture supply for precipitation as snowfall in winter (Ye et al., 1998; Kitaev et al., 2005; Rawlins et al., 2010). Meanwhile, snowmelt from increased snow depth may also lead to higher soil moisture in spring, which ~~promotes~~ promoted enhanced precipitation with increased evapotranspiration (Groisman et al., 1994). ~~Snow depth is an important factor controlling the ground thermal regime (Goodrich, 1982; Zhang et al., 1996, 1997; Zhang, 2005). Kudryavtsev (1992) investigated that a thin snow cover results in cooler soil surface, whereas thick snow cover leads to a warmer soil surface in winter. Frauenfeld et al. (2004) indicated that in permafrost areas the maximum snow depth by the end of winter has a significant influence on the active layer depth during the following summer. As an important parameter, snow depth was included in a surface energy balance-based one-dimensional heat transfer model for estimating the thermal regime of soil (Ling and Zhang, 2004, 2005). The numerical modeling results showed that the rate of mean annual ground surface temperature increases with the increasing maximum snow depth was about a rate of~~

0.1 ℃ cm^{-1} for the maximumuntil up to a snow depth at of 15 cm. Over the Alaskan Arctic coastal plain, mean annual ground surface temperature also increased with snow depth. However, the rate of the mean annual ground surface temperature increase fell dramatically for snow depth greater than 40 cm (Zhang, 2005).

Furthermore, snow accumulation is one of thean important freshwater resources and has direct impact on the hydrological cycle. Snowmelt runoff in spring is a major source of river recharge and water supply, on the other hand, snowmelt floods are of great importance, threatening the ecological and human security (Li, 1988). Approximately 95 % of water resources are derived from snowmelt in spring and early summer in alpine and Arctic areas; in addition, in these areas, half or more of floods are caused by melting snow (AMAP, 2011). Adam et al. (2009) suggested that the variations of in snow depth will significantly affect the hydrological regime of the Arctic in the future.

Using in-situ observational data from meteorological stations and satellite remote sensing data, several studies have documented changes in snow depth over the Northern Hemisphere, demonstrating that snow depth varies regionally: overall, the annual mean snow depth decreased in most areas over North America during 1946 to 2000 (Brown and Braaten, 1998; Dyer and Mote, 2006), and increased in Eurasia and the Arctic during the recent 70 years (Ye et al., 1998; Kitaev et al., 2005; Callaghan et al., 2011a; Liston and Hiemstra, 2011) but there was regional differences (Bulygina et al., 2009, 2011; Ma and Qin, 2012; Stuefer et al., 2013; Terzago et al., 2014). Changes in snow depth were primarily affected by air temperature and precipitation. Ye et al. (1998) and Kitaev et al. (2005) showed that higher air temperatures caused an increase in snowfall in winter from 1936 through 1995, thus greater snow depth was observed in northern Eurasia in response to global warming. Furthermore, snow depth distribution and variation are also controlled by terrain (i.e., elevation, slope, aspect, and roughness) and vegetation (Lehning et al., 2011; Grünewald et al., 2014; Revuelto et al., 2014; Rees et al., 2014; Dickerson-Lange et al., 2015). Snow depth is also closely related to other large-scale atmospheric circulation indices, climatic variables such as the North Atlantic Oscillation /Arctic Oscillation (NAO/AO)

~~index~~indices. For example, Beniston (1997) found that the NAO played a crucial role in fluctuations in the amount of snowfall and snow depth in the Swiss Alps from 1945 to 1994. Kitaev et al. (2002) reported that the NAO index is positively related to snow depth in the northern part of the East European Plain and over western Siberia during the period from1966 to 1990; however, the NAO is negatively correlated with snow depth in most southern regions of northern Eurasia. You et al. (2011) indicated that there is a positive relationship between snow depth and the winter AO/NAO index and Niño-3 region sea surface temperature (SST) in the eastern and central Tibetan Plateau (TP) from 1961 through 2005.

~~In order T~~To ~~obtain a wider range~~increase the spatial coverage of snow depth, researchers have used different instruments (e.g., LIDAR, airborne laser scanning (ALS), and unmanned aerial systems (UASs)) (Hopkinson et al., 2004; Grünewald et al., 2013; Bühler et al., 2016) or have developed and improved the algorithms with passive microwave (Foster et al., 1997; Derksen et al., 2003; Grippaa et al., 2004; Che et al., 2016). Although these observations can mitigate the regional deficiency of in-situ snow depth observations, the satellite data have low spatial resolution (25×25 km) and the accuracy is always affected by clouds, underlying surface conditions, and inversion algorithms; in addition, data acquisition from the large airborne equipment or aerial systems is always costly and some of them need to obtain official permission before using in some countries. Ground-based snow measurement ~~is~~ remains the basis for verification of remote sensing and instrumental data, which can provide more accurate and longer-time-series information, and it is important for investigating climatology and variability of snow depth.

During winter, the average maximum terrestrial snow cover is nearly 47×10^6 km^2 over Northern Hemisphere lands (Robinson et al., 1993; IGOS, 2007). A large fraction of the Eurasian continent is covered by snow during the winter season, and some areas are covered by snow for more than half a year. There are long-term and large-scale snow cover measurements and observations across the Eurasian continent, with the first snow cover record dating back to 1881 in Latvia (Armstrong, 2001). These measurements provide valuable data and information for snow cover phenology and snow cover change detection. In Eurasia, most studies of snow depth have mainly focused on Russia (Ye et al., 1998; Kitaev et al., 2005; Bulygina et al., 2009, 2011), the former Soviet Union (USSR) (Brasnett, 1999), and the TP (Li and Mi, 1983; Ma and Qin, 2012). However, due to the lack of data and information, there has been no integrated and systematic investigation of changes in snow depth across the entire Eurasian continent using ground-based measurements. ~~Using data from ground-based measurements, the~~ The objective of this study is to ~~provide a detailed description of snow depth and to~~ investigate the climatology and variability of snow depth, ~~as well as~~and analyze snow depth ~~its~~ relationships with the~~other~~ topography and climate factors over the Eurasian continent from 1966 to 2012. This study can provide basic information on climate system changes in the region. The dataset and methodology are described in Section 2, with the results, discussion, and conclusions presented in Sections 3, 4, and 5, respectively.

2 Data and Methodology

Measurements of daily snow depth were conducted at 1103 meteorological stations ~~in 17 countries on~~ over the Eurasian continent from 1881 to 2013 (Table 1). Snow depth was measured at these stations on a daily basis. Historical s~~S~~now course data over the former USSR from 1966 to 2011 were also used in this study~~from historical records from 1966 to 2011~~. Snow course data include routine snow surveys ~~that run~~ performed throughout the accumulation season (every ten~~10~~ days) and during snowmelt (every ~~5~~ five days) period over the former USSR. Snow surveys were conducted ~~for~~ over 1–2 km-long transects in both forest and open terrain around each station. Snow depth was measured ~~each~~ every 10 m in the forest, and ~~each~~ every 20 m in open terrain (Bulygina et al. 2011).

SWE is also an important parameter of snow cover that is usually used in hydroclimate research. In this study, we analyzed the relationships among SWE, air temperature, snowfall and snow depth during the accumulation season (from November to March) over the former USSR where SWE data are available. SWE was measured every 100 m ~~at~~ along the 0.5-1.0 km courses and every 200 m ~~at~~ along the 2 km course (Bulygina et al., 2011). Daily p~~P~~recipitation ~~data were~~was ~~divided proportionally~~partitioned into ~~daily~~ a solid and liquid ~~data~~fraction, ~~and the solid-to-liquid fraction was determined according to daily mean temperature~~based on daily mean temperature (Brown, 2000). The solid fraction of precipitation, S_{rat}, was estimated by the following Equation (1):

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

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

Snow depth and SWE at each station were determined as the average value of a series of measurements in each snow course survey (Bulygina et al., 2011). In individual measurements, both random and systematic errors inevitably occur (Kuusisto, 1984). To minimize these errors, quality control of the meteorological data was undertaken prior to the datasets being stored at the Russian Research Institute for Hydrometeorological Information-World Data Center (RIHMI-WDC) (Veselov, 2002). We implemented a second quality control: (1) A threshold of 15 days was selected because the snow cover duration in some areas of China was less than one month, and the data for 15 days' snow depth in a month were relatively stable. ~~daily snow depth observations (equal to or greater than 0 cm, not including missing data) for <15 days in one month were omitted~~Months having less than 15 days with snow depth data were omitted from the analysis~~;~~. (2) Stations with less than 20 years of data during the 1971-2000 period were excluded from the analysis~~snow data from stations with <20 years of measurements during 1971-2000 were excluded; and~~. (3) ~~data~~ At each station, data exceeding two standard deviations compared with the annual average value during 1966-2012 were omitted. In total, we used data from 1814 stations to analyze the climatology and variability of snow depth over the Eurasian continent (Fig. 1 and Table 1).

The snow cover extent is the smallest ~~during~~in July and~~to~~ August, in order to capture ~~the beginning of snow cover~~the entire seasonal snow cycle, w~~W~~e defined a snow year as the period from July 1st of a current year to June 30th of the following year. Because the procedures for taking snow observations ~~had~~ have changed ~~in~~ over ~~the past~~the course of the studies period, there were some inhomogeneities in the data. However, there has been no change in the observation procedure since 1965 (Bulygina et al., 2009). Therefore, we used snow data for the snow years from 1966 to 2012 in this study. The following variables were calculated for each station:

(1) Monthly mean snow depth: In this study, we defined a snow cover day with snow depth equal to or greater than 0 cm according to the standard way for deriving monthly mean snow depth in regular World Meteorological Organization (WMO) climatological products (Ma and Qin, 2012). ~~A threshold of 15 days was selected because the snow cover duration in some areas of China was less than one month, and the data for 15 days' snow depth in a month were relatively stable.~~ According to the quality control, months having more than 15 days with snow data were used. The monthly mean snow depth was computed as the arithmetic sum of daily snow depth divided by the number of days with snow on the ground within each month.

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

(2) Annual mean snow depth: the annual mean snow depth was calculated as the arithmetic sum of the monthly mean snow depth divided by the number of available snow months within each snow year. The annual mean snow depth was averaged from the annual snow depth for ≥20 snow years during 1966-2012.

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

~~(4) Linear trend coefficient of snow depth: the linear trend coefficient of snow depth for each station was the result of linear regression analysis with respect to time, and was thus represents the rate of change in snow depth for a period ofover time. The rate of change in snow depth was considered to be statistically significant at the 95 % level.~~

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

Wavelet analysis was performed to ~~analyze~~ reveal the long-term low-frequency variations of snow depth over the study area as a whole. A wavelet is a wave-like oscillation with an amplitude that begins at 0, increases, and then decreases back to 0 ~~.~~ ~~All wavelet transforms may be considered forms of time-frequency representation for continuous-time (analog) signals and so are related to harmonic analysis. Almost all practically useful discrete wavelet transforms use discrete-time filter banks. These filter banks are called the wavelet and scaling coefficients in wavelets nomenclature. These filter banks may contain either finite impulse response (FIR) or infinite impulse response (IIR) filters. The wavelets forming a continuous wavelet transform (CWT) are subject to the uncertainty principle of Fourier analysis respective sampling theory: given a signal with some event in it, one cannot assign simultaneously an exact time and frequency response scale to that event. The product of the uncertainties of time and frequency response scale has a lower bound. Thus, in the scale gram of a continuous wavelet transform of this signal, such an event marks an entire region in the time-scale plane, instead of just one point. Also, discrete wavelet bases may be considered in the context of other forms of the uncertainty principle. This method is used to solve the problem of recovering a true signal from indirect noisy data~~ (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 ~~get~~obtain what has happened on average during the study period. Linear trend analysis provides an average rate of this change. Despite there is a nonlinearity, the linear trend analysis is also a useful approximation when a systematic low-frequency variations emerged. (Folland and Karl, 2001; Groisman et al., 2006). We used an averaging filter for wavelets analysis. Using this method, values that are too small or too large may be excluded; however, the main features of the dataset are not significantly affected. The wavelet coefficients obtained from filtering were used in an inverse wavelet transformation to reconstruct the data set. The new data set was represented as the smoothed lines of wavelet analysis in figures. Linear regressiontrend analysis of anomalies was applied to obtain the temporal trends for the long-term period. The linear trend coefficient of snow depth was calculated to represent the rate of change at each station. The Student T test was used to assess the statistical significant of the slope in the linear regression analysis and the partial correlation coefficients, and the confidence level above 95% was considered in our study. Meanwhile, to overcome the strong assumption in ordinary least squares (independent and normal distribution), we applied a Mann-Kendall (MK) test to identify the monotonic trend in snow depth. Confidence level above 95% was used to determine the statistically significant increase or decrease in snow depth. These two test methods could provide more robust and comprehensive information of the trend analysis. In order to evaluate the influence of single climatic factor on snow cover, the partial correlation coefficients were calculated and reported the relationships between snow depth, SWE, air temperature and snowfall. The way to do significant test of the correlation coefficient is same to the trend analysis, which includes T-test and MK-test.

3 Results

3.1 Climatology of Snow Depth

The distributions of long-term mean snow depth generally represented the latitudinal zonality: the snow depth for each station generally increased with the latitude across the Eurasian continent (Fig. 2). TheA maximum annual mean snow depth of 106.3 cm was observed in the west of the Yenisey River (dark blue circle) (Fig. 2a). In contrast, the minimum values (~0.01 cm) were observed in some areas of the south of Yangtze River in China (small gray circles) due to wind speed, topography, underlying ground surface, and climatic conditions (Gray and Male, 1981; Sturm et al., 1995, 2001; Callaghan et al., 2011b).

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

Annual mean maximum snow depth also varied with the latitude (Fig. 2b), which showed a spatial distribution pattern similar to the annual mean snow depth pattern. The maximum value (~201.8 cm) was recorded in the same location as the greatest annual mean snow depth. For the majority of Russia, the maximum snow depth was >40 cm. The regions with the maximum snow depths (exceeding 80 cm) were located in the northeastern regions of European Russia, the northern part of the West Siberian Plain, the Yenisey River basin, the Kamchatka Peninsula, and Sakhalin; however, along the coast of the Caspian Sea, the maximum snow depth was <10 cm. Most of the rest of the former USSR had a maximum depth of >10 cm, except for some regions of Ukraine and Uzbekistan. Maximum snow depth was >10 cm in northern Mongolia, and 6–10 cm in the central and eastern parts of the country. Maximum snow depths were higher over the northern part of the Xinjiang Autonomous Region of China, Northeast China, and some regions of the eastern and southwestern TP (>10 cm). The maximum snow depth in some areas was more than 20 cm. In other regions of China, the values were relatively small, ~8 cm or less.

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

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

3.2 Variability of Snow Depth

There were long-term significant increasing trends in the annual mean and maximum snow depth from 1966 to 2012 over the Eurasian continent as a whole with the increasing rates of snow depth of 0.2 cm decade^{-1} and 0.6 cm decade^{-1}, respectively (Fig. 4). Both annual mean snow depth and maximum snow depth exhibited a similar pattern of changes over the four decades, although the amplitude of the maximum snow depth anomaly (about ±2 cm) was much larger than that of the mean snow depth anomaly (about ±1 cm). From the mid-1960s to the early 1970s, the annual mean snow depth decreased slightly, then it increased until the late-1970s (Fig. 4a). Thereafter, it fluctuated from the late 1970s to the early 1990s.

Subsequently, the annual mean snow depth increased steadily from the early 1990s through the early 2000s, and then decreased sharply until 2012 (Fig. 4a).

Maximum snow depth decreased by 2.5 cm from the mid-1960s through the early 1970s (Fig. 4b). There was a sharp increase of 3.5 cm in the maximum snow depth during the 1970s, then it fluctuatefluctuantingfluctuatingd changed from the late 1970s to the early 1990s. The maximum snow depth increased again from the early 1990s through the early 2010s.

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

Statistically significant trends of variations in monthly snow depth occurred from 1966 through 2012 except for November, February, and May (Fig. 56). During the snow cover formation period (October and November), the monthly snow depth decreased slightly (Figs. 5a6a-b). There was a significant decreasinge trend of monthly snow depth in October, with a rate of decrease of approximately 0.1 cm decade^{-1} (Fig. 5a6a).

Inter-annual variations of monthly snow depth were more significant in the winter months (Figs. 5c6c-e). Snow depth was below its long-term mean value from the mid-1960s through the mid-1980s, and then it was above the long-term mean. There were statistically significant increasing trends in monthly snow depth in January and February, and similar inter-annual variations in snow depth for these two months during the period from 1966 to 2012 (Figs. 5d6d, e). Monthly snow depth sharply decreased by about 2 cm prior to the early 1970s, then increased by 2-2.5 cm until the late 1970s. Monthly snow depth displayed a fluctuating increase from the late1970s through 2012.

Significant increasing trend of monthly snow depth also appeared in March and April, the rate of increase ~~was~~ being about 0.6 cm decade^{-1} and 0.3 cm decade^{-1}, respectively (Figs. ~~5f~~6f-g). The trend of monthly snow depth in March was consistent with the change in winter from the mid-1960s through the late 1970s, then it was stable until the early 1990s (Fig. ~~5f~~6f). Monthly snow depth rapidly increased by 2.5 cm from the mid-1990s through the late 1990s, then it decreased slightly. Snow depth presented fluctuant increasing trend during the mid-1960s through the early 1980s (Fig. ~~5g~~6g). Subsequently, snow depth sharply increased ~~dramatically~~ by about 3 cm from the mid-1980s to the early 2000s. It declined rapidly during the early 2000s through 2012.

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

Figure ~~6~~ 8 shows the spatial distributions of linear trend coefficients of annual mean snow depth and maximum snow depth for each station during 1966-2012, with

$p \leqslant 0.05$. The significant increasing trends (blue circles) of annual mean snow depth occurred in most of European Russia, the south of Siberia and the Russian Far East, the northern Xinjiang Autonomous Region of China, and Northeast China (Fig. ~~6a~~8a). In contrast, decreasing trends (red circles) were detected in western European Russia, some regions of Siberia, the north of Russian Far East, and some regions to the south of 40 °N across China. Over the entire Eurasian continent, the most significant linear ~~variability~~ trends in annual mean snow depth were observed in the region north of 50 °N, indicating that the increasing rate of annual mean snow depth was greater in higher latitude regions.

Changes in the maximum snow depth were similar to those in annual mean snow depth in most of Eurasian areas from 1966 to 2012, but the change rates of the maximum snow depth were greater than the values of annual mean snow depth (Fig. ~~6b~~8b). The significant increasing trends were observed in the same regions as those with increases in annual mean snow depth. The decreasing trends were found in generally the same locations as decreases in annual mean snow depth, with greater reductions in the south of Siberia and the Russian Far East.

In October and November, there were few stations with significant changes in snow depth (at the 95 % level) (Figs. ~~7a~~9a, b). The increasing trends were mainly observed in most areas across the Eurasian continent in October. But the increasing trends of snow depth only appeared in Siberia and the Russian Far East in November. The decreasing trends in monthly mean snow depth occurred in the eastern regions of European Russia, the southern areas of the West Siberian Plain, and some areas of the northeast Russian Far East.

In winter months (December, January and February), there was a gradual expansion in areas with monthly mean snow depth variation at the 95 % level (Figs. ~~7c~~9c–e). There were increasing trends of monthly mean snow depth in the eastern regions of European Russia, southern parts of Siberia, the northern Xinjiang Autonomous Region of China, and Northeast China. In contrast, significant decreasing trends were observed in the north and west of European Russia, scattered in Siberia, the northeast of the Russian Far East, and most areas of China.

From March to May, the number of stations with significant changes (at the 95 % level) in monthly mean snow depth ~~fell~~decreased, especially in May because of snow melt (only 78 stations) (Figs. ~~7f~~9f-h). Changes in monthly mean snow depth were consistent with the trends in winter over the former USSR but more stations with ~~the~~ decreasing trends were found in ~~the~~ southern Siberia. There were few stations with statistically significant trends of snow depth across China; for these, ~~and~~ monthly snow depths tended to decrease in most stations. Compared with the south of 50 °N, the changes in monthly mean snow depth were more significant to the north of 50 °N.

3.3 Variability of Snow Depth with Latitude, ~~and~~ Elevation and Continentality

To explore the spatial ~~features~~ variability of snow depth, we conducted a linear regression analysis of annual mean snow depth with latitude, ~~and~~ elevation and continentality (Fig. ~~8~~10). Snow depth is positively correlated with latitude, i.e., snow depth generally increases with latitude (Fig. ~~8a~~10a). The increase rate of snow depth was about 0.81 cm per 1 °N. We detected a closer relationship between latitude and ~~mean~~ snow depth to the north of 40 °N (Figs. ~~8a~~10a, ~~c~~d). In these regions, snow cover was relatively stable (the number of annual mean continuous snow cover days was more than 30) (Zhang and Zhong, 2014), in which snow cover was easier to accumulate by the heavy snowfall and more difficult to melt with low air temperature.

There was a negative correlation between snow depth and elevation across the Eurasian continent (Fig. ~~8b~~10b): with every 100 m increase in elevation, snow depth decreased by ~0.5 cm ($P \leqslant 0.05$). Annual mean snow depth was less than 1 cm in most areas, with an elevation greater than 2000 m, because a –snow depth of 0 cm was used to calculate the mean snow depth. Therefore, although the TP is at high elevation, the shallow snow depth in this area resulted in the generally negative correlation between snow depth and elevation across the Eurasian continent. However, we also determined that snow depth increased with elevation in most regions north of 45 °N (Fig. ~~8c~~10d). This result indicates that elevation is an important factor affecting snow depth in these regions.

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

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

In addition to the terrain factors, Variations variations in snow depth are closely related to climate changevariability. To examine the relationship between snow depth and climatic factors, we calculated the long-term mean snow depth, air temperature and snowfall of 386 stations from November through March across the USSR (Fig. 911). The period (snow cover years) spanned from 1966 through 2009 because data on air temperature and precipitation were recorded only until 2010. Snow depth significantly decreased decreases with increasing air temperature ($P \leqslant 0.05$), but the Goodness of Fit of the relationship was only 16% (Fig. 9a11a). Compared with the air temperature, snowfall exhibited a better relationship with snow depth (Fig. 9b11b). The mean snow depth was less than 20 cm in most stations with the accumulated snowfall being <50 mm from November through March. It increased with the accumulated snowfall increased, and the thickest snow depth reached 120 cm when the maximum cumulative snowfall was 350 mm.

Comparing the long-term inter-annual trends of changes in snow depth, SWE, air temperature and snowfall, the variability of snow depth and SWE were mainly affected by the changes in snowfall. Overall, the trends in long-term air temperature, precipitation, snowfall and SWE displayed increaseincreasing trendss from November to March (Fig. 1012). This was because the increased precipitation fell as snow in cold areas where the increased temperature was still below freezing (Ye et al., 1998; Kitaev et al., 2005). Warmer air led to greater supply of moisture for snowfall, hence the snow accumulation still increased (Ye et al., 1998). The significant increasing snowfall can explain the sudden drop in the bulk snow density from the mid-1990s through the early 2000s (Zhong et al., 2014): increasing snowfall should decrease the density of the surface snowpack, which lowed the whole density of snowpackfresh snow with low snow density. There were basically consistent trends of variations in snow depth, SWE and snowfall accumulation from November through March during 1966-2009 (Figs. ~~10b~~12b-d). The results indicated that the increasing trend ~~of changes~~ in snow depth was the combined effect of the increasing air temperature and snowfall. ~~In fact, the climatology of snow depth not only influenced by air temperature and precipitation, but also with other climatic factors and atmospheric circulation. The mechanism of increasing snow depth in the Eurasian continent requires further investigation in the future.~~

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

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

4 Discussion

4.1 Comparison with Previous Results

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

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

In addition to the above reasons, these differences can be explained by the changes in climatic factors during the different study periods. The sensitivity of snow cover to air temperature and precipitation for each station showed regional differences (Fallot et al., 1997; Park et al., 2013). The amount of snowfall can be affected by climate change, and leading to differences in snow depth at different times (Ye et al., 1998; Kitaev et al., 2005). The results of our study showed that there was significant negative relationship between snow depth and air temperature in the southern Siberia, however, it did not exist in the northern Siberia. This may explain the difference in the results of these studies.

4.2 Topographical effects in snow depth

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

5 Conclusions

In this study, daily snow depth and snow course data from 1814 stations were used to investigate spatial and temporal changes in annual mean snow depth and maximum snow depth over the Eurasian continent for the period from 1966 to 2012. Our results demonstrate that greater long-term average snow depth was observed in northeastern European Russia, the Yenisey River basin, the Kamchatka Peninsula, and

Sakhalin. In contrast, the shallowest snow depths were recorded in China, except for the northern Xinjiang Autonomous Region of China, Northeast China, and in some regions of southwestern TP.

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

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

Compared with elevation, latitude played a more important role in the snow depth climatology. The variations in snow depth and SWE were more affected by snowfall: the greater the snowfall accumulation, the thicker the snow depth and SWE. Variations of snow depth were explained by air temperature and snowfall in most areas of the European Russia and some regions of the southern Siberia, the effects of the two factors on SWE only appeared in some of these areas; however, snowfall was the main driver force of the variance of snow depth and SWE in the former USSR. The mechanism controlling the increase in snow depth and the effects of topography on snow depth will be addressed in future studies.

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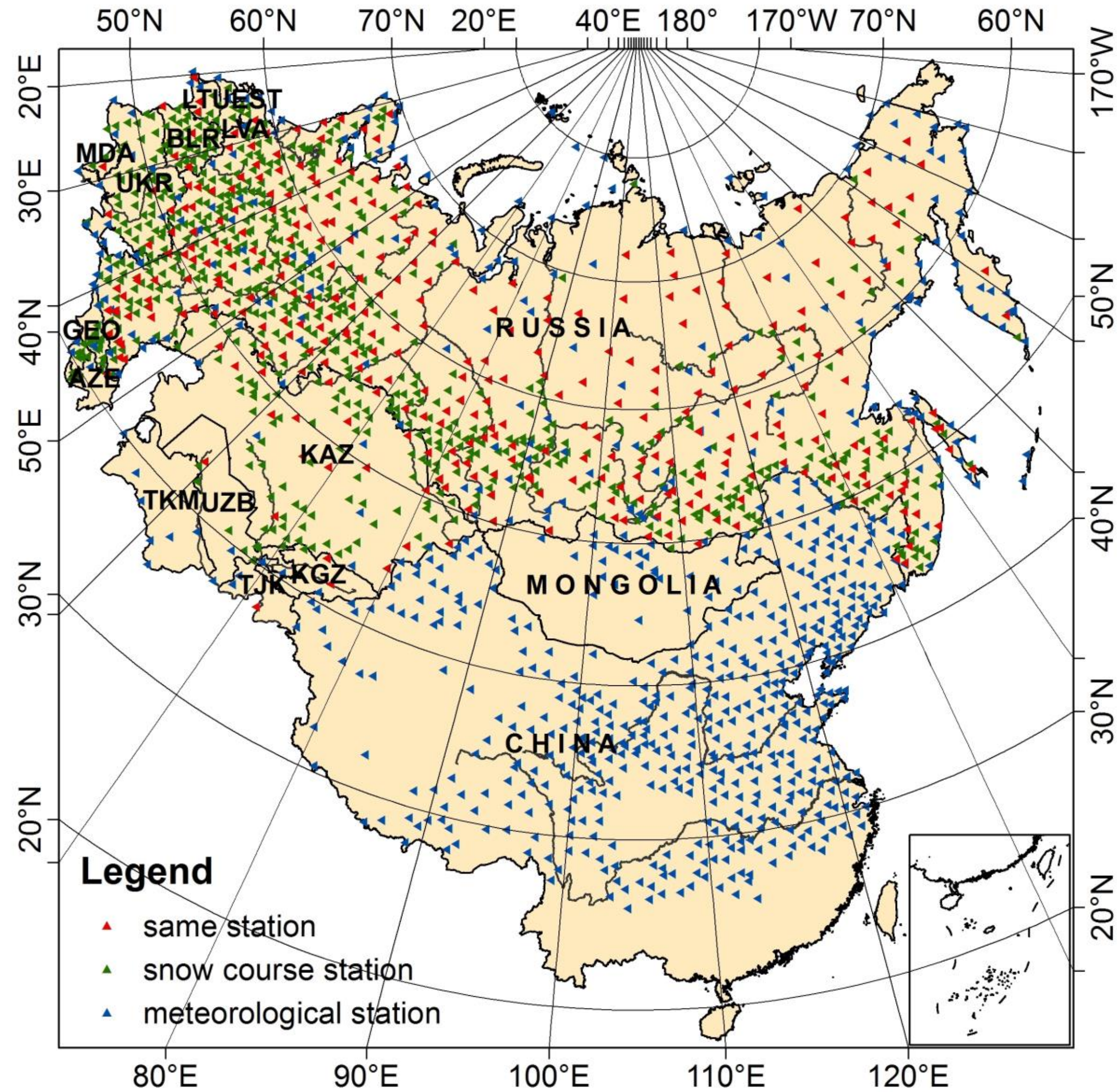
Tables and Figures

Table 1. Sources of snow depth data.

Dataset	Spatial distribution	Number of stations	Source
Daily snow depth	the former USSR	586	Russian Research Institute for Hydrometeorological Information-World Data Center (RIHMI-WDC) National Snow and Ice Data Center (NSIDC), University of Colorado at Boulder
	China	492	National Meteorological Information Center (NMIC) of the China Meteorological Administration
	Mongolia	25	NSIDC
Snow depth from snow course	the former USSR	1044	RIHMI-WDC, NSIDC
Snow water equivalent (SWE)	the former USSR	386	RIHMI-WDC
Daily air temperature and precipitation	the former USSR	386	RIHMI-WDC


50°N
60°N
70°N
20°E
40°E
180°
170°W
70°N
60°N
20°E
30°E
40°N
50°E
30°N
20°N
170°W
50°N
40°N
30°N
20°N
80°E
90°E
100°E
110°E
120°E
LTU
EST
LVA
BLR
MDA
UKR
GEO
AZE
RUSSIA
KAZ
TKM
UZB
KGZ
TJK
MONGOLIA
CHINA
Legend
same station
snow course station
meteorological station

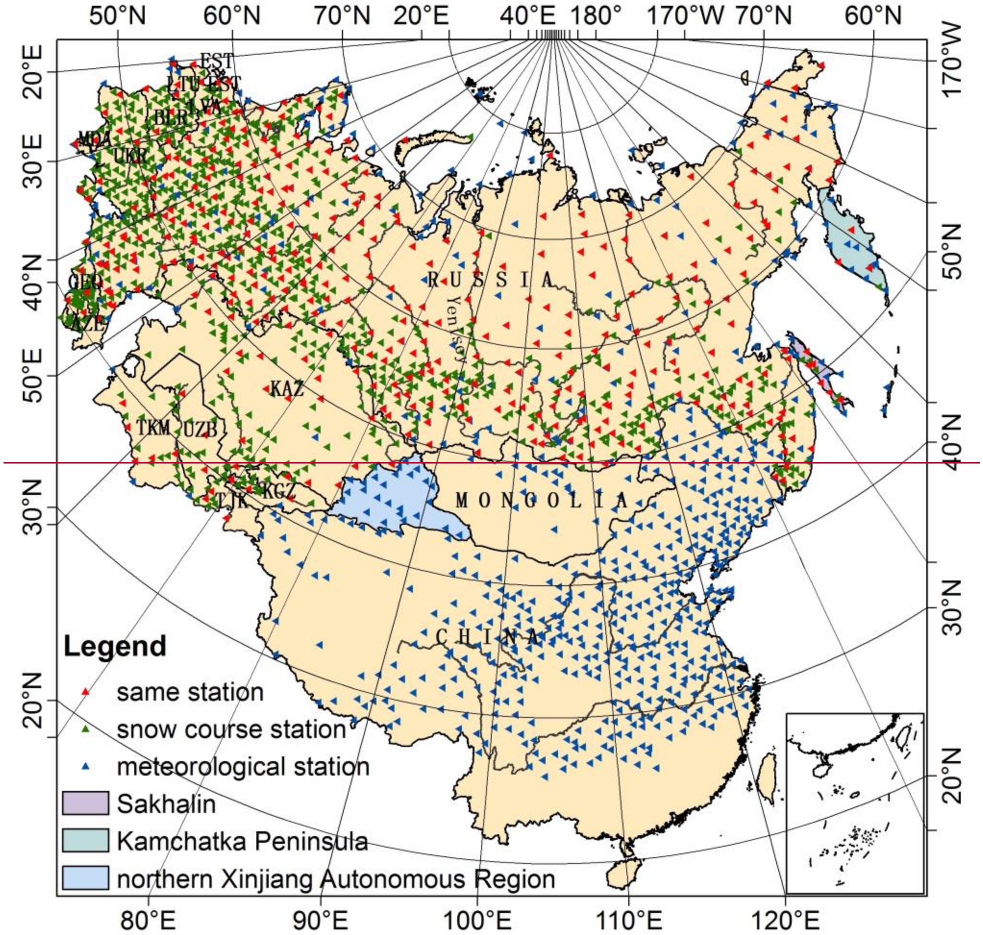


Figure 1. Geographical locations of meteorological and snow course stations across the Eurasian continent. The red triangles represent stations where snow depth was measured at both meteorological stations and snow course surveys, the green triangles show stations where snow depth was measured at snow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

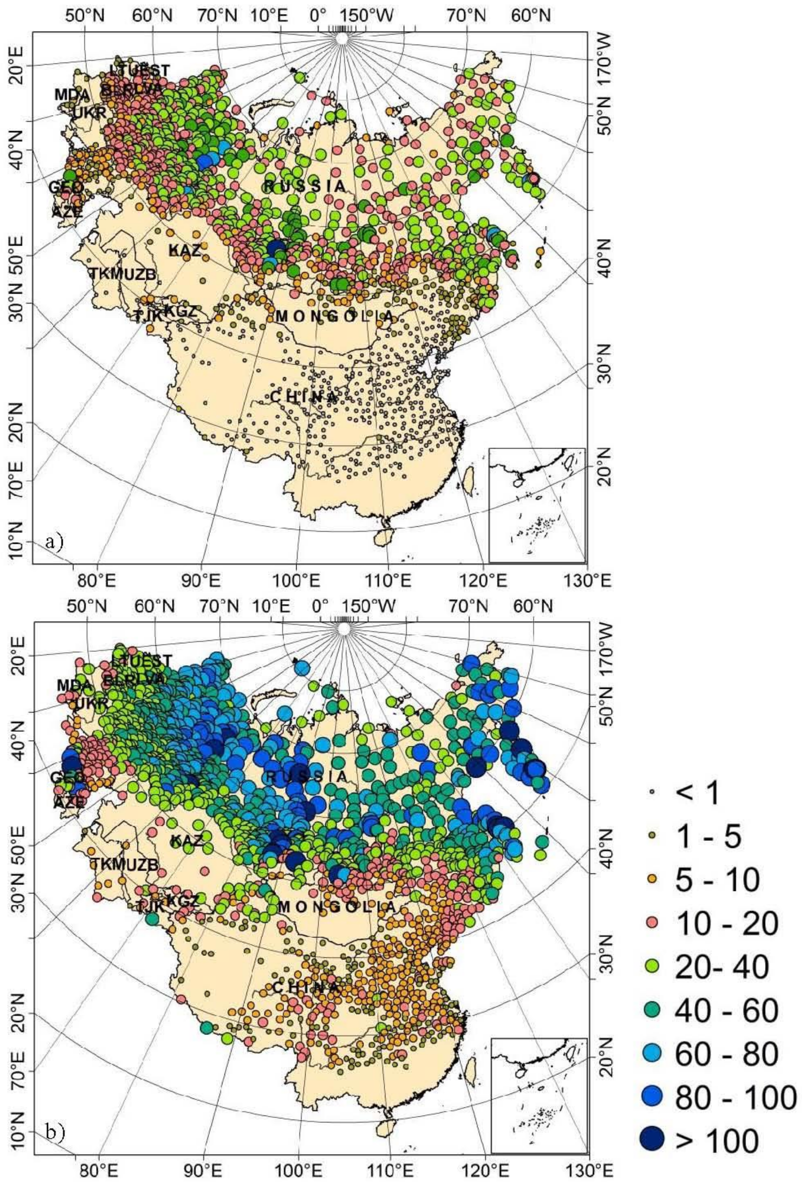
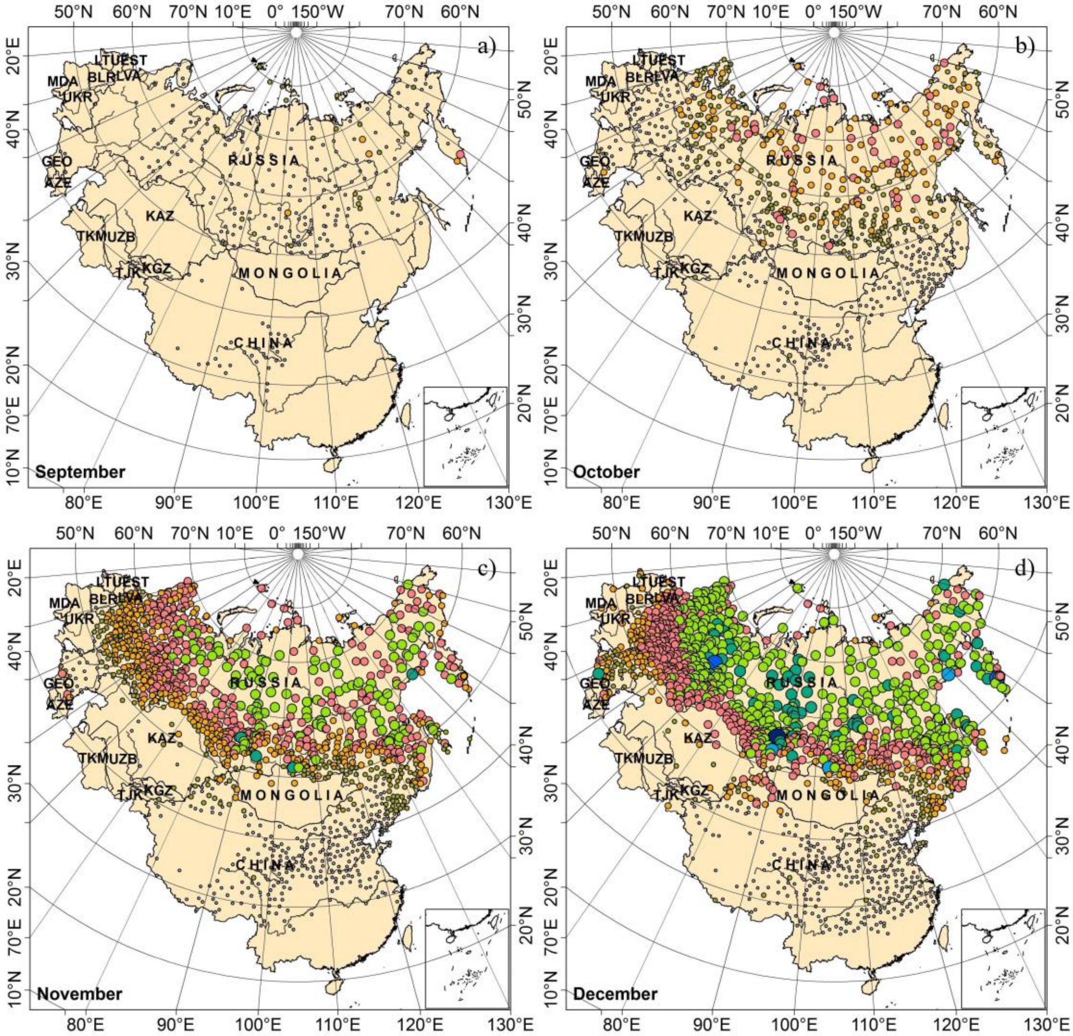


Figure 2. Annual mean snow depth (a) and maximum snow depth (b) across the Eurasian continent (cm) during 1966-2012.

1



a)
b)
c)
d)
September
October
November
December
RUSSIA
MONGOLIA
CHINA
KAZ
TKM
UZB
TJK
KGZ
GEO
AZE
MDA
UKR
LTU
EST
BLR
LVA
50°N
60°N
70°N
10°E
0°
150°W
80°E
90°E
100°E
110°E
120°E
130°E

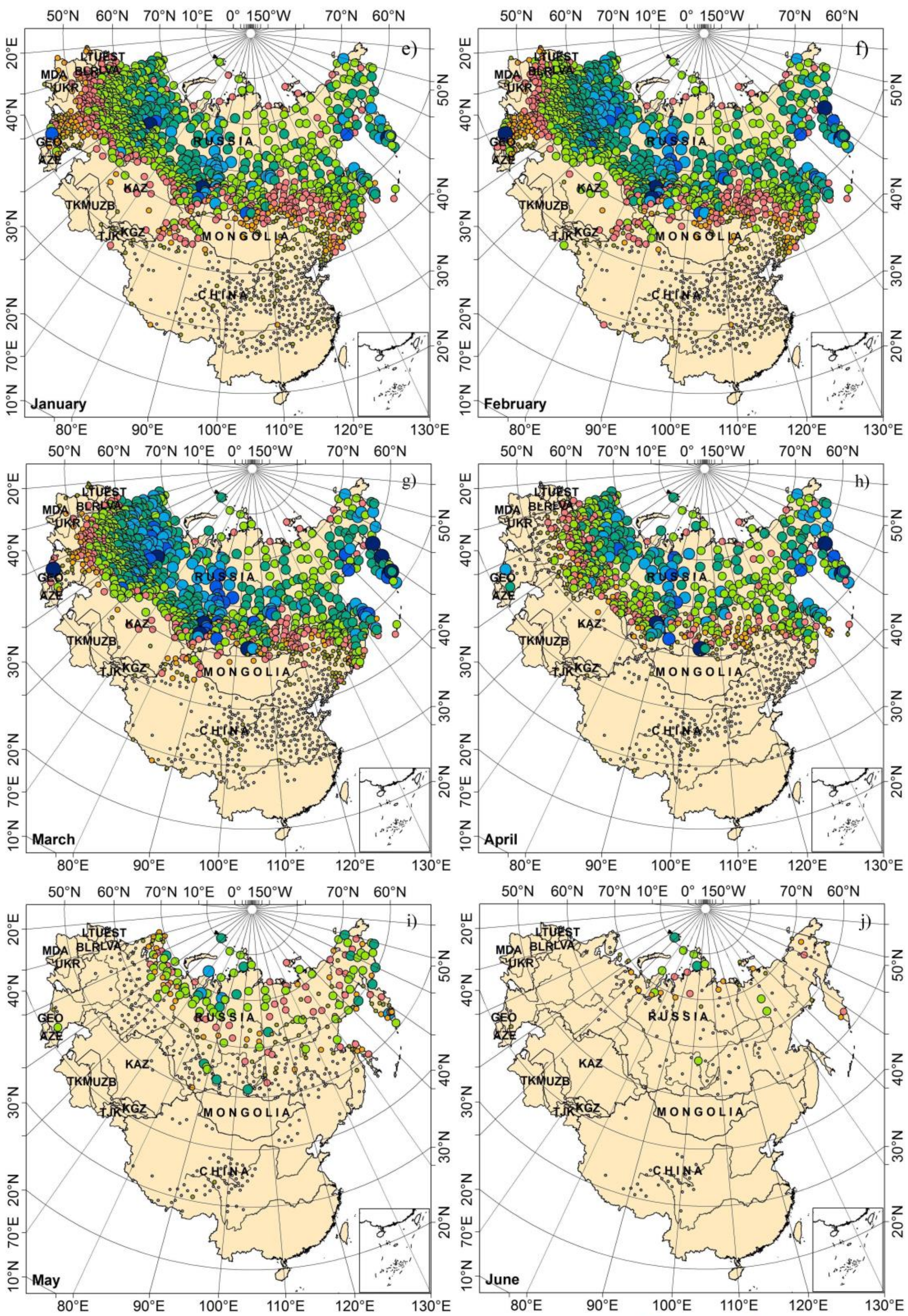
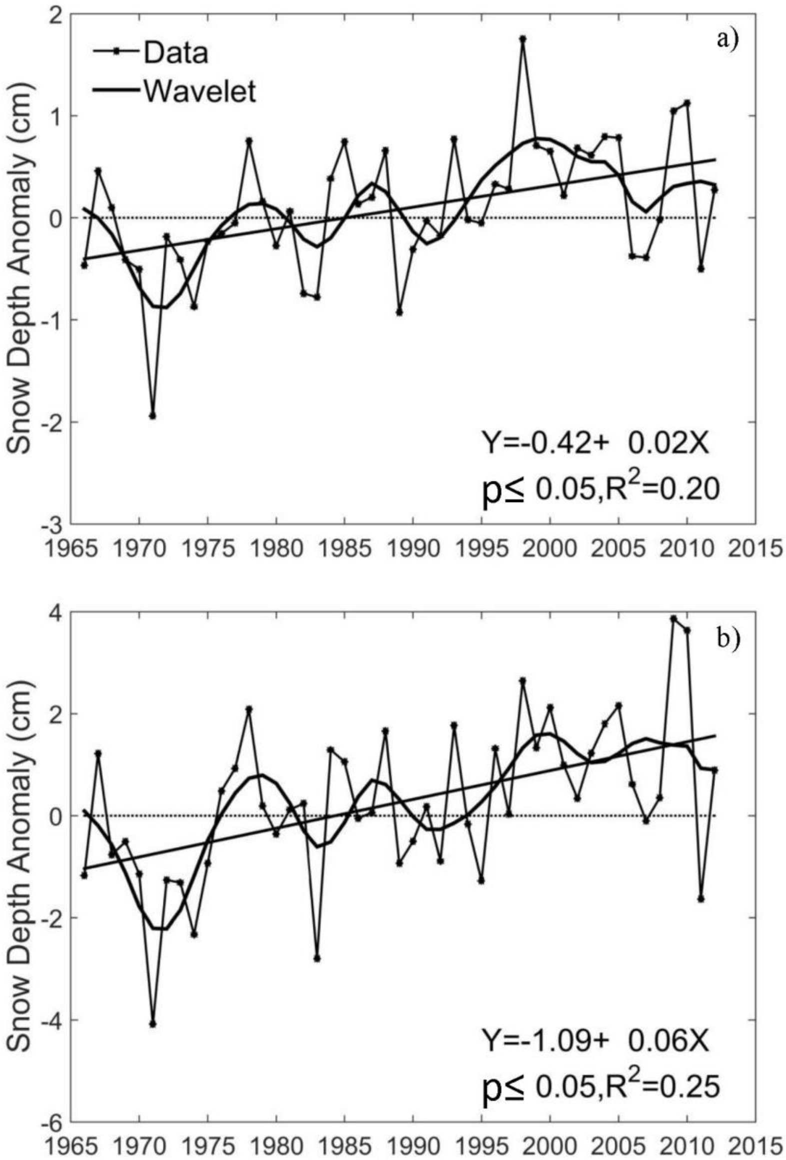


Figure 3. Monthly mean snow depth (from September to June) (cm) across the Eurasian continent (cm) during 1966-2012. (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, (i) May, (j) June.


Data
Wavelet
a)
Snow Depth Anomaly (cm)
Y=-0.42+ 0.02X
p≤ 0.05,R2=0.20
b)
Snow Depth Anomaly (cm)
Y=-1.09+ 0.06X
p≤ 0.05,R2=0.25

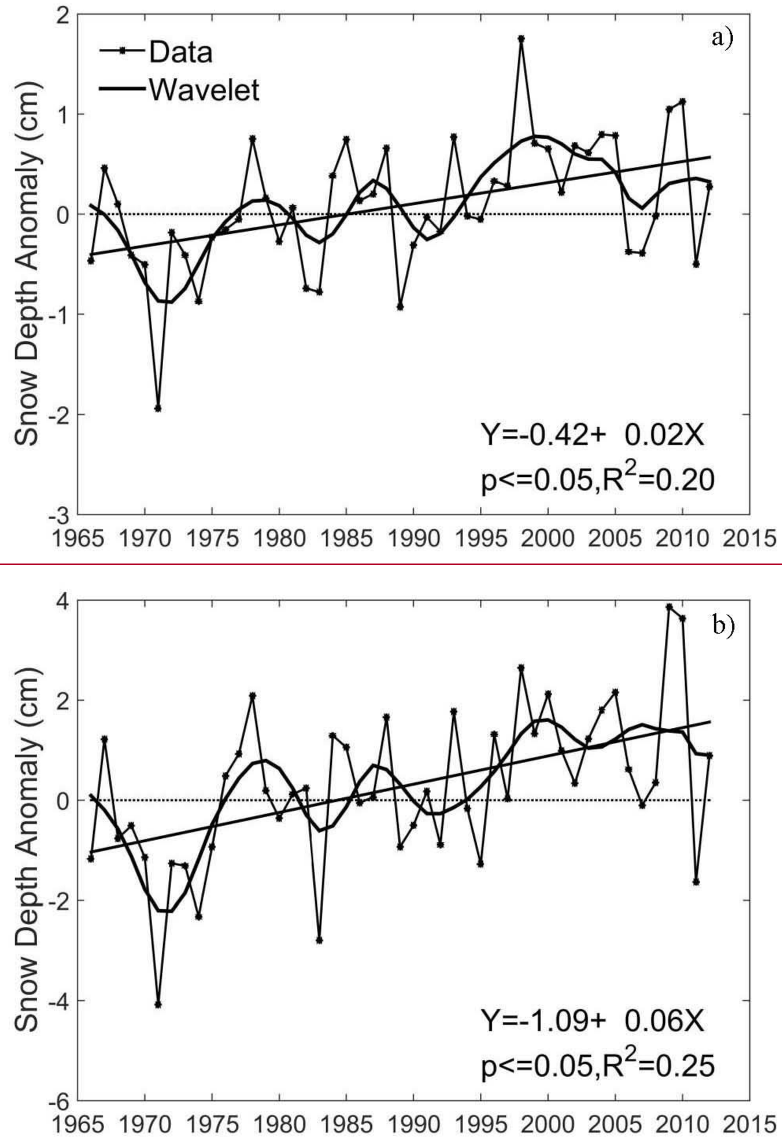


Figure 4. Composite of inter-annual variation of annual mean snow depth (a) and maximum snow depth (b) from 1966 through 2012 with respect to the 1971-2000 mean across the Eurasian continent. The line with dots is the anomaly of snow depth; the thick curve represents the smoothed curve using wavelet analysis; the thick line presents a linear regression trend. Y represents snow depth anomaly in cm and X represents time in snow cover years, 1966 was the first snow cover year, therefore, X ranged from year 1 (1966) to year 47 (2012) in the simulation of annual mean snow depth.

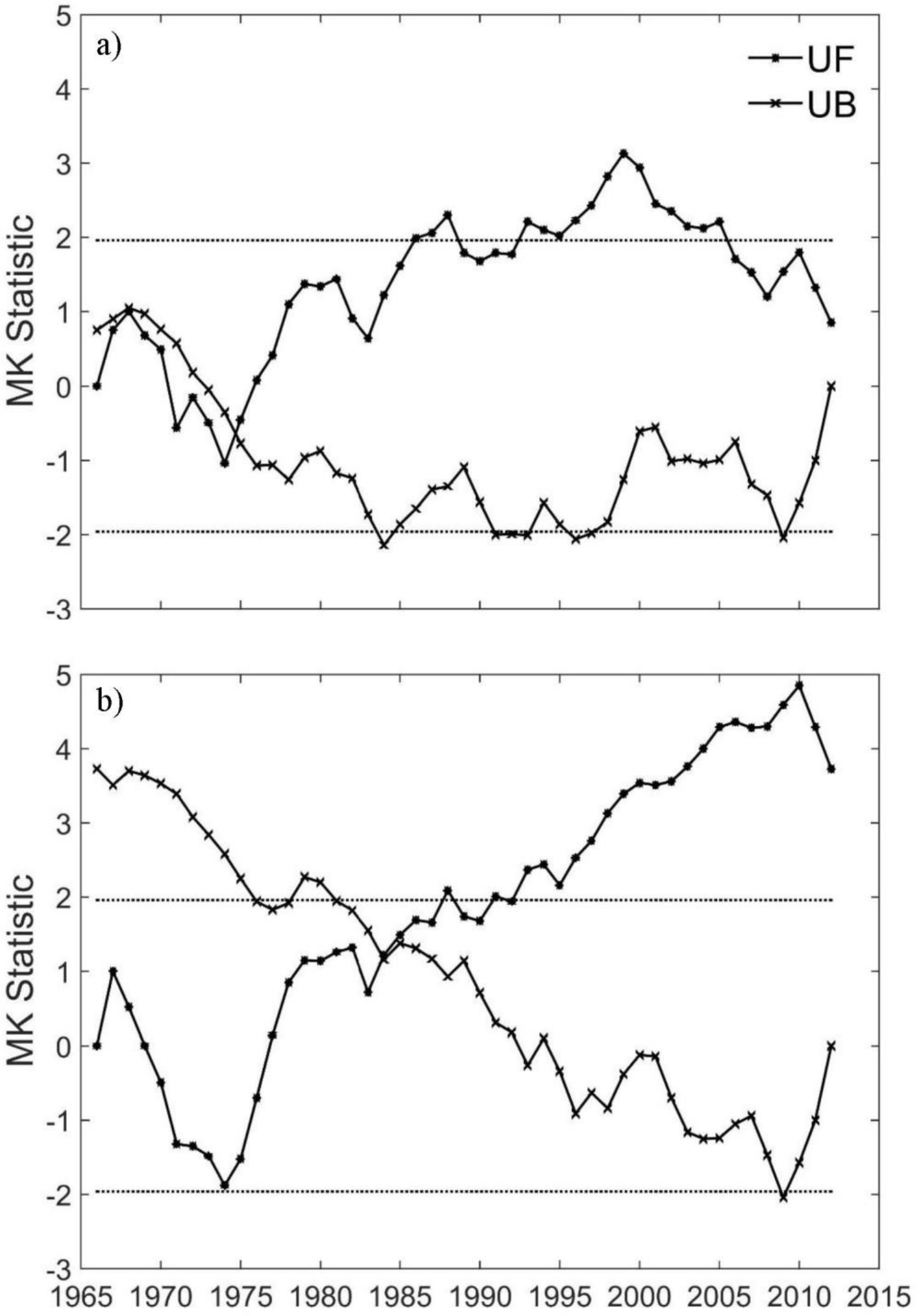
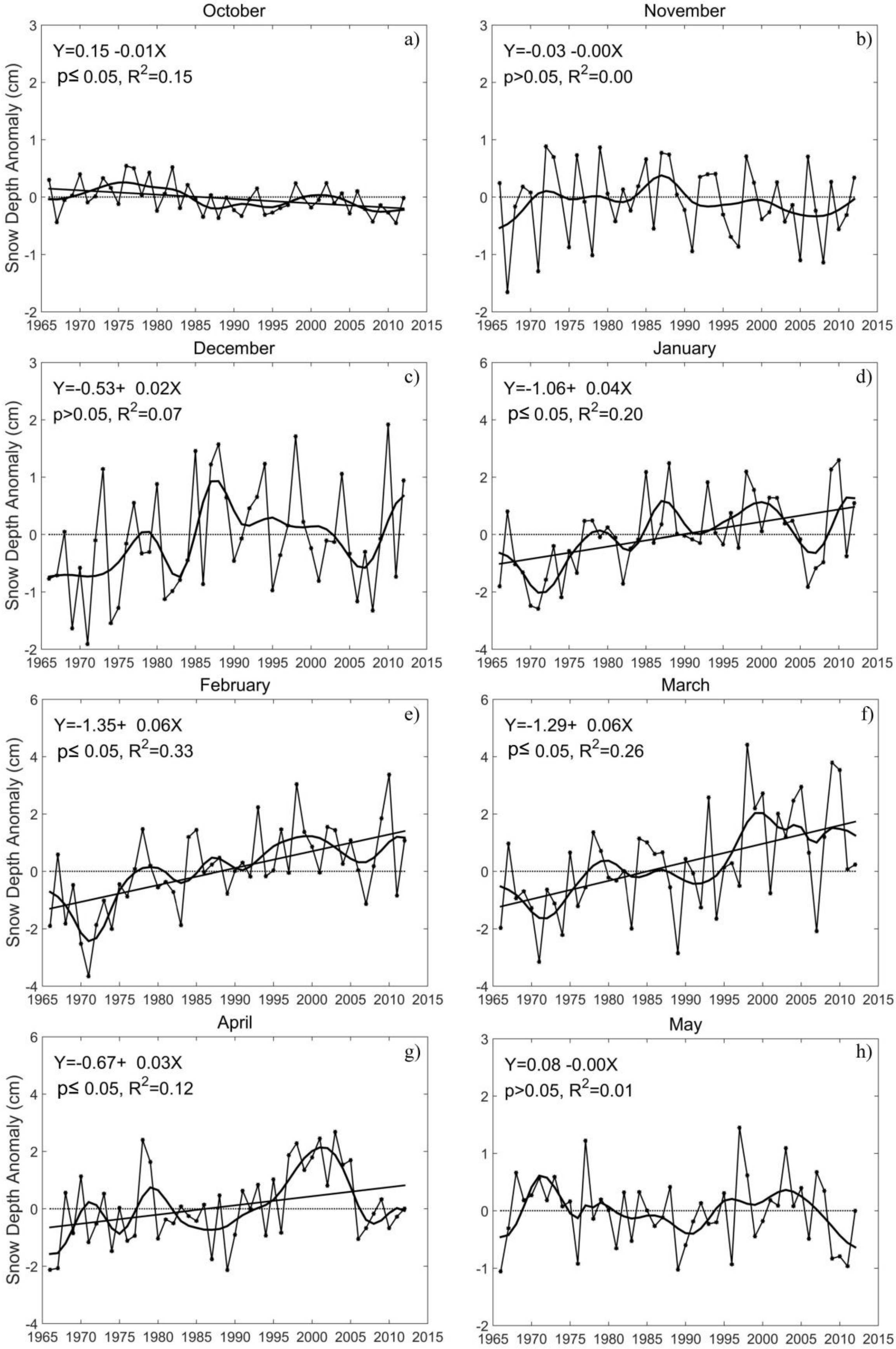


Figure 5. Mann-Kendall statistical curve of annual mean snow depth (a) and maximum snow depth (b) from 1966 through 2012 across the Eurasian continent. Straight line presents significance level at 0.05.


October
Y=0.15 -0.01X
p≤ 0.05, R2=0.15
a)
November
Y=-0.03 -0.00X
p>0.05, R2=0.00
b)
December
Y=-0.53+ 0.02X
p>0.05, R2=0.07
c)
January
Y=-1.06+ 0.04X
p≤ 0.05, R2=0.20
d)
February
Y=-1.35+ 0.06X
p≤ 0.05, R2=0.33
e)
March
Y=-1.29+ 0.06X
p≤ 0.05, R2=0.26
f)
April
Y=-0.67+ 0.03X
p≤ 0.05, R2=0.12
g)
May
Y=0.08 -0.00X
p>0.05, R2=0.01
h)
Snow Depth Anomaly (cm)
1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 2015

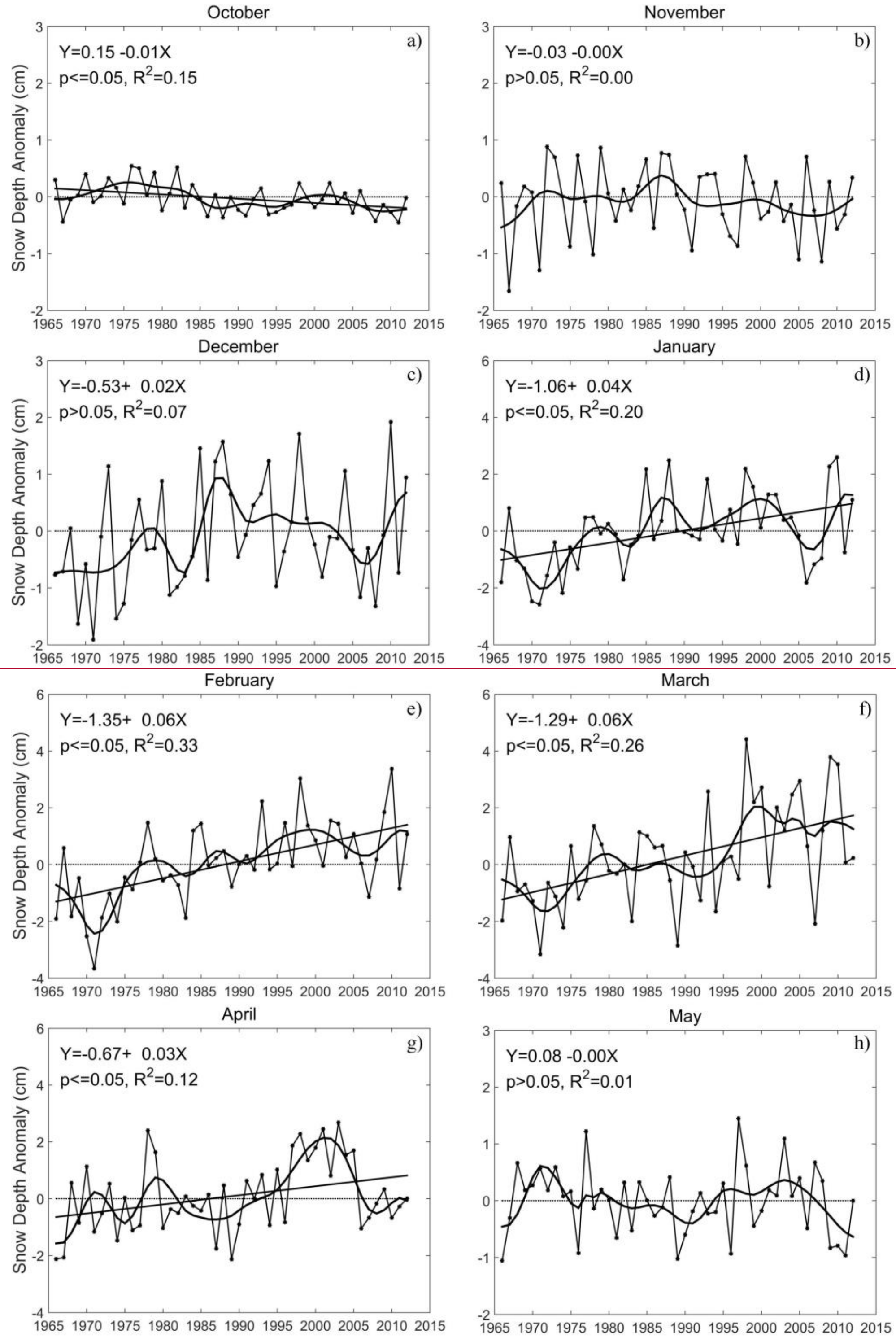


Figure ~~5~~6. Composites of inter-annual variation of monthly mean snow depth (from October to May) from 1966 through 2012 with respect to the 1971-2000 mean across the Eurasian continent. (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May. The line with dots is the anomaly of snow depth; the thick curve represents the smoothed curve using wavelet analysis; the thick line presents a linear regression trend.

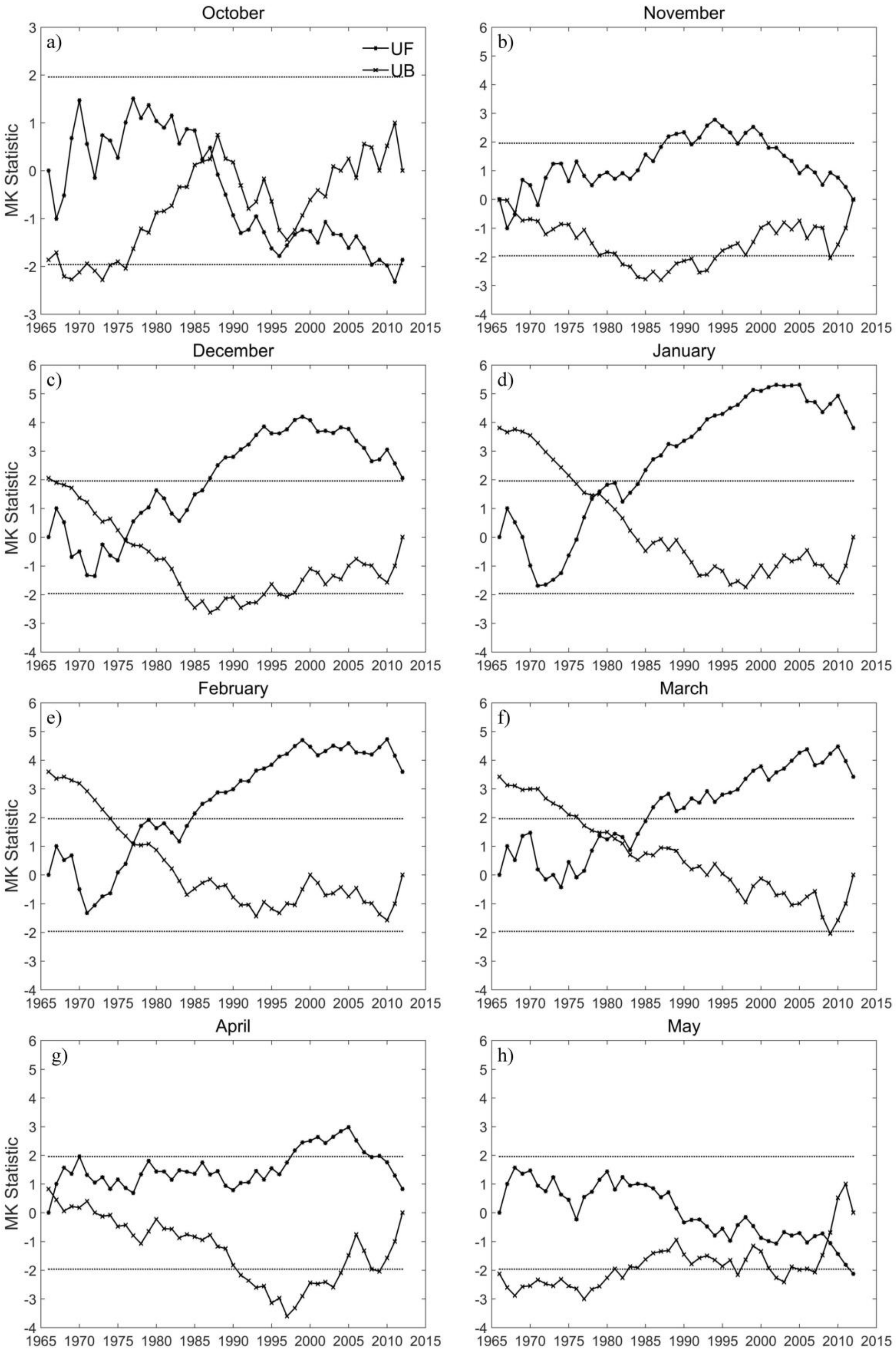


Figure 7. Mann-Kendall statistical curve of monthly mean snow depth (from October to May) from 1966 through 2012 across the Eurasian continent. (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May. Straight line presents significance level at 0.05.

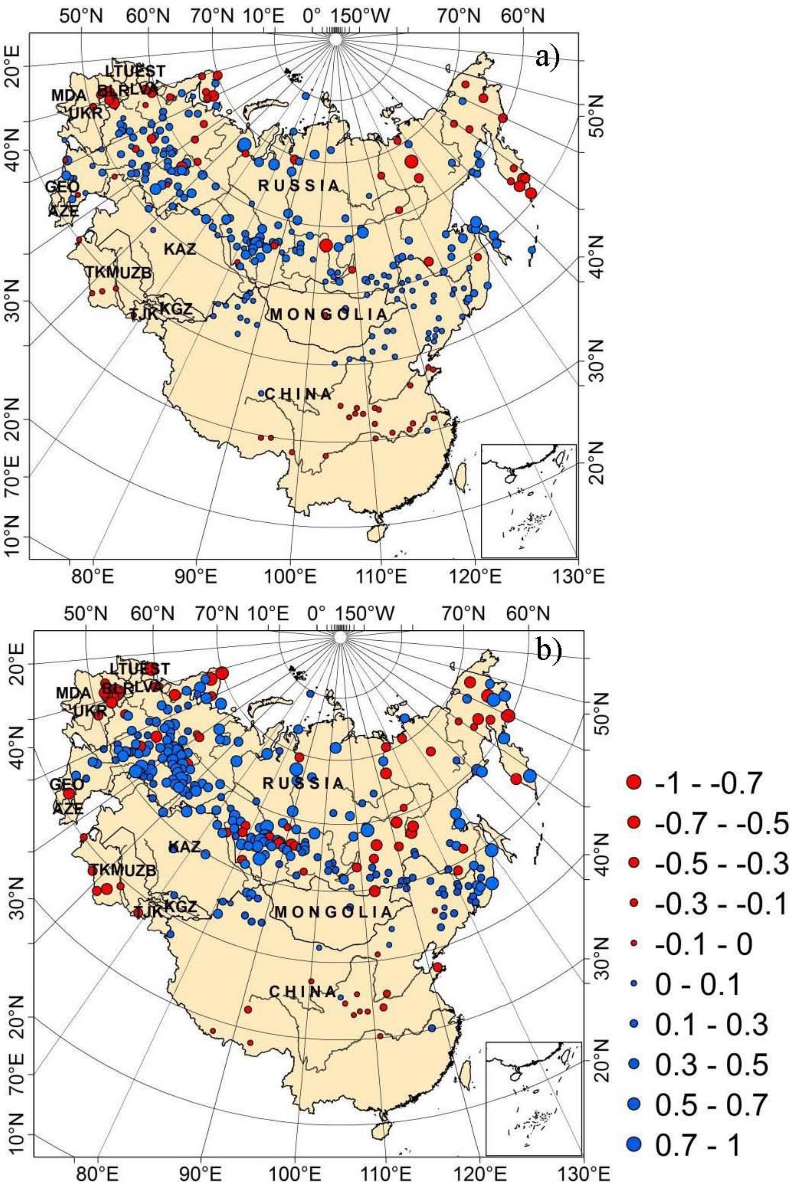


Figure ~~6~~8. Spatial distribution of linear trend coefficients (cm yr^{-1}) of annual mean snow depth (a) and maximum snow depth (b) for each station in 1966-2012. The rate of change was at the 95% level. Red circles represent a decreasing trend, and blue circles represent an increasing trend.

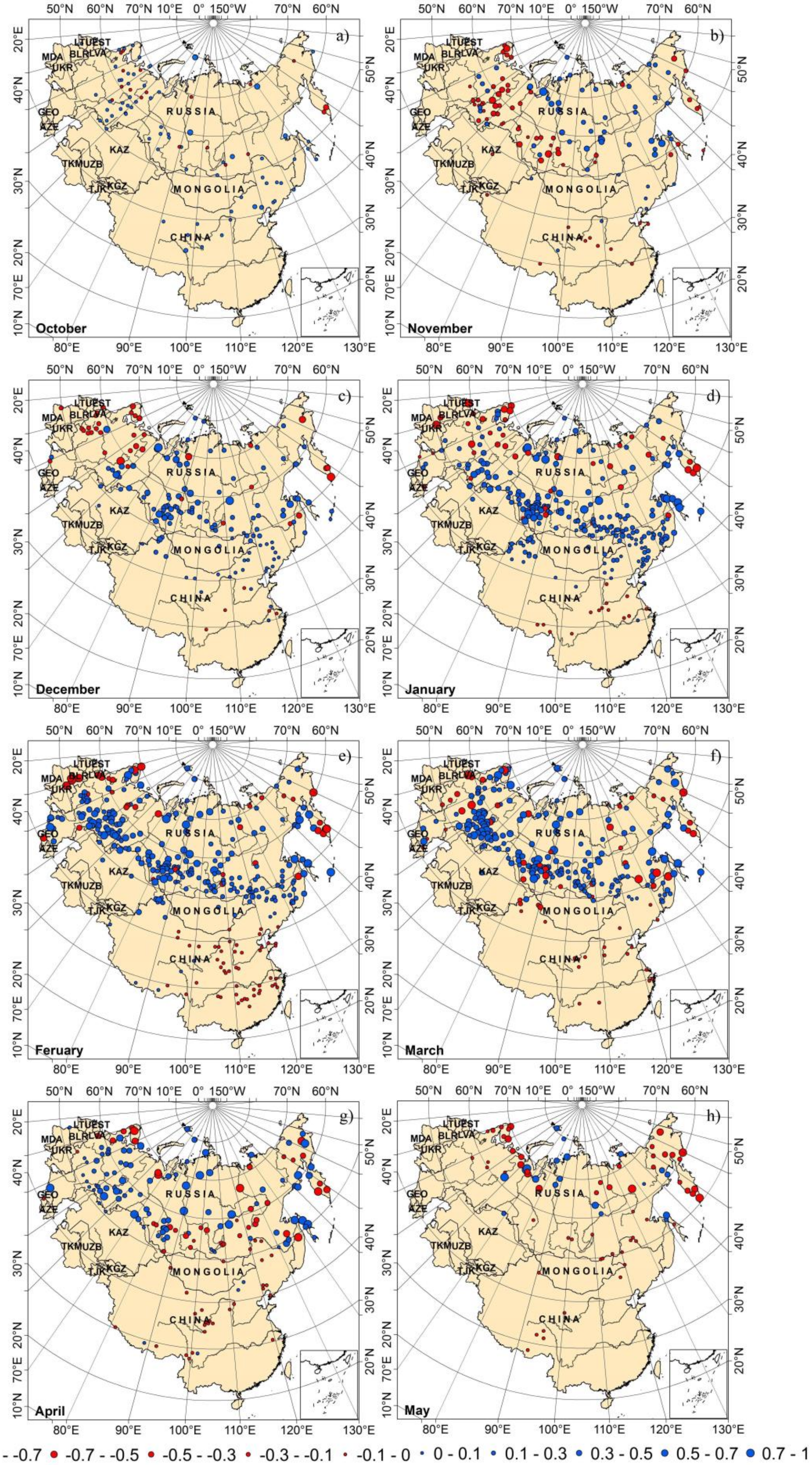
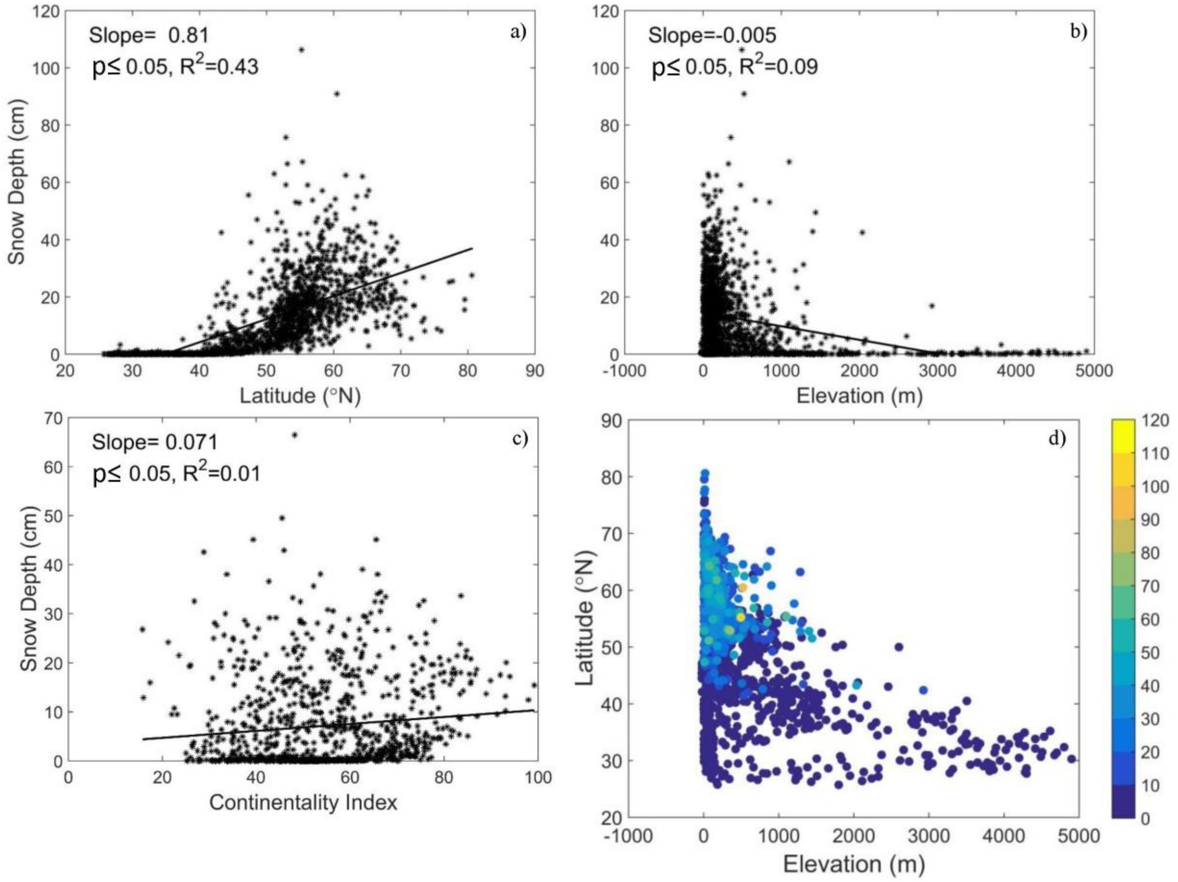

a) October
b) November
c) December
d) January
e) Feruary
f) March
g) April
h) May
RUSSIA
KAZ
MONGOLIA
CHINA
LTU EST
BLR LVA
MDA
UKR
GEO
AZE
TKM UZB
TJK KGZ
80°E 90°E 100°E 110°E 120°E 130°E
50°N 60°N 70°N 10°E 0° 150°W 70°N 60°N
-1 - -0.7
-0.7 - -0.5
-0.5 - -0.3
-0.3 - -0.1
-0.1 - 0
0 - 0.1
0.1 - 0.3
0.3 - 0.5
0.5 - 0.7
0.7 - 1

Figure ~~7~~9. Spatial distributions of linear trend coefficients (cm yr^{-1}) of monthly mean snow depth (from October to May) during 1966 to 2012. (a)October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May. The rate of change was at the 95% level. Red circles represent a decreasing trend, and blue circles represent an increasing trend.



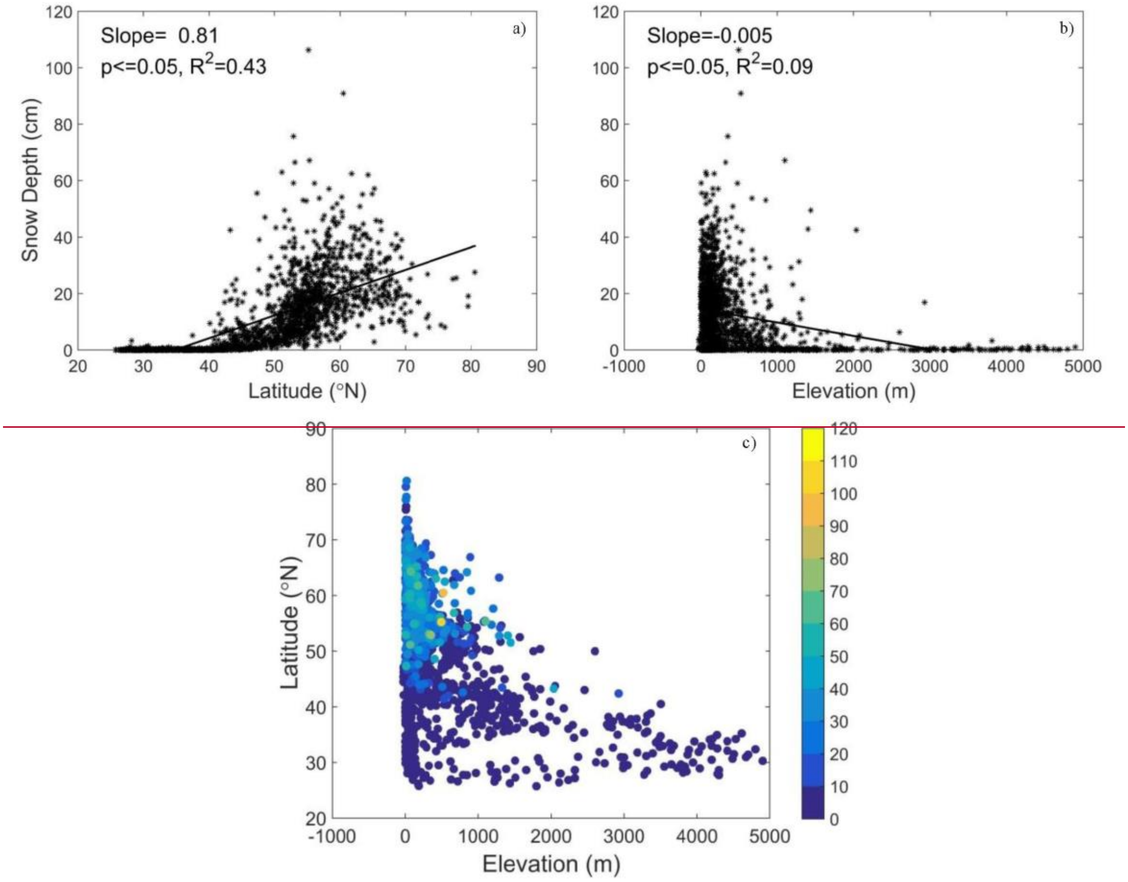
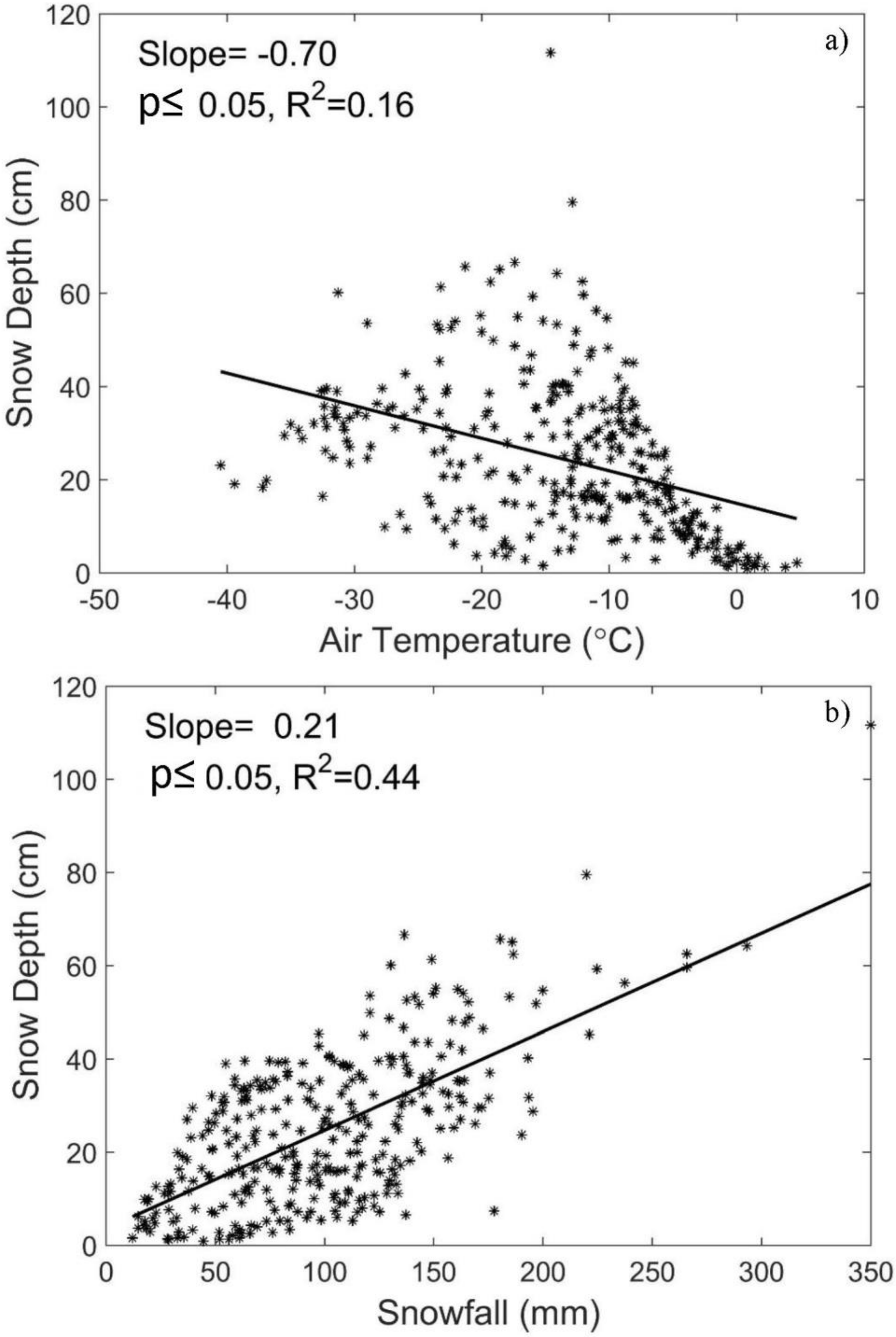


Figure ~~8~~10. The relationship between a~~A~~nnual mean snow depth ~~changes with~~and latitude (a~~)~~)~~and~~ , elevation (b) and continentality (c) for all stations across the Eurasian continent during 1966-2012. Asterisks show the mean snow depth of each station; the thick line is a linear regression trend; the different colors represent snow depth (cm) of each station (~~c~~d).



Slope= -0.70
p≤ 0.05, R2=0.16
a)
Snow Depth (cm)
Air Temperature (°C)
Slope= 0.21
p≤ 0.05, R2=0.44
b)
Snow Depth (cm)
Snowfall (mm)

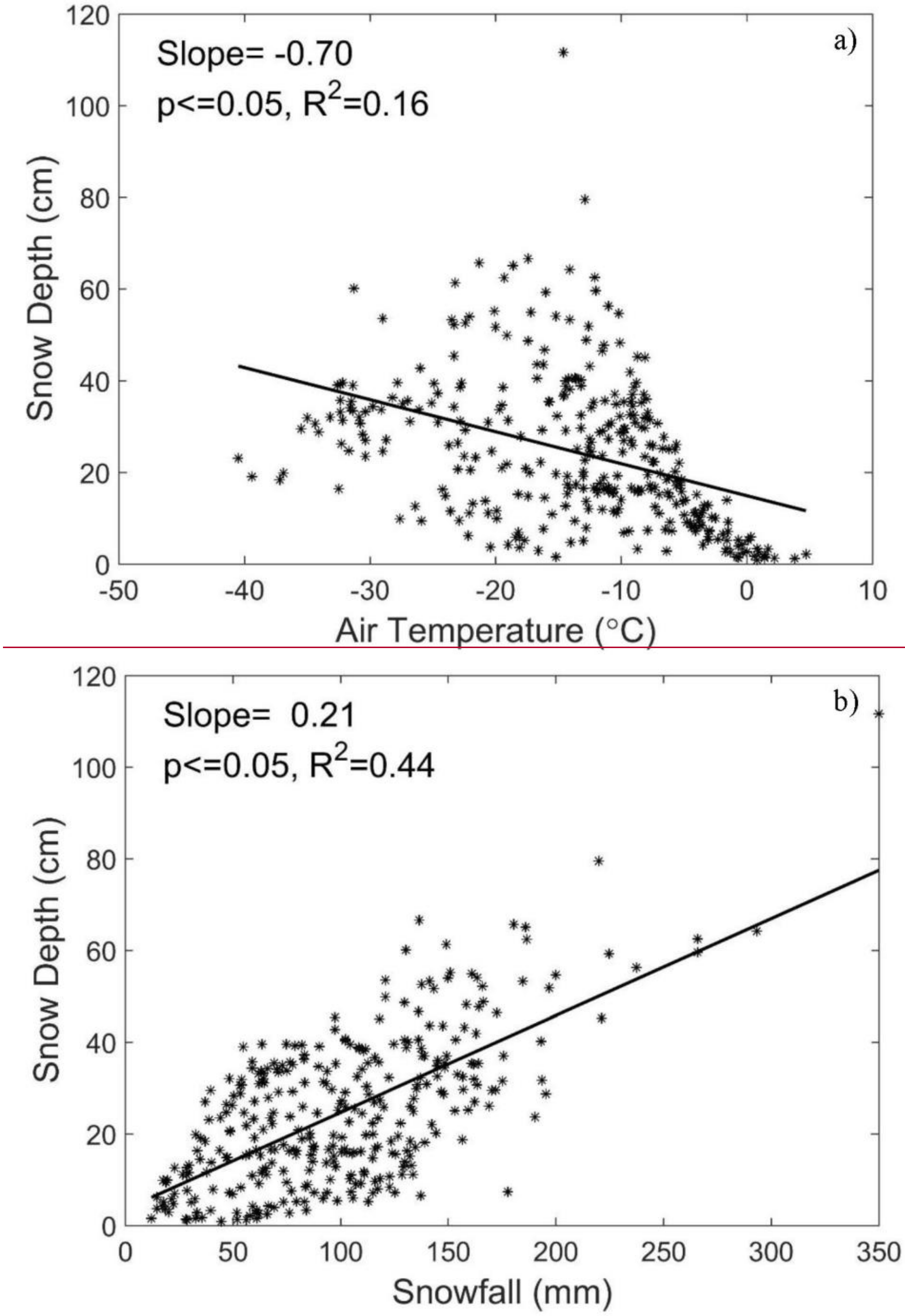
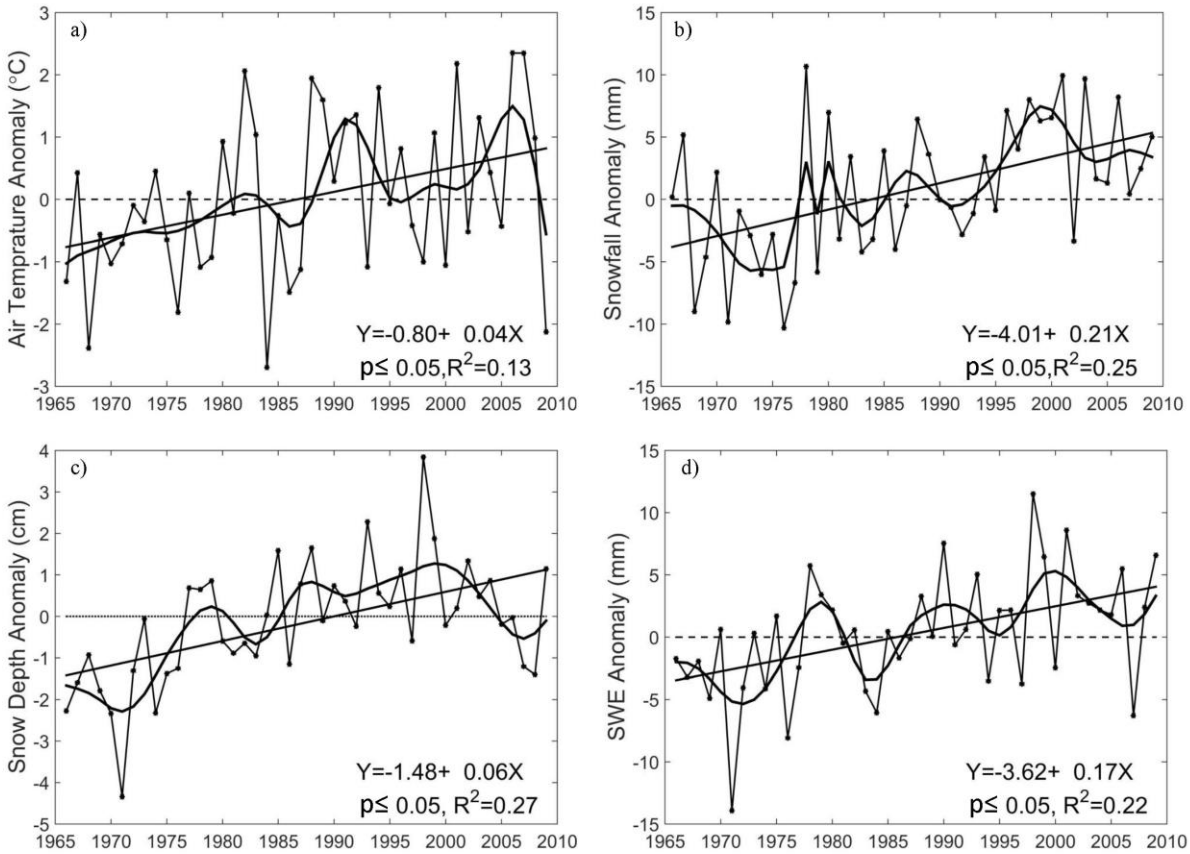


Figure ~~9~~11. The relationships among annual mean snow depth, air temperature and snowfall for 386 stations from November through March during 1966-2009 over the USSR. The thick line is a linear regression trend.


a)
Air Temprature Anomaly (°C)
Y=-0.80+ 0.04X
p≤ 0.05,R^2=0.13
b)
Snowfall Anomaly (mm)
Y=-4.01+ 0.21X
p≤ 0.05,R^2=0.25
c)
Snow Depth Anomaly (cm)
Y=-1.48+ 0.06X
p≤ 0.05, R^2=0.27
d)
SWE Anomaly (mm)
Y=-3.62+ 0.17X
p≤ 0.05, R^2=0.22

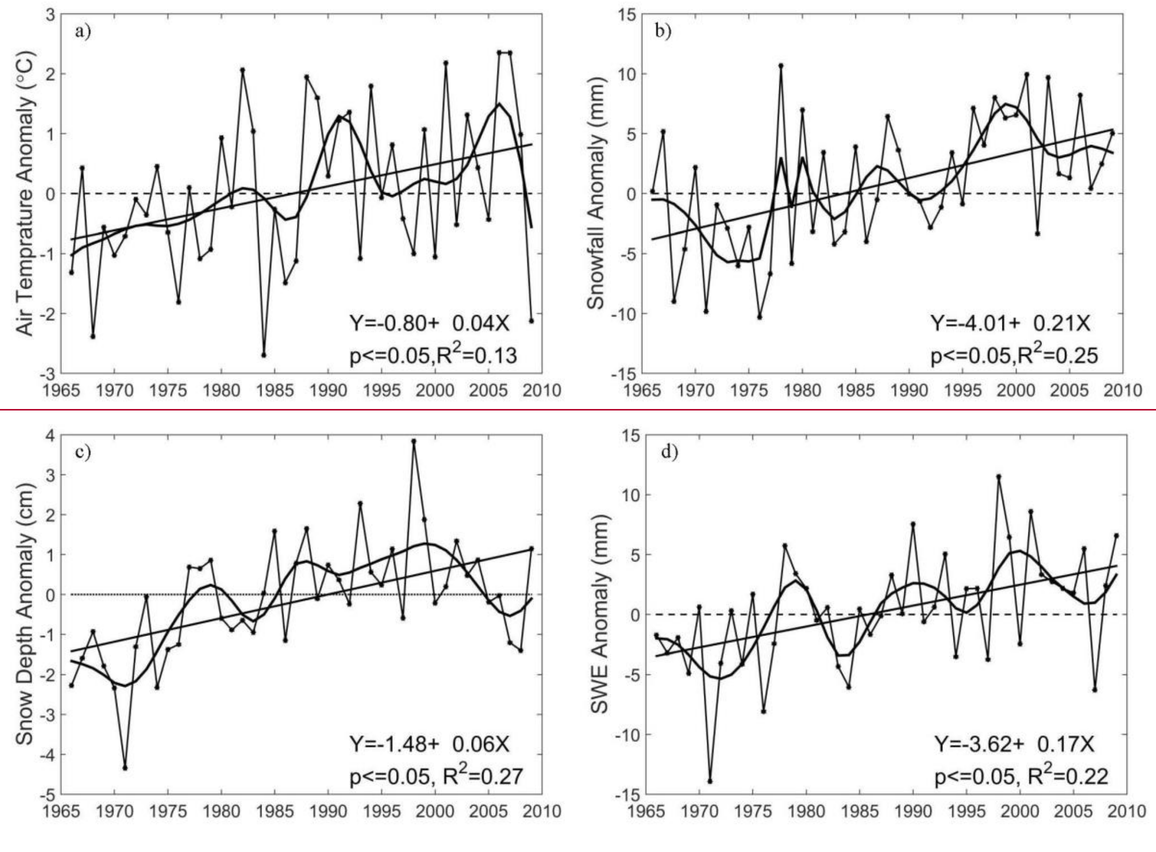

a)
Air Temprature Anomaly (°C)
Y=-0.80+ 0.04X
p<=0.05,R^2=0.13
b)
Snowfall Anomaly (mm)
Y=-4.01+ 0.21X
p<=0.05,R^2=0.25
c)
Snow Depth Anomaly (cm)
Y=-1.48+ 0.06X
p<=0.05, R^2=0.27
d)
SWE Anomaly (mm)
Y=-3.62+ 0.17X
p<=0.05, R^2=0.22

Figure ~~10~~12. Composite of inter-annual variation of annual mean air temperature (a), annual snowfall (b), annual snow depth (c) and snow water equivalent (d) from November through March during 1966-2009 with respect to the 1971-2000 mean across the former USSR. The line with dots is the composite of the annual means; the thick curve represents the smoothed curve using wavelet analysis; the thick line presents a linear regression trend.

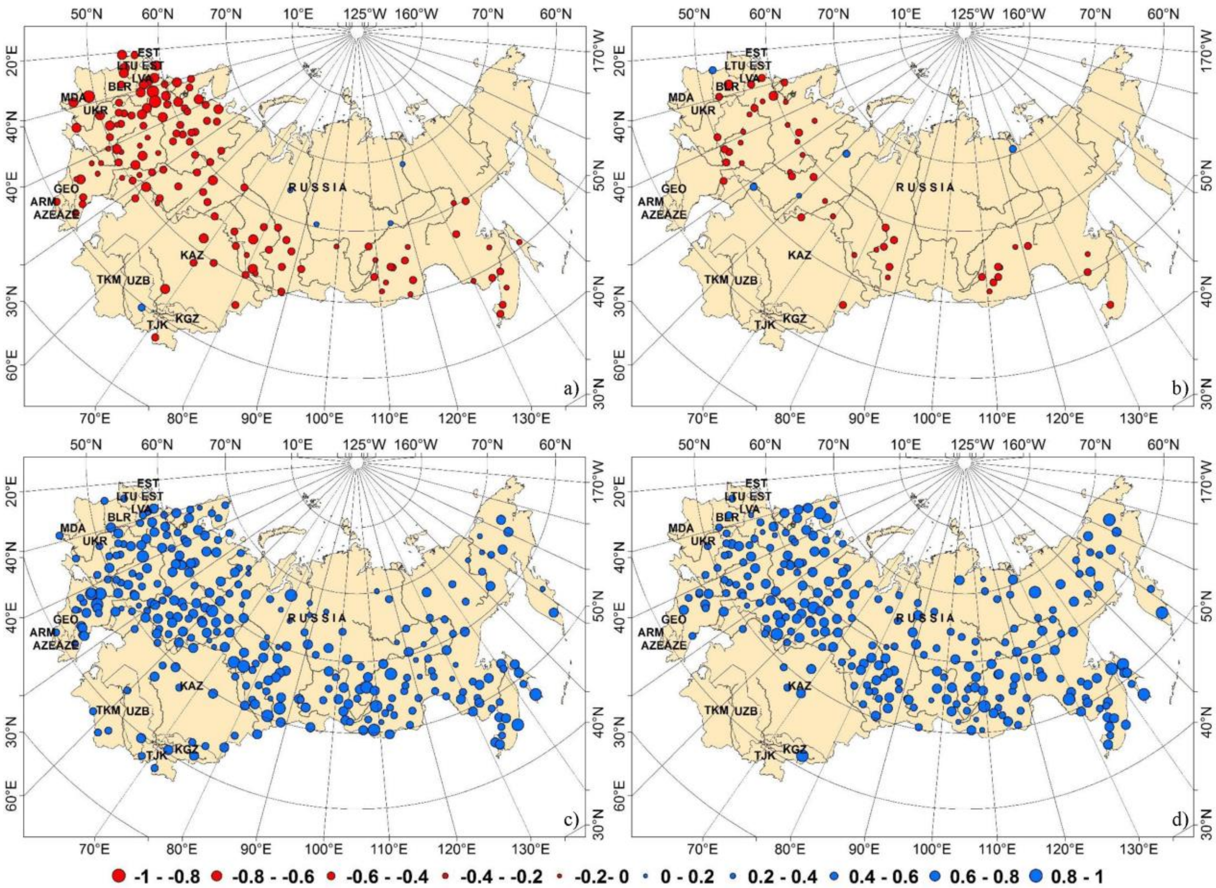


Figure 13. Spatial distributions of partial correlation coefficients of snow depth and air temperature (a), snow depth and snowfall (b), SWE and air temperature (c), SWE and snowfall from November through March during 1966-2009. The coefficients reaching to 0.05 confident level are displayed. Red circles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