

## Response to Referee #1

1. P.3: This is still a problem.

The MK test solves for the normality problem but not for serial correlation, if present. The MK test assumes independent data! If serial correlation is present (other than trend) the variance of the MK statistic will be underestimated and the probability of detecting a false trend will be increased. See Khaled and Rao, *Journal of Hydrology* 1998, for example. The authors seem unaware that serial correlation, while not affecting the trend coefficient, will decrease the degree of freedom and possibly invalidate the statistical test on the slopes if undealt with (either the T test AND the MK test). There is much literature on this topic and applying parametric or non-parametric test on time-series MUST account for serial correlation (if present).

To quote H. Von Storch:

"There are, however, again and again cases in which people simply ignore this condition, in particular when dealing with more exotic tests such as the Mann-Kendall test, which is used to reject the null hypothesis of "no trends". Von Storch and Navarra, 1999. *Analysis of Climate Variability: Chapter 2: Misuses of Statistical Analysis in Climate Research*, p.17.

I highly recommend that the authors read this chapter for guidance on how to correct for serial correlation, if necessary. I also mentioned several methodological papers on trend detection in time series in my first evaluation that have been ignored. I add another one that will be useful:

Khaliq, M. N., Ouarda, T. B. M. J., Gachon, P., Sushama, L., & St-Hilaire, A. (2009b). Identification of hydrological trends in the presence of serial and cross correlations: A review of selected methods and their application to annual flow regimes of Canadian rivers. *Journal of Hydrology*, 368(1-4),

Reply: Thank you very much for your detailed comments and concerns. We have read all recommended articles and book chapters. We have added the analysis of serial correlation as an appendix (another option is to directly add the appendix in the main text). We have used the Durbin-Watson test to check the serial correlation and the Cochran-Orcutt method to correct the variable if serial correlation is present. Then, the trends in annual mean snow depth, maximum snow depth and monthly mean snow depth for each station were recalculated in the text and corrected in the figures throughout the study.

### “Appendix A: Analysis of serial correlation

In this research, the Kolmogorov-Smirnov (K-S) test was used to determine whether snow depth data followed a normal distribution. The results showed that all station data followed a normal distribution (such as annual mean snow depth for all stations, Fig. A1). We used ordinary linear regression (OLR) to detect trends in changes

in snow depth. Failure to consider the serial correlation of data could lead to erroneous results when detecting the trends in a time series of snow depth, which is mainly because the probability of detecting false trends would be increased (Westherhead et al, 1998; Storch, 1999; Khaliq et al., 2009). To avoid this situation, we used the Durbin-Watson test to check the serial correlation (Neter et al., 1989; Tao et al., 2008):

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

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

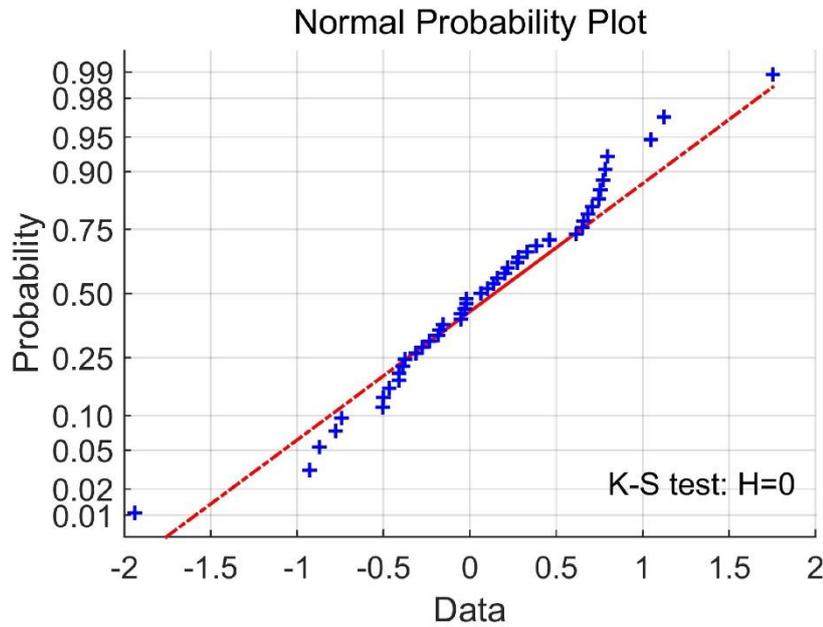


Figure A1. Normal distribution test of annual mean snow depth for all station by K-S test.

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

$$X'_t = X_t - \rho X_{t-1} \quad (A2)$$

$$Y'_t = Y_t - \rho Y_{t-1} \quad (A3)$$

where  $X'$  was the corrected year,  $Y'$  was the corrected anomalies in time series of snow depth for each station in this research, and the autocorrelation coefficient  $\rho$  was replaced by its estimated  $r$ :

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

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

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

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

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

April	1.4872	1.5739	1.6754	0.03	0.0187
May	1.4872	1.5739	2.0703	0.00	0.5811

\*: slope was the trend of changes in snow depth, the unit was cm/yr; P was the confidence level.

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

ID	$d_1$	$d_u$	$d$	$slope$	$P$	$d'_1$	$d'_u$	$d'$	$slope'^*$	$P'^*$
20674	1.4872	1.5739	1.2856	0.113	0.016	1.4872	1.5739	2.0249	0.0942	0.055

\*: slope' was the corrected trend of changes in snow depth, the unit was cm/yr; P' was the corrected confidence level.

2. P.6: That is simply not true. The trend exceed the variability, assuming this variability is independently distributed over time, and, for the t-test, normally distributed. Hence if the noise is 'white' (not serial correlation) then the statement is true, otherwise not. and this was not tested and reported in the study.

Reply: Thank you for your comments. We have used the Durbin-Watson test to check the serial correlation and the Cochrane-Orcutt method to correct the variable if serial correlation is present. The details can be found in the first reply.

3. P.12: the first reply to referee #2 for the general comments, “the same kind of instruments” which one? You could describe measurement methods in one sentence in the text. Manual measurements with a ruler on a snow plate? Automatic ultrasonic range sensors? Incoportate in the text

Reply: We have added more description of the measurement method:

“Snow depth was measured once a day at meteorological stations using a graduated stake installed at a fixed point location within the station or by a wooden ruler.”

4. P. 13: See my long comments in response to a similar comment made by Ref1.

1) If, as you say, you have found your snow depth data to be normally distributed, then this one less concern for parametric statistical testing using the T-test on the regression slope. You would not have to use a non-parametric test such as the MK test. But fine, two tests gab strengthen your conclusions

Reply: We have deleted the MK test because the snow depth data were normally distributed.

2) Both test, the parametric t-test and the non-parametric MK test, assume independent data, and you have completed ignored this comment. The MK test does not overcome the assumption of independent data, which rarely holds for time-series. At the minimum

you need to report, in the manuscript, the range of lag1 autocorrelation coefficient in order to support a claim that the data is approximately independent. I understand this is a tough issue that is often ignored in several studies, and without 'simple fixes' (see Von Storch and Navarra, 1999, p.17 for discussion, and other papers cited), but it MUST be address. Otherwise why bother applying a statistical test on the slopes?

Reply: We have added the analysis of serial correlation as an appendix. We have used the Durbin-Watson test to check the serial correlation and the Cochrane-Orcutt method to correct the variable if serial correlation is present. Then, the trends in annual mean snow depth, maximum snow depth and monthly mean snow depth for each station were recalculated in the text and corrected in the figures throughout the study.

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

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

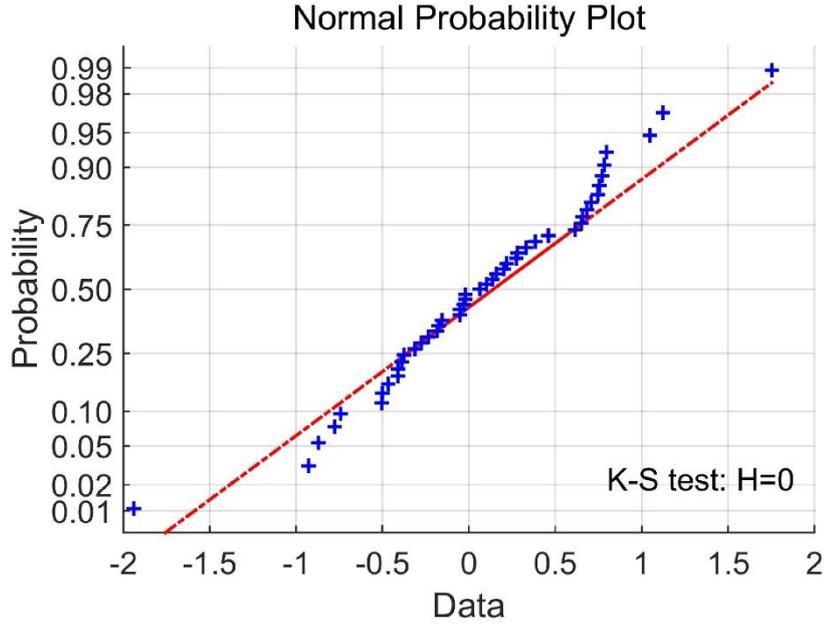


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stations for all of the stations was found in February and was up to 21%. Then, the Cochrane-Orcutt method was used to correct the variables and re-estimated the trends in snow depth for these station (Fig. 6-7 in the text). Using the Dikson site (73.5° N, 80.4° E, 42 m a.s.l.) as an example, the serial correlation was present when the trend in annual mean snow depth was calculated. Compared with the corrected result, the variance of the previous OLR statistic was overestimated, and annual mean snow depth increased at the rate of 0.113 cm/yr (Table A2). The corrected result indicated that the variation of inter-annual mean snow depth was not significant ( $P' > 0.05$ ). The serial correlation cannot be ignored for detecting trends in a time series of snow cover variables, which possibly invalidates the statistical test on slopes if this variable is not dealt with.

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May	1.4872	1.5739	2.0703	0.00	0.5811

\*: slope was the trend of changes in snow depth, the unit was cm/yr; P was the confidence level.

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

ID	$d_1$	$d_u$	$d$	$slope$	$P$	$d'_1$	$d'_u$	$d'$	$slope'^*$	$P'^*$
20674	1.4872	1.5739	1.2856	0.113	0.016	1.4872	1.5739	2.0249	0.0942	0.055

\*: slope' was the corrected trend of changes in snow depth, the unit was cm/yr; P' was the corrected confidence level.

## Response to Referee #2

### General Comments:

1. In my initial review, I commented: “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?” The authors acknowledge the shortcomings of the station distribution used in their study but do not address the point in question. Are the results based on point observations representative of the vast region under study?

Reply: For the instance, all the snow depth data in forest areas are collected just in forest, not at airport or open areas. The basic principle of site selection is as much as possible representing the surrounding environment. At the same time, the snow course data is also a supplement to the site data. 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. These snow depth data can represent the regional variability and this in-situ dataset and its coverage is unprecedented. The purpose of our research is to present the spatiotemporal variations in snow depth. Therefore, we believe that the in-situ data can be used to achieve this goal.

2. The authors provide comprehensive information on snow data collection in the former USSR, but fail to report similar information for other countries. How is snow depth measured across Eurasia? Has sampling changed to automated sensors (e.g. sonic rangefinders) in recent decades? Little information is provided on the data collection process and the accuracy of the measurements.

Reply: snow depth is measured by a graduated stake installed at the station or a wooden ruler on a daily basis, and never change the measurement method. We have added the description of snow depth collection process:

“Snow depth was measured once a day at meteorological stations using a graduated stake installed at a fixed point location within the station or by a wooden ruler. Snow depth was measured using the same method across the Eurasian continent since the meteorological observation standard was established by the former Union of Soviet Socialist Republics (USSR) and followed by all of the former USSR republics, Mongolia and China. Snow depth is one of the standard elements to be measured on a

daily basis (WMO, 1996).”

Further to this, how is homogeneity in the time series of snow depth, SWE, and other variables assured if sampling techniques or instruments have changed over time?

Reply: the procedures for taking snow observation changed in 1965, and there has been no change in procedure and techniques since then. In this study, we only chose to use the data after 1965 (1996-2012) to ensure the homogeneity of the data. We explained this in the manuscript:

“Procedures and techniques for measuring snow depth may have changed over the course of station history. Consequently, snow depth data may not be homogeneous in the time series over the period of the record. Fortunately, there was no change in the procedure and technique of snow depth measurements since 1965 in Russia and the other countries in this study (Bulygina et al., 2009). Therefore, in this study, we chose to use snow depth data from 1966 to 2012.”

Have the time series been tested for homogeneity (i.e. discontinuities in the data)?

Reply: We collected 2160 stations with snow depth data, however, we just selected 1814 stations in this study because of some stations with discontinuous data. The test had been described in the manuscript:

“We implemented additional quality control using the following requirements: (1) To ensure snow depth stability, at a given location, a month with less than 15 days of snow depth measurements was deleted; (2) Stations with sudden and steep changes in snow depth were eliminated from the list; (3) Stations with less than 20 years of data during the 1971-2000 period were excluded from the analysis; and (4) At each station, we eliminated data points that exceeded two standard deviations from their long-term (1971-2000) mean.”

Finally, no information is provided on how air temperature and precipitation measurements were made at the meteorological stations. Snowfall measurements are notoriously difficult to make and gauge undercatch correction factors must be applied to obtain improved estimates of snowfall, particularly in windy environments such as Arctic and alpine tundra. The entire section describing the observational data used in the present study must be improved and expanded. Such details may be provided in a

supplementary document as necessary.

Reply: We have added the description of the air temperature and precipitation measurement. The snowfall data are estimated with air temperature and precipitation because there was no special snowfall observation. The original precipitation data were not corrected by considering the gauge undercatch, etc.

“Daily air temperature was measured using a thermometer, which was placed at a height of 1.5 m above the ground surface in an instrument shelter at the meteorological station (WMO, 1996). The air temperature measurement should be accurate to 0.1 °C. Air temperature was measured four times a day at 0200, 0800, 1400, and 2000 local time. The daily mean air temperature was calculated by a simple arithmetic average of the four measurements, whereas the monthly mean was based on the daily mean and the annual mean was based on the monthly mean. Precipitation was gathered and measured by a precipitation gauge and was reported with a 0.1-mm precision (Groisman and Rankova, 2001). The original precipitation data were not corrected by considering the gauge undercatch.”

“Daily precipitation was partitioned into a solid and liquid fraction based on daily mean temperature (Brown, 2000). The solid fraction of precipitation,  $S_{rat}$ , was estimated by

$$S_{rat} = \begin{cases} 1.0 & \text{for } T_{mean} \leq -2.0^{\circ}C, \\ 0.0 & \text{for } T_{mean} \geq +2.0^{\circ}C, \\ 1.0 - 0.25(T_{mean} + 2.0) & \text{for } -2.0^{\circ}C < T_{mean} < +2.0^{\circ}C. \end{cases} \quad (1)$$

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

3. In response to another comment I made (as well as by Referee #2), the authors now employ the Mann-Kendall test to assess linear trends in addition to linear regressions. However, they fail to address the issue of serial correlation impacts on the trend analyses (as raised by Referee #2). This must be addressed before the paper can be considered for publication.

Reply: We have added the analysis of serial correlation as an appendix. We have used the Durbin-Watson test to check the serial correlation and the Cochrane-Orcutt method to correct the variable if serial correlation is present. Then, the trends in annual mean

snow depth, maximum snow depth and monthly mean snow depth for each station were recalculated in the text and corrected in the figures throughout the study.

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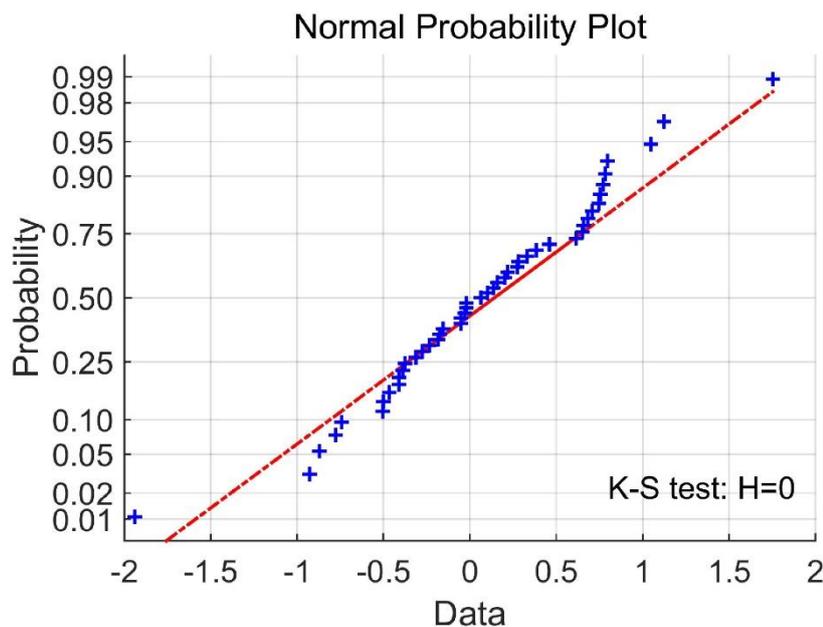


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Maximum	1.3034	1.3871	1.8824	0.06	0.0004
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\*: slope was the trend of changes in snow depth, the unit was cm/yr; P was the confidence level.

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

ID	$d_1$	$d_u$	$d$	$slope$	$P$	$d'_1$	$d'_u$	$d'$	$slope'^*$	$P'^*$
20674	1.4872	1.5739	1.2856	0.113	0.016	1.4872	1.5739	2.0249	0.0942	0.055

\*: slope' was the corrected trend of changes in snow depth, the unit was cm/yr; P' was the corrected confidence level.

4. Further to this, the (revised) Figures 5 and 7 are confusing – what results do these figures represent? The Mann-Kendall trend analysis should give you one slope value over a period of study. No details are provided in the Data/Methods section on how the results presented in these figures are obtained. Further to this, what are “UF” and “UB” in these figures?

Reply: We have found snow depth data to be normally distributed, the ordinary linear regression can be used to analyze the trend in time series. Therefore, we decide not to use the MK test (non-parametric test) again. Fig.5 and Fig.7 have been deleted.

5. In my initial review, I commented: “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?” The authors’ response does not fully address this issue, i.e. whether the slopes of the linear trends (signal) exceed the standard deviation (noise) in the snow parameters of interest.

Reply: We have analyzed the correlation between the slope of the linear trends and the standard deviation. The results present that the noise exceed the signal in many stations (Fig. 1). This is due to the variations of snow depth are effected by a variety of factors, which lead to the large interannual differences in snow depth. However, the long-term trends are not significant and slopes are not large. Then, we calculate the residuals of snow depth and analyze the “white” noise with QQplot for each station (Fig. 2). The results show residuals are the normal distribution, that is, the noise is “white”. The

analysis of serial correlation also prove the same result.

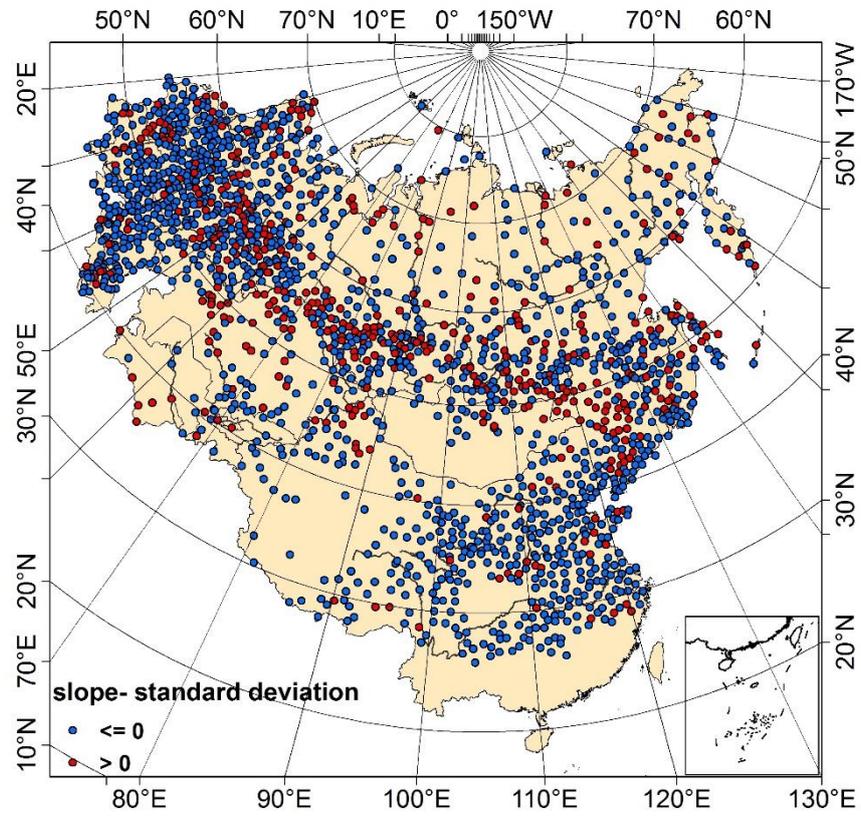


Figure. 1 The correlation between the slope of the linear trends and the standard deviation for annual mean snow depth for each station.

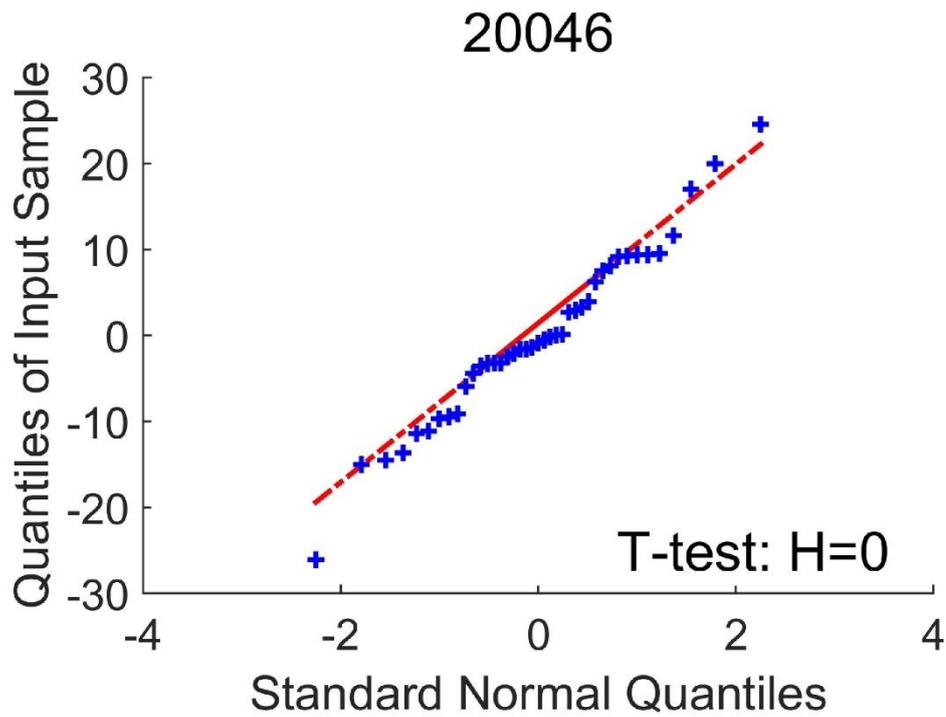


Figure.2 The "white" noise test for site 20046, which the noise exceed the signal.

6. The Discussion remains relatively brief and could be augmented by placing these results in a larger context. Do these results concord with modeling studies of snow across Eurasia? What are the prospects for future snow cover changes in Eurasia? What are the broader implications of the results to regional hydrology, permafrost distribution, ecology and society?

Reply: We have added a comparison with the results of modeling studies and modified the Discussion section. The purpose of our research is to analyze and clarify the climatology and spatiotemporal variations in snow depth across Eurasia. The prediction of the prospects for future snow cover changes should be combined with the model simulation. We hope our results can provide important reference for estimating the simulation.

#### **“4 Discussion**

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

stations locations were also critical reason for deleting many stations from the study. Based on results from this study, we believe that snow depth data in early years (prior to 1965) may be questionable and changes in snow depth prior to 1965 over Russia need further in-depth investigation.

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

The sensitivity of snow depth 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 lead to differences in snow depth at different times (Ye et al., 1998; Kitaev et al., 2005; Ma and Qin, 2012). We found that there was a significant ( $p \leq 0.05$ ) negative relationship between snow depth and air temperature in southern Siberia but not in northern Siberia. In addition to air temperature and precipitation, atmospheric circulation was a key factor affecting snow depth change (Cohen, 2011; Zhao et al., 2013; Ye et al., 2015). Those factors above and related uncertainties may explain the regional and temporal differences in long-term mean snow depth and snow depth change.

Liston and Hiemstra (2011) conducted snow depth assimilation using the SnowModel. Results from the SnowModel assimilations in general agree well with ground-based measurements. For example, both observations from this study and assimilations with the SnowModel (Liston and Hiemstra, 2011) presented that the peak snow depth and SWE occurred more in the western portion of northern Eurasia than the western portion of the Russian Far East. This may be primarily because the SnowModel input data included ground-based measured air temperature, precipitation, wind conditions and in part snow depth. However, results from CMIP5 (Coupled Model Intercomparison Project, Terzago et al., 2014, Wei and Dong, 2015) overestimated snow depth over the Qinghai-Tibetan Plateau and underestimated in the forest regions.

This implies that large uncertainties currently still exist in modeling snow depth.

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

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

7. The names of countries or their abbreviations can be removed on all figures after Figure 1.

Reply: All names and abbreviations are removed after Fig. 1.

8. Please improve the language throughout the paper – there are portions of the text that are difficult to comprehend due to language issues, including all of Section 4.2. Furthermore, the verb tense in the introduction changes constantly and only one tense should be used consistently.

Reply: We have the manuscript proofread and revised by the professional English editing service from American Journal Experts.

**Specific Comments:**

1. P. 3, line 13: Replace “reduced” with “declined”.

Reply: Has been done.

2. P. 3, lines 15-18: The grammar in this sentence is poor – please rephrase.

Reply: We have rephrased the sentence:

“This may be explained in that the warmer air led to a greater moisture supply for snowfall in winter (Ye et al., 1998; Kitaev et al., 2005; Rawlins et al., 2010).”

3. P. 3, line 27: Replace “was” with “were”.

Reply: Replaced “but there was” with “and showed large”.

4. P. 4, line 20: What aspect of “passive microwave” improved the algorithms?

Reply: We have rephrased the sentence:

“...or developed and/or improved passive microwave snow algorithms”

5. P. 4, line 25-27: Language needs much improvement here.

Reply: We have rephrased the sentence:

“In addition, data acquisition from large airborne equipment or aerial systems is costly

and strict data use limitations apply.”

6. P. 4, line 29: Delete the hyphen after “longer”. Insert “the” before “climatology”.

Reply: Has been done.

7. P. 5, line 26: Do you mean “and during the snowmelt period (every five days)”?

Reply: Yes, We have revised it.

8. P. 6, line 7: Delete “the following Equation (1)”

Reply: Has been done.

9. P. 6, lines 25-27: Rephrase this sentence.

Reply: we have rephrased the sentence:

“We defined a snow year starting from July 1<sup>st</sup> through June 30<sup>th</sup> of the following year to capture the entire seasonal snow cycle.”

10. P. 6, line 28: Change to “study period”.

Reply: Has been changed.

11. P. 7, line 14: Replace the colon after “2012” with a period.

Reply: we deleted the sentence.

12. P. 7, lines 23-27: These sentences need to be rephrased.

Reply: we have rephrased the sentence:

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

13. P. 8, line 8: What do you mean with “Despite there is a nonlinearity”.

Reply: we have rephrased the sentence:

“The linear trend analysis is also a useful approximation when systematic low-frequency variations emerged even though there is a nonlinearity.”

14. P. 8, line 9: Delete “a” before “systematic”.

Reply: Has been done.

15. P. 8, line 19: Delete “In order”.

Reply: Has been deleted.

16. P. 8, line 20: Insert “a” before “single”.

Reply: Deleted the sentences.

17. P. 8, lines 27-29: Rephrase this sentence. Insert a space after “(Fig. 2)”.

Reply: we have rephrased the sentence:

“Distributions of long-term mean snow depth indicated a strong latitudinal zonality. Generally, snow depth increased with latitude northward across the Eurasian continent (Fig. 2).”

18. P. 11, line 2: What do you mean by “fluctuating changed”?

Reply: “fluctuating changed” means the changes in snow depth increased in some years, while decreased in the next period, alternating with each period.

19. P. 11, line 6 and elsewhere: Replace “confident level” with “confidence level”.

Reply: Has been done.

20. P. 12, line 5: What do you mean by “fluctuant increasing trend”?

Reply: “fluctuant increasing trend” means there was a generally increasing trend in snow depth, but the changes in snow depth increased in some years, while decreased in the next period, alternating with each period.

21. P. 12, line 10 and elsewhere: Replace “confident level” with “confidence level”.

Reply: Has been done.

22. P. 12, line 30 and elsewhere: Delete spaces between the degree sign and North, i.e. “40°N”.

Reply: Has been deleted.

23. P. 13, line 5: Replace “Eurasian areas” with “Eurasia”.

Reply: Has been done.

24. P. 14, lines 12-13: Language must be improved here.

Reply: we have deleted the sentence.

25. P. 14, line 25: Insert the p-value for the correlation coefficient.

Reply: We have inserted “ $P \leq 0.05$ ,”

26. P. 15, line 9: Change to “at most”.

Reply: Has been done.

27. P. 15, line 22: Replace “lowed” with “lowered”.

Reply: Has been done.

28. P. 16, line 2: Delete “the” before “northern”.

Reply: Has been deleted.

29. P. 16, lines 3-5: This sentence must be re-written.

Reply: we have rephrased the sentence:

“This was because there was no obvious effect of increasing temperature on snow depth when the air temperature was below 0 °C which occurred in most areas of Siberia from December through March.”

30. P. 17, line 12: Delete “the” before “southern”.

Reply: Has been deleted.

31. P. 17, line 16: This entire section is poorly phrased and needs to be completely

revised. Why does the font size change in the middle of the paragraph?

Reply: We have deleted the section and added the statement in “3.3 Variability of Snow Depth with Latitude, Elevation and Continentality” section:

“Topography is an important factor affecting the climatology of snow depth and is the main reason accounting for the inhomogeneity of data (Grünewald and Lehning, 2011, 2013; Grünewald et al., 2014). To explore the spatial variability of snow depth, we conducted a linear regression analysis of the annual mean snow depth with latitude, elevation and continentality (Fig. 8). Snow depth was positively correlated with latitude, i.e., snow depth generally increased with latitude (Fig. 8a). The increased rate of snow depth was approximately 0.81 cm per 1 °N across the Eurasian continent. A closer relationship between latitude and snow depth was found in regions north of 40 °N (Figs. 8a and d) where snow cover was relatively stable with the number of annual mean continuous snow cover days at more than 30 (Zhang and Zhong, 2014).

There was a negative correlation between snow depth and elevation across the Eurasian continent (Fig. 8b); with every 100 m increase in elevation, snow depth decreased by ~0.5 cm ( $P \leq 0.05$ ). 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 a high elevation, the shallow snow depth in this area resulted in a generally negative correlation between snow depth and elevation across the Eurasian continent. However, we also found that snow depth increased with elevation in most regions north of 45 °N (Fig. 8d).

There was a statistically significant positive relationship between snow depth and continentality over the Eurasian continent ( $r=0.1$ ,  $P \leq 0.05$ , Fig. 8c). This indicated that the continentality may be not an important driving factor of snow depth distribution over Eurasia, especially on the TP. Although the previous studies showed that the Tibetan Plateau’s largest snow accumulation occurred in the winter, the precipitation during the winter months was the smallest of the year (Ma, 2008). This

was mainly due to the majority of annual precipitation that occurs during the summer monsoon season on the TP, which causes much less precipitation during the winter half year (or the snow accumulated season). ”

32. P. 18, line 18: Replace “increase” with “increasing”.

Reply: Has been done.

33. P. 18, line 25: Delete “the” before “southern”.

Reply: Has been deleted.

34. P. 20, line 16: Note spelling mistake in “Atmos.”

Reply: Has been revised.

35. P. 20, lines 27-28: Why are editors of a special journal issue listed here?

Reply: Has been revised.

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

36. P. 21, line 18: Is this “Hydrol. Sci. J.”?

Reply: Yes, We have revised it.

37. P. 21, lines 22-23: Why are upper case letters provided for each word in the title of this article?

Reply: Has been revised.

“Foster, J.L., Chang, A.T.C., and Hall, D.K.: Comparison of snow mass estimates from a prototype passive microwave snow algorithm, *Remote Sens. Environ.*, 62, 132-142, 1997.”

38. P. 22, line 19: Insert a hyphen in “Snow atmosphere”.

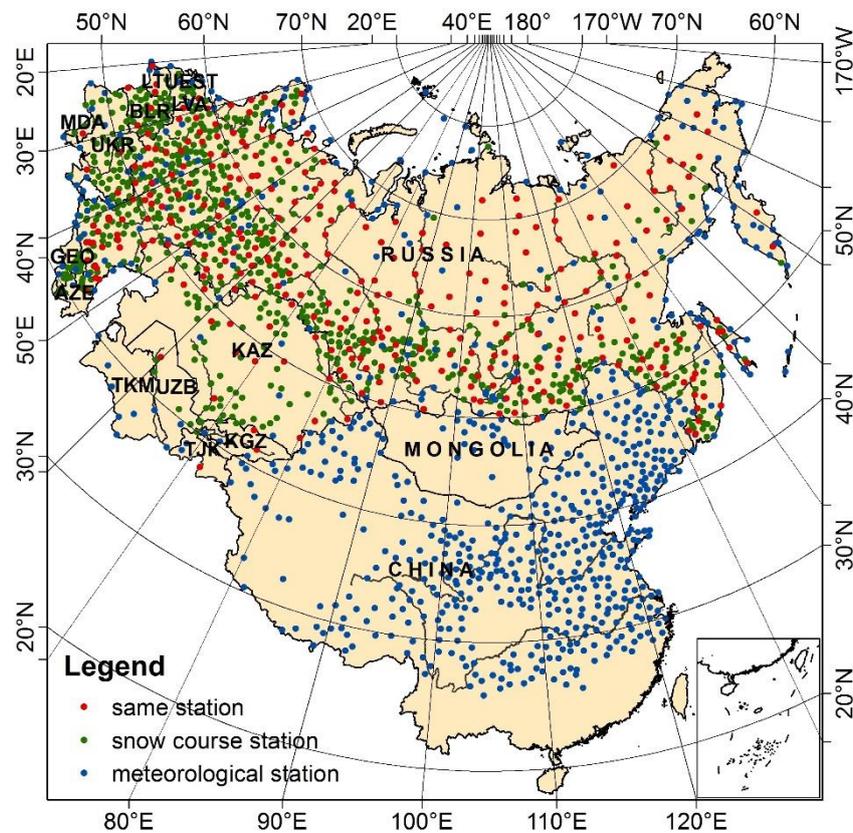
Reply: Has been done.

39. P. 25, Table 1: Change to “snow courses”

Reply: Has been done.

40. P. 26, Figure 1: Why does the orientation of the triangles change across the figure? The top of the triangle should point directly northward to provide a consistent pattern across the figure.

Reply: The figure was drawn by ArcGIS, and the projection coordinate was used. Therefore, it seemed the top of triangle did not point directly northward. We have replaced triangle with circle.



41. P. 27, Figure 2 and subsequent figures: Delete all country names/abbreviations on the maps providing spatial results as this can be found on Figure 1.

Reply: Has been done.

42. P. 30, Figure 4: It is unclear why the authors use wavelets to extract low frequency in the time series of snow depth anomalies. Why not just use a running mean of the data?

Reply: running mean is the average statistics of the data, then simulated the trends in snow depth on the basis of average. This method will result in the missing information

of the former and later years.

43. P. 31, Figure 5: The results presented in this figure and in Figure 7 are difficult to interpret as details on what is being shown are not provided. Linear trends inferred from the Mann-Kendall test should yield only one slope value for a period of record, so it is unclear what the time series in Figures 5 and 7 denote. What do the two lines “UF” and “UB” represent, the figure caption does not state what these are.

Reply: We have found snow depth data to be normally distributed, the ordinary linear regression can be used to analyze the trend in time series. Therefore, we decide not to use the MK test (non-parametric test) again. Fig.5 and Fig.7 have been deleted.

## List of all relevant changes

- (1) P1, L.4: deleted “4” in superscript of the first author; replaced “6” with “4” in superscript of the third author; inserted a new author “Kang Wang<sup>5</sup>” as the fourth author; replaced “5” with “6” in superscript of the fourth author.
- (2) P1, L.6: inserted “Key Laboratory of Remote Sensing of Gansu Province,” before “Cold”.
- (3) P1, L.12: replace the fourth affiliation with the sixth affiliation.
- (4) P1, L.13: inserted a new affiliation “<sup>5</sup> Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, Colorado, 80309, USA”
- (5) P1, L.13: replaced “5” with “6” in superscript of the fifth affiliation.
- (6) P1, L.14: deleted the sixth affiliation.
- (7) P1, L.19: deleted “the”.
- (8) P1, L.20: deleted “regional-and continental-scale”.
- (9) P1, L.21: inserted “from local community to regional industrial water supply” after “resources”; inserted new sentences “Data and knowledge on snow in general and snow depth/snow water equivalent in particular are prerequisites for climate change studies and local/regional development planning. Past studies by using in-situ data are mostly site-specific, while data from satellite remote sensing may cover a large area or in global scale, uncertainties are huge, evening misleading.” before “In this study,”; deleted “a snow depth climatology and its”; replaced “variations were” with “change and variability in snow depth was”.
- (10)P1, L.22: deleted “the”.
- (11)P1, L.24: replaced “northeastern” with “north-eastern”.
- (12)P1, L.25: replaced “during 1966-2012” with “from 1966 through 2012”.
- (13)P1, L.26-27: deleted the comma; replaced “that period of time” with “the study period”.
- (14)P1, L.27: deleted “the”; deleted the space between the degree sign and North.
- (15)P2, L.1: replaced “provides” with “provided”.

- (16)P2, L.2: replaced “changes in snow depth” with “snow depth climatology and changes”; replaced “are” with “were”.
- (17)P3, L.3: inserted “, including snow depth and snow area extent,” after “cover”; inserted “an” after “as”; replaced “indicators” with “indicator”.
- (18)P3, L.3: replaced “circulation” with “circulations”.
- (19)P3, L.4: replaced “its” with “their”.
- (20)P3, L.10-13: replaced the sentence with “Changes in snow depth could have dramatic impacts on weather and climate through surface energy balance (Sturm et al., 2001), soil temperature and frozen ground (Zhang, 2005), spring runoff, water supply, and human activity (AMAP, 2011).”
- (21)P3, L.13: inserted “the” after “Although”; replaced “reduced” with “declined”.
- (22)P3, L.14: replaced “still increased” with “showed an increasing trend”; deleted “the”.
- (23)P3, L.15-18: replaced the sentence by “This may be explained in that the warmer air led to a greater moisture supply for snowfall in winter (Ye et al., 1998; Kitaev et al., 2005; Rawlins et al., 2010).”
- (24)P3, L.20: replaced “promoted” with “promotes”.
- (25)P3, L.20: inserted “local and regional” after “increased”.
- (26)P3, L.21: replaced “in-situ” with “in situ”.
- (27)P3, L.22: deleted “data”.
- (28)P3, L.23: deleted the comma; replaced “demonstrating” with “and demonstrated”; replaced “varies regionally:” with “varied differently over different regions.”; deleted “overall, the”
- (29)P3, L.24: replaced “annual” with “Annual”.
- (30)P3, L.25: deleted the comma before “and”.
- (31)P3, L.26: replaced “recent” with “last”.
- (32)P3, L.27: replaced “but there was” with “and showed large”.
- (33)P4, L.1: replaced “thus” with “and thus,”.
- (34)P4, L.2: inserted “the” before “snow”.
- (35)P4, L.3: replaced “are” with “were”; deleted “also”.

- (36)P4, L.5: replaced “is” with “was”.
- (37)P4, L.6: deleted “also”; replaced “other large” with “synoptic”; deleted the comma.
- (38)P4, L.7: deleted the space after “Oscillation”; deleted “indices”.
- (39)P4, L.8: deleted the first “the”.
- (40)P4, L.10: replaced “is” with “was”.
- (41)P4, L.11: inserted “of Russia” after “Plain”; deleted “during the period”.
- (42)P4, L.12: deleted “the”; replaced “is” with “was”.
- (43)P4, L.13: replaced “indicated” with “demonstrated”; replaced “is” with “was”.
- (44)P4, L.14: inserted “between snow depth and” before “Ni ño-3”.
- (45)P4, L.15: replaced “in” with “on”.
- (46)P4, L.20: deleted “have”; inserted “/or” after “and”; deleted “the algorithms with”, inserted “snow algorithms” after “microwave”.
- (47)P4, L.21-22: replaces “these observations” with “snow depth and snow water equivalent obtained by satellite remote sensing”.
- (48)P4, L.22: replaced “can” with “could”; deleted “the”; replaced “in-situ” with “the in situ”.
- (49)P4, L.23: replaced “the satellite data” with “they”; inserted a comma after “(25×25)”.
- (50)P4, L.24: replaced “inversion” with “perfect”; replaced the semicolon with the period; inserted the sentences “Using ground-based snow depth measurements across the Eurasian continent against snow depth obtained from passive microwave satellite remote sensing, Zheng et al. (2015) found that the mean percentage error was greater than 50% and can be up to approximately 200%. Utilization of snow depth obtained from satellite remote sensing has large uncertainties and is impractical.” before “in”; replaced “in” with “In”.
- (51)P4, L.25: deleted “the”.
- (52)P4, L.26: deleted “always”.
- (53)P4, L.26-27: replaced “some of them need to obtain official permission before using in some countries” with “strict data use limitations apply”.

- (54)P4, L.27-30: replaced the sentence with “Ground-based measurements provide currently available and accurate snow depth over long time-series, which are critical data and information for investigating snow depth climatology and variability.”
- (55)P5, L.1: replaced “nearly” with “approximately”.
- (56)P5, L.2: inserted “the” after “over”; replaced “lands” with “land surfaces”.
- (57)P5, L.4-5: deleted “and large-scale” and “cover”, deleted the comma.
- (58)P5, L.6: replaced “cover” with “depth”.
- (59)P5, L.8-11: replaced the sentence with “Many studies on snow depth have focused on local and regional-scales over Russia (Ye et al., 1998; Kitaev et al., 2005; Bulygina et al., 2009, 2011; Brasnett, 1999) and on the TP (Li and Mi, 1983; Ma and Qin, 2012).”; deleted “However, due to the lack of data and information,”
- (60)P5, L.13: replaced “is” with “was”.
- (61)P5, L.14: deleted “the”; deleted “, and analyze snow depth relationships with the topography and climate factors”.
- (62)P5, L.16: inserted a sentence “In addition, we analysed the spatial and temporal changes in snow depth with topography and climate factors over the study area.” After “2012.”
- (63)P5, L.16-17: deleted the sentence “This study can provide basic information on climate system changes in the region.”; deleted the comma.
- (64)P5, L.21: inserted a sentence “The data used in this study include daily snow depth, snow water equivalent (SWE), air temperature and precipitation.” before the first sentence.
- (65)P5, L.22-23: deleted the sentence “Snow depth was measured at these stations on a daily basis”, inserted the sentences “Snow depth was measured once a day at meteorological stations using a graduated stake installed at a fixed point location within the station or by a wooden ruler. Snow depth was measured using the same method across the Eurasian continent since the meteorological observation standard was established by the former USSR and followed by all of the former

USSR republics, Mongolia and China. Snow depth is one of the standard elements measured on a daily basis (WMO, 1996).” before “Historical”.

(66)P5, L.26: inserted “the” before “during”; moved “period” to the back of “snowmelt”.

(67)P5, L.28: deleted the comma.

(68)P5, L.30: replaced the first sentence with “SWE is an important parameter that is often used in water resource evaluation and hydroclimate studies.”

(69)P6, L.1-3: deleted the sentence.

(70)P6, L.4: inserted “using a snow tube” after “measured”.

(71)P6, L.5: inserted the sentences “Daily air temperature was measured using a thermometer, which was placed at a height of 1.5 m above the ground surface in an instrument shelter at the meteorological station (WMO, 1996). The air temperature measurement should be accurate to 0.1 °C. Air temperature was measured four times a day at 0200, 0800, 1400, and 2000 local time. The daily mean air temperature was calculated by a simple arithmetic average of the four measurements, whereas the monthly mean was based on the daily mean and the annual mean was based on the monthly mean. Precipitation was gathered and measured by a precipitation gauge and was reported with a 0.1-mm precision (Groisman and Rankova, 2001). The original precipitation data were not corrected by considering the gauge undercatch.” before “Daily” as a new paragraph.

(72)P6, L.6: deleted the comma.

(73)P6, L.7: deleted “the following Equation (1):”.

(74)P6, L.13: inserted “a” before “quality”; deleted “the”.

(75)P6, L.14: inserted “automatically” after “was”.

(76)P6, L.14: inserted “and the National Meteorological Information Center (NMIC) of China Meteorological Administration (Ma and Qin, 2012)” after “(Veselov, 2002)”.

(77)P6, L.16-24: replaced the sentences with “We implemented additional quality control using the following requirements: (1) To ensure snow depth stability, at a

given location, a month with less than 15 days of snow depth measurements was deleted; (2) Stations with sudden and steep changes in snow depth were eliminated from the list; (3) Stations with less than 20 years of data during the 1971-2000 period were excluded from the analysis; and (4) At each station, we eliminated data points that exceeded two standard deviations from their long-term (1971-2000) mean. After these four steps of snow depth quality control, we used data from 1814 stations to investigate the climatology and variability of snow depth over the Eurasian continent (Fig. 1 and Table 1).”

(78)P6, L.25-27: replaced the sentence with “We defined a snow year starting from July 1<sup>st</sup> through June 30<sup>th</sup> of the following year to capture the entire seasonal snow cycle.”

(79)P6, L.27-P7, L3: replaced the sentences with “Procedures and techniques for measuring snow depth may have changed over the course of station history. Consequently, snow depth data may not be homogeneous in the time series over the period of the record. Fortunately, there was no change in the procedure and technique of snow depth measurements since 1965 in Russia and the other countries in this study (Bulygina et al., 2009). Therefore, in this study, we chose to use snow depth data from 1966 to 2012.”

(80)P7, L5: replaced “In” with “in”.

(81)P7, L6: replaced “way” with “method”.

(82)P7, L7: replaced “in regular” with “based on”; inserted “the” before “World”.

(83)P7, L10: replaced “the” with “an”.

(84)P7, L11: replaced the period with the semicolon.

(85)P7, L.12-14: deleted the sentence.

(86)P7, L15: replaced the two “the” with “an”.

(87)P7, L.17-18: replaced “from the annual snow depth for  $\geq 20$ ” with “for stations with more than 20”; inserted “the” after “during”; inserted “period” after “1966-2012”; replaced the period with the semicolon.

(88)P7, L19: replaced “the” with “an”.

(89)P7, L21: replaced “values” with “value”, inserted “the” before “annual”; deleted

the second “the”.

(90)P7, L22: replaced “ $\geq 20$ ” with “more than 20”; inserted “the” after “during”; inserted “period” after “1966-2012”; replaced the period with the semicolon.

(91)P7, L.23-30: replaced the paragraph with “Anomalies of monthly, annual mean, and annual mean maximum snow depth from their long-term (1971-2000) records were calculated for each station across the Eurasian continent. Composite time series of monthly and annual anomalies were obtained by using all of the available station data across the study area.”

(92)P8, L.2: replaced “of” with “in”; inserted “entire” before “study”; deleted “as a whole”.

(93)P8, L.7: replaced “happened” with “occurred”; inserted “A” before “linear”.

(94)P8, L.8: deleted “Despite there is a nonlinearity,”

(95)P8, L.9: deleted “a” after “when”; replaced “emerged” with “emerge”; inserted “even though there is a nonlinearity” after “emerge”, deleted the period.

(96)P8, L.11: replaced “The Student T test” with “The Student’s t-test”.

(97)P8, L.12: deleted the first “the”; replaced “significant” with “significance”.

(98)P8, L.13: replaced the second “the” with “a”.

(99)P8, L.14: inserted “significant” after “considered”; inserted the sentences “The Durbin-Watson test was used to detect serial correlation of data in the time series, and the Cochrane-Orcutt test was used to correct the serial correlation. Then, the serial correlations of the new data were rechecked and recalculated trends in the time series of the new data. The methods and test results were described in the appendix.” after “in our study.”

(100) P8, L.14-23: deleted the sentences.

(101) P8, L.27-29: replaced the sentence with “Distributions of long-term mean snow depth indicated a strong latitudinal zonality. Generally, snow depth increased with latitude northward across the Eurasian continent (Fig. 2).”; inserted a space before “A”.

(102) P8, L.30: deleted “in the”.

(103) P9, L.1: deleted “of the”.

- (104) P9, L.2: inserted “the” after “of”; replaced “gray” with “grey”.
- (105) P9, L.3: replaced “Depths” with “Snow depths”.
- (106) P9, L.4: replaced “northeastern” with “north-eastern”.
- (107) P9, L.5: deleted the second comma; replaced “The regions” with “Regions”.
- (108) P9, L.10: deleted the comma.
- (109) P9, L.11: replaced “north” with “northern part”.
- (110) P9, L.12: inserted the comma after “China”.
- (111) P9, L.13: replaced “northeastern” with “north-eastern”.
- (112) P9, L.15-16: replaced the sentence with “Annual mean maximum snow depth (Fig. 2b) showed a similar spatial distribution pattern compared to the annual mean snow depth pattern.”
- (113) P9, L.17-18: replaced the sentence with “The maximum value was approximately 201.8 cm in snow depth.”
- (114) P9, L.19: deleted “the”.
- (115) P9, L.20: deleted “located”; replaced “northeastern” with “north-eastern”.
- (116) P9, L.24: inserted “the” after “of”.
- (117) P9, L.25: deleted the comma; inserted “decreased to” before “6-10”; replaced “in the” with “when moving south to”; replaced “parts of the country” with “Mongolia”.
- (118) P9, L.26-29: replaced the sentences with “Maximum snow depths were higher over the northern part of the Xinjiang Autonomous Region of China, Northeast China, and eastern and southwestern TP, were mostly greater than 10 cm and even greater than 20 cm in some areas. For the remaining regions of China, the maximum snow depths were relatively small and mostly less than 10 cm.”
- (119) P9, L.30- P10, L.3: deleted the paragraph.
- (120) P10, L.6: deleted “the” and the comma.
- (121) P10, L.7: inserted “Moving southward,” before “monthly”; replaced “Monthly” with “the monthly”.
- (122) P10, L.8: deleted “in the”; deleted “most regions”.

- (123) P10, L.9: replaced “areas covered by snow” with “snow cover extent”.
- (124) P10, L.10: replaced “Most monthly” with “Monthly”.
- (125) P10, L.11: replaced “in most regions” with “for the majority”.
- (126) P10, L.12-13: replaced with “except the northern Xinjiang Autonomous Region of China, Northeast China, and south-western TP where snow depth exceeded 10 cm.”
- (127) P10, L.14-15: replaced the sentence with “In spring (March through May), snow cover areas decreased significantly (Figs. 3g–i), which was mainly because of snow disappearance in the majority of China.”
- (128) P10, L.18: inserted “in” before “the”.
- (129) P10, L.21: inserted “both” after “in”; deleted “the”; inserted “snow depth” after “mean”.
- (130) P10, L.22: inserted the period after “continent”; deleted “as a whole with”.
- (131) P10, L.23-24: replaced the sentence with “Mean annual snow depth increased at a rate of approximately 0.2 cm decade<sup>-1</sup>, whereas annual mean maximum snow depth increased at a rate of approximately 0.6 cm decade<sup>-1</sup> (Fig. 4).”
- (132) P10, L.26: deleted “the”; replaced “about” with “approximately”.
- (133) P10, L.27: replaced “about” with “approximately”.
- (134) P10, L.28: deleted the first “the”; deleted the second comma; deleted “it”.
- (135) P10, L.29: deleted the comma.
- (136) P11, L.1: replaced “3.5” with “approximately 3 to 4”.
- (137) P11, L.1-2: deleted the comma; replaced with “and then there was a large fluctuation without a significant trend from the late 1970s to the early 1990s.”
- (138) P11, L.4-13: deleted the paragraph.
- (139) P11, L.14- P12, L.7: replaced the paragraphs with “Monthly snow depth changed significantly across the Eurasian continent from 1966 through 2012 (Fig. 5). Snow depth decreased in October at a rate of approximately -0.1 cm decade<sup>-1</sup> (Fig. 5a), and there were no significant trends in November and December with large inter-annual variations (Fig. 5b-c). From January through April, snow depth showed statistically increased trends with rates between 0.3 cm decade<sup>-1</sup> and 0.6

cm decade<sup>-1</sup> (Fig. 5d-g). Overall, snow depth decreased or there was no change in autumn and increased in winter and spring with large inter-annual variations over the study period.”

- (140) P12, L.8-22: deleted the paragraph.
- (141) P12, L.23: replaced “Figure 8” with “Figure 6”.
- (142) P12, L.24: deleted the comma.
- (143) P12, L.26: deleted “most of” and the first “the”.
- (144) P12, L.27: replaced “Fig. 8a” with “Fig. 6a”.
- (145) P12, L.29: deleted the first “the”; inserted “the” before “Russian”.
- (146) P12, L.30: replaced “across” with “in”.
- (147) P12, L.30 and P13, L1: deleted the space between the degree sign and North, replaced “the region” with “regions”.
- (148) P13, L.2: replaced “indicating” with “which indicated”.
- (149) P13, L.4: deleted “the”.
- (150) P13, L.5: replaced “Eurasian areas” with “Eurasia”; replaced “but the change rates of the maximum snow depth” with “but the magnitude of changing rates in the maximum snow depth”.
- (151) P13, L.7: replaced “8b” with “6b”; replaced “The significant” with “Significant”.
- (152) P13, L.8-10: replaced the sentence with “Generally, the decreasing trends were found in the same regions where annual mean snow depth decreased and there were greater reductions in southern Siberia and the Far East.”
- (153) P13, L.11: replaced “changes” with “increasing trends”; replaced “at the 95 % level” with “ $P \leq 0.05$ ”.
- (154) P13, L.12: replaced “Figs. 9a, b” with “Fig. 7a and b”.
- (155) P13, L.13: inserted “although the magnitudes were generally small” after “October”.
- (156) P13, L.13-17: replaced the sentences with “Over November, the increasing trends in snow depth only appeared in Siberia and the Russian Far East, whereas decreasing trends occurred in monthly mean snow depth over eastern European

Russia, the southern West Siberian Plain, and the northeast Russian Far East.”

- (157) P13, L.18-24: replaced the paragraph with “In winter months (December-February), there was a gradual expansion in areas with increasing trends in monthly mean snow depth variation with  $P \leq 0.05$  (Figs. 7c–e), and this mainly occurred in eastern European Russia, southern Siberia, the northern Xinjiang Autonomous Region of China, and Northeast China. In contrast, significant decreasing trends were observed in northern and western European Russia and were scattered in Siberia, the northeast Russian Far East, and northern China.”
- (158) P13, L.25-26: replaced “at the 95 % level” with “ $P \leq 0.05$ ”.
- (159) P13, L.27: replaced “Figs. 9f-h” with “Figs. 7f-h”.
- (160) P13, L.28: inserted the comma after “USSR”.
- (161) P13, L.30: replaced “of” with “in”; inserted “stations” after “these”.
- (162) P14, L.1: replaced “in” with “at”.
- (163) P14, L.1-2: replaced the sentence with “Compared with regions south of 50 °N, changes in monthly mean snow depth were more significant over regions north of 50 °N.”
- (164) P14, L.5: inserted the sentence “Topography is an important factor affecting the climatology of snow depth and is the main reason accounting for the inhomogeneity of data (Grünwald and Lehning, 2011, 2013; Grünwald et al., 2014).” before the first sentence.
- (165) P14, L.6: inserted “the” before “annual”.
- (166) P14, L.7: replaced “10” with “8”; replaced “is” with “was”.
- (167) P14, L.8: replaced “increases” with “increased”; replaced “10a” with “8a”; replaced “increase” with “increased”; replaced “about” with “approximately”.
- (168) P14, L.9: deleted the space between the degree sign and North; inserted “across the Eurasian continent” after “1 °N”.
- (169) P14, L.9-13: replaced the sentences with “A closer relationship between latitude and snow depth was found in regions north of 40 °N (Figs. 8a and d) where snow cover was relatively stable with the number of annual mean

continuous snow cover days at more than 30 (Zhang and Zhong, 2014).”

- (170) P14, L.15: replaced “(Fig. 10b)” with “(Fig. 8b);”.
- (171) P14, L.17: deleted the second comma.
- (172) P14, L.18: inserted “a” after “at”.
- (173) P14, L.19: replaced “the” with “a”.
- (174) P14, L.20: replaced “determined” with “found”.
- (175) P14, L.21: deleted the space between the degree sign and North, replaced “10d” with “8d”.
- (176) P14, L.22-23: deleted the sentence.
- (177) P14, L.24: inserted “statistically” before “significant”.
- (178) P14, L.25: inserted “over the Eurasian continent” after “continentality”; inserted “ $P \leq 0.05$ ,” before “Fig.”, replaced “10c” with “8c”.
- (179) P14, L.26: replaced “is” with “may be”.
- (180) P14, L.26-27: replaced “snow cover climatology” with “snow depth distribution”.
- (181) P14, L.27: inserted “especially on the TP” after “Eurasia”, deleted “though it will determine the snowfall rate”, and inserted the sentences “Although the previous studies showed that the Tibetan Plateau’s largest snow accumulation occurred in the winter, the precipitation during the winter months was the smallest of the year (Ma, 2008). This was mainly due to the majority of annual precipitation that occurs during the summer monsoon season on the TP, which causes much less precipitation during the winter half year (or the snow accumulated season).” after the last sentence.
- (182) P15, L.3: inserted “former” before “USSR”; replaced “Fig. 11” with “Fig. 9”.
- (183) P15, L.3-5: replaced the sentence with “The period (snow cover years) spanned from 1966 through 2009 using available data.”
- (184) P15, L.6: deleted the comma.
- (185) P15, L.7: replaced “11a” with “9a”, deleted “the”.
- (186) P15, L.8: replaced “better” with “strong”; replaced “11b” with “9b”.
- (187) P15, L.9: replaced “in” with “at”; replaced “the” with “an”; replaced “being”

with “of”.

- (188) P15, L.10-11: replaced sentence with “Snow depth increased with an increase in accumulated snowfall, and the thickest snow depth of approximately 120 cm had a maximum cumulative snowfall of approximately 350 mm.”
- (189) P15, L.12: replaced “Comparing” with “Compared with”; replaced “of changes” with “in change”.
- (190) P15, L.13: replaced “variability of” with “variabilities in”.
- (191) P15, L.16: replaced “Fig. 12” with “Fig. 10”.
- (192) P15, L.18: inserted “a” after “to”; replaced the comma with “and”.
- (193) P15, L.19: replaced “The significant” with “Significant”.
- (194) P15, L.20: deleted the second “the”.
- (195) P15, L.22: replaced “lowed” with “lowered”; replaced “whole” with “entire”; inserted “the” before “snowpack”.
- (196) P15, L.23: replaced “of” with “in”
- (197) P15, L.24: replaced “12b-d” with “10b-d”.
- (198) P15, L.26: deleted “the”.
- (199) P15, L.27: deleted the comma; replaced “as well as” with “and”.
- (200) P15, L.29: replaced “Fig. 13” with “Fig. 11”; replaced “The” with “A”.
- (201) P15, L.30: replaced “presented” with “was present”; deleted “the”.
- (202) P16, L.1: replaced “13a” with “11a”.
- (203) P16, L.2: replaced “correlation” with “correlations”; deleted “the”.
- (204) P16, L.3: replaced “13b” with “11b”; replaced “It” with “This”; inserted “there was no obvious effect of increasing temperature on snow depth when” after “because”; inserted “which occurred” after “0 °C”.
- (205) P16, L.4-5: replaced “during” with “from”; deleted “, the increasing temperature did not have an obvious effect on snow depth”.
- (206) P16, L.9: deleted the first two “the”; inserted “and” before the third “the”.
- (207) P16, L.11: inserted “the” after “and”.
- (208) P16, L.14: deleted “4.1 Comparison with Previous Results”.
- (209) P16, L.15-25: replaced the paragraph with “Studies on changes in snow

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

- (210) P16, L.26-P17, L.5: replaced the paragraph with “Ye et al. (1998) found that historical winter snow depth increased in northern Russia (1.86 cm/yr) and decreased in southern Russia at a rate of -0.23 cm/yr during 1936-1983 (Ye et al., 1998). Results from this study were essentially consistent with Ye et al. (1998) in northern Russia, however, in southern Siberia where snow depth increased at a rate of 0.42 cm/yr during the period from 1966 to 2012. We believe that the

difference is mainly due to the time periods covered by the two studies.”

- (211) P17, L.6-7: deleted the sentence.
- (212) P17, L.8: replaced “cover” with “depth”.
- (213) P17, L.10: deleted the comma; replaced “leading” with “lead”.
- (214) P17, L.11: inserted “; Ma and Qin, 2012” after “2005”; replaced “The results of our study showed” with “We found”; inserted “a” after “was”; inserted “(p≤ 0.05) after “significant”.
- (215) P17, L.12: deleted the last “the”, deleted the comma.
- (216) P17, L.13: replaced “however, it did not exist” with “but not”; deleted the first “the”; inserted new sentences “In addition to air temperature and precipitation, atmospheric circulation was a key factor affecting snow depth change (Cohen, 2011; Zhao et al., 2013; Ye et al., 2015). Those factors above and related uncertainties may explain the regional and temporal differences in long-term mean snow depth and snow depth change.” after “Siberia.”
- (217) P17, L.13-14: deleted the last sentence.
- (218) P17, L.15: inserted three paragraphs

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

Snow depth is an important factor of controlling the ground thermal regime (Goodrich, 1982; Zhang et al., 1996; Zhang, 2005; Ling and Zhang, 2005; Park et al,

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

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

(219) P17, L.16- P18, L6: deleted the paragraph.

(220) P18, L.13: replaced “northeastern” with “north-eastern”.

(221) P18, L.16: inserted “the” after “of”.

(222) P18, L.17: replaced “of” with “in”.

(223) P18, L.18: inserted “entire” before “Eurasian”; deleted “as a whole”; replaced “increase” with “increasing”.

- (224) P18, L.21: inserted “a” after “presented”.
- (225) P18, L.22: replaced “while” with “whereas”; replaced the two “of” with “in”; inserted “the” before “variations”.
- (226) P18, L.25: deleted the first “the”; inserted “the” before “northern”.
- (227) P18, L.26: replaced “northeastern” with “north-eastern”.
- (228) P18, L.28: replaced “northeastern” with “north-eastern”.
- (229) P18, L.30: deleted “the”.
- (230) P19, L.1: replaced “of” with “in”.
- (231) P19, L.2: deleted the two “the”.
- (232) P19, L.3: replaced the comma with “and”.
- (233) P19, L.4: replaced “driver” with “driving”.
- (234) P19, L.6: inserted an appendix:

### “Appendix A: Analysis of serial correlation

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

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

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

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

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

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

where  $X'$  was the corrected year,  $Y'$  was the corrected anomalies in time series of snow depth for each station in this research, and the autocorrelation coefficient  $\rho$  was replaced by its estimated  $r$ :

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

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

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

- (235) P20, L.9: inserted a new reference “Barnett, T.P., Adam, J.C., and Letternmaier, D.P.: Potential impact of a warming climate on water availability in snow-dominated regions, *Nature*, 438, 303-309, 2005.”
- (236) P20, L.16: replaced “Atoms.” with “Atmos.”
- (237) P20, L.27-28: deleted “Arctic cryosphere-Changes and impacts, T.V. Callaghan, M. Johansson, and T.D. Prowse, Eds.”
- (238) P21, L.2: inserted a new reference “Cohen, J.: Eurasian snow cover variability and links with stratosphere-troposphere coupling and their potential use in seasonal to decadal climate predictions, US National Oceanic and Atmospheric Administration, Climate test bed joint seminar series, NCEP, Camp Springs, Maryland, 6pp, 2011.”
- (239) P21, L.18: inserted “J.” after “Sci.”
- (240) P21, L.22-23: revised the upper case letter in the title of the article with “Comparison of snow mass estimates from a prototype passive microwave snow algorithm,”
- (241) P21, L.24: inserted a new reference “Goodrich, L.E.: The influence of snow cover on the ground thermal regime, *Can. Geotech. J.*, 19, 421-432, 1982.”
- (242) P22, L.3: inserted a new reference “Groisman, P.Y. and Rankova, E.Y.: Precipitation trends over the Russian permafrost-free zone: removing the artifacts of pre-processing, *Int. J. Climatol.*, 21, 657-678, 2001.”
- (243) P22, L.15: inserted a new reference “Hedstrom, N.R. and Pimeroy, J.W.: Measurement and modelling of snow interception in the boreal forest, *Hydrol. Process.*, 12, 1611-1625, 1998.”
- (244) P22, L.18: inserted three new references:
- “IPCC: Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, edited by: T.F. Stocker et al., Cambridge University Press, Cambridge, UK, and New York, USA, 1535 pp, 2013.”
- “Ji, Z., and Kang, S.: Projection of snow cover changes over China under RCP scenarios, *Clim. Dyn.*, 41: 589-600, 2013.”

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

(245) P22, L.19: Insert a hyphen in “Snow atmosphere”.

(246) P23, L.6: inserted a new reference “Ling, F. and Zhang, T.: Modeling the effect of variations in snowpack-disappearance date on surface-energy balance on the Alaskan north slope, *Arct. Antarct. Alp. Res.*, 37, 483-489, 2005.”

(247) P23, L.22: inserted a new reference “Neter, J., Wasserman, W., and Kutner, M.H.: *Applied linear regression model*, Boston, IRWIN, 1989.”

(248) P23, L.24: inserted three new references:

“Park, H., Fedorov, A.N., Zheleznyak, M.N., Konstantinov, P.Y., and Walsh, J.E.: Effect of snow cover on pan-Arctic permafrost thermal regimes, *Clim. Dyn.*, doi: 10.1007/s00382-014-2356-5, 2014.”

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

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

(249) P24, L.4: inserted a new reference “Storch, H.V.: Misuses of Statistical Analysis in Climate Research, in: *Analysis of Climate Variability*, edited by: Storch, H.V. and Navarra, A.: Springer Press, Berlin Heidelberg, Germany, 11–26, 1999.”

(250) P24, L.9: inserted a new reference “Tao, J., Zhang, X., Tao, J., and Shen, Q.: The checking and removing of the autocorrelation in climatic time series, *Journal of Applied Meteorological Science*, 19, 47-52, 2008.”

(251) P24, L.15: inserted three new references:

“Weatherhead, E.C., Reinsel, G.C., Tiao, G.C., Meng, X., Choi, D., Cheang, W., Keller, T., DeLuisi, J., Wuebbles, D.J., Kerr, J.B., Miller, A.J., Oltmans, S.J., and

Frederick, J.E.: Factors affecting the detection of trends: Statistical considerations and applications to environmental data, *J. Geophys. Res.*, 103(D14), 17149-17161, 1998.”

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

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

(252) P24, L.17: inserted a new reference “Ye, K., Wu, R., and Liu Y.: Interdecadal change of Eurasian snow, surface temperature, and atmospheric circulation in the late 1980s, *J. Geophys. Res. Atmos.*, 120, 2738-2753, 2015.”

(253) P24, L.22: inserted three new references:

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

“Zhang, T., Osterkamp, T. E., and Stamnes, K.: Influence of the depth hoar layer of the seasonal snow cover on the ground thermal regime, *Water Resour. Res.*, 32, 2075-2086, 1996.”

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

(254) P24, L.25: inserted two new references:

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

“Zheng, L., Zhang, T., Che, T., Zhong, X., and Wang, K.: Evaluation of snow depth products derived from passive microwave satellite remote sensing data using ground-based snow measurements, *Remote Sensing Technology and Application*, 30, 413-423, 2015 (in Chinese with English abstract).”

(255) P25: replaced “snow course” with “snow courses”.

(256) P25, L.4: inserted two new tables as Table A1 and Table A2:

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

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

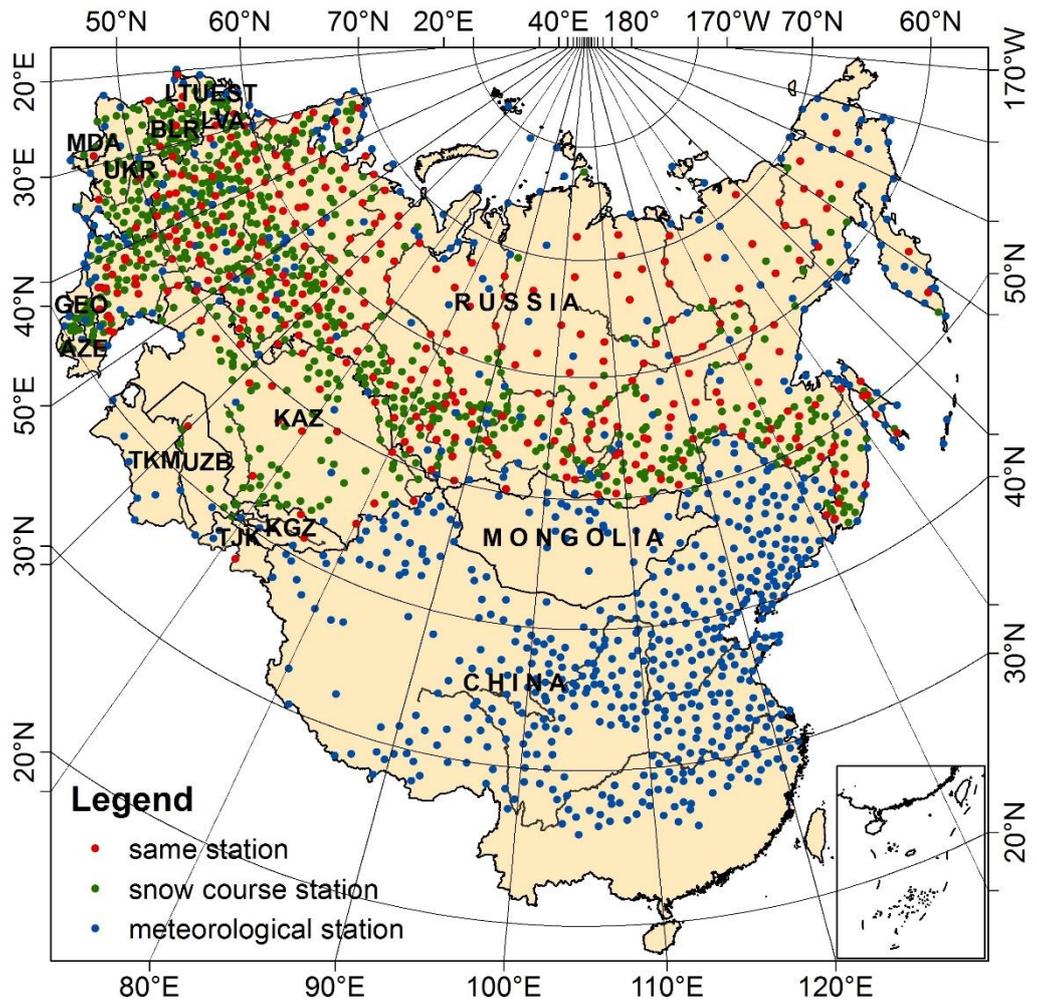
\*: slope was the trend of changes in snow depth, the unit was cm/yr; P was the confidence level.

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

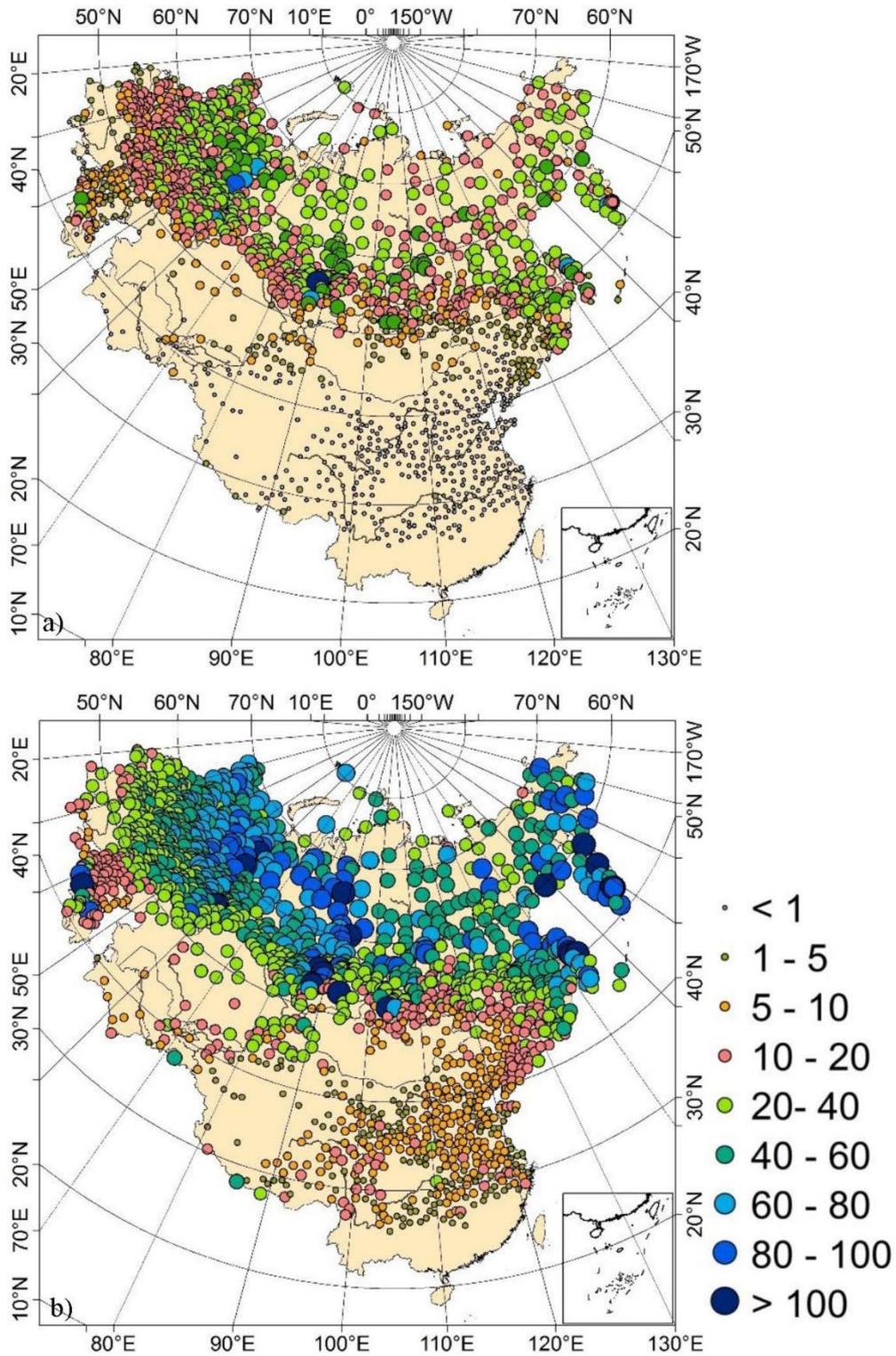
ID	$d_1$	$d_u$	$d$	$slope$	$P$	$d'_1$	$d'_u$	$d'$	$slope'^*$	$P'^*$
20674	1.4872	1.5739	1.2856	0.113	0.016	1.4872	1.5739	2.0249	0.0942	0.055

\*: slope' was the corrected trend of changes in snow depth, the unit was cm/yr; P' was the corrected confidence level.

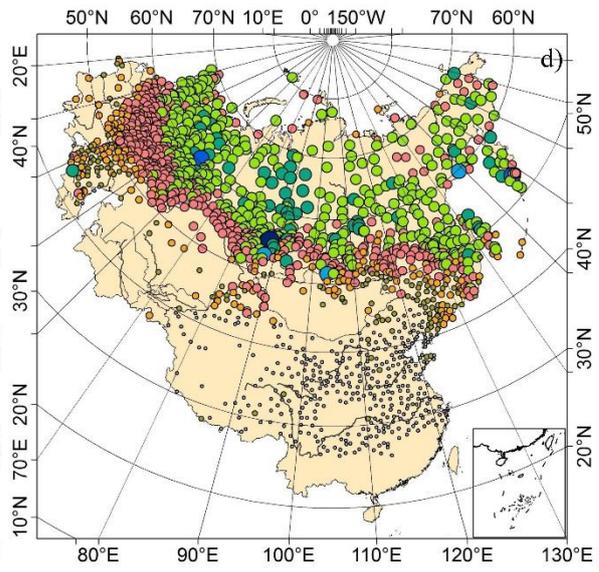
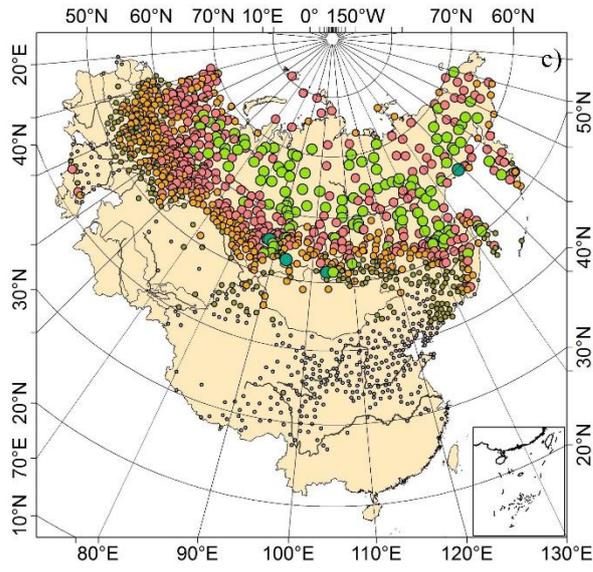
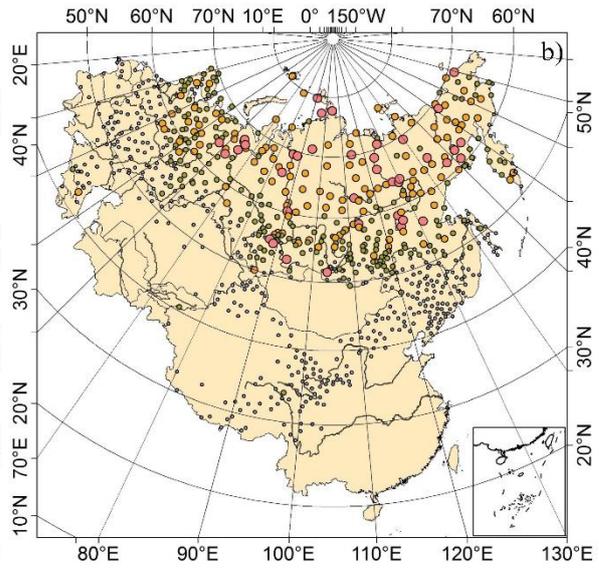
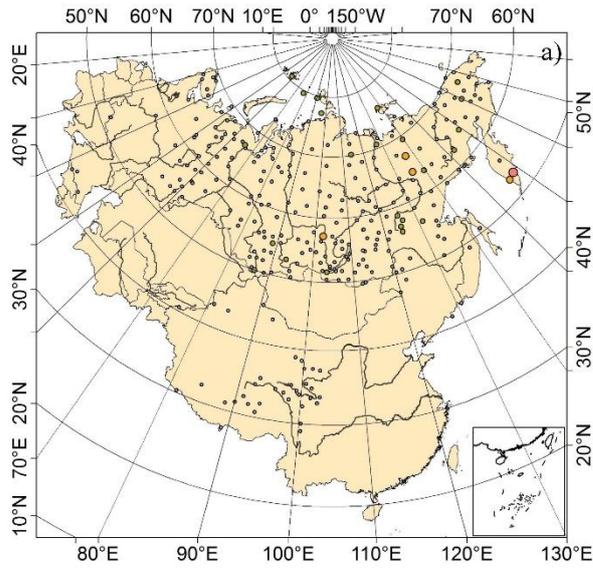
(257) P26: replaced figure 1 with a new figure

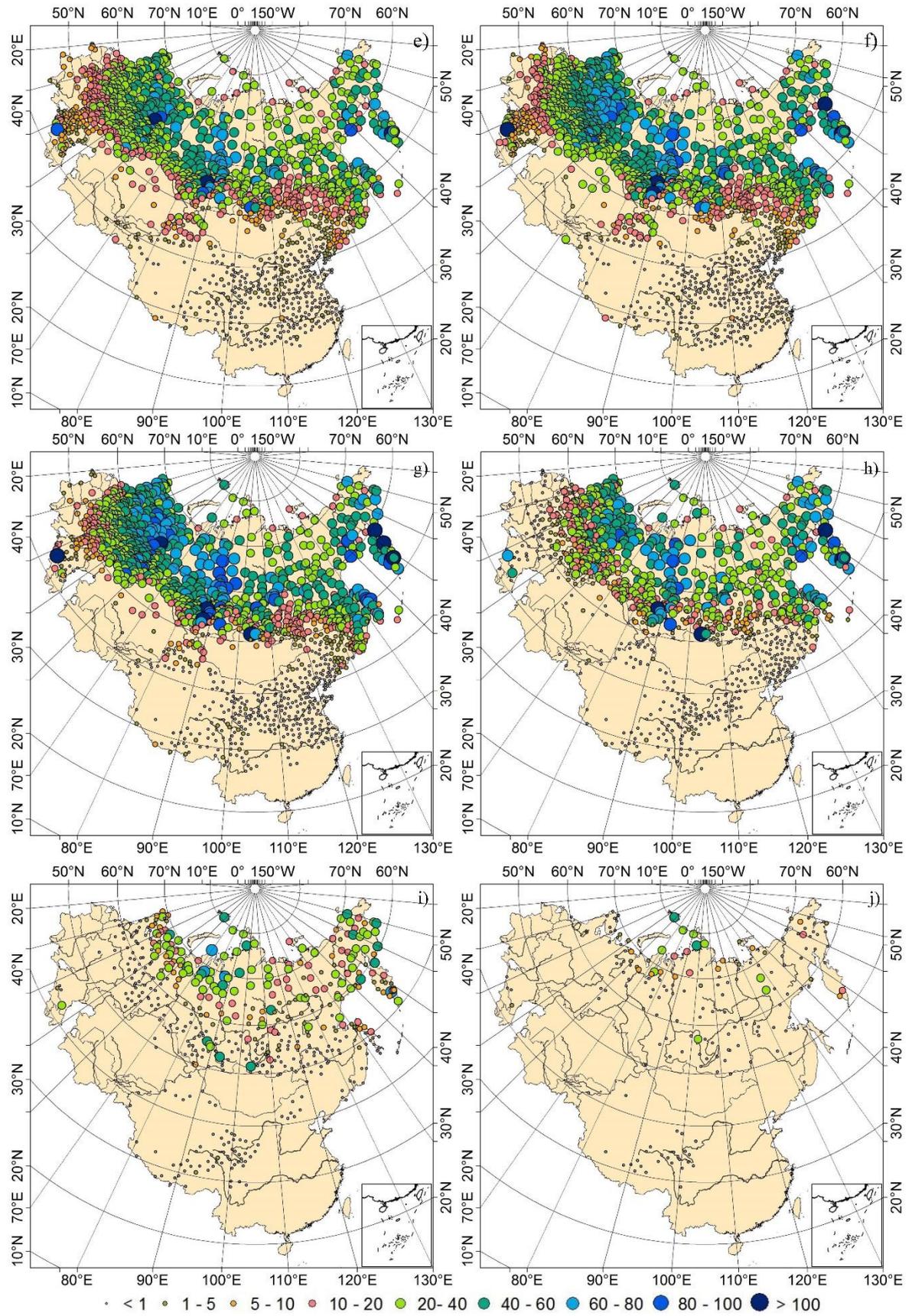


(258) P27: replaced figure 2 with a new figure



(259) P28-29: replaced figure 3 with a new figure



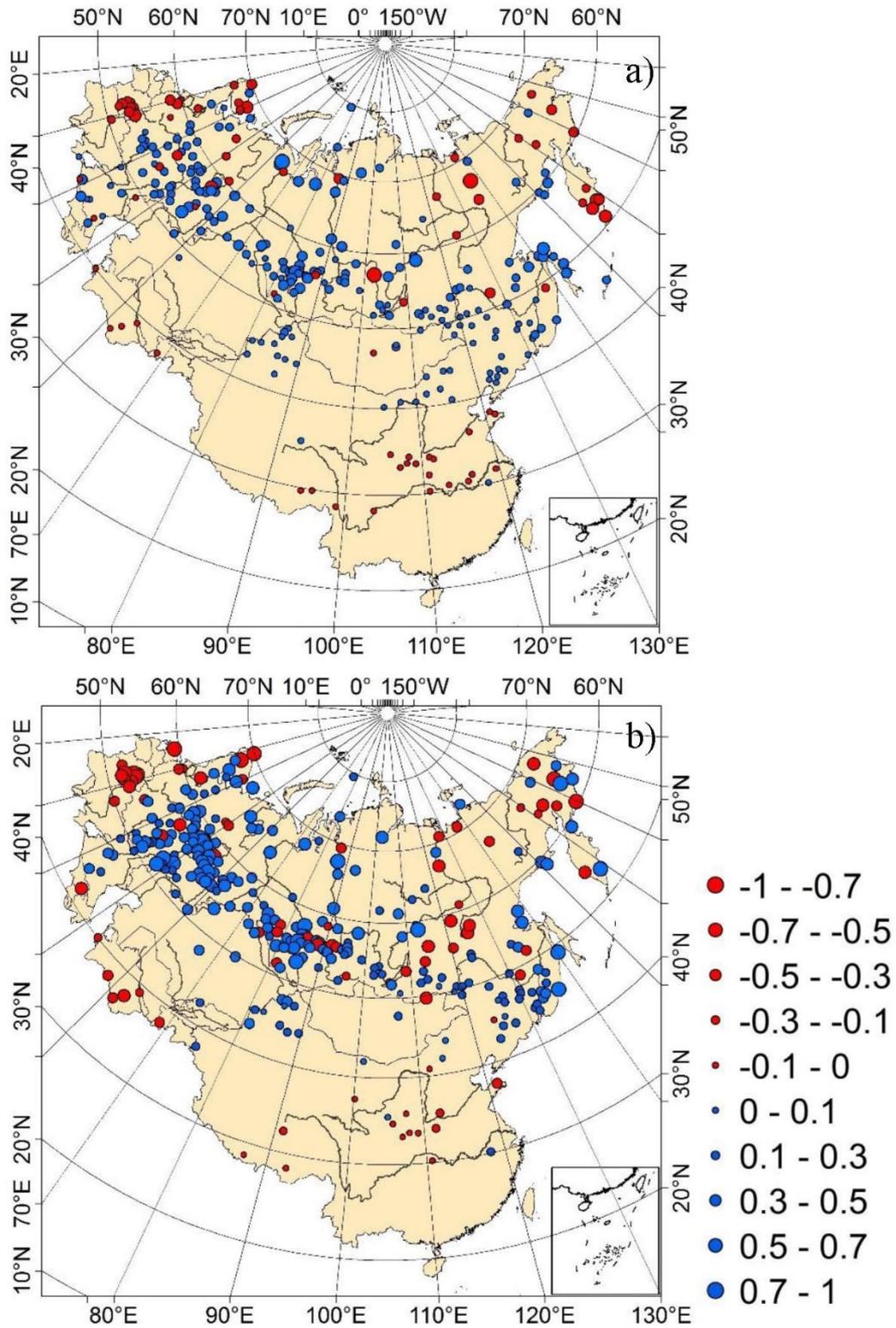


(260) P30: deleted figure 5.

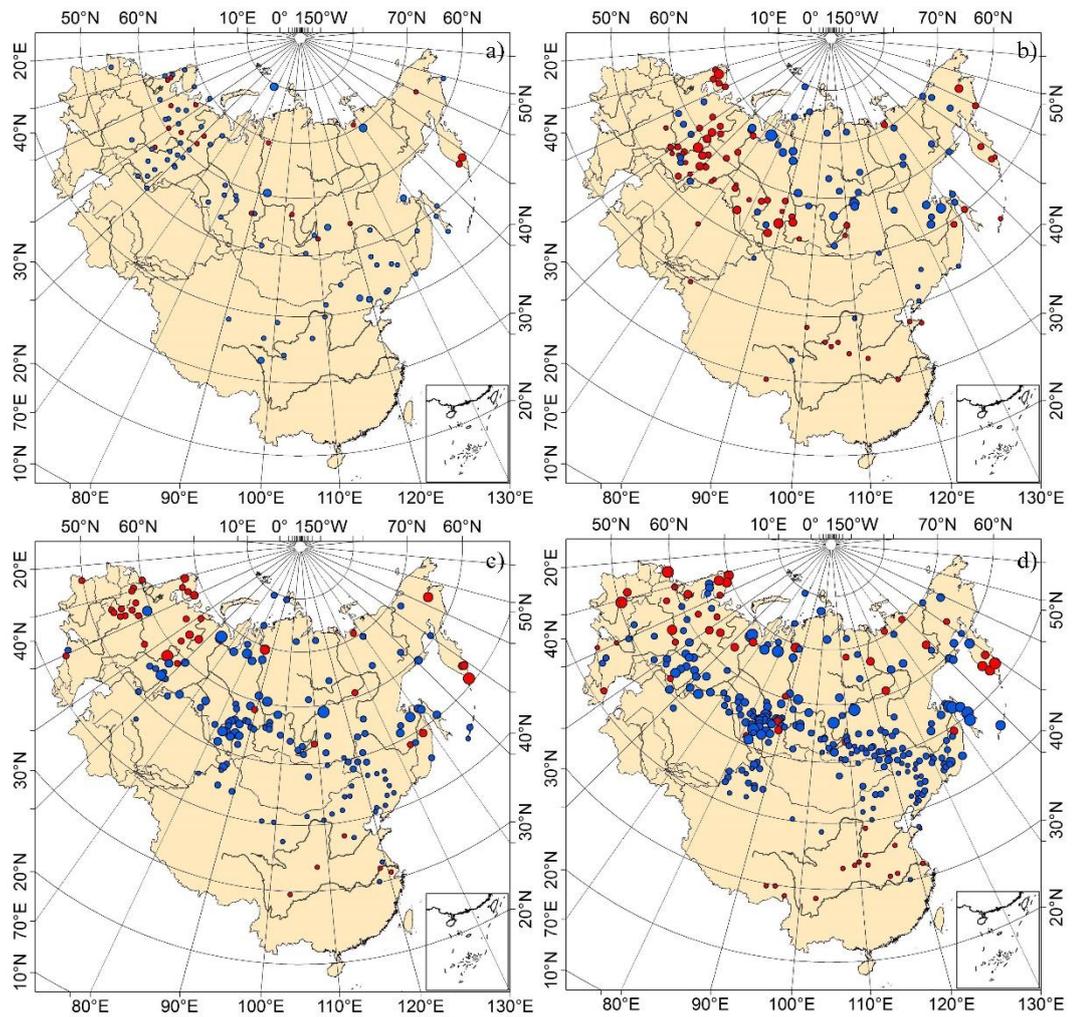
(261) P32: replaced "Figure 6" with "Figure 5".

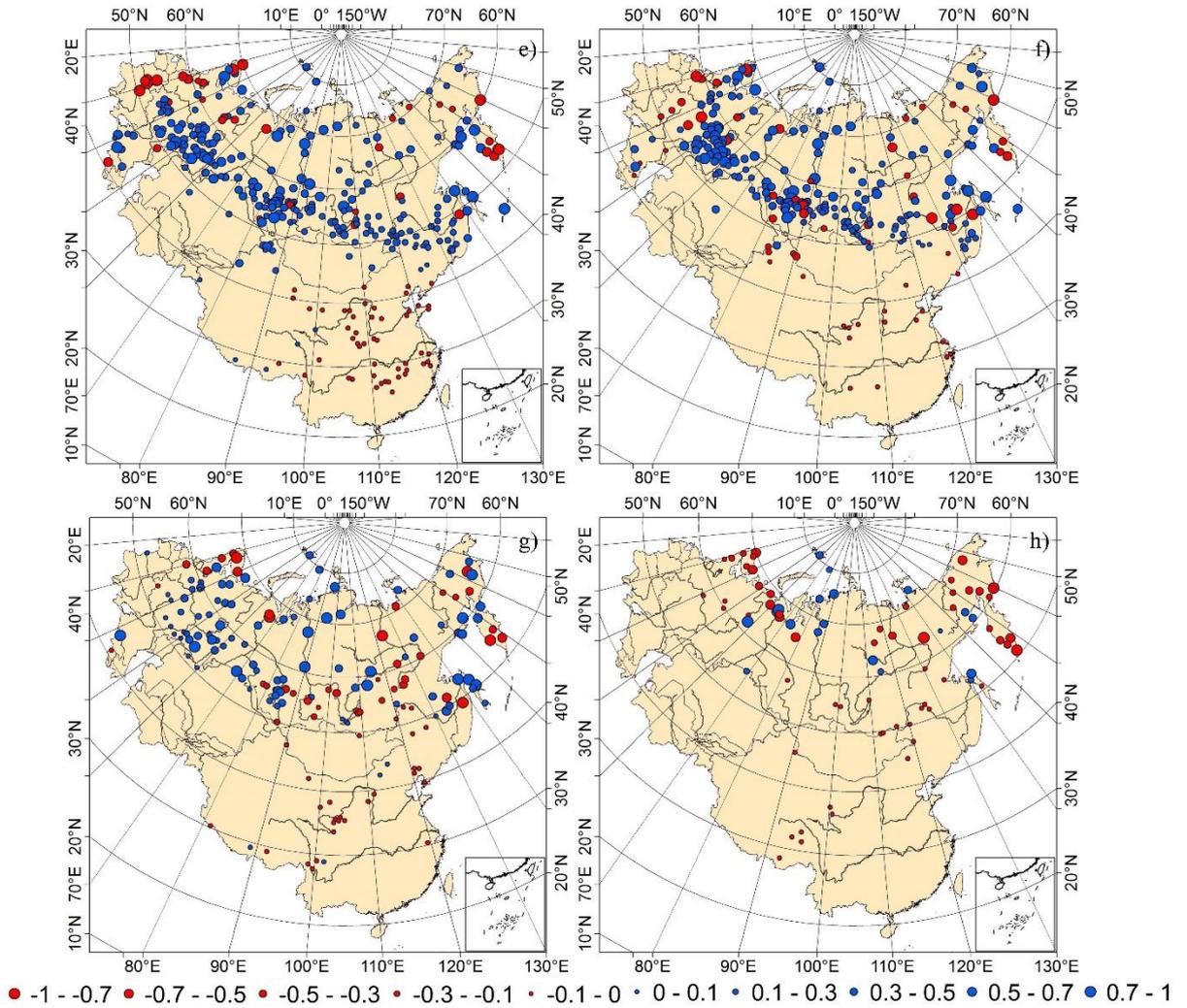
(262) P34: deleted figure 7.

(263) P35: replaced figure 8 with a new figure, replaced "Figure 8" with "Figure 6".



(264) P36-37: replaced figure 9 with a new figure, replaced “Figure 9” with “Figure 7”, replaced “Figure 10” with “Figure 8”.

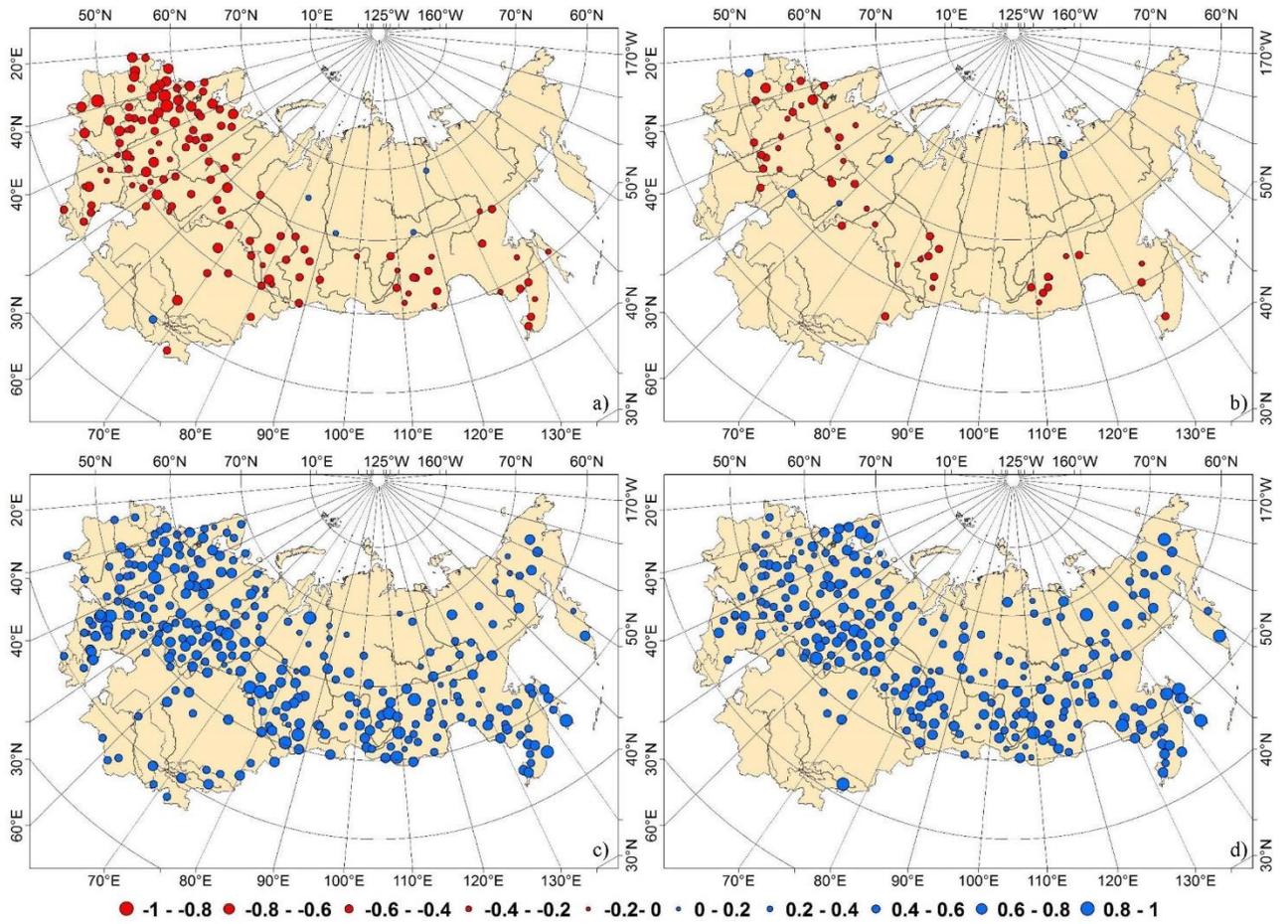




(265) P38: replaced “Figure 11” with “Figure 9”.

(266) P39: replaced “Figure 12” with “Figure 10”.

(267) P40: replaced figure 13 with a new figure, replaced “Figure 13” with “Figure 11”, replaced “confident level” with “confidence level”.



(268) P40, L.6: inserted a new figure as Figure A1.

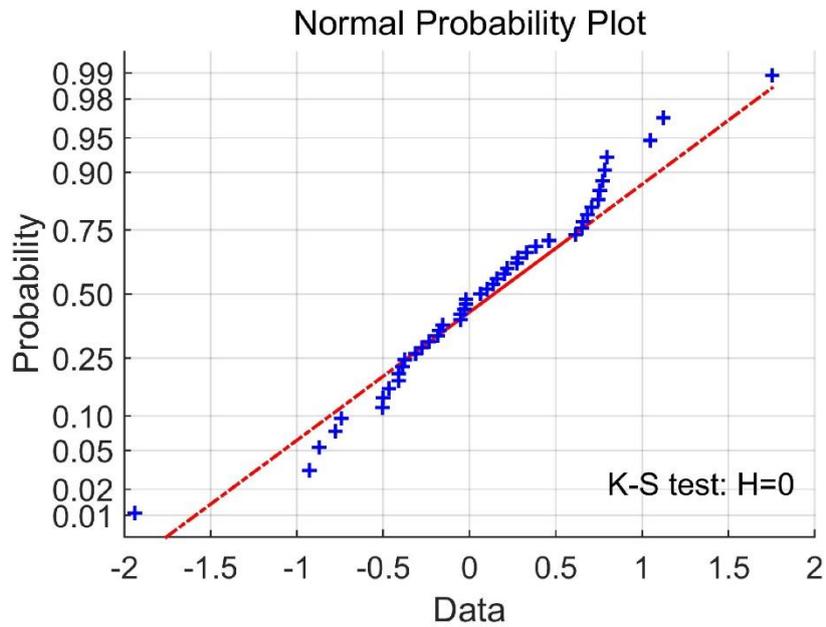


Figure A1. Normal distribution test of annual mean snow depth for all station by K-S test.

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

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<sup>4</sup> *~~Key Laboratory of Remote Sensing, Gansu Province, Lanzhou 730000, China~~ [CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China](#)*

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<sup>65</sup> *Chinese Antarctic Center of Surveying and Mapping, Wuhan University, Wuhan 430079, China*

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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 [from local community to regional industrial water supply](#). [Data and knowledge on snow in general and snow depth/snow water equivalent in particular are prerequisites for climate change studies and local/regional development planning. Past studies by using in-situ data are](#)

1 ~~mostly site-specific, while data from satellite remote sensing may cover a large area or in global~~  
2 ~~scale. uncertainties are huge, evening misleading.~~ In this study, ~~a snow depth climatology and its~~  
3 spatiotemporal ~~change and variability in snow depth~~ ~~variations were~~ ~~was~~ investigated using ~~the~~  
4 long-term (1966-2012) ground-based measurements from 1814 stations across the Eurasian  
5 continent. Spatially, mean snow depths of >20 cm were recorded in north-eastern European Russia,  
6 the Yenisey River basin, Kamchatka Peninsula, and Sakhalin. Annual mean and maximum snow  
7 depth increased significantly ~~during from~~ 1966- ~~through~~ 2012. Seasonally, monthly snow depth  
8 decreased in autumn, and increased in winter and spring over ~~that the study~~ period ~~of time~~.  
9 Regionally, snow depth significantly increased in ~~the~~ areas north of 50 °N. Compared with air  
10 temperature, snowfall had more influence on snow depth and snow water equivalent during  
11 November through March across the former Soviet Union. This study ~~provides~~ ~~provided~~ a  
12 baseline for ~~snow depth climatology and~~ ~~changes in snow depth~~ ~~changes~~, which ~~are~~ ~~were~~  
13 significant in climate system changes over the Eurasian continent.

14

# 1 Introduction

2 Snow cover is a key part of the cryosphere, which is a critical component of the  
3 global climate system. Changes in snow cover, including snow depth and snow area  
4 extent, serve as an indicators of climate change because of ~~its~~-their interactions and  
5 feedbacks with surface energy and moisture fluxes, hydrological processes, and  
6 atmospheric and oceanic circulations (Brown and Goodison, 1996; Armstrong and  
7 Brown, 2008; King et al., 2008). Snow depth, snow water equivalent (SWE) and snow  
8 density are all important parameters for water resource assessment, hydrological and  
9 climate model inputs and validation (Dressler et al., 2006; Lazar and Williams, 2008;  
10 Nayak et al., 2010).

11 Changes in Snow-snow depth could have dramatic impacts on weather and is a  
12 basic and important parameter of snow cover, which can provide additional  
13 information related to climate through, surface energy balance (Sturm et al., 2001),  
14 soil temperature and frozen ground (Zhang, 2005), moisture budgets, spring runoff,  
15 water supply, and human activity (Sturm et al., 2001; Zhang, 2005; AMAP, 2011).  
16 Although the snow cover extent ~~reduced~~declined with climate warming, snow depth  
17 showed an~~still~~ increasing trend in ~~the~~ northern Eurasia during 1936 to 2010 (Kitaev  
18 et al., 2005; Bulygina et al., 2011). This may ~~was~~ be ~~due to~~ explained in that the  
19 changes in the atmospheric moisture budget altering the atmospheric circulation, the  
20 warmer air led to a greater moisture supply for precipitation as snowfall in winter (Ye  
21 et al., 1998; Kitaev et al., 2005; Rawlins et al., 2010). Meanwhile, snowmelt from  
22 increased snow depth may also lead to higher soil moisture in spring, which ~~promoted~~  
23 promotes enhanced precipitation with increased local and regional evapotranspiration  
24 (Groisman et al., 1994).

25 Using in-situ observational data from meteorological stations and satellite  
26 remote sensing ~~data~~, several studies have documented changes in snow depth over the  
27 Northern Hemisphere, and ~~demonstrated~~ ing that snow depth varied s differently over  
28 different regions. regionally: overall, the a Annual mean snow depth decreased in most  
29 areas over North America during 1946 to 2000 (Brown and Braaten, 1998; Dyer and  
30 Mote, 2006), and increased in Eurasia and the Arctic during the ~~recent~~ last 70 years

1 (Ye et al., 1998; Kitaev et al., 2005; Callaghan et al., 2011a; Liston and Hiemstra,  
2 2011) ~~but there was~~ and showed large regional differences (Bulygina et al., 2009, 2011;  
3 Ma and Qin, 2012; Stuefer et al., 2013; Terzago et al., 2014). Changes in snow depth  
4 were primarily affected by air temperature and precipitation. Ye et al. (1998) and  
5 Kitaev et al. (2005) showed that higher air temperatures caused an increase in  
6 snowfall in winter from 1936 through 1995, and thus, greater snow depth was  
7 observed in northern Eurasia in response to global warming. Furthermore, the snow  
8 depth distribution and variation ~~are were also~~ controlled by terrain (i.e., elevation,  
9 slope, aspect, and roughness) and vegetation (Lehning et al., 2011; Gr ünewald et al.,  
10 2014; Revuelto et al., 2014; Rees et al., 2014; Dickerson-Lange et al., 2015). Snow  
11 depth ~~is was also~~ closely related to ~~other large~~ synoptic-scale atmospheric circulation  
12 indices, such as the North Atlantic Oscillation-/Arctic Oscillation (NAO/AO) ~~indices~~.  
13 For example, Beniston (1997) found that ~~the~~-NAO played a crucial role in fluctuations  
14 in the amount of snowfall and snow depth in the Swiss Alps from 1945 to 1994.  
15 Kitaev et al. (2002) reported that the NAO index ~~is was~~ positively related to snow  
16 depth in the northern part of the East European Plain of Russia and over western  
17 Siberia ~~during the period~~ from 1966 to 1990; however, ~~the~~-NAO ~~is was~~ negatively  
18 correlated with snow depth in most southern regions of northern Eurasia. You et al.  
19 (2011) ~~indicated demonstrated~~ that there ~~is was~~ a positive relationship between snow  
20 depth and the winter AO/NAO index and between snow depth and Ni ño-3 region sea  
21 surface temperature (SST) ~~in on~~ the eastern and central Tibetan Plateau (TP) from  
22 1961 through 2005.

23 To increase the spatial coverage of snow depth, researchers have used different  
24 instruments (e.g., LIDAR, airborne laser scanning (ALS), and unmanned aerial  
25 systems (UASs)) (Hopkinson et al., 2004; Gr ünewald et al., 2013; B ühler et al., 2016)  
26 or ~~have~~—developed and/or improved ~~the algorithms with~~ passive microwave snow  
27 algorithms (Foster et al., 1997; Derksen et al., 2003; Grippaa et al., 2004; Che et al.,  
28 2016). Although snow depth and snow water equivalent obtained by satellite remote  
29 sensing these observations ~~can could~~ mitigate ~~the~~ regional deficiency of the in-situ  
30 snow depth observations, ~~the satellite data~~ they have low spatial resolution (25×25

1 km), and the accuracy is always affected by clouds, underlying surface conditions,  
2 and ~~inversion-perfect~~ algorithms. Using ground-based snow depth measurements  
3 across the Eurasian continent against snow depth obtained from passive microwave  
4 satellite remote sensing, Zheng et al. (2015) found that the mean percentage error was  
5 greater than 50% and can be up to approximately 200%. Utilization of snow depth  
6 obtained from satellite remote sensing has large uncertainties and is impractical. In  
7 addition, data acquisition from ~~the~~ large airborne equipment or aerial systems is  
8 ~~always~~ costly and strict data use limitations apply. some of them need to obtain  
9 official permission before using in some countries. Ground-based ~~snow~~ measurements  
10 ~~remains the basis for verification of remote sensing and instrumental data, which can~~  
11 provide currently available and more accurate snow depth over and longer  
12 ~~time-series, which information, and it is are critical data and information important~~  
13 for investigating snow depth climatology and variability ~~of snow depth~~.

14 During winter, the average maximum terrestrial snow cover is ~~nearly~~  
15 approximately  $47 \times 10^6$  km<sup>2</sup> over ~~the~~ Northern Hemisphere land surfaces (Robinson  
16 et al., 1993; IGOS, 2007). A large fraction of the Eurasian continent is covered by  
17 snow during the winter season, and some areas are covered by snow for more than  
18 half a year. There are long-term ~~and large-scale~~ snow ~~cover~~ measurements and  
19 observations across the Eurasian continent, with the first snow ~~cover~~ depth record  
20 dating back to 1881 in Latvia (Armstrong, 2001). These measurements provide  
21 valuable data and information for snow cover phenology and snow cover change  
22 detection. ~~In Eurasia, most~~ Many studies ~~of on~~ snow depth have ~~mainly~~ focused on  
23 local and regional-scales over Russia (Ye et al., 1998; Kitaev et al., 2005; Bulygina et  
24 al., 2009, 2011), ~~the former Soviet Union (USSR) (;~~ Brasnett, 1999), and on the TP  
25 (Li and Mi, 1983; Ma and Qin, 2012). ~~However, due to the lack of data and~~  
26 ~~information, there~~ has been no integrated and systematic investigation of changes in  
27 snow depth across the entire Eurasian continent using ground-based measurements.  
28 The objective of this study ~~is was~~ to investigate ~~the~~ climatology and variability of  
29 snow depth, ~~and analyze snow depth relationships with the topography and climate~~  
30 factors over the Eurasian continent from 1966 to 2012. In addition, we analysed the

1 spatial and temporal changes in snow depth with topography and climate factors over  
2 the study area. This study can provide basic information on climate system changes in  
3 the region. The dataset and methodology are described in Section 2, with the results,  
4 discussion, and conclusions presented in Sections 3, 4, and 5, respectively.

## 6 **2 Data and Methodology**

7 The data used in this study include daily snow depth, snow water equivalent  
8 (SWE), air temperature and precipitation. Measurements of daily snow depth were  
9 conducted at 1103 meteorological stations over the Eurasian continent from 1881 to  
10 2013 (Table 1). ~~Snow depth was measured at these stations on a daily basis.~~ Snow  
11 depth was measured once a day at meteorological stations using a graduated stake  
12 installed at a fixed point location within the station or by a wooden ruler. Snow depth  
13 was measured using the same method across the Eurasian continent since the  
14 meteorological observation standard was established by the former Union of Soviet  
15 Socialist Republics (USSR) and followed by all of the former USSR republics,  
16 Mongolia and China. Snow depth is one of the standard elements to be measured on a  
17 daily basis (WMO, 1996). Historical snow course data over the former USSR from  
18 1966 to 2011 were also used in this study. Snow course data include routine snow  
19 surveys performed throughout the accumulation season (every ten days) and during  
20 ~~the snowmelt (every five days)~~ period (every five days) over the former USSR. Snow  
21 surveys were conducted over 1–2 km-long transects in both forest and open terrain  
22 around each station. Snow depth was measured every 10 m in the forest, and every 20  
23 m in open terrain (Bulygina et al. 2011).

24 SWE is ~~also~~ an important parameter ~~of snow cover~~ that is usually often used in  
25 water resource evaluation and hydroclimate research studies. ~~In this study, we~~  
26 ~~analyzed the relationships among SWE, air temperature, snowfall and snow depth~~  
27 ~~during the accumulation season (from November to March) over the former USSR~~  
28 ~~where SWE data are available.~~ SWE was measured using a snow tube every 100 m  
29 along the 0.5-1.0 km courses and every 200 m along the 2 km course (Bulygina et al.,  
30 2011).

1 Daily air temperature was measured using a thermometer, which was placed at a  
 2 height of 1.5 m above the ground surface in an instrument shelter at the  
 3 meteorological station (WMO, 1996). The air temperature measurement should be  
 4 accurate to 0.1 °C. Air temperature was measured four times a day at 0200, 0800,  
 5 1400, and 2000 local time. The daily mean air temperature was calculated by a simple  
 6 arithmetic average of the four measurements, whereas the monthly mean was based  
 7 on the daily mean and the annual mean was based on the monthly mean. Precipitation  
 8 was gathered and measured by a precipitation gauge and was reported with a 0.1-mm  
 9 precision (Groisman and Rankova, 2001). The original precipitation data were not  
 10 corrected by considering the gauge undercatch. Daily precipitation was partitioned  
 11 into a solid and liquid fraction, based on daily mean temperature (Brown, 2000). The  
 12 solid fraction of precipitation,  $S_{rat}$ , was estimated by ~~the following Equation (1):~~

$$S_{rat} = \begin{cases} 1.0 & \text{for } T_{mean} \leq -2.0^{\circ}C, \\ 0.0 & \text{for } T_{mean} \geq +2.0^{\circ}C, \\ 1.0 - 0.25(T_{mean} + 2.0) & \text{for } -2.0^{\circ}C < T_{mean} < +2.0^{\circ}C. \end{cases} \quad (1)$$

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

15 Snow depth and SWE at each station were determined as the average value of a  
 16 series of measurements in each snow course survey (Bulygina et al., 2011). In  
 17 individual measurements, both random and systematic errors inevitably occur  
 18 (Kuusisto, 1984). To minimize these errors, a quality control of ~~the~~ meteorological  
 19 data was automatically undertaken prior to the datasets being stored at the Russian  
 20 Research Institute for Hydrometeorological Information-World Data Center  
 21 (RIHMI-WDC) (Veslov, 2002) and the National Meteorological Information Center  
 22 (NMIC) of China Meteorological Administration (Ma and Qin, 2012). We  
 23 implemented ~~a second~~ additional quality control using the following requirements: (1)  
 24 To ensure snow depth stability, at a given location, a month with less than 15 days of  
 25 snow depth measurements was deleted; (2) Stations with sudden and steep changes in  
 26 snow depth were eliminated from the list; (3) Stations with less than 20 years of data  
 27 during the 1971-2000 period were excluded from the analysis; and (4) At each station,  
 28 we eliminated data points that exceeded two standard deviations from their long-term

1 ~~(1971-2000) mean. (1) A threshold of 15 days was selected because the snow cover~~  
2 ~~duration in some areas of China was less than one month, and the data for 15 days'~~  
3 ~~snow depth in a month were relatively stable. Months having less than 15 days with~~  
4 ~~snow depth data were omitted from the analysis. (2) Stations with less than 20 years~~  
5 ~~of data during the 1971-2000 period were excluded from the analysis. (3) At each~~  
6 ~~station, data exceeding two standard deviations compared with the annual average~~  
7 ~~value during 1966-2012 were omitted. After these four steps of snow depth quality~~  
8 ~~control, in total, we used data from 1814 stations to investigate analyze the~~  
9 climatology and variability of snow depth over the Eurasian continent (Fig. 1 and  
10 Table 1).

11 ~~The snow cover extent is the smallest in July and August. We defined a snow~~  
12 ~~year starting from July 1<sup>st</sup> of a current year through June 30<sup>th</sup> of the following year in~~  
13 ~~order to capture the entire seasonal snow cycle, we defined a snow year as the period~~  
14 ~~from July 1<sup>st</sup> of a current year to June 30<sup>th</sup> of the following year. Procedures and~~  
15 ~~techniques for measuring snow depth may have changed over the course of station~~  
16 ~~history. Consequently, snow depth data may not be homogeneous in the time series~~  
17 ~~over the period of the record. Fortunately, there was no change in the procedure and~~  
18 ~~technique of snow depth measurements since 1965 in Russia and the other countries~~  
19 ~~in this study (Bulygina et al., 2009). Therefore, in this study, we chose to use snow~~  
20 ~~depth data from 1966 to 2012. Because the procedures for taking snow observations~~  
21 ~~have changed over the course of the studies period, there were some inhomogeneities~~  
22 ~~in the data. However, there has been no change in the observation procedure and~~  
23 ~~techniques since 1965 (Bulygina et al., 2009). Therefore, we used snow data for the~~  
24 ~~snow years from 1966 to 2012 in this study.~~ The following variables were calculated  
25 for each station:

26 (1) Monthly mean snow depth: ~~i~~In this study, we defined a snow cover day with  
27 snow depth equal to or greater than 0 cm according to the standard ~~way~~method for  
28 deriving monthly mean snow depth ~~in regular~~based on the World Meteorological  
29 Organization (WMO) climatological products (Ma and Qin, 2012). According to the  
30 quality control, months having more than 15 days with snow data were used. The

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

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

6 (2) Annual mean snow depth: ~~the an~~ annual mean snow depth was calculated as  
7 ~~anthe~~ arithmetic sum of the monthly mean snow depth divided by the number of  
8 available snow months within each snow year. The annual mean snow depth was  
9 averaged ~~for stations with more than~~~~from the annual snow depth for~~  $\geq 20$  snow years  
10 during ~~the~~ 1966-2012 ~~period:-~~

11 (3) Annual mean maximum snow depth: ~~anthe~~ annual mean maximum snow  
12 depth was determined from the maximum daily snow depth in each snow year. It was  
13 calculated using the average values of ~~the~~ annual maximum snow depth from ~~the~~  
14 stations with  ~~$\geq$ more than~~ 20 years of data during ~~the~~ 1966-2012 ~~period:-~~

15 Anomalies of monthly, annual mean, and annual mean maximum snow depth  
16 from their long-term (1971-2000) records were calculated for each station across the  
17 Eurasian continent. Composite time series of monthly and annual anomalies were  
18 obtained by using all of the available station data across the study area.~~To overcome~~  
19 ~~the systematic differences between stations related to climate/elevation and station~~  
20 ~~distributions, the anomaly of snow depth from the long term mean was used in this~~  
21 ~~study. According to each 30 years as a climate reference period, the annual mean~~  
22 ~~snow depths of the period 1971-2000 were computed as climate reference values in~~  
23 ~~this study. We calculated the anomalies of monthly, annual mean and maximum snow~~  
24 ~~depth relative to the mean for the period from 1971 to 2000 for each station and~~  
25 ~~averaged the anomalies for all stations to obtain mean anomalies for the whole~~  
26 Eurasian continent.

27 Wavelet analysis was performed to reveal the long-term low-frequency variations  
28 ~~inof~~ snow depth over the entire study area ~~as a whole~~. A wavelet is a wave-like  
29 oscillation with an amplitude that begins at 0, increases, and then decreases back to 0  
30 (Graps, 1995). We applied a discrete wavelet transform, excluded the high-frequency

1 components and then used the inverse transform to reconstruct the lower frequency  
2 signal. Any trend analysis is an approximate and simple approach to obtain what has  
3 ~~happened-occurred~~ on average during the study period. ~~A~~ Linear trend analysis  
4 provides an average rate of this change. ~~Despite there is a nonlinearity, the~~ The linear  
5 trend analysis is also a useful approximation when ~~a~~-systematic low-frequency  
6 variations emerged ~~even though there is a nonlinearity~~; (Folland and Karl, 2001;  
7 Groisman et al., 2006). The linear trend coefficient of snow depth was calculated to  
8 represent the rate of change at each station. The Student's ~~T~~-test was used to assess  
9 ~~the~~-statistical significan~~ce~~t of the slope in the linear regression analysis and the partial  
10 correlation coefficients, and ~~the~~-a confidence level above 95% was considered  
11 significant in our study. The Durbin-Watson test was used to detect serial correlation  
12 of data in the time series, and the Cochrane-Orcutt test was used to correct the serial  
13 correlation. Then, the serial correlations of the new data were rechecked and  
14 recalculated trends in the time series of the new data. The methods and test results  
15 were described in the supplement appendix. ~~Meanwhile, to overcome the strong~~  
16 ~~assumption in ordinary least squares (independent and normal distribution), we~~  
17 ~~applied a Mann-Kendall (MK) test to identify the monotonic trend in snow depth.~~  
18 ~~Confidence level above 95% was used to determine the statistically significant~~  
19 ~~increase or decrease in snow depth. These two test methods could provide more~~  
20 ~~robust and comprehensive information of the trend analysis. In order to evaluate the~~  
21 ~~influence of single climatic factor on snow cover, the partial correlation coefficients~~  
22 ~~were calculated and reported the relationships between snow depth, SWE, air~~  
23 ~~temperature and snowfall. The way to do significant test of the correlation coefficient~~  
24 ~~is same to the trend analysis, which includes T test and MK test.~~

## 25

### 26 3 Results

#### 27 3.1 Climatology of Snow Depth

28 ~~The~~ Distributions of long-term mean snow depth ~~generally represented~~  
29 indicated the a strong latitudinal zonality; ~~the~~ Generally, snow depth ~~for each station~~  
30 generally increased with ~~the~~-latitude northward across the Eurasian continent (Fig. 2).

1 A maximum annual mean snow depth of 106.3 cm was observed ~~in the~~ west of the  
2 Yenisey River (dark blue circle) (Fig. 2a). In contrast, the minimum values (~0.01 cm)  
3 were observed in some areas ~~of the~~ south of ~~the~~ Yangtze River in China (small ~~grey~~  
4 circles).

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

17 Annual mean maximum snow depth ~~varied with the latitude~~ (Fig. 2b), ~~which~~  
18 showed a ~~similar~~ spatial distribution pattern ~~compared similar~~ to the annual mean  
19 snow depth pattern. The maximum value ~~was approximately (~201.8 cm) was~~  
20 ~~recorded in the same location as the greatest annual mean~~ snow depth. For the  
21 majority of Russia, the maximum snow depth was >40 cm. The regions with ~~the~~  
22 maximum snow depths (exceeding 80 cm) were ~~located~~ in the north-eastern regions of  
23 European Russia, the northern part of the West Siberian Plain, the Yenisey River basin,  
24 the Kamchatka Peninsula, and Sakhalin; however, along the coast of the Caspian Sea,  
25 the maximum snow depth was <10 cm. Most of the rest of the former USSR had a  
26 maximum depth of >10 cm, except for some regions of ~~the~~ Ukraine and Uzbekistan.  
27 Maximum snow depth was >10 cm in northern Mongolia, and ~~decreased to~~ 6–10 cm  
28 ~~when moving in south to the~~ central and eastern ~~parts of the country~~ Mongolia.

29 Maximum snow depths were higher over the northern part of the Xinjiang  
30 Autonomous Region of China, Northeast China, and ~~some regions of the~~ eastern and

1 southwestern TP, were mostly greater than ~~→~~ 10 cm and even greater than 20 cm in  
2 some areas. For the remaining regions of China, the maximum snow depths were  
3 relatively small and mostly less than 10 cm. ~~The maximum snow depth in some areas~~  
4 ~~was more than 20 cm. In other regions of China, the values were relatively small, ~8~~  
5 ~~cm or less.~~

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

10 In the autumn months (September to November), the snow depth was shallow  
11 (Figs. 3a-c). Monthly mean snow depth was <20 cm in most areas of European Russia  
12 and ~~the~~ south of Siberia, but ranged from ~20 cm to 40 cm in northern Siberia and the  
13 Russian Far East in November (Fig. 3c). Moving southward, the mMonthly mean  
14 snow depth was less than 5 cm ~~in the~~ north of Mongolia and ~~most regions~~ across  
15 China. From December to February, the snow depth increased and the ~~areas covered~~  
16 ~~by snow~~ snow cover extent expanded significantly (Figs. 3d-f). ~~Most~~ monthly snow  
17 depth values were >20 cm over the former USSR. Monthly mean snow depth was still  
18 <1 cm ~~in most regions~~ for the majority of China, ~~but more than 10 cm~~ except in the  
19 northern Xinjiang Autonomous Region of China, Northeast China, and ~~some regions~~  
20 ~~of~~ south-western TP where snow depth exceeded 10 cm. The snow depth was even  
21 more than 20 cm in some places of the Altai Mountains. In spring ~~months~~ (March  
22 through May), ~~the~~ snow cover areas decreased significantly (Figs. 3g-i), which was  
23 mainly because of snow disappearance in the majority of China. However, the  
24 monthly mean snow depth still exceeded 20 cm in most areas of Russia. Snow cover  
25 areas and snow depth gradually decreased in April and May. Snow cover was  
26 observed only in Russia and in the TP in June (Fig. 3j).

### 28 3.2 Variability of Snow Depth

29 There were long-term significant increasing trends in ~~the both~~ annual mean snow  
30 depth and maximum snow depth from 1966 to 2012 over the Eurasian continent ~~as a~~

1 ~~whole with the.~~ Mean annual snow depth increasing-increased at a rates of  
2 approximately snow depth of 0.2 cm decade<sup>-1</sup>, whereas annual mean maximum snow  
3 depth increased at a rate of approximately-and 0.6 cm decade<sup>-1</sup>, respectively (Fig. 4).  
4 Both annual mean snow depth and maximum snow depth exhibited a similar pattern  
5 of changes over the four decades, although the amplitude of ~~the~~ maximum snow depth  
6 anomaly (~~about~~ approximately  $\pm 2$  cm) was much larger than that of the mean snow  
7 depth anomaly (approximately~~about~~  $\pm 1$  cm). From the mid-1960s to the early 1970s,  
8 ~~the~~ annual mean snow depth decreased slightly, then ~~it~~ increased until the early 2000s,  
9 and then decreased sharply until 2012 (Fig. 4a). Maximum snow depth decreased by  
10 2.5 cm from the mid-1960s through the early 1970s (Fig. 4b). There was a sharp  
11 increase of ~~3.5~~ approximately 3 to 4 cm in the maximum snow depth during the 1970s,  
12 and then it there was a large fluctuationng without a significant trend changed from  
13 the late 1970s to the early 1990s. The maximum snow depth increased again from the  
14 early 1990s through the early 2010s.

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

25 Monthly snow depth changed significantly across the Eurasian continent from  
26 1966 through 2012 (Fig. 5). Snow depth decreased in October at a rate of  
27 approximately -0.1 cm decade<sup>-1</sup> (Fig. 5a), and there were no significant trends in  
28 November and December with large inter-annual variations (Fig. 5b-c). From January  
29 through April, snow depth showed statistically increased trends with rates between 0.3  
30 cm decade<sup>-1</sup> and 0.6 cm decade<sup>-1</sup> (Fig. 5d-g). Overall, snow depth decreased or there

1 was no change in autumn and increased in winter and spring with large inter-annual  
2 variations over the study period. Statistically significant trends of variations in  
3 monthly snow depth occurred from 1966 through 2012 except for November,  
4 February, and May (Fig. 6). During the snow cover formation period (October and  
5 November), the monthly snow depth decreased slightly (Figs. 6a-b). There was a  
6 significant decreasing trend of monthly snow depth in October, with a rate of decrease  
7 of approximately 0.1 cm decade<sup>-1</sup> (Fig. 6a).

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

17 Significant increasing trend of monthly snow depth also appeared in March and April,  
18 the rate of increase being about 0.6 cm decade and 0.3 cm decade, respectively (Figs.  
19 6f-g). The trend of monthly snow depth in March was consistent with the change in  
20 winter from the mid-1960s through the late 1970s, then it was stable until the early  
21 1990s (Fig. 6f). Monthly snow depth rapidly increased by 2.5 cm from the mid-1990s  
22 through the late 1990s, then it decreased slightly. Snow depth presented fluctuant  
23 increasing trend during the mid-1960s through the early 1980s (Fig. 6g). Subsequently,  
24 snow depth sharply increased by about 3 cm from the mid-1980s to the early 2000s. It  
25 declined rapidly during the early 2000s through 2012.

26 In order to identify the monotonic trend in monthly snow depth, we conducted  
27 the MK test (Fig. 7). In October, snow depth represented a decreasing trend and it  
28 reached to the 0.05 confident level only after 2010. The statistically significant  
29 changes of monthly snow depth in November during the period of the late 1980s  
30 through the early 2000s, though it was not statistically significant with the linear

1 regression. From December through March, there were increasing trends in monthly  
2 snow depth and the abrupt change point appeared in the mid-1970s. In the linear  
3 regression analysis, the variation of snow depth was not significant in December.  
4 However, the results of M-K test showed that the increasing trend of monthly snow  
5 depth reached to the 0.01 confident level during the mid-1980s through the late 1990s,  
6 and then it decreased during the 2000s. From January to March, monthly snow depth  
7 increased significantly ( $p \leq 0.01$ ) from the mid-1980s to the early 2010s. In April, the  
8 statistically significant increase was found from the late 1990s to the late 2000s, and it  
9 reached to the 0.01 confident level after 2000. Consistent with the linear regression,  
10 the trend in monthly snow depth was not significant in May.

11 Figure 8-6 shows the spatial distributions of linear trend coefficients of annual  
12 mean snow depth and maximum snow depth for each station during 1966-2012, with  
13  $p \leq 0.05$ . The significant increasing trends (blue circles) of annual mean snow depth  
14 occurred in most of European Russia, the south of Siberia and the Russian Far East,  
15 the northern Xinjiang Autonomous Region of China, and Northeast China (Fig. 8a6a).  
16 In contrast, decreasing trends (red circles) were detected in western European Russia,  
17 some regions of Siberia, the north of the Russian Far East, and some regions to the  
18 south of 40 °N across in China. Over the entire Eurasian continent, the most  
19 significant linear trends in annual mean snow depth were observed in the regions  
20 north of 50 °N, which indicated that the increasing rate of annual mean snow depth  
21 was greater in higher latitude regions.

22 Changes in the maximum snow depth were similar to those in annual mean snow  
23 depth in most of Eurasian areas from 1966 to 2012, but the magnitude of changing the  
24 change rates in of the maximum snow depth were greater than the values of annual  
25 mean snow depth (Fig. 8b6b). The significant increasing trends were observed in the  
26 same regions as those with increases in annual mean snow depth. Generally, the  
27 decreasing trends were found in generally in the same regions where the same  
28 locations as decreases in annual mean snow depth decreased and there were, with  
29 greater reductions in the southern of Siberia and the Russian Far East.

30 In October and November, there were few stations with significant increasing

1 ~~trend~~changes in snow depth ( $P \leq 0.05$  at the 95 % level) (Figs. 9a7a- and b). The  
2 increasing trends were mainly observed in most areas across the Eurasian continent in  
3 October ~~although the magnitudes were generally small. Over November, But~~ the  
4 increasing trends ~~of in~~ snow depth only appeared in Siberia and the Russian Far East,  
5 ~~in November. The~~ whereas decreasing trends ~~occurred~~ in monthly mean snow depth  
6 ~~occurred in the~~ over eastern ~~regions of~~ European Russia, the southern ~~areas of the~~  
7 West Siberian Plain, and ~~some areas of~~ the northeast Russian Far East.

8 In winter months (December, ~~January and~~ February), there was a gradual  
9 expansion in areas with increasing trends in monthly mean snow depth variation with  
10  $P \leq 0.05$  at the 95 % level (Figs. 9e7c-e), ~~and this mainly occurred in. There were~~  
11 ~~increasing trends of monthly mean snow depth in the~~ eastern ~~regions of~~ European  
12 Russia, southern ~~parts of~~ Siberia, the northern Xinjiang Autonomous Region of China,  
13 and Northeast China. In contrast, significant decreasing trends were observed in ~~the~~  
14 northern and western ~~of~~ European Russia, ~~and were~~ scattered in Siberia, the northeast  
15 ~~of the~~ Russian Far East, and northernmost areas of China.

16 From March to May, the number of stations with significant changes ( $P \leq 0.05$  at  
17 ~~the 95 % level~~) in monthly mean snow depth decreased, especially in May because of  
18 snow melt (only 78 stations) (Figs. 9f7f-h). Changes in monthly mean snow depth  
19 were consistent with the trends in winter over the former USSR, but more stations  
20 with decreasing trends were found in southern Siberia. There were few stations with  
21 statistically significant trends ~~of in~~ snow depth across China; for these stations,  
22 monthly snow depths tended to decrease ~~in at~~ most stations. Compared with  
23 ~~regions~~ the south of 50 °N, ~~the~~ changes in monthly mean snow depth were more  
24 significant ~~over regions to the~~ north of 50 °N.

### 26 3.3 Variability of Snow Depth with Latitude, Elevation and Continentality

27 Topography is an important factor affecting the climatology of snow depth and is  
28 the main reason accounting for the inhomogeneity of data (Grünwald and Lehning,  
29 2011, 2013; Grünwald et al., 2014). To explore the spatial variability of snow depth,  
30 we conducted a linear regression analysis of the annual mean snow depth with latitude,

1 elevation and continentality (Fig. 108). Snow depth ~~is was~~ positively correlated with  
2 latitude, i.e., snow depth generally ~~increases increased~~ with latitude (Fig. 10a8a). The  
3 ~~increased~~ rate of snow depth was ~~about approximately~~ 0.81 cm per 1 °N ~~across the~~  
4 ~~Eurasian continent~~. ~~We detected a~~ closer relationship between latitude and snow  
5 depth ~~was found in regions to the~~ north of 40 °N (Figs. 10a8a, ~~and d~~) ~~where. In these~~  
6 ~~regions~~, snow cover was relatively stable ~~with~~ (the number of annual mean  
7 continuous snow cover days ~~was at~~ more than 30) (Zhang and Zhong, 2014), ~~in which~~  
8 ~~snow cover was easier to accumulate by the heavy snowfall and more difficult to melt~~  
9 ~~with low air temperature~~.

10 There was a negative correlation between snow depth and elevation across the  
11 Eurasian continent (Fig. 10b8b); ~~with every 100 m increase in elevation, snow~~  
12 ~~depth decreased by ~0.5 cm ( $P \leq 0.05$ ). Annual mean snow depth was less than 1 cm~~  
13 ~~in most areas, with an elevation greater than 2000 m, because a snow depth of 0 cm~~  
14 ~~was used to calculate the mean snow depth. Therefore, although the TP is at a high~~  
15 ~~elevation, the shallow snow depth in this area resulted in the a generally negative~~  
16 ~~correlation between snow depth and elevation across the Eurasian continent. However,~~  
17 ~~we also determined found~~ that snow depth increased with elevation in most regions  
18 north of 45 °N (Fig. 10d8d). ~~This result indicates that elevation is an important factor~~  
19 ~~affecting snow depth in these regions~~.

20 There was a statistically significant positive relationship between snow depth and  
21 continentality over the Eurasian continent, ~~but the correlation coefficient was not high~~  
22 ( $r=0.1$ ,  $P \leq 0.05$ , Fig. 10e8c). This indicated that the continentality ~~is may be~~ not an  
23 important driving factor of snow ~~cover climatology~~ depth distribution over Eurasia,  
24 especially on the TP. ~~though it will determine the snowfall rate.~~ Although the  
25 previous studies showed that the Tibetan Plateau's largest snow accumulation  
26 occurred in the winter, the precipitation during the winter months was the smallest of  
27 the year (Ma, 2008). This was mainly due to the majority of annual precipitation that  
28 occurs during the summer monsoon season on the TP, which causes much less  
29 precipitation during the winter half year (or the snow accumulated season).

30

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

In addition to the terrain factors, variations in snow depth are closely related to climate variability. To examine the relationship between snow depth and climatic factors, we calculated the long-term mean snow depth, air temperature and snowfall of 386 stations from November through March across the former USSR (Fig. 449). The period (snow cover years) spanned from 1966 through 2009 because data on air temperature and precipitation were recorded only until 2010 using available data. Snow depth significantly decreases with increasing air temperature ( $P \leq 0.05$ ), but the Goodness of Fit of the relationship was only 16% (Fig. 449a). Compared with the air temperature, snowfall exhibited a better-strong relationship with snow depth (Fig. 449b). The mean snow depth was less than 20 cm at most stations with the accumulated snowfall being of <50 mm from November through March. Snow depth increased with an increase in the accumulated snowfall increased, and the thickest snow depth of approximately reached 120 cm when had the a maximum cumulative snowfall was of approximately 350 mm.

Compared with the long-term inter-annual trends of changes in snow depth, SWE, air temperature and snowfall, the variabilities of snow depth and SWE were mainly affected by the changes in snowfall. Overall, the trends in long-term air temperature, precipitation, snowfall and SWE displayed increasing trends from November to March (Fig. 4210). 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 a greater supply of moisture for snowfall, and hence the snow accumulation still increased (Ye et al., 1998). The significant increasing snowfall can explain the sudden drop in the bulk snow density from the mid-1990s through the early 2000s (Zhong et al., 2014): increasing snowfall should decrease the density of the surface snowpack, which lowered the whole entire density of the snowpack. There were basically consistent trends of variations in snow depth, SWE and snowfall accumulation from November through March during 1966-2009 (Figs. 42b10b-d). The results indicated that the increasing trend in snow depth was the combined effect of the increasing air temperature and snowfall.

1 The partial correlation coefficients between snow cover and air temperature, ~~as~~  
2 ~~well as~~ and snow cover and snowfall were calculated to discuss the spatial  
3 relationship between them (Fig. 1311). ~~The~~ A significant negative correlation ( $p \leq$   
4 0.05) between snow depth and air temperature ~~was~~ presented in most areas of  
5 European Russia and ~~the~~ southern Siberia (Fig 13a11a). The stations with negative  
6 effects of air temperature on SWE were fewer, and there were no statistically  
7 significant correlations in ~~the~~ northern Siberia (Fig 13b11b). ~~It~~ This was because there  
8 was no obvious effect of increasing temperature on snow depth when the air  
9 temperature was below 0 °C which occurred in most areas of Siberia during from  
10 December through March, ~~the increasing temperature did not have an obvious effect~~  
11 ~~on snow depth.~~

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

## 19 4 Discussion

### 20 4.1 Comparison with Previous Results

21 Studies on changes in snow depth have received much attention over different  
22 regions across Eurasian continent. This study, for the first time, investigated changes  
23 in snow depth using ground-based data and information over the region as a whole.  
24 Ma and Qin (2012) investigated changes in snow depth across China over period from  
25 1957 to 2009. Comparing our results with previous research across the Eurasian  
26 continent, we We found that the climatology (1966-2012) of ~~mean~~ snow depth from  
27 this study was basically consistent with that the results from described in the previous  
28 studies in China (Ma and Qin, (2012), over China. In terms of changes in snow depth,  
29 both studies showed increase in snow depth but with slight difference in magnitude.  
30 This may be caused by using different number of stations and covering different study

1 periods. Over northern Eurasia, Kitaev et al. (2005) and Bulygina et al. (2011)  
2 investigated snow depth and its change. The long-term (1966-2012) mean snow depth  
3 from this study but was approximately 5-10 cm higher than the results from Kitaev et  
4 al. (2005) and Bulygina et al. (2011) over that in northern Eurasia (~~Kitaev et al., 2005;~~  
5 ~~Bulygina et al., 2011~~). These discrepancies may result from differences in the time  
6 frame of data collection, the number of stations, calculation methods, and data quality  
7 control. For example, Kitaev et al. (2005) investigated ~~reported a~~ historical ~~record~~  
8 ~~of changes in~~ snow depth spanning 65 years ~~the period~~ from 1936 to 2000, while this  
9 study covered 47 years from 1966 through 2010. In this study, we intentionally did  
10 not use the earlier (1936-1965) data due primarily to data quality. The earlier Russian  
11 snow depth data were discontinuous and did not meet the data quality control  
12 requirements used in this study. Historical changes of the hydrometeorological  
13 stations locations were also critical reason for deleting many stations from the study.  
14 Based on results from this study, we believe that snow depth data in early years (prior  
15 to 1965) may be questionable and changes in snow depth prior to 1965 over Russia  
16 need further in-depth investigation. ~~with the onset and end of the snow year earlier~~  
17 ~~than the definition used in this study. Nevertheless, the distributions of high snow~~  
18 ~~depth in the two studies were located in the same regions and the regional and~~  
19 ~~continental inter-annual and inter-decadal variations were consistent.~~

20 Ye et al. (1998) ~~Previous research~~ found that historical winter snow depth  
21 increased in northern Russia most areas (30-140°E, 50-70°N 1.86 cm/yr) and  
22 decreased in southern Russia at a rate of -0.23 cm/yr ~~with the exception of European~~  
23 ~~Russia~~, during 1936-1983 (Ye et al., 1998). Results from this study were essentially  
24 consistent with Ye et al. (1998) in northern Russia, however, in southern Siberia  
25 where snow depth increased at a rate of 0.42 cm/yr during the period from 1966 to  
26 2012. We believe that the difference is mainly due to the time periods covered by the  
27 two studies., which was similarly to our results. However, in the present study, we  
28 found that decreasing trends also appeared in some regions of the southern portion of  
29 western and central Siberia. The time sequence of the observations may be the main  
30 reason for this difference. Compared with our study, the areas with increasing trends

1 ~~in snow depth reported by Ma and Qin (2012) were larger in China. Snow depth~~  
2 ~~increased significantly in on the north-eastern TP in their results. The differences may~~  
3 ~~have been caused by the different statistical methods and interpolation of nearby~~  
4 ~~stations in the study of Ma and Qin (2012).~~

5 ~~In addition to the above reasons, these differences can be explained by the~~  
6 ~~changes in climatic factors during the different study periods.~~ The sensitivity of snow  
7 ~~cover depth~~ to air temperature and precipitation for each station showed regional  
8 differences (Fallot et al., 1997; Park et al., 2013). The amount of snowfall can be  
9 affected by climate change, and leading to differences in snow depth at different times  
10 (Ye et al., 1998; Kitaev et al., 2005; Ma and Qin, 2012). ~~We found~~~~The results of our~~  
11 ~~study showed~~ that there was a significant ( $p \leq 0.05$ ) negative relationship between  
12 snow depth and air temperature in ~~the~~ southern Siberia, ~~however, it did not exist but~~  
13 ~~not~~ in ~~the~~ northern Siberia. ~~This may explain the difference in the results of these~~  
14 ~~studies.~~In addition to air temperature and precipitation, atmospheric circulation was a  
15 key factor affecting snow depth change (Cohen, 2011; Zhao et al., 2013; Ye et al.,  
16 2015). Those factors above and related uncertainties may explain the regional and  
17 temporal differences in long-term mean snow depth and snow depth change.

18  
19 Liston and Hiemstra (2011) conducted snow depth assimilation using the  
20 SnowModel. Results from the SnowModel assimilations in general agree well with  
21 ground-based measurements. For example, both observations in our research from this  
22 study and assimilations with the SnowModel (Liston and Hiemstra, 2011) presented  
23 that the peak snow depth and SWE occurred more in the western portion of northern  
24 Eurasia than the western portion of the Russian Far East. This may be primarily  
25 because the SnowModel input data included ground-based measured air temperature,  
26 precipitation, wind conditions and in part snow depth. However, results from CMIP5  
27 (Coupled Model Intercomparison Project, Terzago et al., 2014, Wei and Dong, 2015)  
28 overestimated snow depth over the Qinghai-Tibetan Plateau and underestimated in the  
29 forest regions. This implies that large uncertainties currently still exist in modeling  
30 snow depth.

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

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

1 of snow depth, and is the main reason causing the inhomogeneity of data. Previous  
2 studies have analyzed the representation of snow depth for single stations to solve the  
3 issue (Grünewald and Lehning, 2011, 2013; Grünewald et al., 2014). However, in the  
4 present study, we did not discuss this question because of the complexity of spatial  
5 difference. But we still got some interesting conclusions: There was a closely relationship  
6 between snow depth and elevation at the local scale. However, compared with latitude, the  
7 correlation between them was not so significant in the whole Eurasian Continent. Moreover,  
8 the continentality did not play a great role in spatial distribution of snow depth, especially on  
9 TP. The previous studies showed that the Tibetan Plateau's largest snow accumulation  
10 occurred in the winter, but the snowfall during winter months is the smallest of the year (Ma,  
11 2008). This was mainly due to majority of annual precipitation occurs during the summer  
12 monsoon season on TP which cause very less snowfall during winter half year (or snow-  
13 accumulated season). Furthermore, the water vapor from the east and west was blocked by the  
14 Hengduan Mountains and Nyainqentanglha Mountains, respectively, which resulted in less  
15 snowfall. Although there was more snowfall in spring, snow cover was not easy to  
16 accumulate with higher temperatures. Therefore, snow depth was shallow on TP in general. In  
17 addition to topographic factors, spatial distribution of snow depth was also affected by  
18 atmospheric circulation. We will discuss this issue in the future studies.

## 19 20 **5 Conclusions**

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

29 There were statistically significant trends in variations in long-term snow depth  
30 over the entire Eurasian continent as a whole. A similar increasing pattern of changes

1 was exhibited in both annual snow depth and maximum snow depth, although the  
2 amplitude of the maximum snow depth anomaly was much larger than the equivalent  
3 value for mean snow depth. Monthly snow depth in autumn presented a decreasing  
4 trend, ~~while-whereas~~ there were increasing trends in the~~of~~ variations ~~of-in~~ snow depth  
5 during winter and spring, especially during the period of the mid-1980s through the  
6 2000s.

7 Significant increasing trends in snow depth were detected in the eastern regions  
8 of European Russia, ~~the~~ southern Siberia, the Russian Far East, the northern areas of  
9 the Xinjiang Autonomous Region of China, and north-eastern China. Decreasing  
10 linear trends were observed in most western areas of European Russia, some regions  
11 of southern Siberia, the north-eastern Russian Far East and most areas in the southern  
12 40 °N across China.

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

19

## Appendix A: Analysis of serial correlation

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

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

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

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

$$X'_t = X_t - \rho X_{t-1} \quad (A2)$$

$$Y'_t = Y_t - \rho Y_{t-1} \quad (A3)$$

where  $X'$  was the corrected year,  $Y'$  was the corrected anomalies in time series of snow depth for each station in this research, and the autocorrelation coefficient  $\rho$  was replaced by its estimated  $r$ :

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

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

3 The Durbin-Watson test results show that there were no serial correlations in the  
4 inter-annual trends in annual mean snow depth, maximum snow depth and monthly  
5 mean snow depth for all of the composite data ( $d_u \leq d \leq 4 - d_u$ ) (Table A1).

6 However, the serial correlation was present in some stations when we calculated the  
7 linear trend of annual snow depth, maximum depth and monthly mean snow depth for  
8 each station. The percentage of the stations with a serial correlation for annual snow  
9 depth and maximum depth were 18% and 21%, respectively. In the monthly test, the  
10 smallest proportion appeared in October approximately 11%; the largest percentage of  
11 these stations for all of the stations was found in February and was up to 21%. Then,  
12 the Cochran-Orcutt method was used to correct the variables and re-estimated the  
13 trends in snow depth for these station (Fig. 6-7 in the text). Using the Dikson site  
14 (73.5° N, 80.4° E, 42 m a.s.l.) as an example, the serial correlation was present when  
15 the trend in annual mean snow depth was calculated. Compared with the corrected  
16 result, the variance of the previous OLR statistic was overestimated, and annual mean  
17 snow depth increased at the rate of 0.113 cm/yr (Table A2). The corrected result  
18 indicated that the variation of inter-annual mean snow depth was not significant  
19 ( $P' > 0.05$ ). The serial correlation cannot be ignored for detecting trends in a time series  
20 of snow cover variables, which possibly invalidates the statistical test on slopes if this  
21 variable is not dealt with.

22  
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- 3

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2

1 **Tables and Figures**

2 **Table 1.** Sources of snow depth data

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

3

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

	$\underline{d}_1$	$\underline{d}_u$	$\underline{d}$	$\underline{slope}^*$	$\underline{P}^*$
<u>Mean</u>	<u>1.3034</u>	<u>1.3871</u>	<u>1.6435</u>	<u>0.02</u>	<u>0.0016</u>
<u>Maximum</u>	<u>1.3034</u>	<u>1.3871</u>	<u>1.8824</u>	<u>0.06</u>	<u>0.0004</u>
<u>October</u>	<u>1.3034</u>	<u>1.3871</u>	<u>2.1377</u>	<u>-0.01</u>	<u>0.0069</u>
<u>November</u>	<u>1.4872</u>	<u>1.5739</u>	<u>2.3667</u>	<u>0.00</u>	<u>0.7408</u>
<u>December</u>	<u>1.4872</u>	<u>1.5739</u>	<u>1.9684</u>	<u>0.02</u>	<u>0.0793</u>
<u>January</u>	<u>1.3034</u>	<u>1.3871</u>	<u>1.6326</u>	<u>0.04</u>	<u>0.0014</u>
<u>February</u>	<u>1.3034</u>	<u>1.3871</u>	<u>1.8469</u>	<u>0.06</u>	<u>0.0000</u>
<u>March</u>	<u>1.3034</u>	<u>1.3871</u>	<u>1.9874</u>	<u>0.06</u>	<u>0.0003</u>
<u>April</u>	<u>1.4872</u>	<u>1.5739</u>	<u>1.6754</u>	<u>0.03</u>	<u>0.0187</u>
<u>May</u>	<u>1.4872</u>	<u>1.5739</u>	<u>2.0703</u>	<u>0.00</u>	<u>0.5811</u>

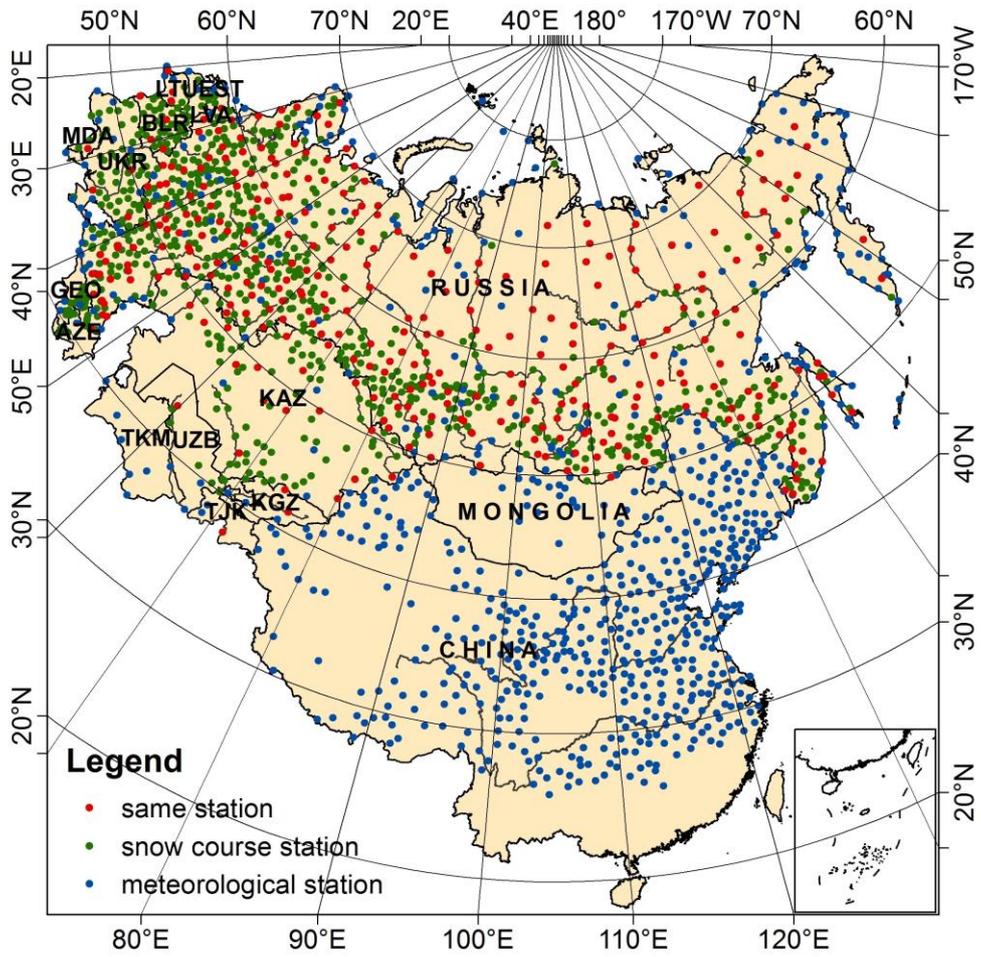
5 \*: slope was the trend of changes in snow depth, the unit was cm/yr; P was the confidence level.

6 **Table A2.** Trends in annual mean snow depth with the Durbin-Watson test for Dikson site during  
7 1966-2012

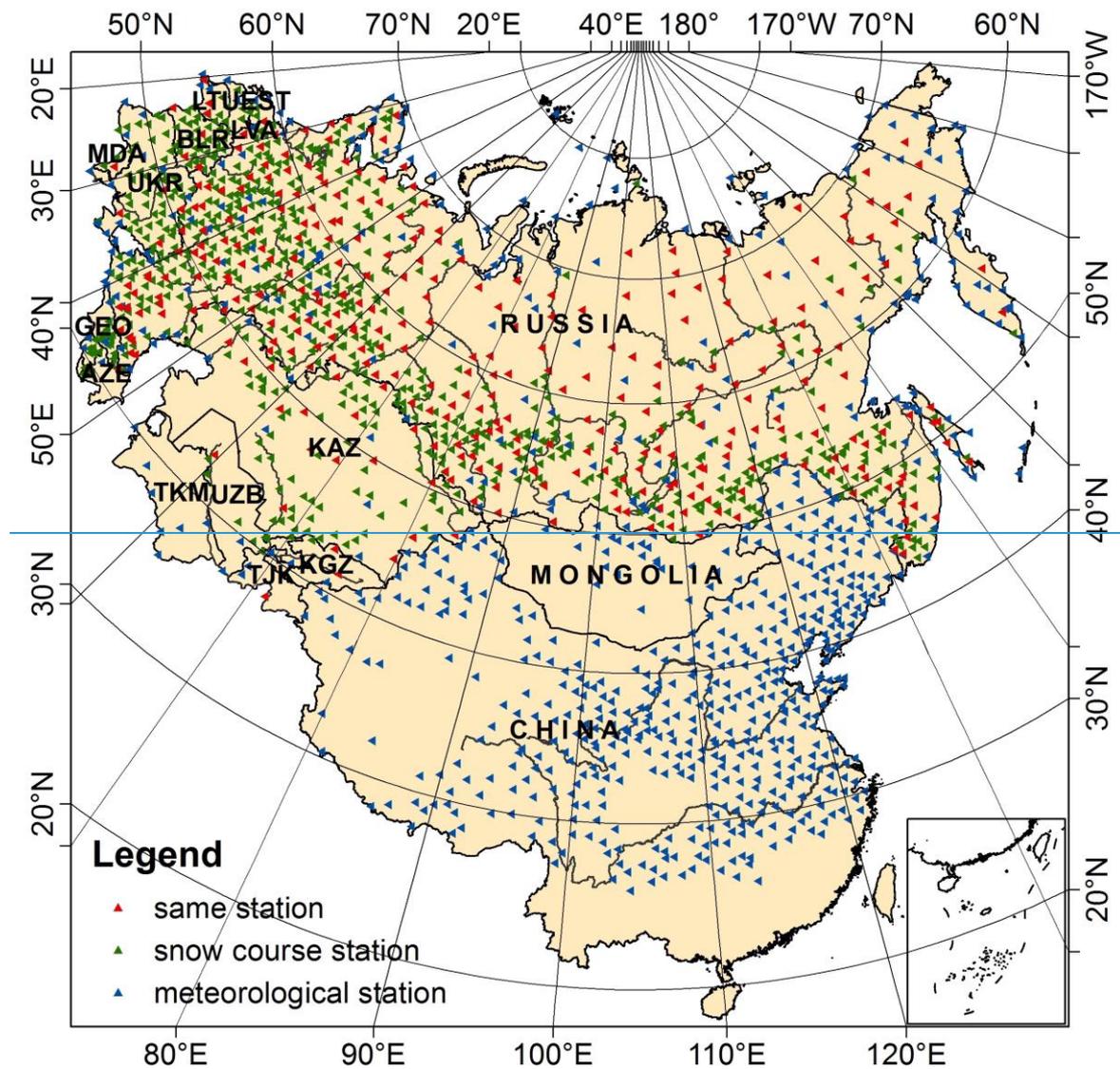
<u>ID</u>	<u>d<sub>1</sub></u>	<u>d<sub>u</sub></u>	<u>d</u>	<u>slope</u>	<u>P</u>	<u>d'<sub>1</sub></u>	<u>d'<sub>u</sub></u>	<u>d'</u>	<u>slope'<sup>*</sup></u>	<u>P'<sup>*</sup></u>
<u>20674</u>	<u>1.4872</u>	<u>1.5739</u>	<u>1.2856</u>	<u>0.113</u>	<u>0.016</u>	<u>1.4872</u>	<u>1.5739</u>	<u>2.0249</u>	<u>0.0942</u>	<u>0.055</u>

1 \*: slope' was the corrected trend of changes in snow depth, the unit was cm/yr; P' was the corrected confidence  
2 level.

3



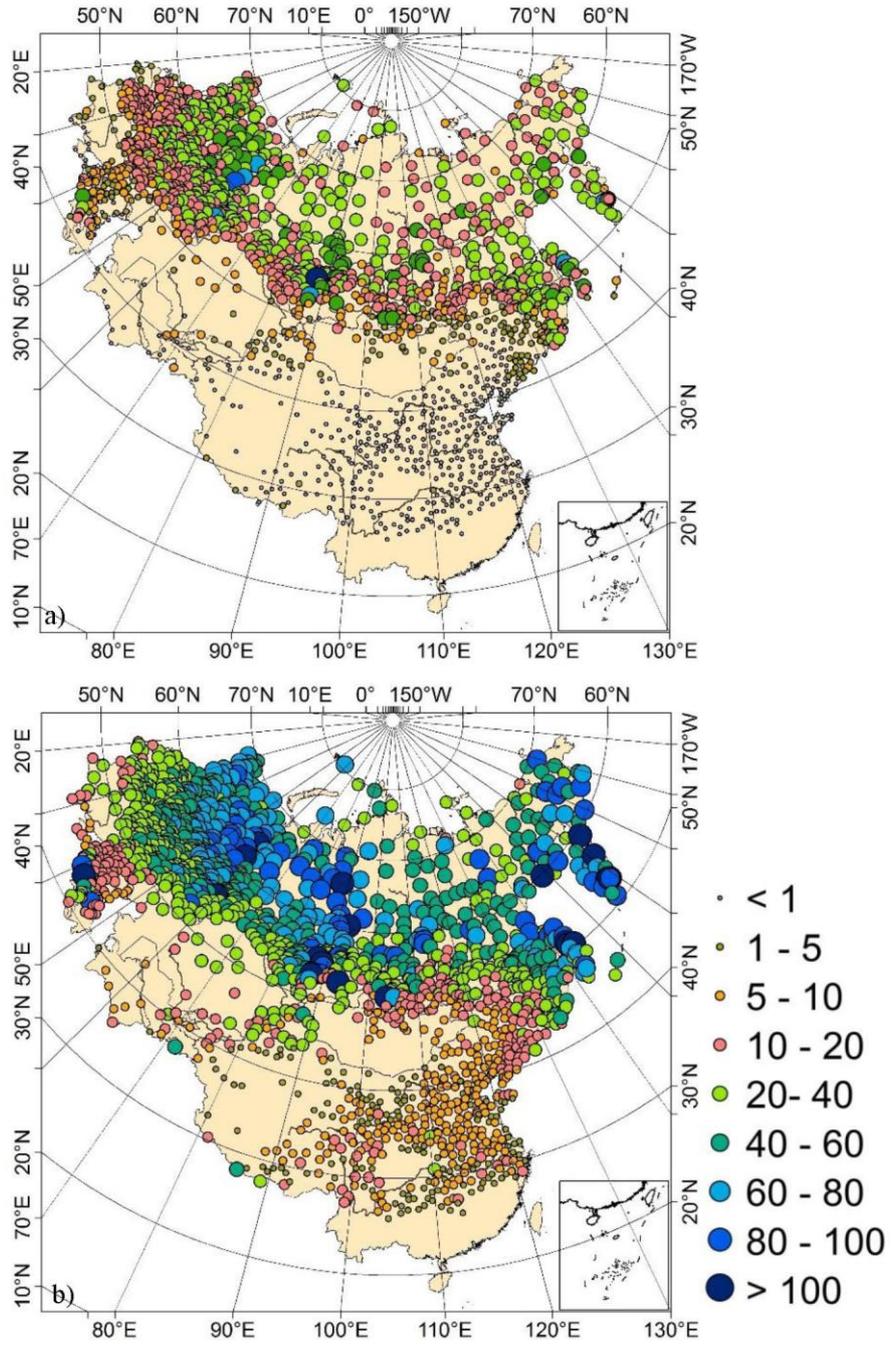
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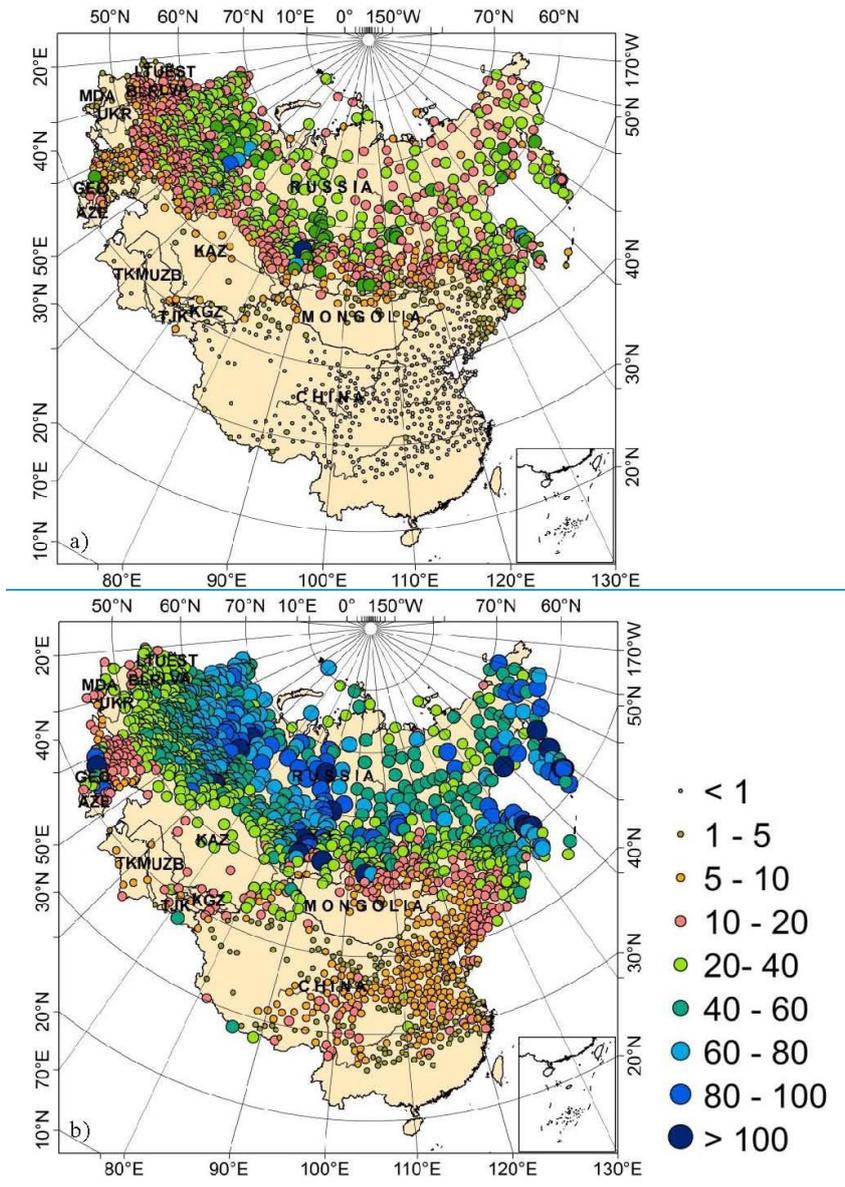


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2 **Figure 1.** Geographical locations of meteorological and snow course stations across the Eurasian  
 3 continent. The red triangles represent stations where snow depth was measured at both  
 4 meteorological stations and snow course surveys, the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

7

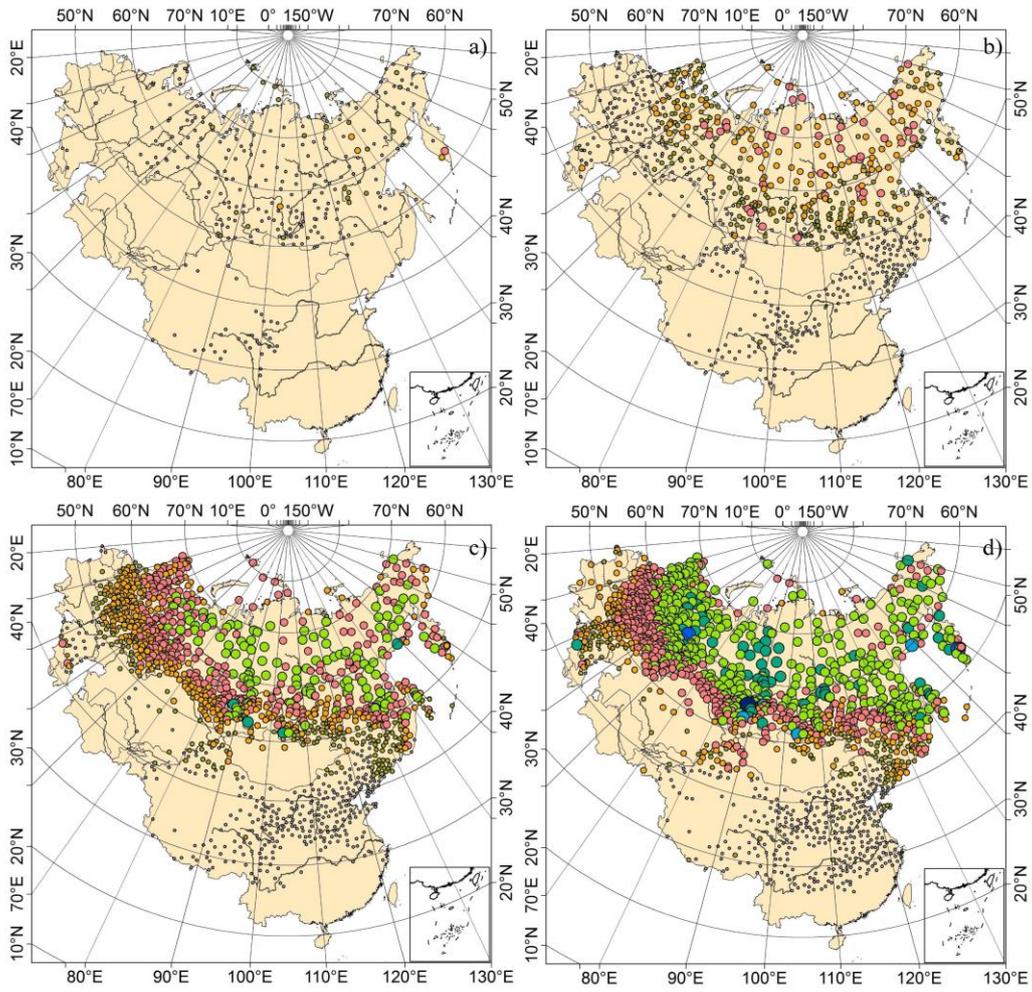




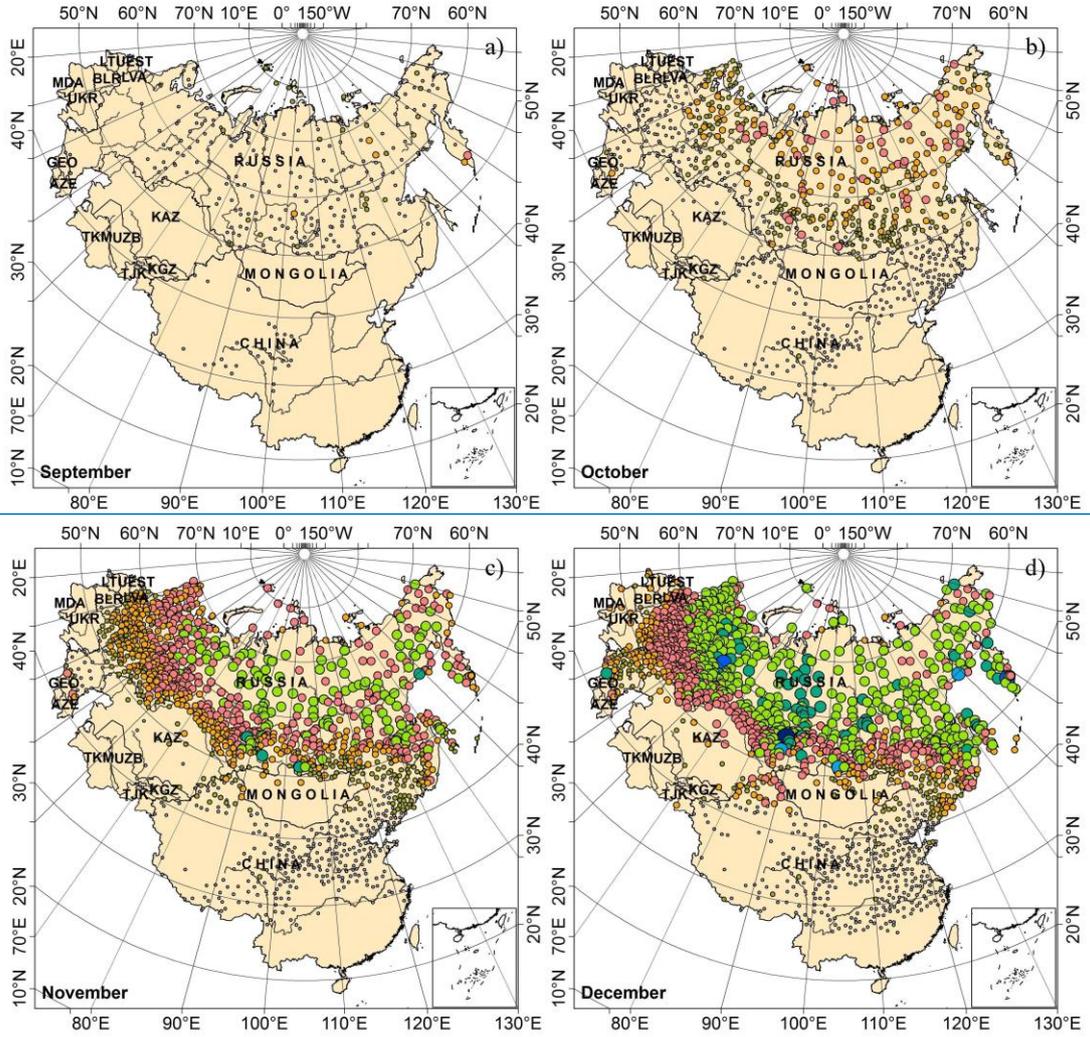
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2 **Figure 2.** Annual mean snow depth (a) and maximum snow depth (b) across the Eurasian  
 3 continent (cm) during 1966-2012.

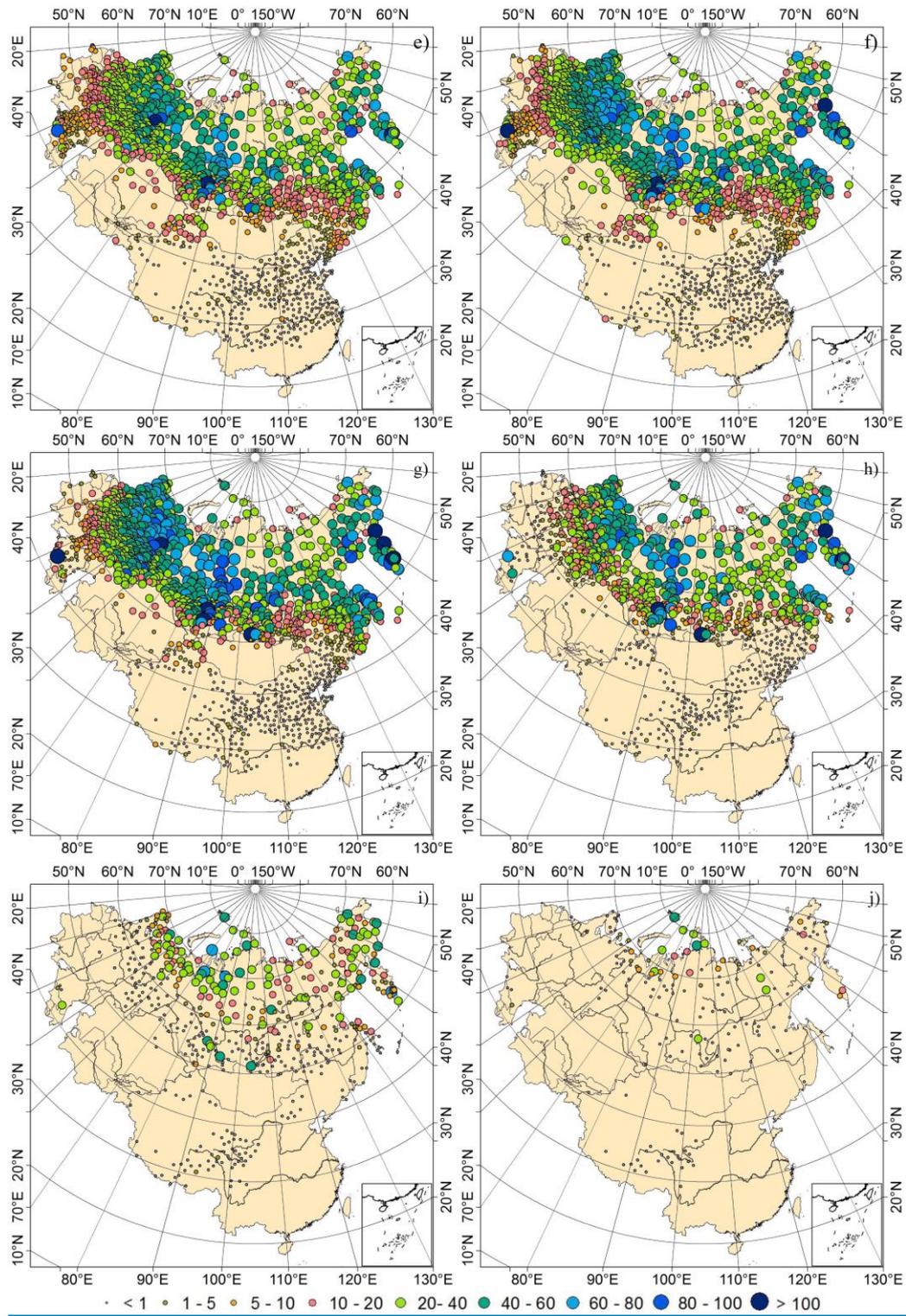
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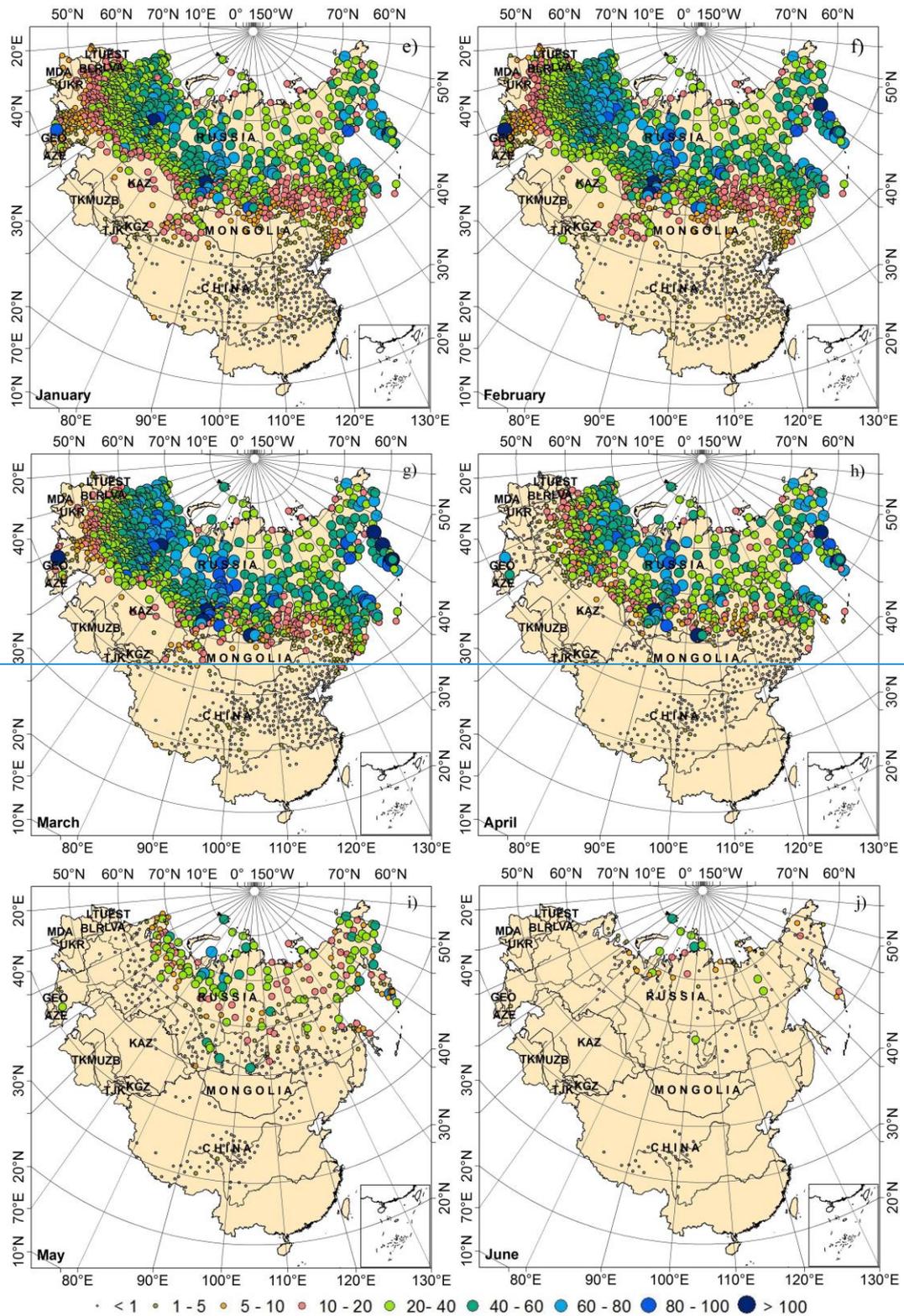
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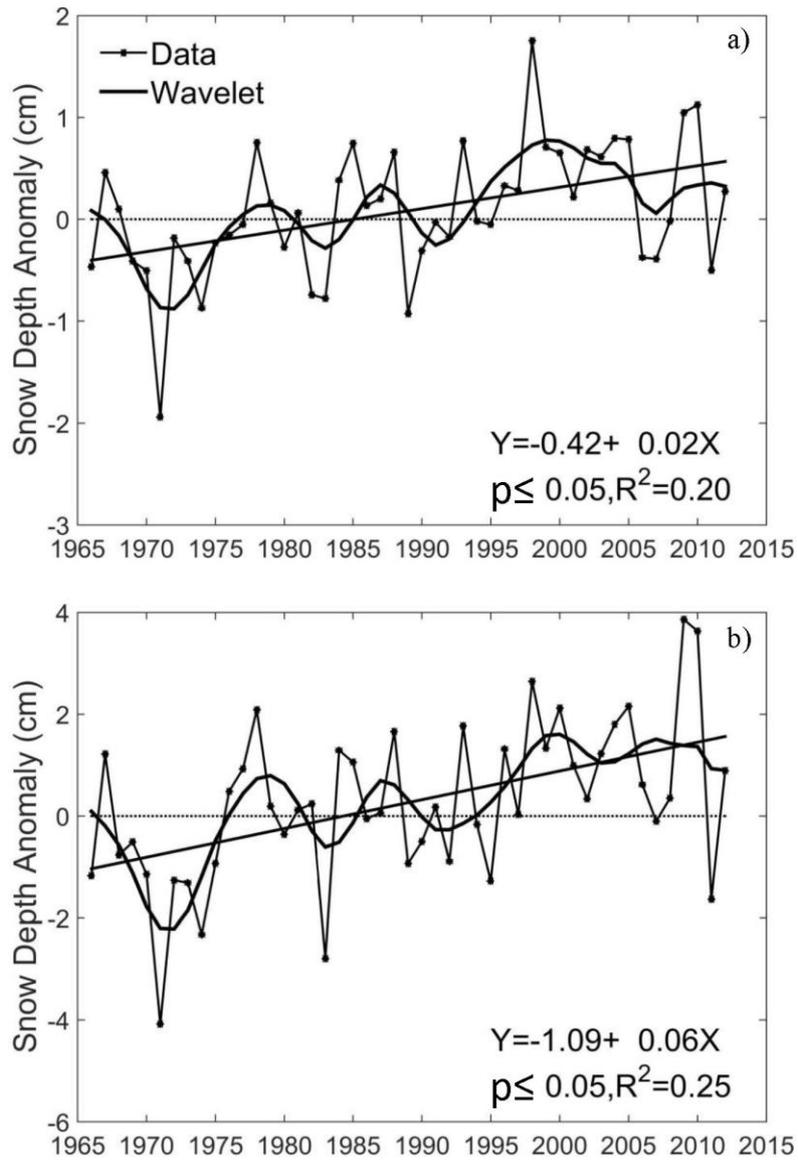


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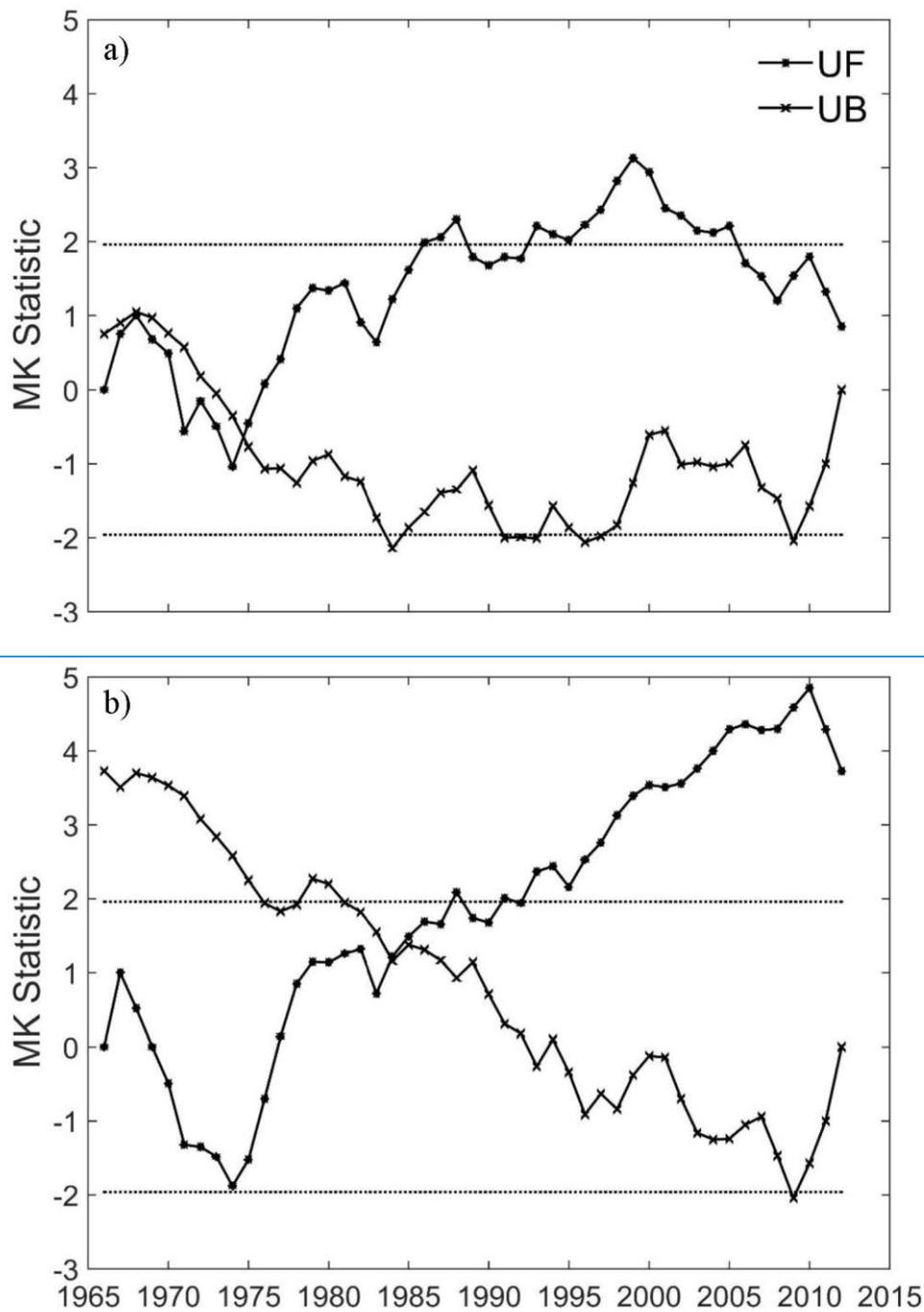


1

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



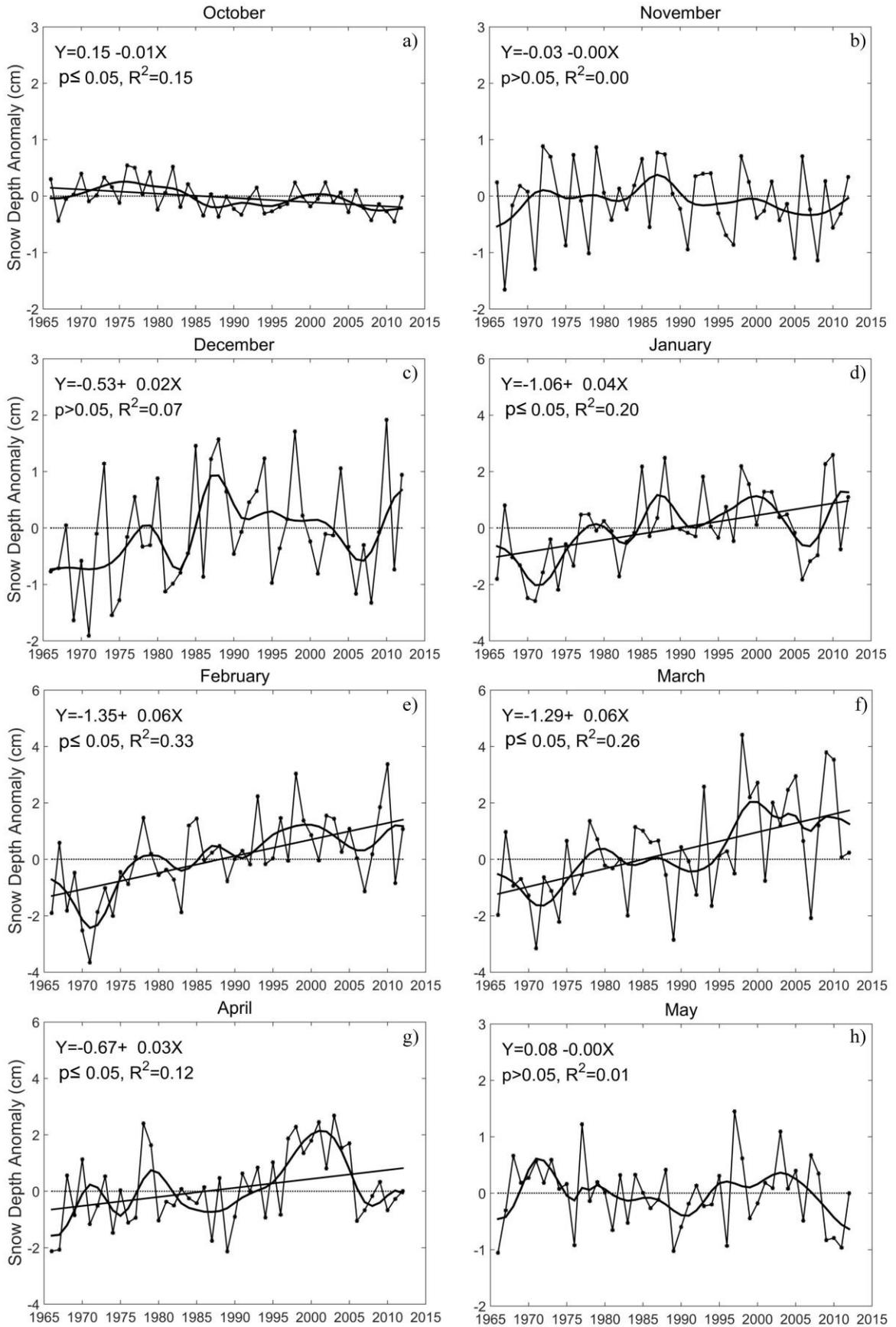
1  
2 **Figure 4.** Composite of inter-annual variation of annual mean snow depth (a) and maximum snow  
3 depth (b) from 1966 through 2012 with respect to the 1971-2000 mean across the Eurasian  
4 continent. The line with dots is the anomaly of snow depth; the thick curve represents the  
5 smoothed curve using wavelet analysis; the thick line presents a linear regression trend.  
6



1

2 [Figure 5. Mann-Kendall statistical curve of annual mean snow depth \(a\) and maximum snow depth \(b\) from 1966-](#)

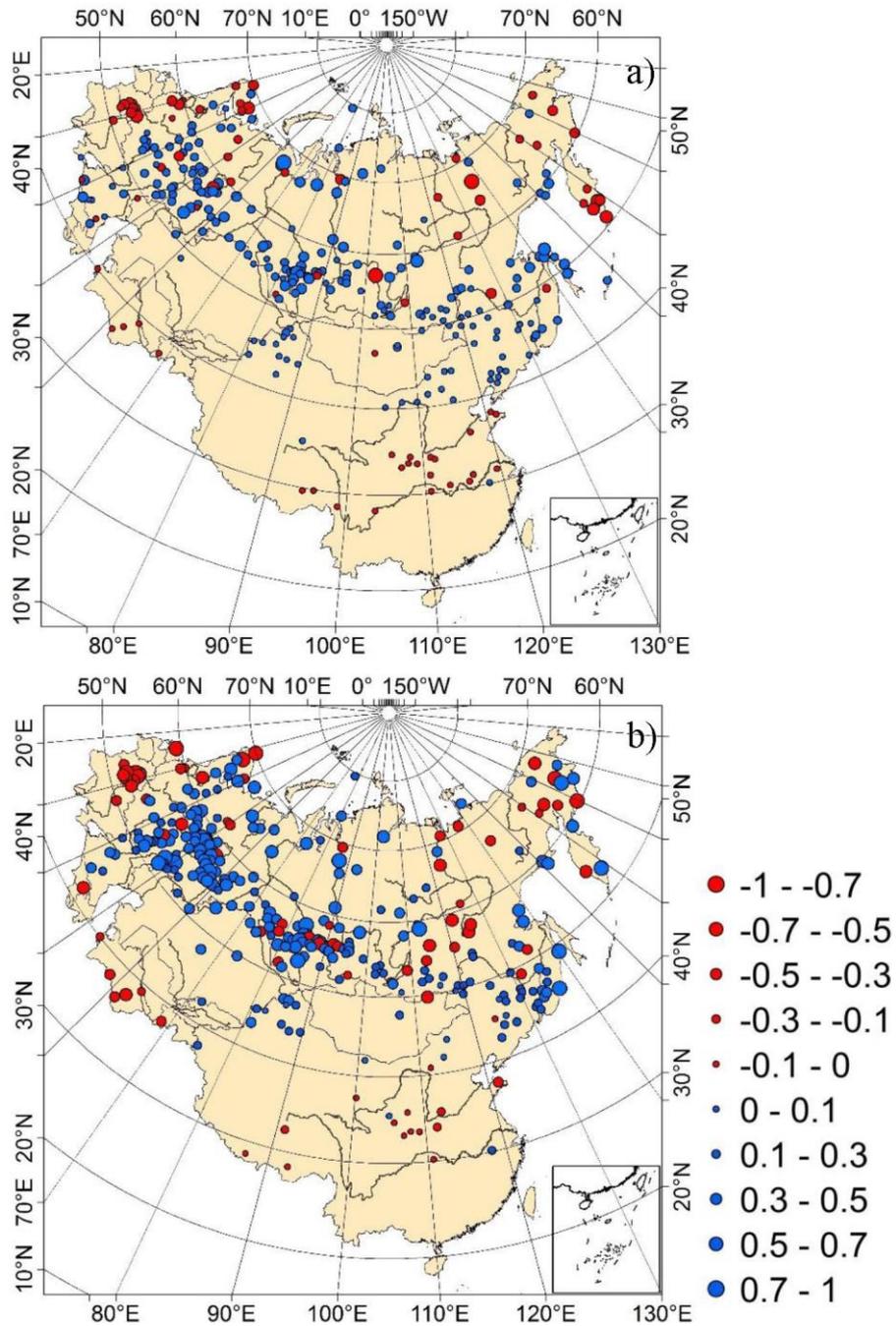
3 [through 2012 across the Eurasian continent. Straight line presents significance level at 0.05.](#)



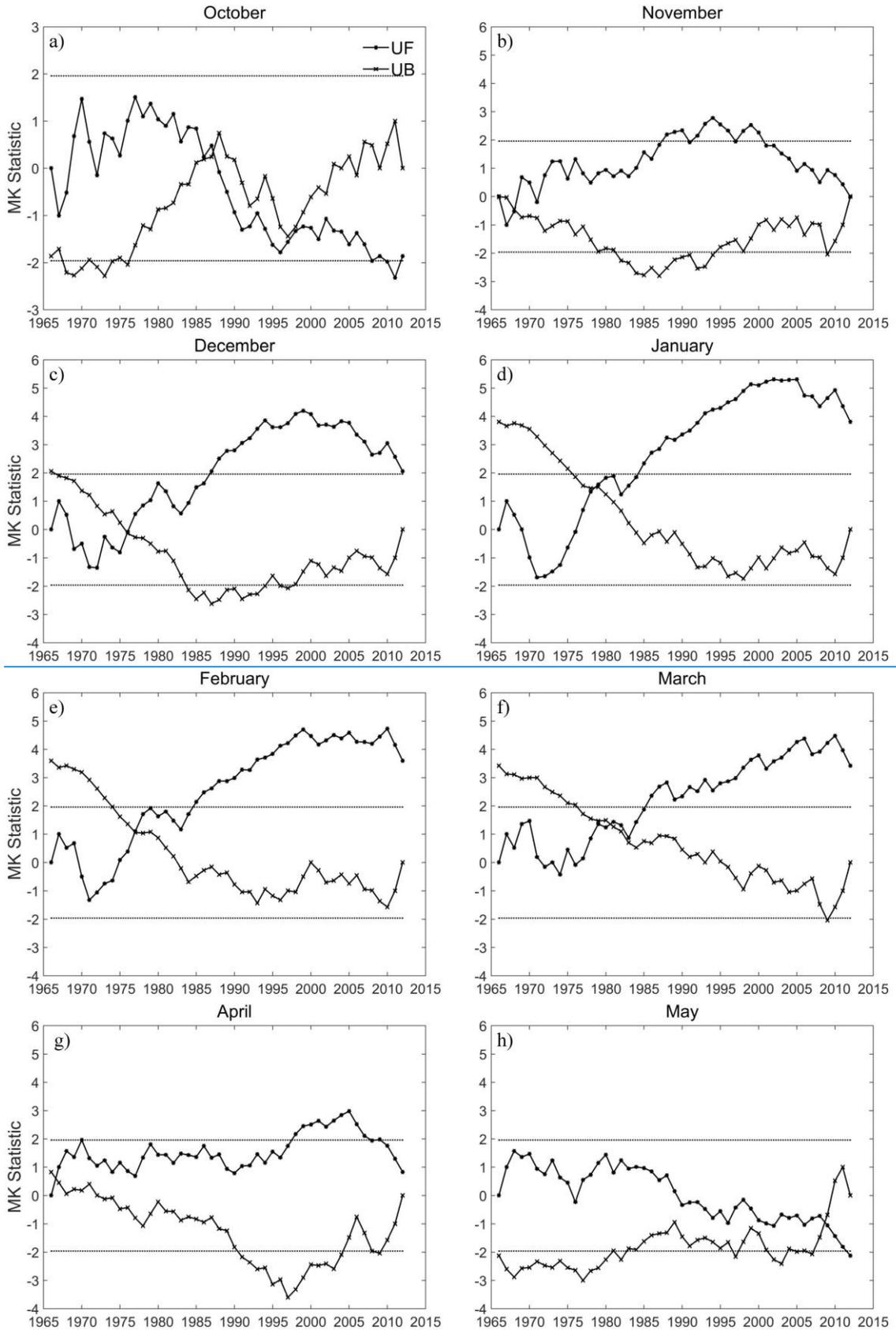
1

2 **Figure 65.** Composites of inter-annual variation of monthly mean snow depth (from October to

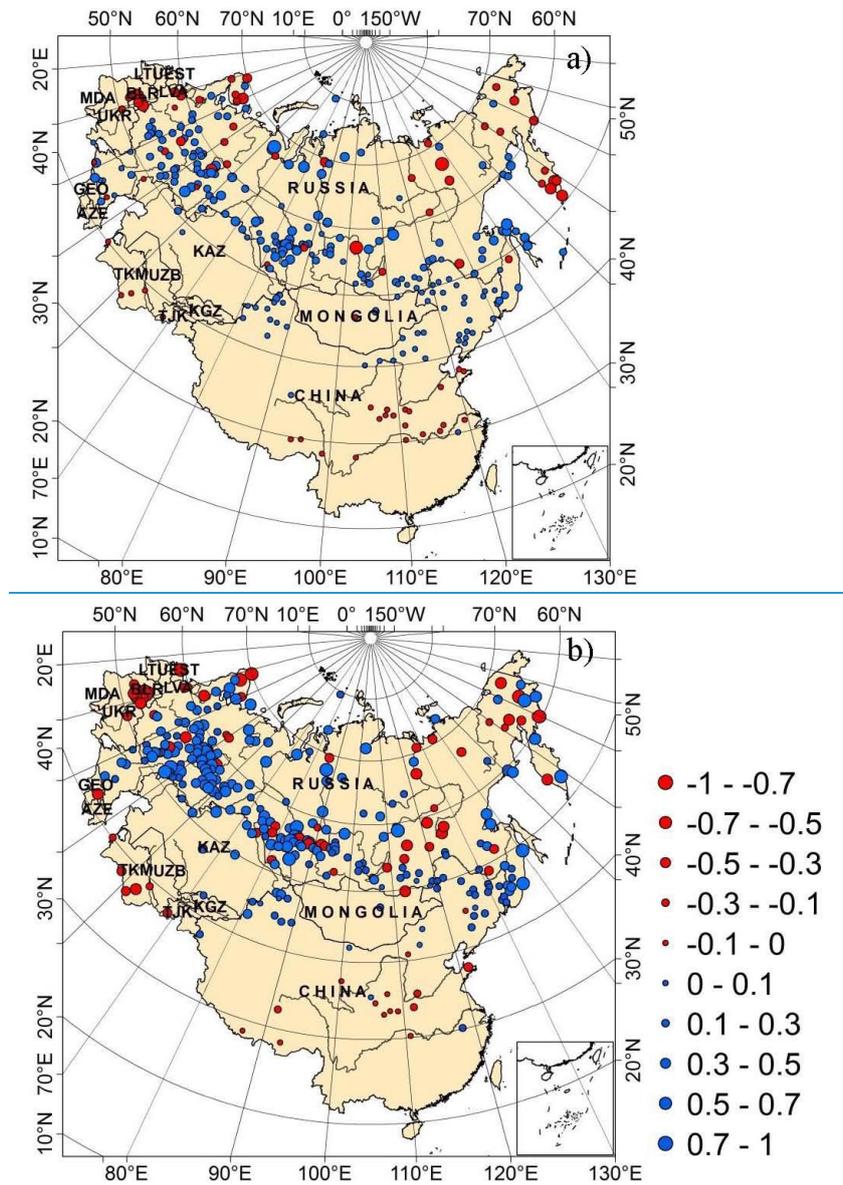
1 May) from 1966 through 2012 with respect to the 1971-2000 mean across the Eurasian continent.  
 2 (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May.  
 3 The line with dots is the anomaly of snow depth; the thick curve represents the smoothed curve 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



6



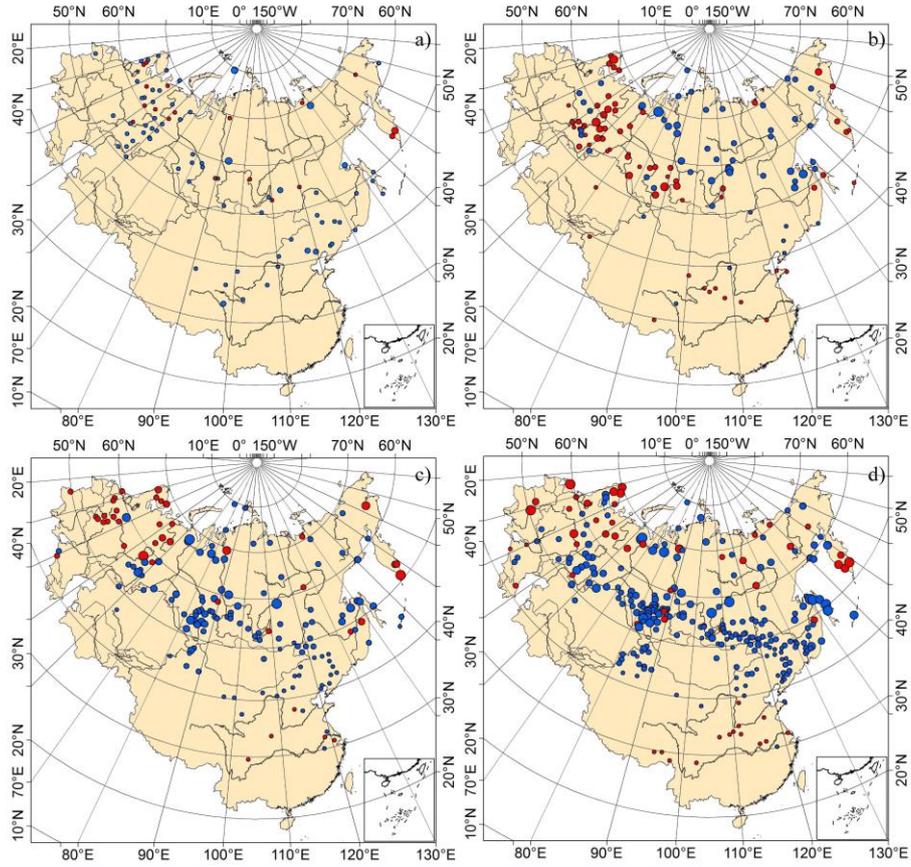
1  
 2 [Figure 7. Mann-Kendall statistical curve of monthly mean snow depth \(from October to May\) from 1966 through](#)  
 3 [2012 across the Eurasian continent. \(a\) October, \(b\) November, \(c\) December, \(d\) January, \(e\) February, \(f\) March,](#)  
 4 [\(g\) April, \(h\) May. Straight line presents significance level at 0.05.](#)



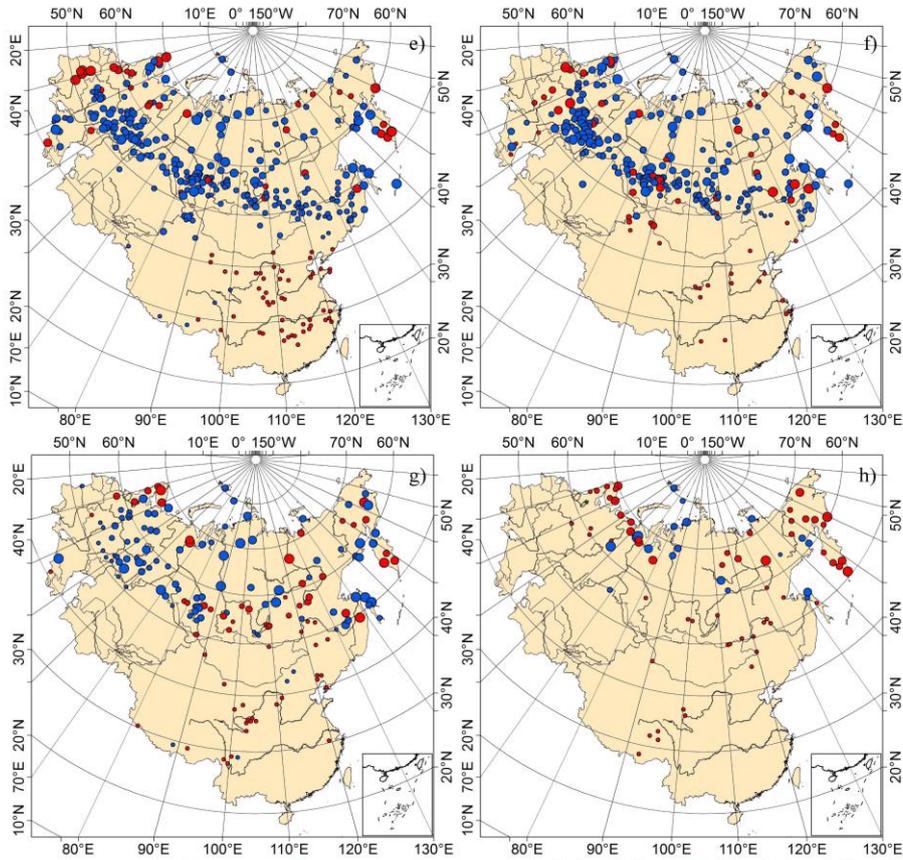
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2 **Figure 86.** Spatial distribution of linear trend coefficients (cm yr<sup>-1</sup>) of annual mean snow depth (a)  
 3 and maximum snow depth (b) for each station in 1966-2012. The rate of change was at the 95%  
 4 level. Red circles represent a decreasing trend, and blue circles represent an increasing trend.

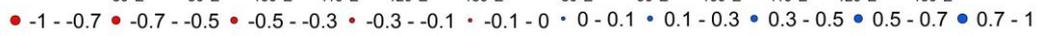
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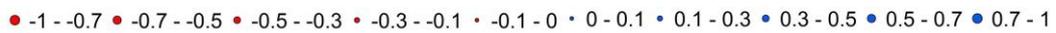
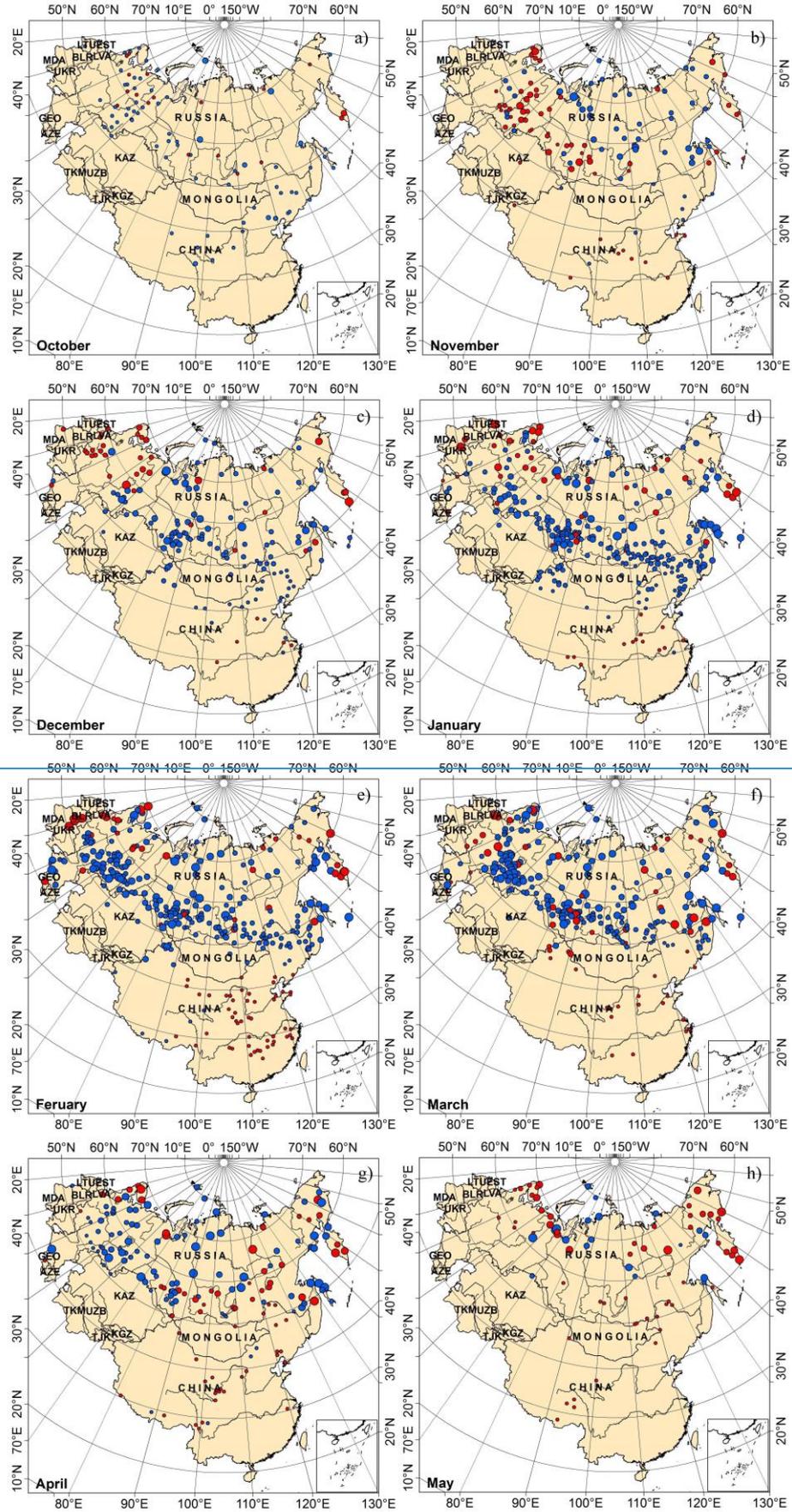


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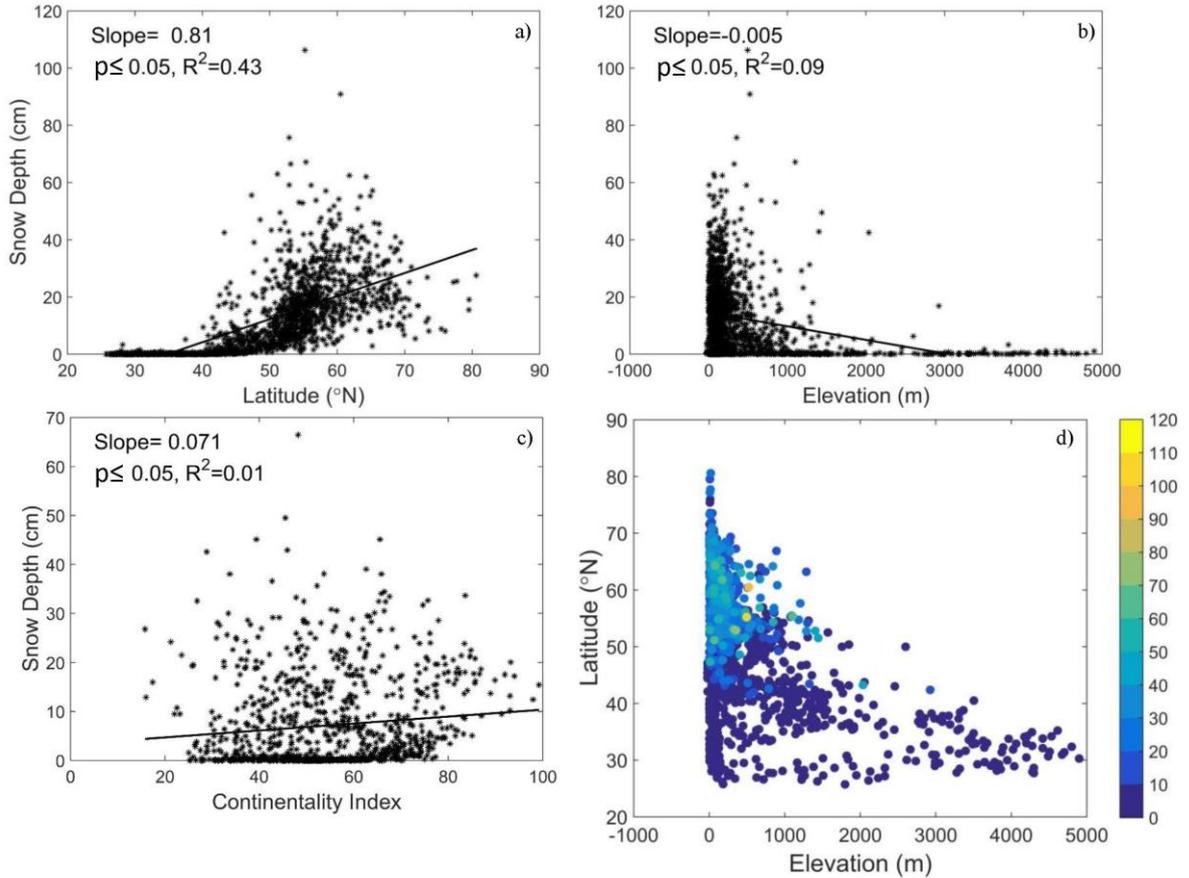
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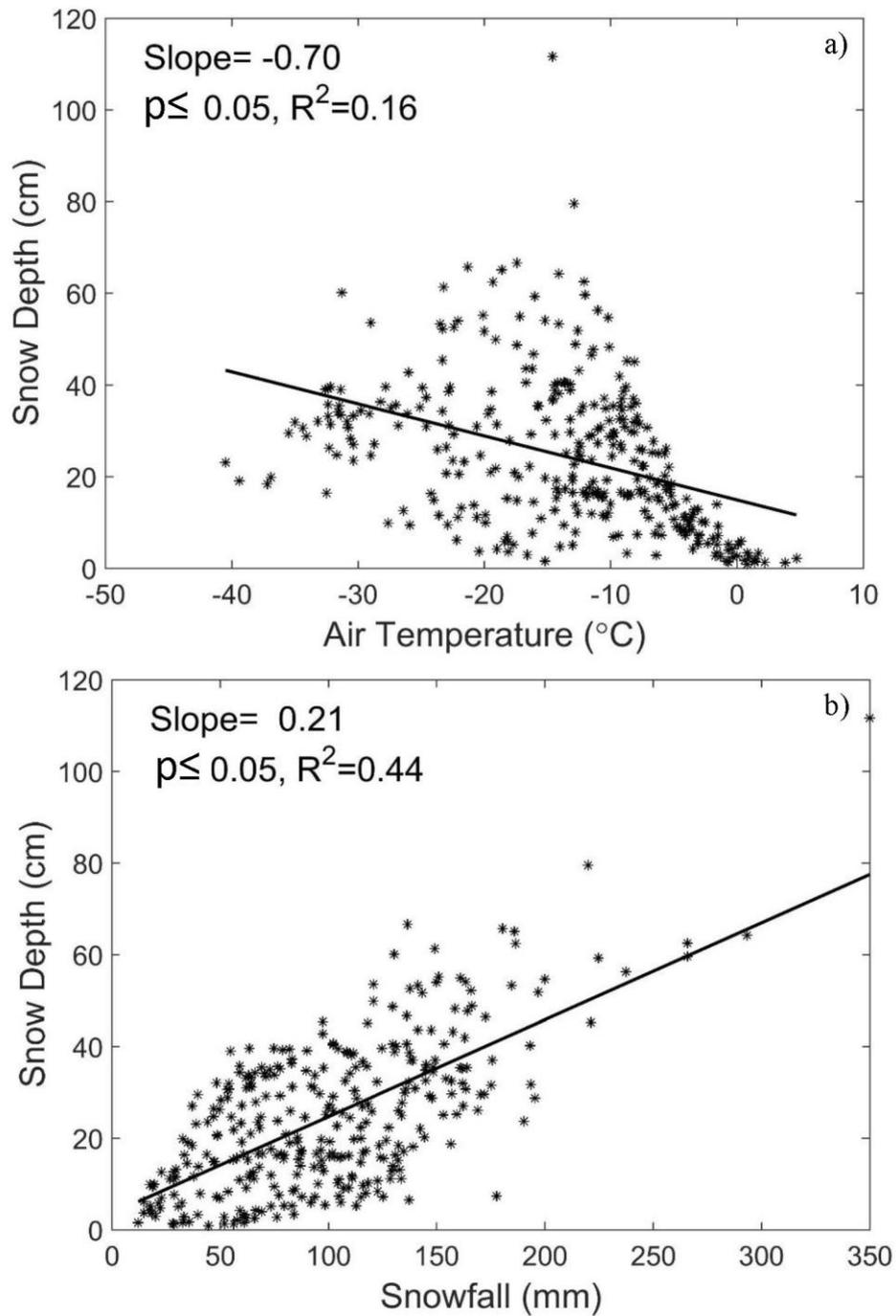
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1 **Figure 97.** Spatial distributions of linear trend coefficients (cm yr<sup>-1</sup>) of monthly mean snow depth  
 2 (from October to May) during 1966 to 2012. (a)October, (b) November, (c) December, (d) January,  
 3 (e) February, (f) March, (g) April, (h) May. The rate of change was at the 95% level. Red circles  
 4 represent a decreasing trend, and blue circles represent an increasing trend.  
 5



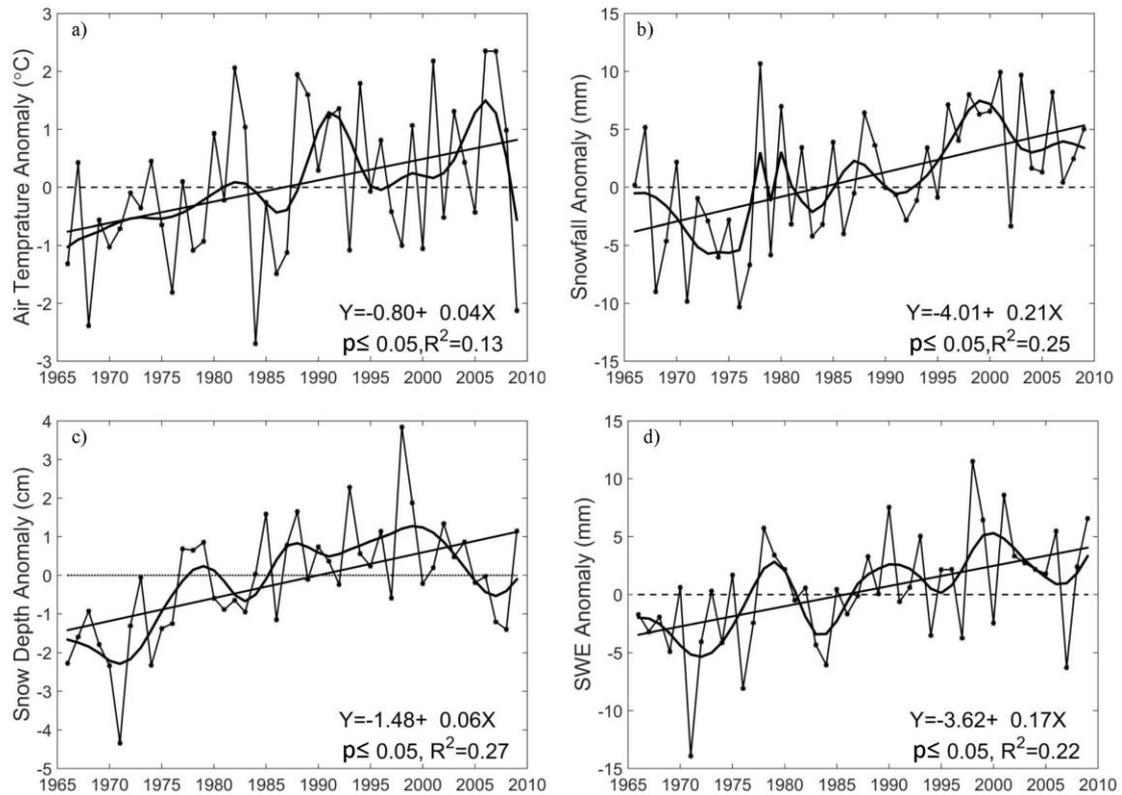
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 7

8 **Figure 108.** The relationship between annual mean snow depth and latitude (a), elevation (b) and  
 9 continentality (c) for all stations across the Eurasian continent during 1966-2012. Asterisks show  
 10 the mean snow depth of each station; the thick line is a linear regression trend; the different colors  
 11 represent snow depth (cm) of each station (d).



1

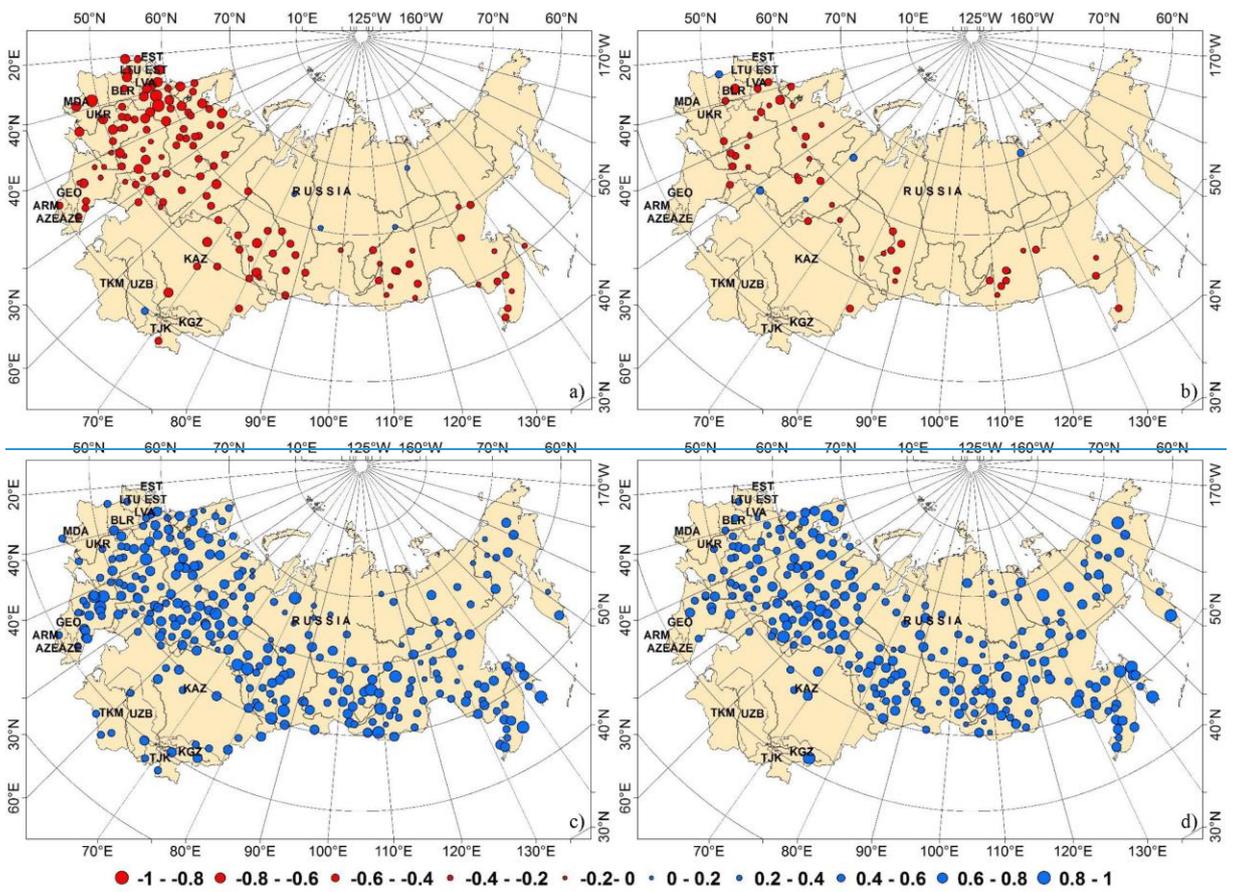
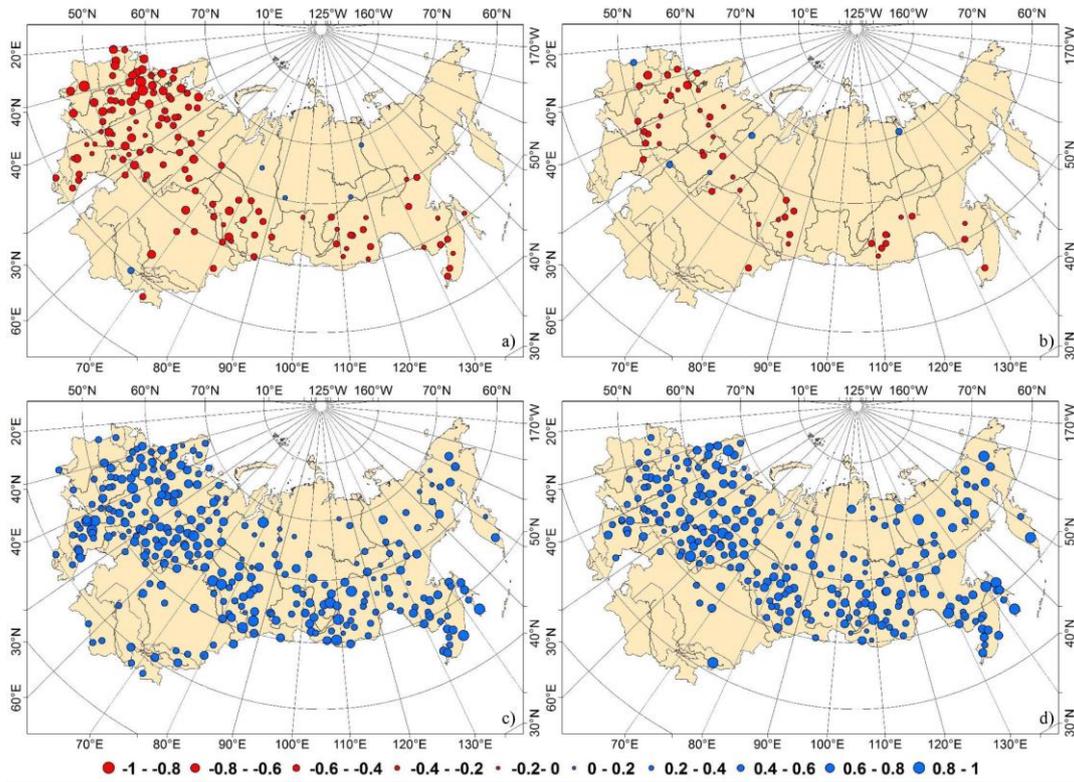
2 **Figure 119.** The relationships among annual mean snow depth, air temperature and snowfall for  
 3 386 stations from November through March during 1966-2009 over the USSR. The thick line is a  
 4 linear regression trend.



1

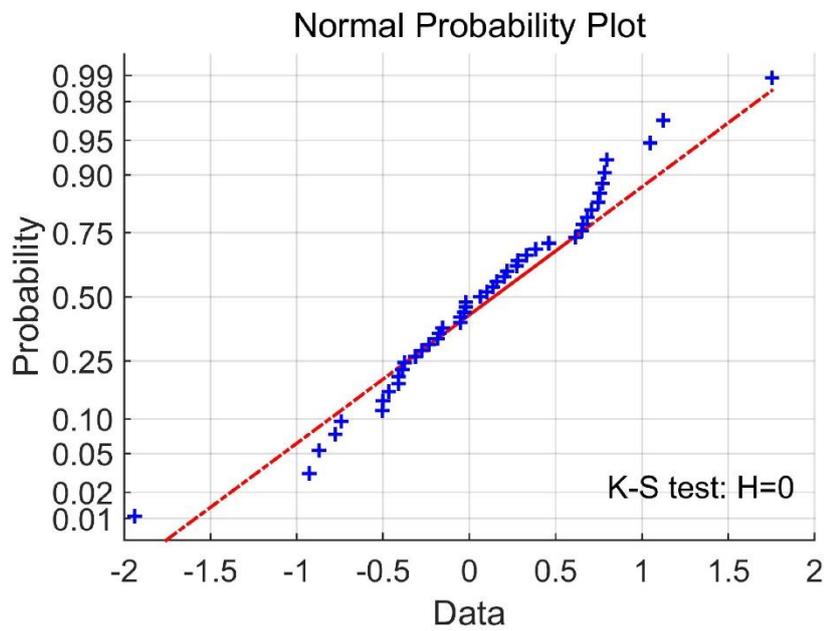
2 **Figure 1210.** Composite of inter-annual variation of annual mean air temperature (a), annual  
 3 snowfall (b), annual snow depth (c) and snow water equivalent (d) from November through March  
 4 during 1966-2009 with respect to the 1971-2000 mean across the former USSR. The line with dots  
 5 is the composite of the annual means; the thick curve represents the smoothed curve using wavelet  
 6 analysis; the thick line presents a linear regression trend.

7



3 **Figure 1311.** 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  
 4 from November through March during 1966-2009. The coefficients reaching to 0.05 **confident**  
 5

1 [level confidence level](#) are displayed. Red circles represent a negative relationship, and blue circles  
2 indicate a positive relationship.  
3



4  
5  
6

[Figure A1. Normal distribution test of annual mean snow depth for all station by K-S test.](#)