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 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.

"**Appendix:** Analysis of serial correlation

In this research, the Kolmogorov-Smirnov (K-S) test was used to determine whether snow depth data could have come from a normal distribution. The results showed that all station data were in a normal distribution (such as annual mean snow depth for all station, Fig. 1). We used ordinary linear regression (OLR) to detect trends of changes in snow depth. Failure to consider the serial correlation of data could lead to erroneous results when detect the trends in time series of snow depth mainly because the probability of detecting false trends would be increased (Westherhead et al, 1998; Storch, 1999; Khaliq et al., 2009). In order to avoid this situation, we used the Durbin-Watson test to check the serial correlation (Neter et al., 1989; Tao et al., 2008):

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

where e_t is the residual estimated by the OLR. d_1 is the lower limit, d_u is the upper limit. If $d_u \leq d \leq 4 - d_u$ serial correlation is not absent, if $d \leq d_1$ or $d \geq 4 - d_1$ serial correlation is present.

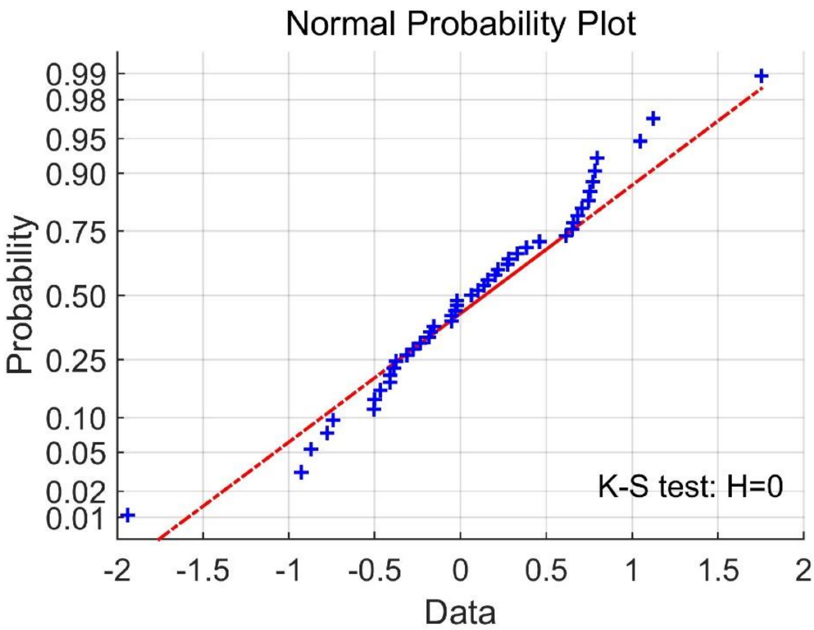

Figure 1. Normal distribution test of annual mean snow depth for all station by K-S test.

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

$$X_t' = X_t - \rho X_{t-1} \qquad (2)$$

$$Y_t' = Y_t - \rho Y_{t-1} \qquad (3)$$

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

$$\mathrm{r} = \frac{\sum_{t-2}^{n} e_{t-1} e_t}{\sum_{t-2}^{n} e_{t-1}^2} \qquad (4)$$

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

The Durbin-Watson test results showed that there were no serial correlations in the inter-annual trends of annual mean snow depth, maximum snow depth and monthly mean snow depth for all composite data ($d_u \leq d \leq 4 - d_u$) (Table 1). 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 serial correlation for annual snow depth and maximum depth were 18% and 21%, respectively. In the monthly test, the smallest proportion appeared in October, about 11%; the largest percentage of these stations for all stations was found in February, up to 21%. Then 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). Took Dikson site (73.5ºN, 80.4ºE, 42m a.s.l.) as an example: the serial correlation was present when the trend in annual mean snow depth was calculated. Comparing with the corrected result, the variance of the previous OLR statistic was overestimated (Table 2). 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 time series of snow cover variables, which possibly invalidate the statistical test on the slopes if undealt with.

Table1. Trends in snow depths with the Durbin-Watson test across Eurasia during 1966-2012

	d_u	d	$slope$	P^*
Mean	1.3525	1.6435	0.02	0.0016
Maximum	1.6534	1.8824	0.06	0.0004
October	1.6324	2.1377	-0.01	0.0069
November	1.6277	2.3667	0.00	0.7408
December	1.6532	1.9684	0.02	0.0793
January	1.3542	1.6326	0.04	0.0014
February	1.6521	1.8469	0.06	0.0000
March	1.4536	1.9874	0.06	0.0003
April	1.3242	1.6754	0.03	0.0187
May	1.7726	2.0703	0.00	0.5811

*: P is the confidence level.

Table 2. Trends in annual mean snow depth with the Durbin-Watson test for Dikson site during

1966-2012								
ID	d_u	d	$slope$	P	d'_u	d'	$slope'$	P'
20674	1.7234	1.2856	0.113	0.016	1.6345	2.0249	0.0942	0.055

References

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

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

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.

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.

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."

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? Incoroportate 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 papes 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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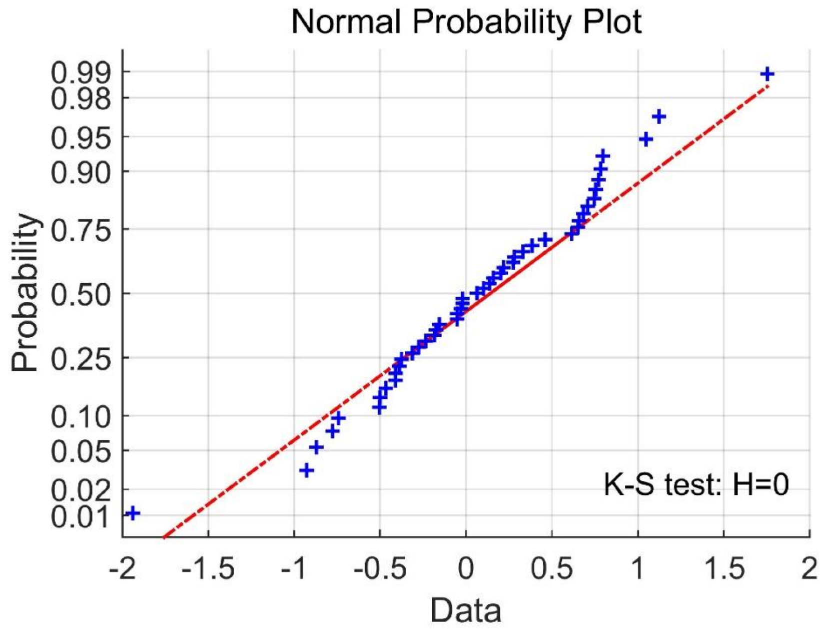

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April	1.3242	1.6754	0.03	0.0187
May	1.7726	2.0703	0.00	0.5811

*: P is the confidence level.

Table 2. Trends in annual mean snow depth with the Durbin-Watson test for Dikson site during 1966-2012

ID	d_u	d	$slope$	P	d'_u	d'	$slope'$	P'
20674	1.7234	1.2856	0.113	0.016	1.6345	2.0249	0.0942	0.055

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 rangers) 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 Eurasian continent since the meteorological observation standard was established by the former USSR and followed by all the former USSR republics, Mongolia and China. Snow depth is one of the standard elements to be measured on daily basis (WMO, 1996)."

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 have inhomogeneities in the time series over the period of record. Forturnately, there was no change in procedure and technique of snow depth measurements since 1965 in Russia and the other countries in this study (Bulygina et al., 2009). In this study, therefore, we chose to use snow depth data from 1966 to 2012."

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 is deleted. (2) Stations with sudden step changes of snow depth are eliminated from the list. (3) Stations with less than 20 years of data during the 1971-2000 period were excluded from the analysis. (4) At each station, we eliminated data points which exceed two standard deviations from their long-term (1971-2000) mean."

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

“Daily precipitation was partitioned into a solid and liquid fraction, based on daily mean temperature (Brown, 2000). The solid fraction of precipitation, Srat, was estimated by:

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

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

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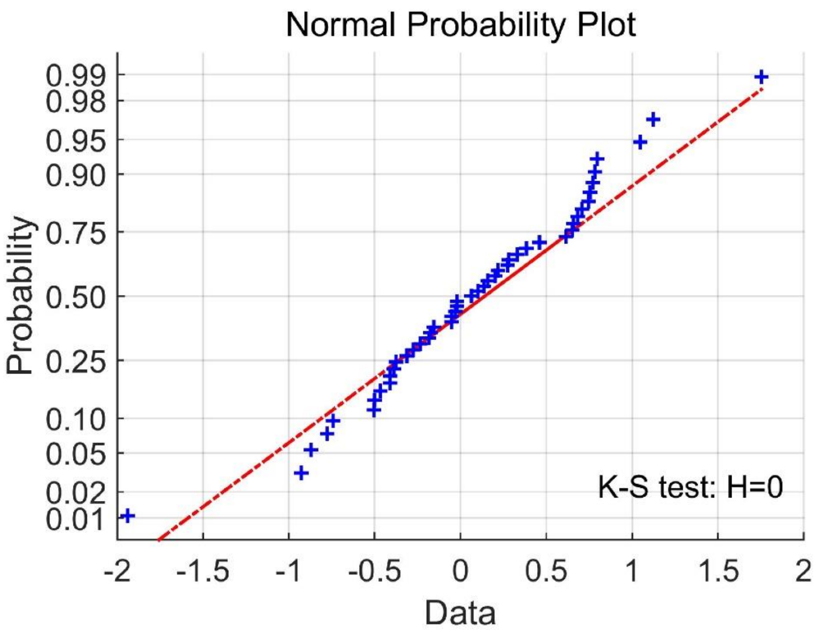
$$\mathrm{d} = \frac{\sum_{t=2}^{n}(e_t - e_{t-1})^2}{\sum_{t=1}^{n} e_t^{\,2}} \qquad (1)$$

where e_t is the residual estimated by the OLR. d_1 is the lower limit, d_u is the upper limit. If $d_u \le d \le 4 - d_u$ serial correlation is not absent, if $d \le d_1$ or $d \ge 4 - d_1$ serial correlation is present.



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

$$r = \frac{\sum_{t-2}^{n} e_{t-1} e_t}{\sum_{t-2}^{n} e_{t-1}^2} \tag{4}$$

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

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October	1.6324	2.1377	-0.01	0.0069
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April	1.3242	1.6754	0.03	0.0187
May	1.7726	2.0703	0.00	0.5811

*: P is the confidence level.

Table 2. Trends in annual mean snow depth with the Durbin-Watson test for Dikson site during 1966-2012

ID	d_u	d	$slope$	P	d'_u	d′	$slope'$	P′
20674	1.7234	1.2856	0.113	0.016	1.6345	2.0249	0.0942	0.055

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.

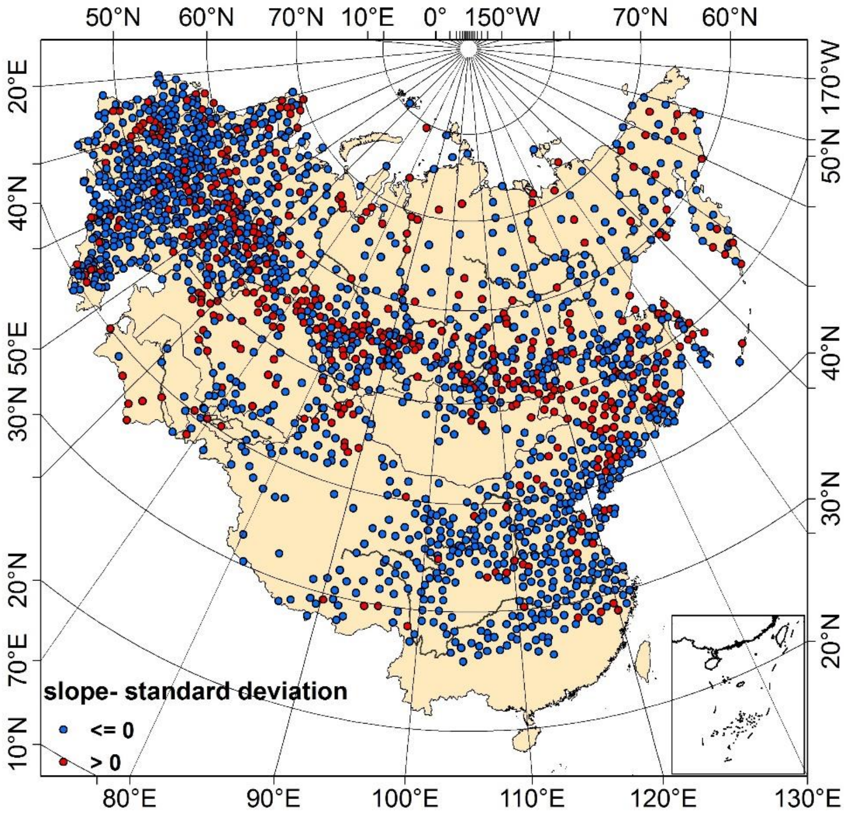


Figure. 1 The correlation between the slope of the linear trends and the standard deviation for annual mean snow depth for each station.

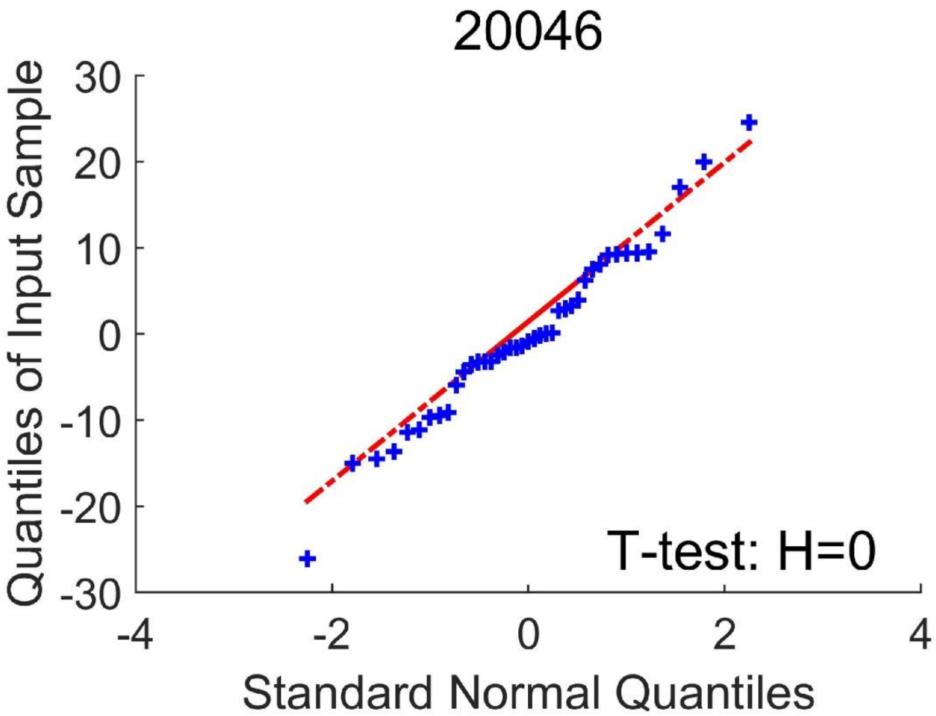


Figure.2 The “white” noise test for site 20046, which the noise exceed the signal.

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 in 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.

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

Snow depth is an important factor of controlling the ground thermal regime (Goodrich, 1982; Zhang et al., 1996; Zhang, 2005; Ling and Zhang, 2005). The research showed that thin snow cover resulted in cooler soil surface, while thick snow cover led to a warmer soil surface (Kudryavtsev, 1992). Frauenfeld et al. (2004) indicated that the maximum snow depth by the end of winter had significant influence on active layer depth in the following summer. In our results, snow depth significantly decreased on TP and increased in Siberia, which would inevitably accelerate the influence on permafrost freezing and thawing. We hope our research can provide an important reference for estimating the thermal regime of soil in these regions."

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

Reply: All names and abbreviations are removed from 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 revised them.

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 by warmer air led to 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: Has been done.

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 are costly and strict data use limitation applies.”

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 1st of a current year through June 30th of the following year in order 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: Has been done.

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

Reply: we have rephrased the sentence:

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

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: Has been inserted.

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. Snow depth generally increased with latitude nothrward across 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 “$P \leqslant 0.05$,”

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:

“It was because there was no obvious effect of increasing temperature on snow depth when the air temperature was below 0℃ in most areas of Siberia during December through March.”

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

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

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

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.

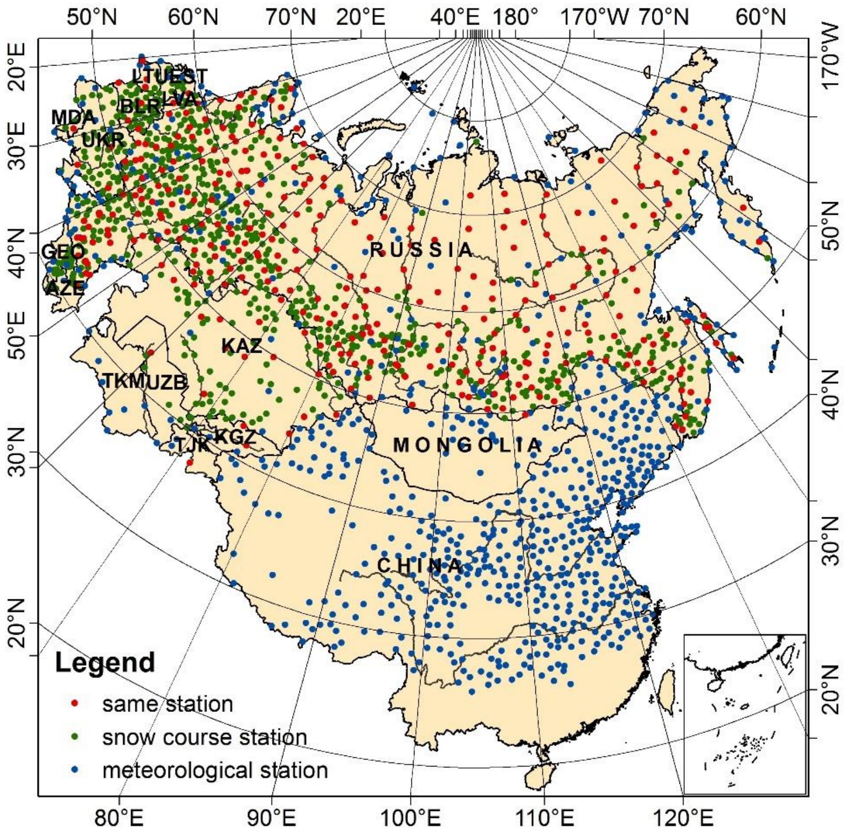
39. P. 25, Table 1: Change to “snow course

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 in 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[5]" 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 "[5] 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"; deleted "a snow depth climatology and its"; replaced "variations were" with "change and variability of snow depth was".

(10) P1, L.22: deleted "the".

(11) P1, L.26-27: replaced "that period of time" with "the study period".

(12) P1, L.27: deleted "the"; deleted the space between the degree sign and North.

(13) P2, L.2: replaced "changes in snow depth" with "snow depth climatology and changes".

(14) P3, L.2: deleted the first "the".

(15) P3, L.3: inserted ", including snow depth and snow area extent," after "cover"; inserted "an" after "as"; replaced "indicators" with "indicator".

(16) P3, L.3: replaced "circulation" with "circulations".

(17) P3, L.10-13: replaced the sentence with "Changes in snow depth would have dramatic impacts on weather and climate through surface energy balance (Sturm et al., 2001), soil temperature and frozen ground (Zhang, 2005), spring runoff,

water supply, and human activity (AMAP, 2011).”

(18) P3, L.13: replaced “reduced” with “declined”.

(19) P3, L.14: replaced “still increased” with “showed an increasing trend”; deleted “the”.

(20) P3, L.15-18: replaced the sentence by “This may be explained by warmer air led to greater moisture supply for snowfall in winter (Ye et al., 1998; Kitaev et al., 2005; Rawlins et al., 2010).”

(21) P3, L.20: inserted “local and regional” after “increased”.

(22) P3, L.22: deleted “data”; replaced “have” with “had”.

(23) P3, L.23: replaced “varies regionally:” with “varied differently over different regions.”; deleted “overall, the”

(24) P3, L.24: replaced “annual” with “Annual”.

(25) P3, L.27: replaced “but there was” with “with large”.

(26) P4, L.3: replaced “are” with “were”; deleted “also”.

(27) P4, L.5: replaced “is” with “was”.

(28) P4, L.6: deleted “also”; replaced “other large” with “synoptic”.

(29) P4, L.7: deleted “indices”.

(30) P4, L.8: deleted the first “the”.

(31) P4, L.9: deleted “the”.

(32) P4, L.10: deleted the two “the”; replaced “is” with “was”.

(33) P4, L.11: inserted “of Russia” after “Plain”.

(34) P4, L.12: deleted “the”; replaced “is” with “was”.

(35) P4, L.13: replaced “indicated” with “demonstrated”; replaced “is” with “was”.

(36) P4, L.14: deleted “the”; inserted “between snow depth and” before “Niño-3”.

(37) P4, L.15: replaced “in” with “on”.

(38) P4, L.17: deleted “have”.

(39) P4, L.20: deleted “have”; inserted “/or” after “and”; deleted “the algorithms with”, inserted “snow algorithms” after “microwave”.

(40) P4, L.21-22: replaces “these observations” with “snow depth and snow water equivalent obtained by satellite remote sensing”.

(41) P4, L.22: replaced “can” with “could”; deleted “the”.

(42) P4, L.23: replaced “the satellite data” with “they”.

(43) P4, L.24: replaced “inversion” with “imperfect”; replaced the semicolon with the period; inserted the sentences “Using ground-based snow depth measurements across Eurasian continent against snow depth obtained from passive microwave satellite remote sensing, Zheng et al. (2015) found that the mean percentage error is greater than 50% and can be up to about 200%. Utilization of snow depth obtained from satellite remote sensing has large uncertainties and impractical.”; replaced “in” with “In”.

(44) P4, L.25: deleted “the”.

(45) P4, L.25-26: replaced “is always” with “are”.

(46) P4, L.26-27: replaced “some of them need to obtain official permission before using in some countries” with “strict data use limitation applies”.

(47) P4, L.27-30: replaced the sentence with “Ground-based measurement provides currently available accurate snow depth with long time-series, which are critical data and information for investigating snow depth climatology and variability.”

(48) P5, L.1: replaced “nearly” with “approximately”.

(49) P5, L.3: deleted the two “the”.

(50) P5, L.4-5: deleted “and large-scale” and “cover”.

(51) P5, L.6: replaced “cover” with “depth”.

(52) P5, L.8-11: replaced the sentence with “Many studies on snow depth were focused on local and regional-scales over Russia (Ye et al., 1998; Kitaev et al., 2005; Bulygina et al., 2009, 2011; Brasnett, 1999) and on TP (Li and Mi, 1983; Ma and Qin, 2012).”; deleted “However, due to the lack of data and information,”

(53) P5, L.14: deleted “the”; deleted “, and analyze snow depth relationships with the topography and climate factors”.

(54) P5, L.16: inserted a sentence “We will further analyze spatial and temporal changes of snow depth with topography and climate factors over the study area.” After “2012.”

(55) P5, L.16-17: deleted the sentence “This study can provide basic information on

climate system changes in the region.”

(56) P5, L.21: inserted a sentence “Data used in this study includes daily snow depth, snow water equivalent (SWE), air temperature and precipitation.” before the first sentence.

(57) P5, L.22: deleted “the”.

(58) 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 Eurasian continent since the meteorological observation standard was established by the former USSR and followed by all the former USSR republics, Mongolia and China. Snow depth is one of the standard elements to be measured on daily basis (WMO, 1996).” before “Historical”.

(59) P5, L.26: moved “period” to the back of “snowmelt”.

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

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

(62) P6, L.4: inserted “by snow tube” after “measured”.

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

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

(65) P6, L.14: inserted “automatically” after “was”; deleted the first “the”.

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

(67) 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 is deleted. (2) Stations with sudden step changes of snow depth are eliminated from the list. (3) Stations with less than 20 years of data during the 1971-2000 period were excluded from the analysis. (4) At each station, we eliminated data points which exceed two standard deviations from their long-term (1971-2000) mean. After these four steps of snow depth quality control, we used data from 1814 stations to investigate climatology and variability of snow depth over Eurasian continent (Fig. 1 and Table 1).”

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

(69) 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 have inhomogeneities in the time series over the period of record. Fortunately, there was no change in procedure and technique of snow depth measurements since 1965 in Russia and the other countries in this study (Bulygina et al., 2009). In this study, therefore, we chose to use snow depth data from 1966 to 2012.”

(70) P7, L7: replaced “in regular” with “by”.

(71) P7, L8: deleted “the”.

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

(73) P7, L11: deleted “the”.

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

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

(76) P7, L.17-18: replaced “from the annual snow depth for ≥20” with “for stations with more than 20”; inserted “period” after “1966-2012”.

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

(78) P7, L21: replaced “values” with “value”, deleted the second “the”.

(79) P7, L22: replaced “≥20” with “more than 20”; inserted “period” after “1966-2012”.

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

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

(82) P8, L.9: deleted “a” after “when”.

(83) P8, L.10: inserted “even though there is a nonlinearity” after “emerged”, deleted the period.

(84) P8, L.12: deleted the two “the”.

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

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

(87) P8, L.27: replaced the sentence with “Distributions of long-term mean snow depth indicated a strong latitudinal zonality.”

(88) P8, L.28: replaced the colon with the period; deleted the two “the” and “for each station”.

(89) P8, L.29: inserted “northward” after “latitude”; deleted “the”; inserted a space before “A”.

(90) P9, L.3: replaced “Depths” with “Snow depths”.

(91) P9, L.5: replaced “The regions” with “Regions”.

(92) P9, L.15-16: replaced the sentence with "Annual mean maximum snow depth (Fig. 2b) showed a similar spatial distribution pattern as compared to annual mean snow depth pattern."

(93) P9, L.17-18: replaced the sentence with "The maximum value of about 201.8 cm in snow depth."

(94) P9, L.20: deleted "located".

(95) P9, L.25: inserted "decreased to" before "6-10"; replaced "in" with "as moving to"; replaced "parts of the country" with "Mongolia".

(96) 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 the eastern and southwestern TP, mostly greater than 10 cm, even greater than 20 cm in some areas. For the remaining regions of China, maximum snow depth were relatively small, mostly less than 10 cm."

(97) P9, L.30- P10, L.3: deleted the paragraph.

(98) P10, L.4: deleted the two "the".

(99) P10, L.7: inserted "As moving southward," before "monthly".

(100) P10, L.8: deleted "the" and "most regions".

(101) P10, L.9: deleted the first "the"; replaced "the areas covered by snow" with "snow cover extent".

(102) P10, L.10: replaced "Most monthly" with "Monthly".

(103) P10, L.11: replaced "in most regions" with "for the majority part".

(104) P10, L.12-13: replaced with "but except the northern Xinjiang Autonomous Region of China, Northeast China, and southwestern TP where snow depth exceeded 10 cm."

(105) P10, L.14-15: replaced the sentence with "In spring (March through May), snow cover areas decreased significantly (Figs. 3g–i) mainly because of snow disappearance in the majority part of China."; deleted "the".

(106) P10, L.21: inserted "both" after "in"; deleted "the"; inserted "snow depth" after "mean".

(107) P10, L.22: inserted the period after "continent"; deleted "as a whole with".

(108) P10, L.23-24: replaced the sentence with “Mean annual snow depth increased at a rate of about 0.2 cm decade^{-1}, while annual mean maximum snow depth increased at a rate of about 0.6 cm decade^{-1} (Fig. 4).”

(109) P10, L.26: deleted “the”.

(110) P10, L.27: deleted the first “the”.

(111) P10, L.28: deleted the first “the”.

(112) P11, L.1: replaced “3.5” with “about 3 to 4”.

(113) P11, L.1-2: replaced with “then with large fluctuation without significant trend from the late 1970s to the early 1990s.”

(114) P11, L.4-13: deleted the paragraph.

(115) P11, L.14- P12, L.7: replaced the paragraphs with “Monthly snow depth changed significantly across Eurasian continent from 1966 through 2012 (Fig. 5). Snow depth decreased in October at a rate of about -0.1 cm decade^{-1} (Fig. 5a), there were no significant trend in November and December with large inter-annual variations (Fig. 5b-c). From January through April, snow depth showed statistically increased trends with rates between 0.3 cm decade^{-1} and 0.6 cm decade^{-1} (Fig. 5d-g). Overall, snow depth decreased or no change in autumn and increased in winter and spring with large inter-annual variations over the study period.”

(116) P12, L.8-22: deleted the paragraph.

(117) P12, L.23: replaced “Figure 8” with “Figure 6”.

(118) P12, L.26: deleted “most of” and the first “the”.

(119) P12, L.27: deleted “the”; replaced “Fig. 8a” with “Fig. 6a”.

(120) P12, L.29: deleted “the”.

(121) P12, L.30: replaced “across” with “in”.

(122) P12, L.30 and P13, L1: deleted the space between the degree sign and North, replaced “the region” with “regions”.

(123) P13, L.4: deleted “the”.

(124) 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

maximum snow depth”.

(125) P13, L.7: replaced “8b” with “6b”.

(126) P13, L.8-10: replaced the sentence with “The decreasing trends were found generally in the same regions where annual mean snow depth decreased, with greater reductions in southern Siberia and the Far East.”

(127) P13, L.11: replaced “at the 95 % level” with “$P \leqslant 0.05$”; replaced “changes” with “increasing trends”

(128) P13, L.12: replaced “Figs. 9a, b” with “Fig. 7a, b”.

(129) P13, L.13: inserted “although the magnitudes were generally small” after “October”.

(130) P13, L.13-17: replaced the sentences with “Over November, the increasing trends of snow depth only appeared in Siberia and the Russian Far East, while decreasing trends in monthly mean snow depth occurred over eastern European Russia, southern West Siberian Plain, and northeast Russian Far East.”

(131) 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 $P<0.05$ (Figs. 7c–e), mainly in eastern European Russia, southern Siberia, northern Xinjiang Autonomous Region of China, and Northeast China. In contrast, significant decreasing trends were observed in northern and western European Russia, scattered in Siberia, northeast Russian Far East, and northern China.”

(132) P13, L.25-26: replaced “at the 95 % level” with “$P<0.05$”.

(133) P13, L.27: replaced “Figs. 9f-h” with “Figs. 7f-h”.

(134) 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.”

(135) P14, L.5: inserted the sentence “Topography is an important factor affecting climatology of snow depth, and is the main reason accounting for the inhomogeneity of data (Grünewald and Lehning, 2011, 2013; Grünewald et al., 2014).” before the first sentence.

(136) P14, L.7: replaced “10” with “8”.

(137) P14, L.8: replaced “10a” with “8a”.

(138) P14, L.9: deleted the space between the degree sign and North; inserted “across Eurasian continent” after “1°N”.

(139) 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, d), where snow cover was relatively stable with number of annual mean continuous snow cover days of more than 30 (Zhang and Zhong, 2014).”

(140) P14, L.15: replaced “10b” with “8b”.

(141) P14, L.20: replaced “determined” with “found”.

(142) P14, L.21: deleted the space between the degree sign and North, replaced “10d” with “8d”.

(143) P14, L.22-23: deleted the sentence.

(144) P14, L.24: inserted “statistically” before “significant”.

(145) P14, L.25: inserted “over Eurasian continent” after “continentality”; inserted “$P \leqslant 0.05$,” before “Fig.”, replaced “10c” with “8c”.

(146) P14, L.26: replaced “is” with “may be”.

(147) P14, L.26-27: replaced “snow cover climatology” with “snow depth distribution”.

(148) P14, L.27: inserted “especially on 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, but precipitation during winter months was the smallest of the year (Ma, 2008). This was mainly due to the majority of annual precipitation occurs during the summer monsoon season on TP which cause much less precipitation during winter half year (or snow accumulated season).” after the last sentence.

(149) P15, L.3: inserted “former” before “USSR”; replaced “Fig. 11” with “Fig. 9”.

(150) P15, L.3-5: replaced the sentence with “The period (snow cover years) spanned from 1966 through 2009 using available data.”

(151) P15, L.7: replaced “11a” with “9a”, deleted “the”.

(152) P15, L.8: replaced “better” with “strong”; replaced “11b” with “9b”.

(153) P15, L.9: replaced “in” with “at”; replaced “being” with “of”.

(154) P15, L.10-11: replaced sentence with “Snow depth increased with increased accumulated snowfall increased, and the thickest snow depth of about 120 cm had the maximum cumulative snowfall of about 350 mm.”

(155) P15, L.16: replaced “Fig. 12” with “Fig. 10”.

(156) P15, L.22: replaced “lowed” with “lowered”.

(157) P15, L.24: replaced “12b-d” with “10b-d”.

(158) P15, L.29: replaced “Fig. 13” with “Fig. 11”.

(159) P15, L.29: deleted “the”.

(160) P16, L.1: replaced “13a” with “11a”.

(161) P16, L.2: deleted “the”.

(162) P16, L.3: replaced “13b” with “11b”, inserted “there was no obvious effect of increasing temperature on snow depth when” after “because”.

(163) P16, L.4-5: deleted “, the increasing temperature did not have an obvious effect on snow depth”.

(164) P16, L.9: deleted “the”.

(165) P16, L.14: deleted “4.1 Comparison with Previous Results”.

(166) P16, L.16: deleted “the” and “mean”.

(167) P16, L.27: deleted the space between the degree sign and North and East.

(168) P17, L.3: replace the first “in” with “on”.

(169) P17, L.5: inserted “ (2012)” after “Qin”.

(170) P17, L.12: deleted the last “the”.

(171) P17, L.13: deleted the first “the”.

(172) P17, L.15: inserted two paragraphs

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

Snow depth is an important factor of controlling the ground thermal regime (Goodrich, 1982; Zhang et al., 1996; Zhang, 2005; Ling and Zhang, 2005). The research showed that thin snow cover resulted in cooler soil surface, while thick snow cover led to a warmer soil surface (Kudryavtsev, 1992). Frauenfeld et al. (2004) indicated that the maximum snow depth by the end of winter had significant influence on active layer depth in the following summer. In our results, snow depth significantly decreased on TP and increased in Siberia, which would inevitably accelerate the influence on permafrost freezing and thawing. We hope our research can provide an important reference for estimating the thermal regime of soil in these regions."

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

(174) P18, L.18: replaced "increase" with "increasing".

(175) P18, L.25: deleted the first "the".

(176) P19, L.2: deleted the last "the".

(177) P20, L.16: replaced "Atoms." with "Atmos."

(178) P20, L.27-28: deleted "Arctic cryosphere-Changes and impacts, T.V. Callaghan, M. Johansson, and T.D. Prowse, Eds.,"

(179) P21, L.18: inserted " J." after "Sci."

(180) 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,"

(181) 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."

(182) 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.”

(183) P22, L.18: inserted a new reference “Ji, Z., and Kang, S.: Projection of snow cover changes over China under RCP scenarios, Clim. Dyn., 41: 589-600, 2013.”

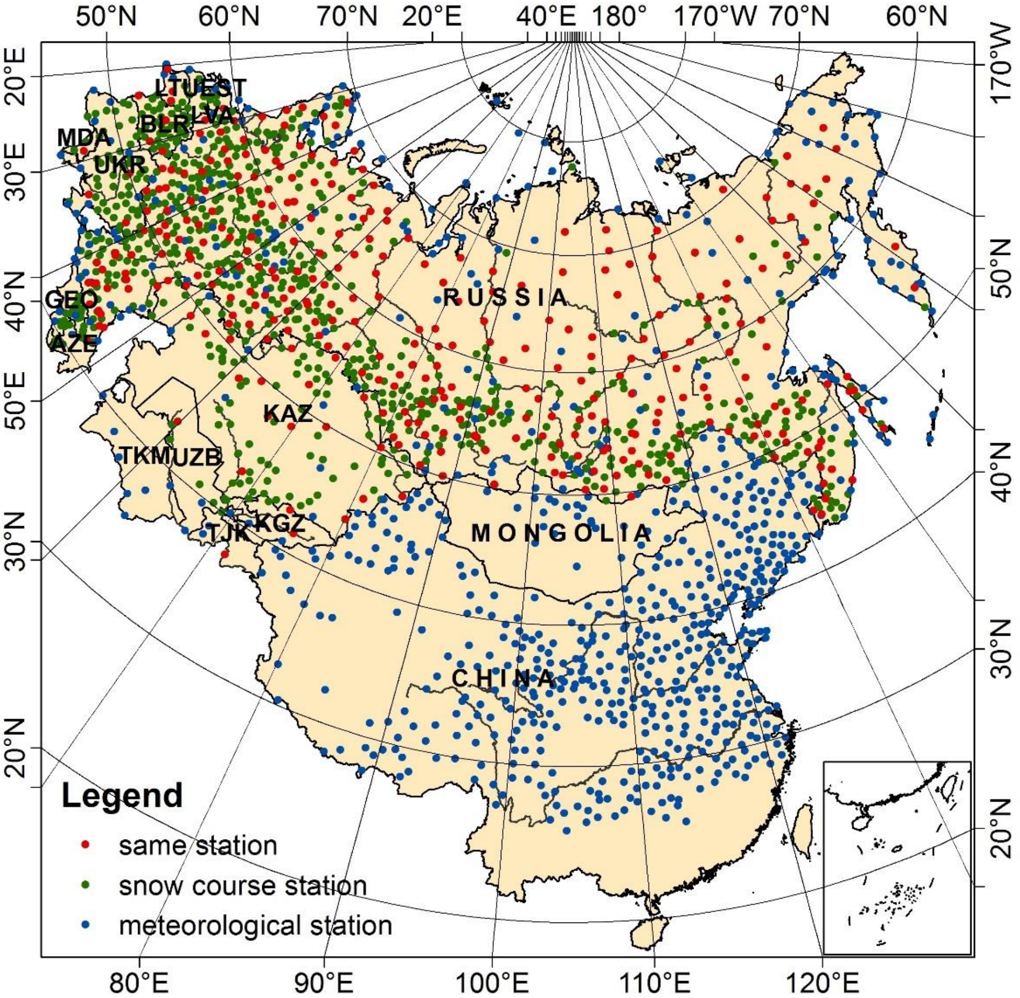
(184) P23, L.6: inserted a new reference “Ling, F. and Zhang, T.: Modeling the effect of variations in snowpack-disappearence date on suiface-energy balance on the Alaskan north slope, Arct. Antarct. Alp. Res., 37, 483-489, 2005.”

(185) P24, L.15: inserted two new references “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.”

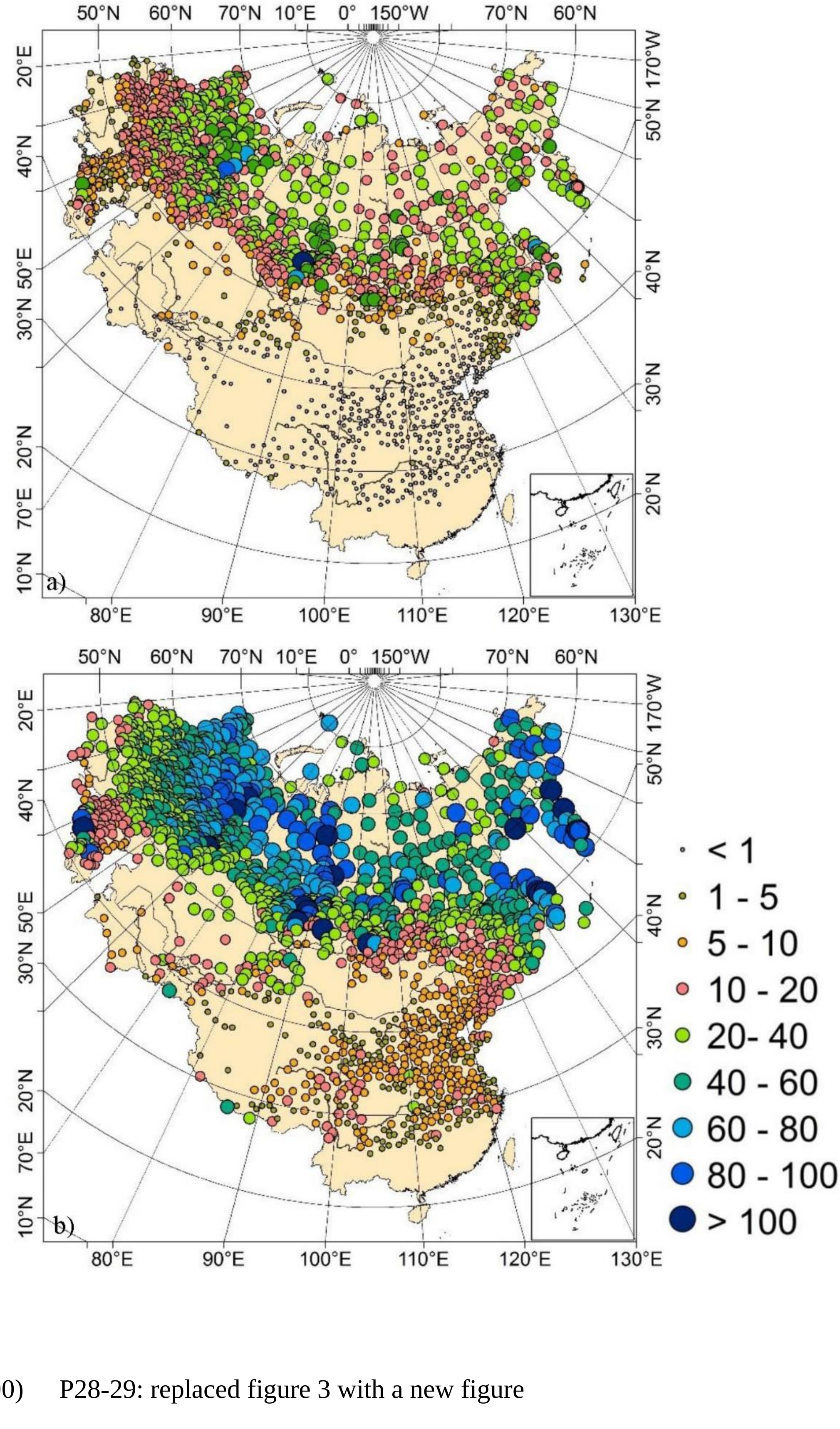
(186) P24, L.22: inserted a new reference “Zhang, T., Osterkamp, T. E., and Stamnes, K.: Influence of the depth hoar layer of the seasonal snow cover on the ground thermal regime, Water Resour. Res., 32, 2075-2086, 1996.”

(187) P24, L.25: inserted a new reference “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).”

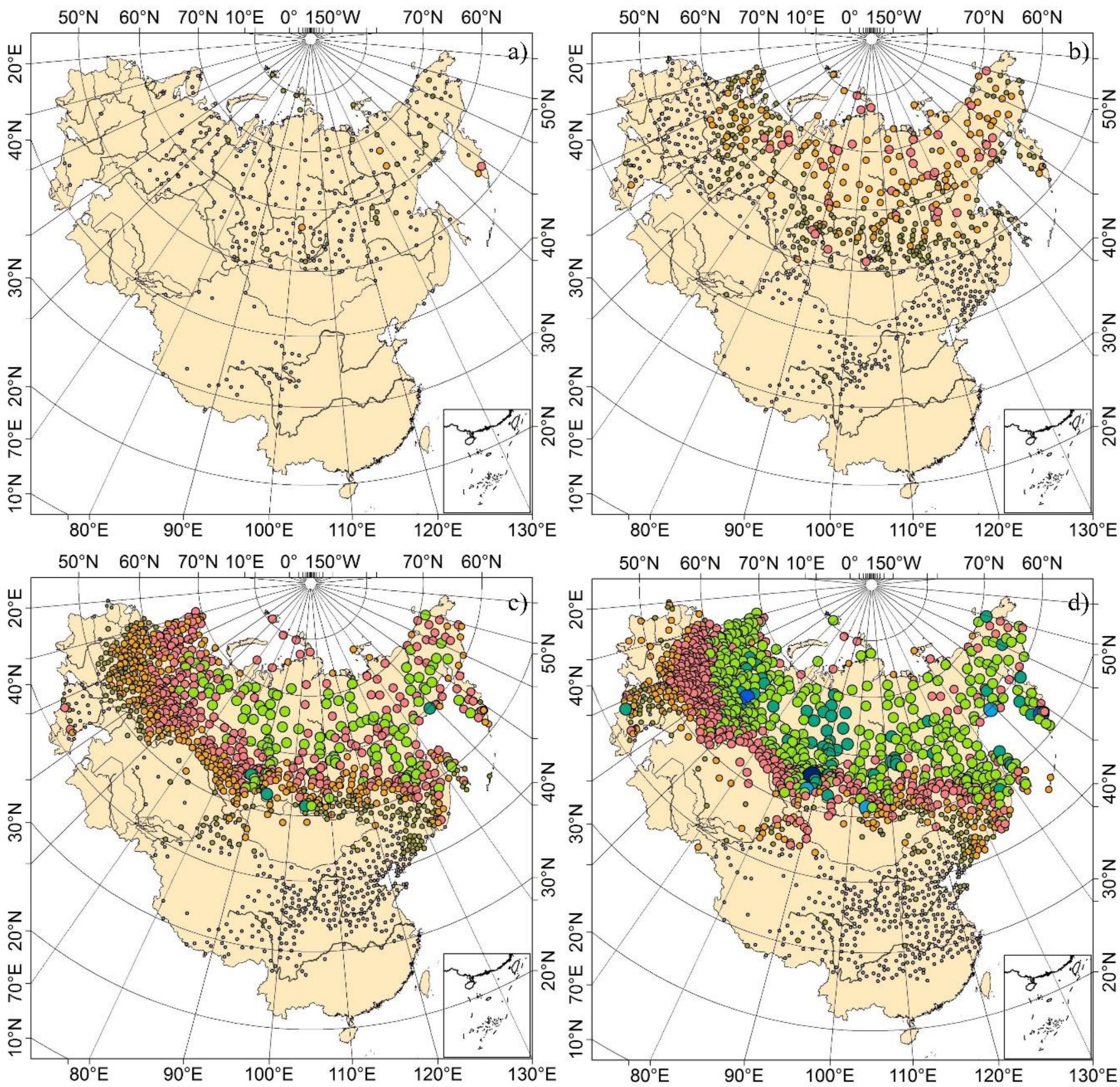
(188) P26: replaced figure 1 with a new figure



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



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


a)
b)
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50°N
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0°
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40°N
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70°E
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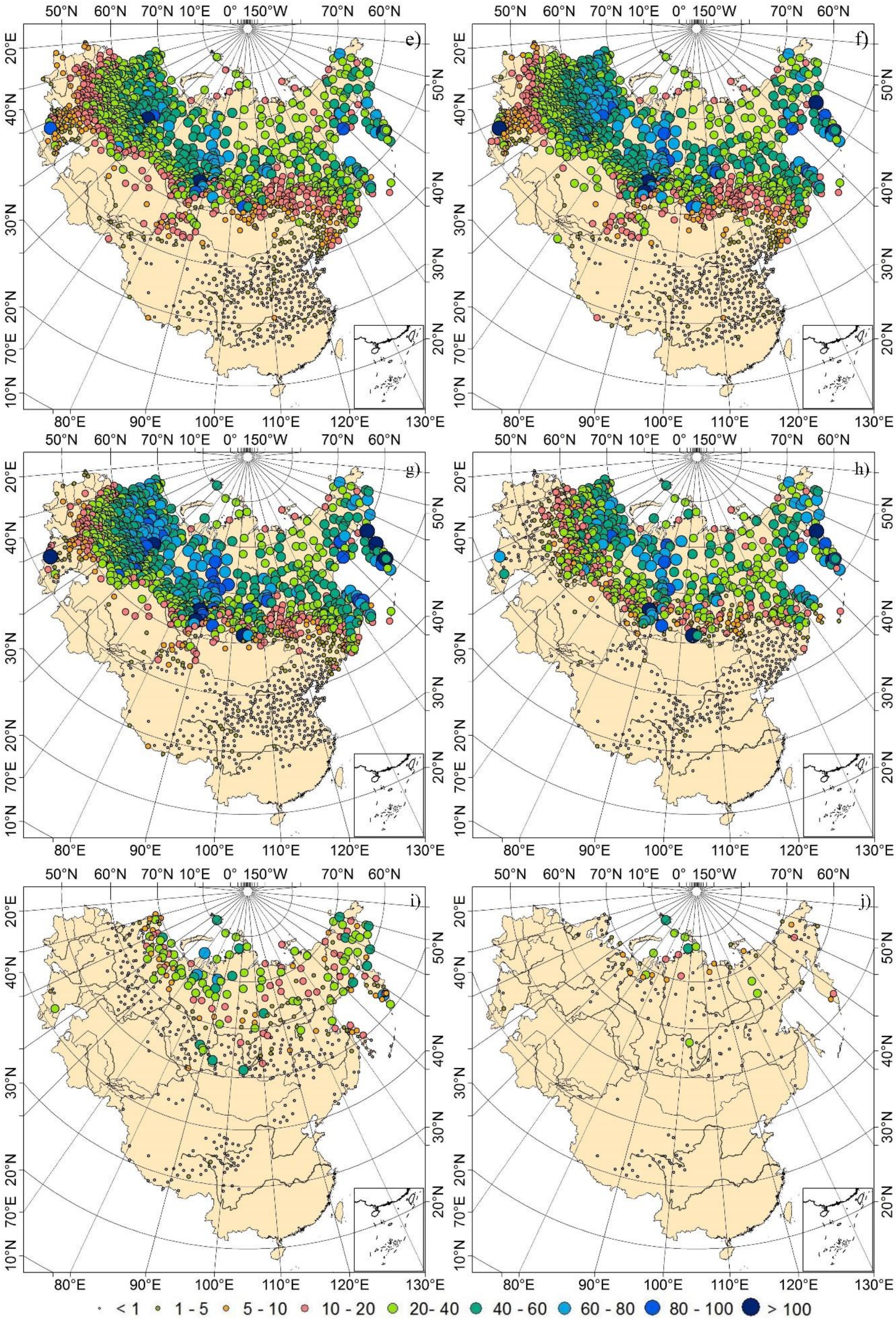
110°E
120°E
130°E

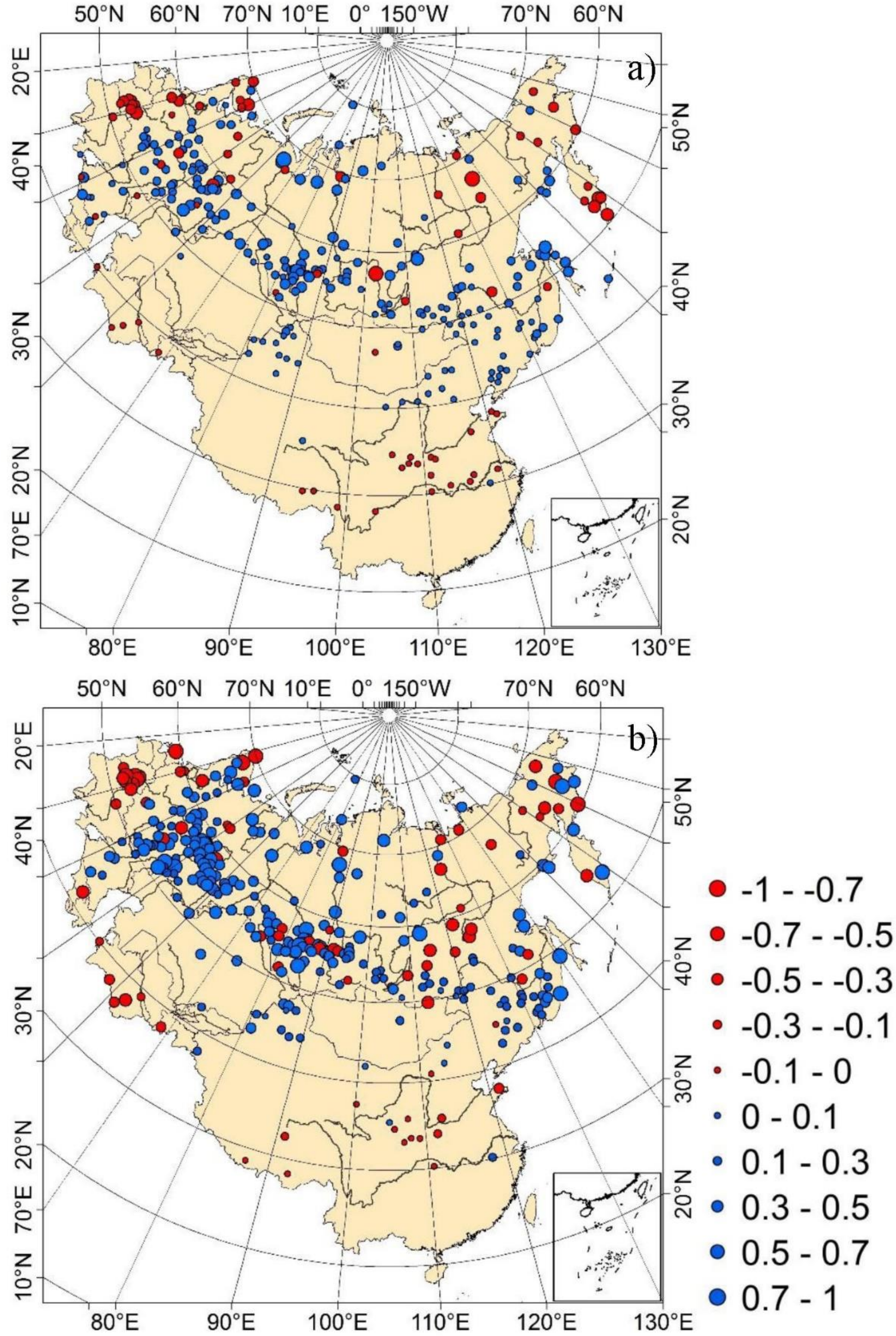


(191) P30: deleted figure 5.

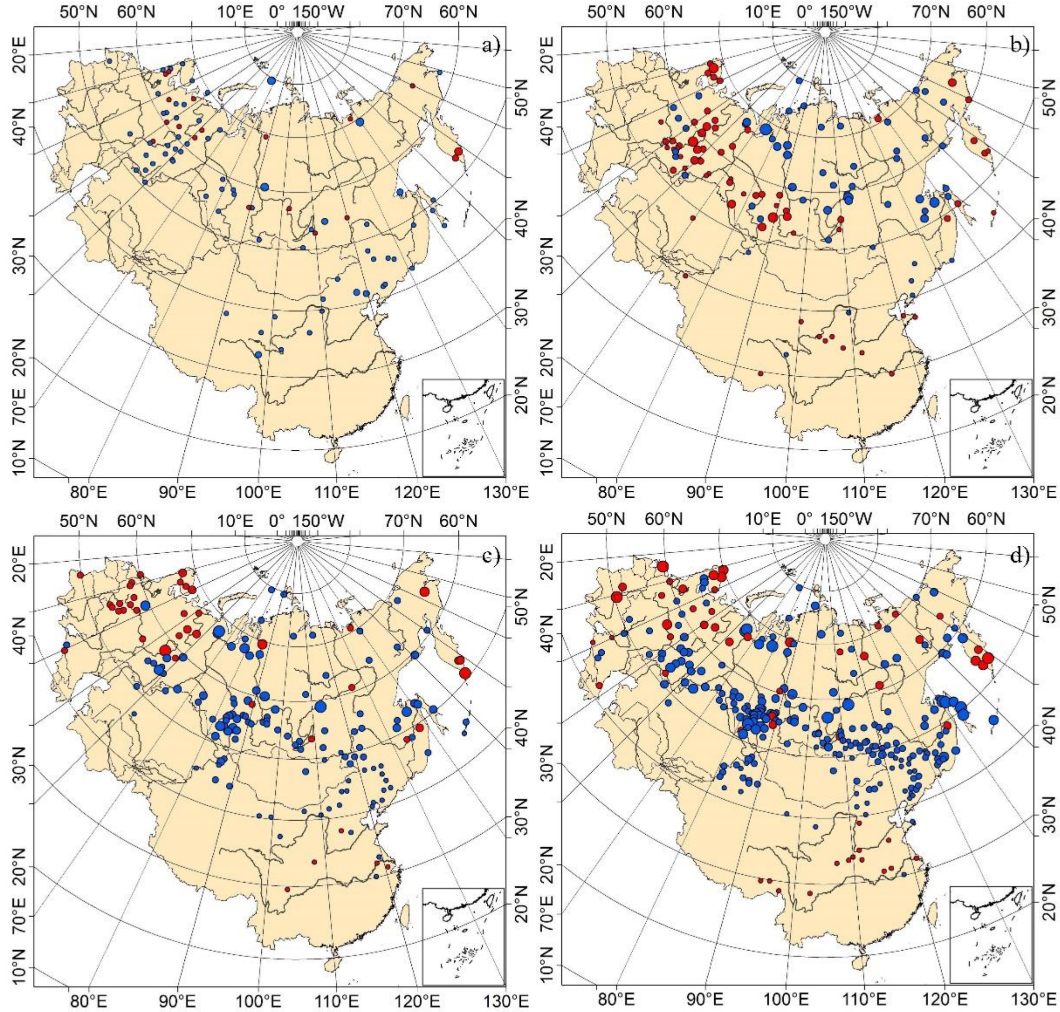
(192) P32: replaced “Figure 6” with “Figure 5”.

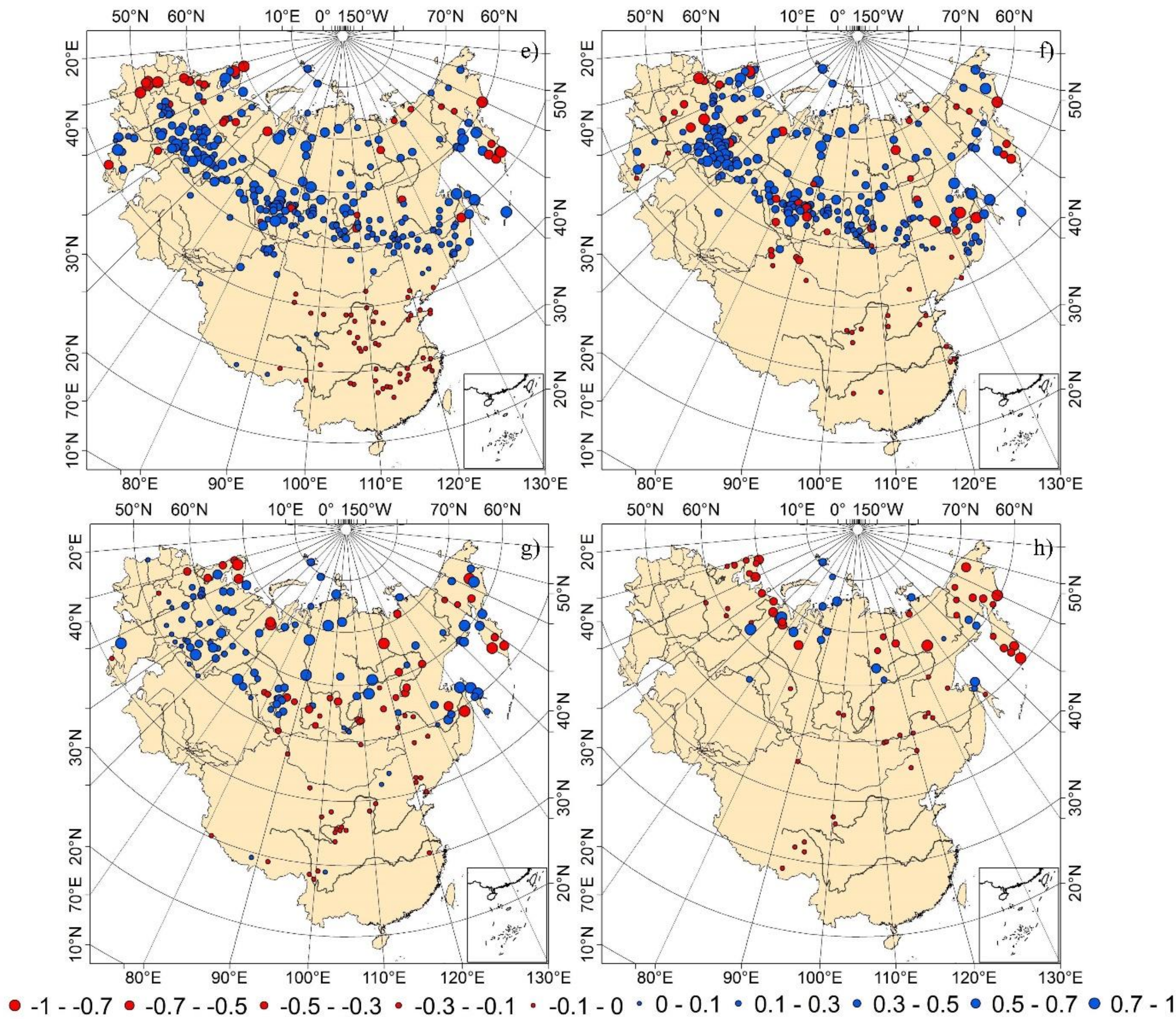
(193) P34: deleted figure 7.

(194) P35: replaced figure 8 with a new figure, replaced “Figure 8” with “Figure 6”.



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

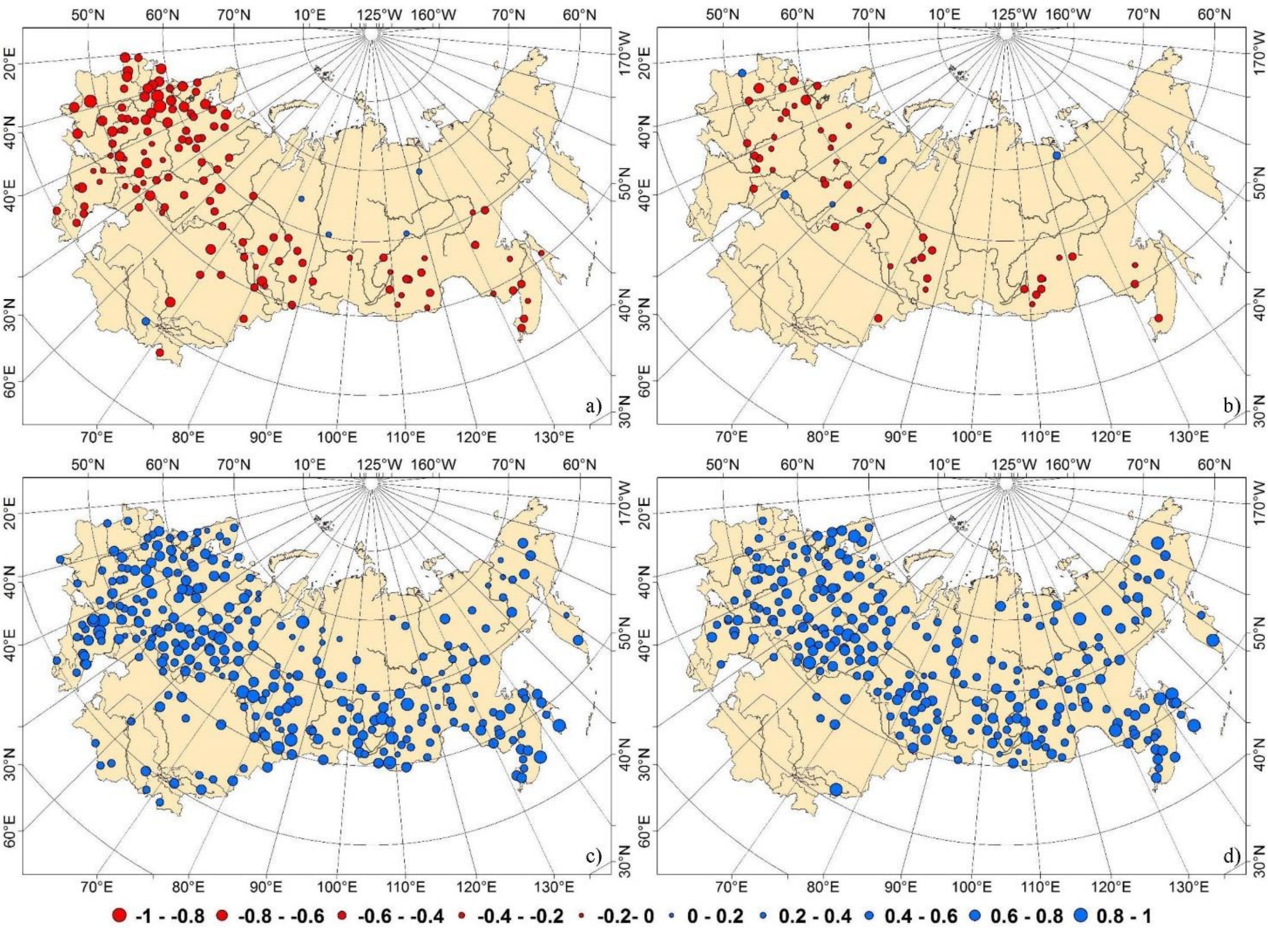




(196) P38: replaced “Figure 11” with “Figure 9”.

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

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


a)
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-1 - -0.8
-0.8 - -0.6
-0.6 - -0.4
-0.4 - -0.2
-0.2- 0
0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1

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

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ABSTRACT

Snow depth is one of key physical parameters for understanding~~ the~~ land surface energy balance, soil thermal regimes, ~~regional- and continental-scale~~ water cycles, as well as assessing water resources from local community to regional industrial water supply. In this study, ~~a snow depth climatology and its~~ spatiotemporal change and variability of snow depth~~variations were~~ was investigated using ~~the~~ long-term (1966-2012) ground-based measurements from 1814 stations across the Eurasian continent. Spatially, mean snow depths of >20 cm were recorded in northeastern European Russia, the Yenisey River basin, Kamchatka Peninsula, and Sakhalin. Annual mean and maximum snow depth increased significantly during 1966-2012. Seasonally, monthly snow depth decreased in autumn, and increased in winter and spring over ~~that~~ the study period~~ of time~~. Regionally, snow depth significantly increased in ~~the~~ areas north of 50°~~-~~N. Compared with air temperature, snowfall had more influence on snow depth and snow water equivalent during November through March across the former Soviet Union. This study provides a baseline for snow depth climatology and ~~changes in snow depth~~changes, which are significant in climate system changes over the Eurasian continent.

1 Introduction

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

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

Using in-situ observational data from meteorological stations and satellite remote sensing~~ data~~, several studies ~~have~~ had documented changes in snow depth over the Northern Hemisphere, demonstrating that snow depth varied~~s~~ differently over different regions. ~~regionally: overall, the a~~Annual mean snow depth decreased in most areas over North America during 1946 to 2000 (Brown and Braaten, 1998; Dyer and Mote, 2006), and increased in Eurasia and the Arctic during the recent 70 years (Ye et al., 1998; Kitaev et al., 2005; Callaghan et al., 2011a; Liston and Hiemstra, 2011) ~~but there was~~with large regional differences (Bulygina et al., 2009, 2011; Ma and Qin, 2012; Stuefer et al., 2013; Terzago et al., 2014). Changes in snow depth were primarily affected by air temperature and precipitation. Ye et al. (1998) and Kitaev et al. (2005) showed that higher air temperatures caused an increase in snowfall in winter from 1936 through 1995, thus greater snow depth was observed in northern Eurasia in response to global warming. Furthermore, snow depth distribution and variation ~~are~~ were ~~also~~ controlled by terrain (i.e., elevation, slope, aspect, and roughness) and vegetation (Lehning et al., 2011; Grünewald et al., 2014; Revuelto et al., 2014; Rees et al., 2014; Dickerson-Lange et al., 2015). Snow depth ~~is~~ was ~~also~~ closely related to ~~other large~~synoptic-scale atmospheric circulation indices, such as the North Atlantic Oscillation /Arctic Oscillation (NAO/AO)~~ indices~~. For example, Beniston (1997) found that ~~the~~ NAO played a crucial role in fluctuations in the amount of snowfall and snow depth in ~~the~~ Swiss Alps from 1945 to 1994. Kitaev et al. (2002) reported that ~~the~~ NAO index ~~is~~ was positively related to snow depth in ~~the~~ northern part of the East European Plain of Russia and over western Siberia during the period from1966 to 1990; however, ~~the~~ NAO ~~is~~ was negatively correlated with snow depth in most southern regions of northern Eurasia. You et al. (2011) ~~indicated~~ demonstrated that there ~~is~~ was a positive relationship between snow depth and ~~the~~ winter AO/NAO index and between snow depth and Niño-3 region sea surface temperature (SST) ~~in~~ on the eastern and central Tibetan Plateau (TP) from 1961 through 2005.

To increase the spatial coverage of snow depth, researchers ~~have~~ used different instruments (e.g., LIDAR, airborne laser scanning (ALS), and unmanned aerial systems (UASs)) (Hopkinson et al., 2004; Grünewald et al., 2013; Bühler et al., 2016) or ~~have~~ developed and/or improved ~~the algorithms with~~ passive microwave snow algorithms (Foster et al., 1997; Derksen et al., 2003; Grippaa et al., 2004; Che et al., 2016). Although snow depth and snow water equivalent obtained by satellite remote sensing~~these observations~~ ~~can~~ could mitigate ~~the~~ regional deficiency of in-situ snow depth observations, ~~the satellite data~~they have low spatial resolution (25×25 km) and the accuracy is always affected by clouds, underlying surface conditions, and ~~inversion~~ perfect algorithms~~;~~. Using ground-based snow depth measurements across Eurasian continent against snow depth obtained from passive microwave satellite remote sensing, Zheng et al. (2015) found that the mean percentage error is greater than 50% and can be up to about 200%. Utilization of snow depth obtained from satellite remote sensing has large uncertainties and impractical. ~~in~~ In addition, data acquisition from ~~the~~ large airborne equipment or aerial systems ~~is~~ are ~~always~~ costly and strict data use limitation applies. ~~some of them need to obtain official permission before using in some countries.~~ Ground-based ~~snow~~ measurement ~~remains the basis for verification of remote sensing and instrumental data, which can~~ provides currently available ~~more~~ accurate snow depth with ~~and~~ long~~er~~ -time-series, which ~~information, and it is~~ are critical data and information~~important~~ for investigating snow depth – climatology and variability ~~of snow depth~~.

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

2 Data and Methodology

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

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

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

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

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

Snow depth and SWE at each station were determined as the average value of a series of measurements in each snow course survey (Bulygina et al., 2011). In individual measurements, both random and systematic errors inevitably occur (Kuusisto, 1984). To minimize these errors, quality control of ~~the~~ meteorological data was automatically undertaken prior to ~~the~~ datasets being stored at the Russian Research Institute for Hydrometeorological Information-World Data Center (RIHMI-WDC) (Veselov, 2002) and the National Meteorological Information Center (NMIC) of China Meteorological Administration (Ma and Qin, 2012). We implemented ~~a second~~additional quality control using the following requirements: (1) to ensure snow depth stability, at a given location, a month with less than 15 days of snow depth measurements is deleted. (2) Stations with sudden step changes of snow depth are eliminated from the list. (3) Stations with less than 20 years of data during the 1971-2000 period were excluded from the analysis. (4) At each station, we eliminated data points which exceed two standard deviations from their long-term (1971-2000) mean. ~~(1) A threshold of 15 days was selected because the snow cover duration in some areas of China was less than one month, and the data for 15 days'~~

~~snow depth in a month were relatively stable. Months having less than 15 days with snow depth data were omitted from the analysis. (2) Stations with less than 20 years of data during the 1971-2000 period were excluded from the analysis. (3) At each station, data exceeding two standard deviations compared with the annual average value during 1966-2012 were omitted.~~ After these four steps of snow depth quality control,~~In total,~~ we used data from 1814 stations to investigate~~analyze the~~ climatology and variability of snow depth over~~the~~ Eurasian continent (Fig. 1 and Table 1).

~~The snow cover extent is the smallest in July and August,~~ We defined a snow year starting from July 1st of a current year through June 30th of the following year in order to capture the entire seasonal snow cycle~~, we defined a snow year as the period from July 1st of a current year to June 30th of the following year~~. Procedures and techniques for measuring snow depth may have changed over the course of station history. Consequently, snow depth data may have inhomogeneities in the time series over the period of record. Fortunately, there was no change in procedure and technique of snow depth measurements since 1965 in Russia and the other countries in this study (Bulygina et al., 2009). In this study, therefore, we chose to use snow depth data from 1966 to 2012.~~Because the procedures for taking snow observations have changed over the course of the studies period, there were some inhomogeneities in the data. However, there has been no change in the observation procedure and techniques since 1965 (Bulygina et al., 2009). Therefore, we used snow data for the snow years from 1966 to 2012 in this study.~~ The following variables were calculated for each station:

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

~~To capture the primary long-term spatial patterns of snow cover distribution, we~~

~~calculated the annual mean snow depth and annual mean maximum snow depth during 1966-2012:~~

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

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

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

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

3 Results

3.1 Climatology of Snow Depth

~~The d~~Distributions of long-term mean snow depth ~~generally represented~~ indicated ~~the~~ a strong latitudinal zonality.~~:~~ ~~the~~ Snow depth ~~for each station~~ generally increased with ~~the~~ latitude northward across ~~the~~ Eurasian continent (Fig. 2). A maximum annual mean snow depth of 106.3 cm was observed in the west of the Yenisey River (dark blue circle) (Fig. 2a). In contrast, the minimum values (~0.01 cm) were observed in some areas of the south of Yangtze River in China (small gray circles).

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

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

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

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

3.2 Variability of Snow Depth

There were long-term significant increasing trends in ~~the~~ both annual mean snow depth and maximum snow depth from 1966 to 2012 over the Eurasian continent ~~as a whole with the~~. Mean annual snow depth ~~increasing~~ increased at a rate~~s~~ of about ~~snow depth of~~ 0.2 cm decade^{-1}, while annual mean maximum snow depth increased at a rate of about ~~and~~ 0.6 cm decade^{-1}~~, respectively~~ (Fig. 4). Both annual mean snow depth and maximum snow depth exhibited a similar pattern of changes over the four decades, although the amplitude of ~~the~~ maximum snow depth anomaly (about ±2 cm) was much larger than that of ~~the~~ mean snow depth anomaly (about ±1 cm). From the mid-1960s to the early 1970s, ~~the~~ annual mean snow depth decreased slightly, then it increased until the early 2000s, and then decreased sharply until 2012 (Fig. 4a). Maximum snow depth decreased by 2.5 cm from the mid-1960s through the early 1970s (Fig. 4b). There was a sharp increase of ~~3.5~~about 3 to 4 cm in the maximum snow depth during the 1970s, then ~~it~~ with large fluctuation~~ng~~ without significant trend ~~changed~~ from the late 1970s to the early 1990s. The maximum snow depth increased again from the early 1990s through the early 2010s.

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

Monthly snow depth changed significantly across Eurasian continent from 1966 through 2012 (Fig. 5). Snow depth decreased in October at a rate of about -0.1 cm decade^{-1} (Fig. 5a), there were no significant trend in November and December with large inter-annual variations (Fig. 5b-c). From January through April, snow depth showed statistically increased trends with rates between 0.3 cm decade^{-1} and 0.6 cm decade^{-1} (Fig. 5d-g). Overall, snow depth decreased or no change in autumn and increased in winter and spring with large inter-annual variations over the study period.~~Statistically significant trends of variations in monthly snow depth occurred from 1966 through 2012 except for November, February, and May (Fig. 6). During the snow cover formation period (October and November), the monthly snow depth decreased slightly (Figs. 6a-b). There was a significant decreasing trend of monthly~~

~~snow depth in October, with a rate of decrease of approximately 0.1 cm decade^{-1} (Fig. 6a).~~

~~Inter-annual variations of monthly snow depth were more significant in the winter months (Figs. 6c-e). Snow depth was below its long-term mean value from the mid-1960s through the mid-1980s, and then it was above the long-term mean. There were statistically significant increasing trends in monthly snow depth in January and February, and similar inter-annual variations in snow depth for these two months during the period from 1966 to 2012 (Figs. 6d, e). Monthly snow depth sharply decreased by about 2 cm prior to the early 1970s, then increased by 2-2.5 cm until the late 1970s. Monthly snow depth displayed a fluctuating increase from the late1970s through 2012.~~

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

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

~~and then it decreased during the 2000s. From January to March, monthly snow depth increased significantly (p≤0.01) from the mid-1980s to the early 2010s. In April, the statistically significant increase was found from the late 1990s to the late 2000s, and it reached to the 0.01 confident level after 2000. Consistent with the linear regression, the trend in monthly snow depth was not significant in May.~~

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

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

In October and November, there were few stations with significant increasing trends~~changes~~ in snow depth ($P \leq 0.05$~~at the 95 % level~~) (Figs. ~~9a~~7a, b). The increasing trends were mainly observed in most areas across the Eurasian continent in October although the magnitudes were generally small. Over November, ~~But~~ the increasing trends of snow depth only appeared in Siberia and the Russian Far East ~~in November. The~~while decreasing trends in monthly mean snow depth occurred ~~in~~

~~the~~over eastern ~~regions of~~ European Russia,~~ the~~ southern ~~areas of the~~ West Siberian Plain, and ~~some areas of the~~ northeast Russian Far East.

In winter months (December~~-, January and~~ February), there was a gradual expansion in areas with increasing trends in monthly mean snow depth variation with $P \leqslant 0.05$~~at the 95 % level~~ (Figs. ~~9c~~7c–e), mainly in~~. There were increasing trends of monthly mean snow depth in the~~ eastern ~~regions of~~ European Russia, southern ~~parts of~~ Siberia, ~~the~~ northern Xinjiang Autonomous Region of China, and Northeast China. In contrast, significant decreasing trends were observed in ~~the~~ northern and western ~~of~~ European Russia, scattered in Siberia, ~~the~~ northeast ~~of the~~ Russian Far East, and northern~~most areas of~~ China.

From March to May, the number of stations with significant changes ($P \leqslant 0.05$~~at the 95 % level~~) in monthly mean snow depth decreased, especially in May because of snow melt (only 78 stations) (Figs. ~~9f~~7f-h). Changes in monthly mean snow depth were consistent with the trends in winter over the former USSR but more stations with decreasing trends were found in southern Siberia. There were few stations with statistically significant trends of snow depth across China; for these, monthly snow depths tended to decrease in most stations. Compared with regions~~the~~ south of 50°~~-~~N, ~~the~~ changes in monthly mean snow depth were more significant over regions~~to the~~ north of 50°~~-~~N.

3.3 Variability of Snow Depth with Latitude, Elevation and Continentality

Topography is an important factor affecting climatology of snow depth, and is the main reason accounting for the inhomogeneity of data (Grünewald and Lehning, 2011, 2013; Grünewald et al., 2014). To explore the spatial variability of snow depth, we conducted a linear regression analysis of annual mean snow depth with latitude, elevation and continentality (Fig. ~~10~~8). Snow depth is positively correlated with latitude, i.e., snow depth generally increases with latitude (Fig. ~~10a~~8a). The increase rate of snow depth was about 0.81 cm per 1°~~-~~N across Eurasian continent. ~~We detected a~~A closer relationship between latitude and snow depth was found in regions~~to the~~ north of 40°N (Figs. ~~10a~~8a, d), where~~. In these regions,~~ snow cover was relatively stable ~~(the~~with number of annual mean continuous snow cover days ~~was~~ of more than 30~~)~~ (Zhang and Zhong, 2014)~~, in which snow cover was easier to accumulate by the heavy snowfall and more difficult to melt with low air temperature~~.

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

There was a statistically significant positive relationship between snow depth and continentality over Eurasian continent~~, but the correlation coefficient was not high~~ (r=0.1, P≤0.05, Fig. ~~10c~~8c). This indicated that the continentality ~~is~~ may be not an important driving factor of snow ~~cover climatology~~depth distribution over Eurasia, especially on TP.~~though it will determine the snowfall rate.~~ Although the previous studies showed that the Tibetan Plateau's largest snow accumulation occurred in the winter, but the precipitation during winter months was the smallest of the year (Ma, 2008). This was mainly due to the majority of annual precipitation occurs during the summer monsoon season on TP which cause much less precipitation during winter half year (or snow accumulated season).

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

In addition to the terrain factors, variations in snow depth are closely related to climate variability. To examine the relationship between snow depth and climatic factors, we calculated the long-term mean snow depth, air temperature and snowfall of 386 stations from November through March across the former USSR (Fig. ~~11~~9). 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≤0.05), but the Goodness of Fit of the relationship was only 16% (Fig. ~~11a~~9a). Compared with ~~the~~ air temperature, snowfall exhibited a ~~better~~ strong relationship with snow depth (Fig. ~~11b~~9b). The mean snow depth was less than 20 cm at~~in~~ most stations with the accumulated snowfall ~~being~~ of <50 mm from November through March. ~~It~~ Snow depth increased with increased~~the~~ accumulated snowfall increased, and the thickest snow depth of about ~~reached~~ 120 cm ~~when~~ had the maximum cumulative snowfall ~~was~~ of about 350 mm.

Comparing the long-term inter-annual trends of changes in snow depth, SWE, air temperature and snowfall, the variability of snow depth and SWE were mainly affected by the changes in snowfall. Overall, the trends in long-term air temperature, precipitation, snowfall and SWE displayed increasing trends from November to March (Fig. ~~12~~10). This was because the increased precipitation fell as snow in cold areas where the increased temperature was still below freezing (Ye et al., 1998; Kitaev et al., 2005). Warmer air led to greater supply of moisture for snowfall, hence the snow accumulation still increased (Ye et al., 1998). The significant increasing snowfall can explain the sudden drop in the bulk snow density from the mid-1990s through the early 2000s (Zhong et al., 2014): increasing snowfall should decrease the density of the surface snowpack, which lowered the whole density of snowpack. There were basically consistent trends of variations in snow depth, SWE and snowfall accumulation from November through March during 1966-2009 (Figs. ~~12b~~10b-d). The results indicated that the increasing trend in snow depth was the combined effect of the increasing air temperature and snowfall.

The partial correlation coefficients between snow cover and air temperature, as well as snow cover and snowfall were calculated to discuss the spatial relationship between them (Fig. ~~13~~11). The significant negative correlation (p≤0.05) between snow depth and air temperature presented in most areas of European Russia and ~~the~~ southern Siberia (Fig ~~13a~~11a). The stations with negative effects of air temperature on SWE were fewer, and there were no statistically significant correlation in ~~the~~ northern

Siberia (Fig ~~13b~~11b). It was because there was no obvious effect of increasing temperature on snow depth when the air temperature was below 0℃ in most areas of Siberia during December through March.~~, the increasing temperature did not have an obvious effect on snow depth.~~

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

4 Discussion

~~4.1 Comparison with Previous Results~~

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

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

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

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

Snow depth is an important factor of controlling the ground thermal regime (Goodrich, 1982; Zhang et al., 1996; Zhang, 2005; Ling and Zhang, 2005). The research showed that thin snow cover resulted in cooler soil surface, while thick snow cover led to a warmer soil surface (Kudryavtsev, 1992). Frauenfeld et al. (2004) indicated that the maximum snow depth by the end of winter had significant influence on active layer depth in the following summer. In our results, snow depth significantly decreased on TP and increased in Siberia, which would inevitably accelerate the influence on permafrost freezing and thawing. We hope our research can provide an important reference for estimating the thermal regime of soil in these regions.

~~**4.2 Topographical effects in snow depth**~~

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

5 Conclusions

In this study, daily snow depth and snow course data from 1814 stations were used to investigate spatial and temporal changes in annual mean snow depth and maximum snow depth over the Eurasian continent for the period from 1966 to 2012.

Our results demonstrate that greater long-term average snow depth was observed in northeastern European Russia, the Yenisey River basin, the Kamchatka Peninsula, and Sakhalin. In contrast, the shallowest snow depths were recorded in China, except for the northern Xinjiang Autonomous Region of China, Northeast China, and in some regions of southwestern TP.

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

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

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

Acknowledgements. We express our gratitude to the researchers who assembled and digitized the snow depth data at meteorological stations and snow surveys across the Eurasian continent over a period of >40 years. This work was funded by the National Key Scientific Research Program of China (2013CBA01802), the Open Foundation from the State Key Laboratory of Cryospheric Sciences (SKLCS-OP-2016-12), the

Project for Incubation of Specialists in Glaciology and Geocryology of the National Natural Science Foundation of China (J1210003/ J0109), and the Foundation for Excellent Youth Scholar of Cold and Arid Research Environmental and Engineering Research Institute, Chinese Academy of Sciences.

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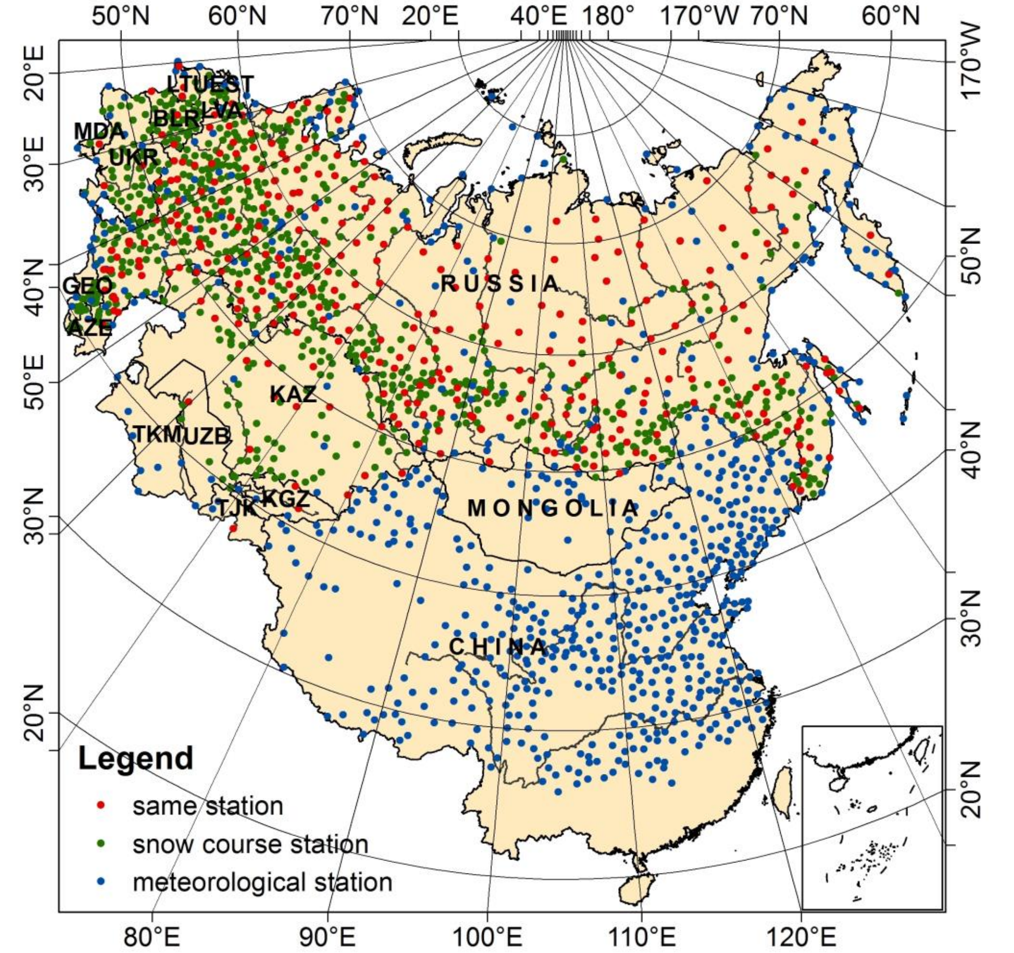
Tables and Figures

Table 1. Sources of snow depth data.

Dataset	**Spatial distribution**	**Number of stations**	**Source**
Daily snow depth	the former USSR	586	Russian Research Institute for Hydrometeorological Information-World Data Center (RIHMI-WDC) National Snow and Ice Data Center (NSIDC), University of Colorado at Boulder
	China	492	National Meteorological Information Center (NMIC) of the China Meteorological Administration
	Mongolia	25	NSIDC
Snow depth from snow 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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60°N
70°N
20°E
40°E
180°
170°W
70°N
60°N
20°E
30°E
40°N
50°E
30°N
20°N
170°W
50°N
40°N
30°N
20°N
80°E
90°E
100°E
110°E
120°E
LTU
EST
LVA
BLR
MDA
UKR
GEO
AZE
RUSSIA
KAZ
TKM
UZB
TJK
KGZ
MONGOLIA
CHINA
Legend
same station
snow course station
meteorological station

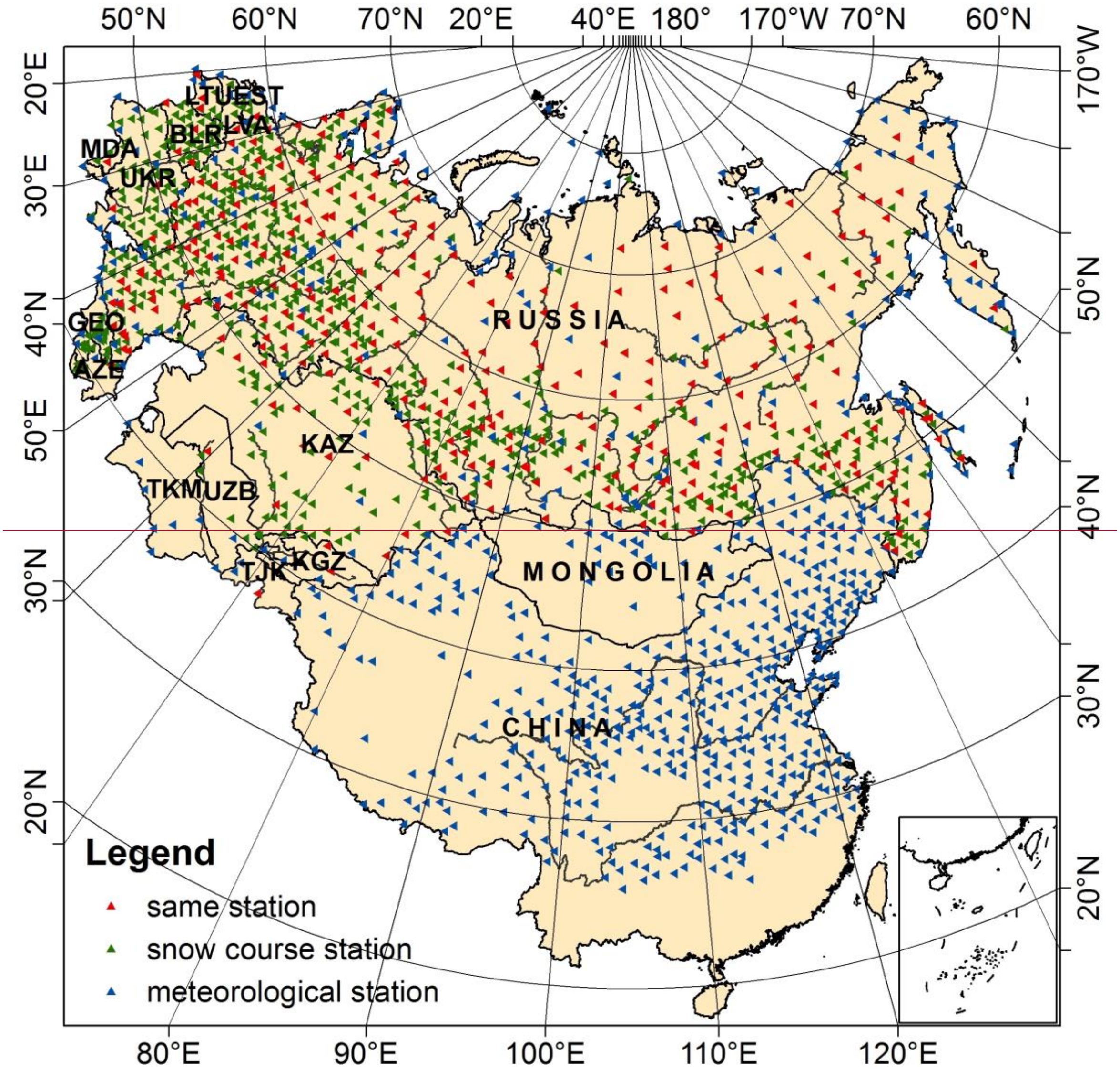
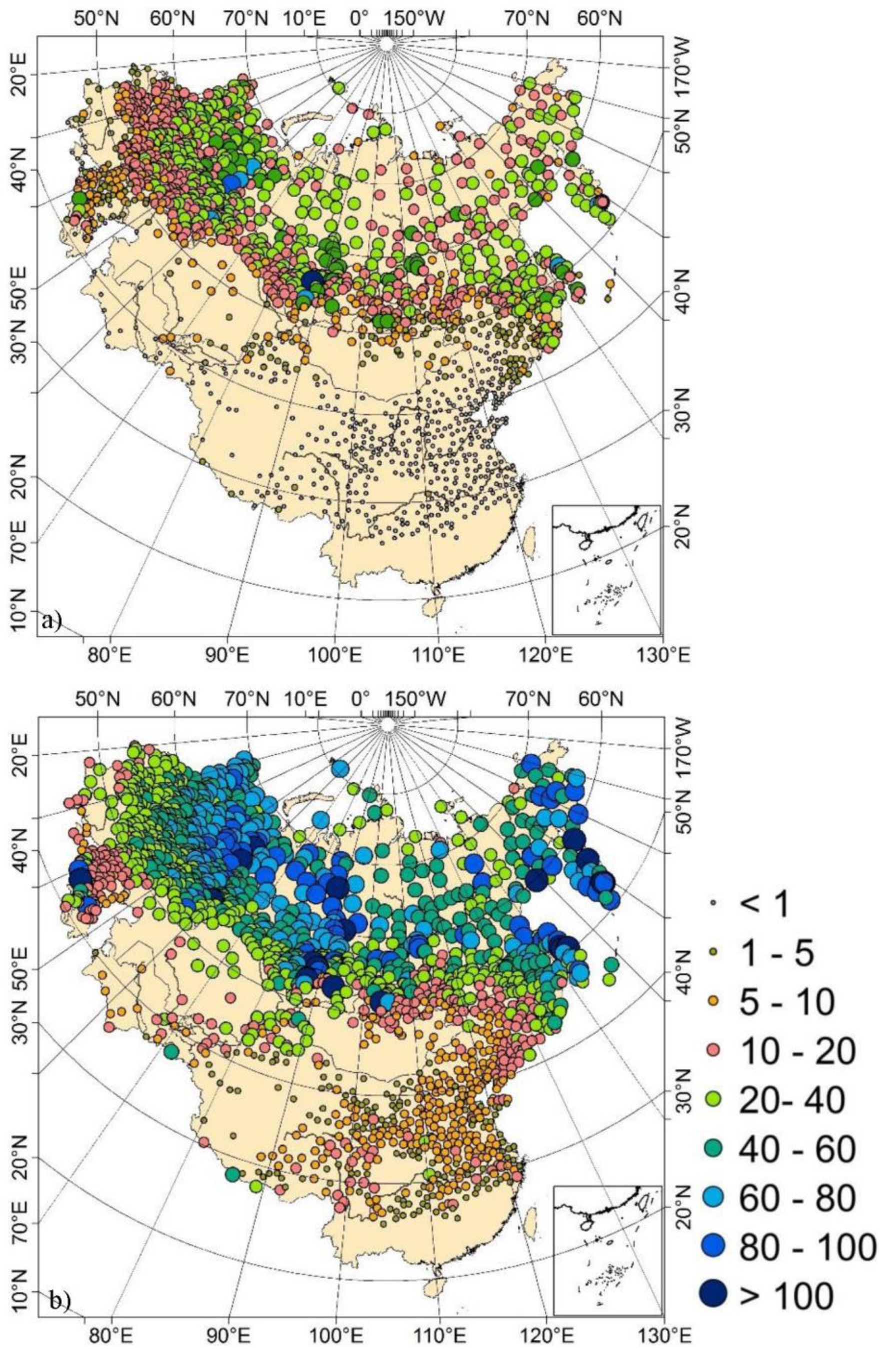


Figure 1. Geographical locations of meteorological and snow course stations across the Eurasian continent. The red triangles represent stations where snow depth was measured at both meteorological stations and snow course surveys, the green triangles show stations where snow depth was measured at snow surveys only, and the blue triangles show stations where snow depth was measured at meteorological stations only.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40°N
50°E
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20°N
70°E
10°N
80°E
90°E
100°E
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120°E
130°E
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1 - 5
5 - 10
10 - 20
20- 40
40 - 60
60 - 80
80 - 100
> 100

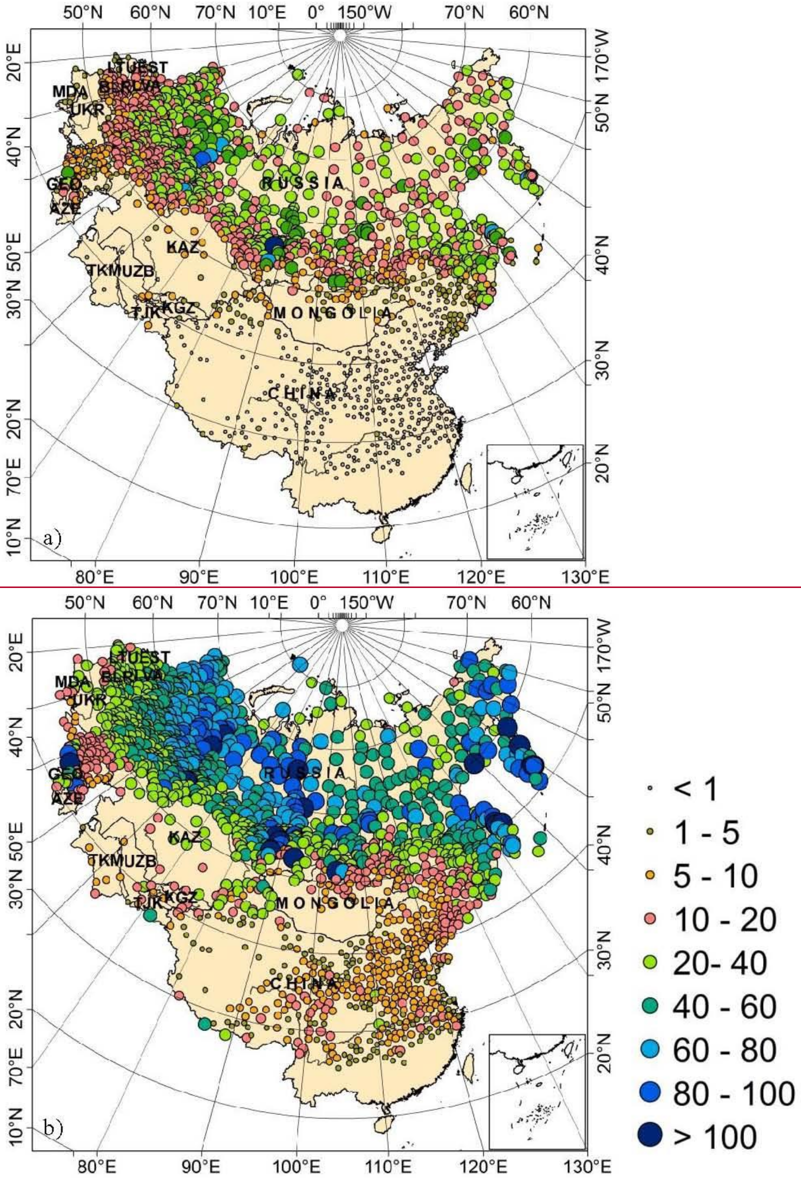
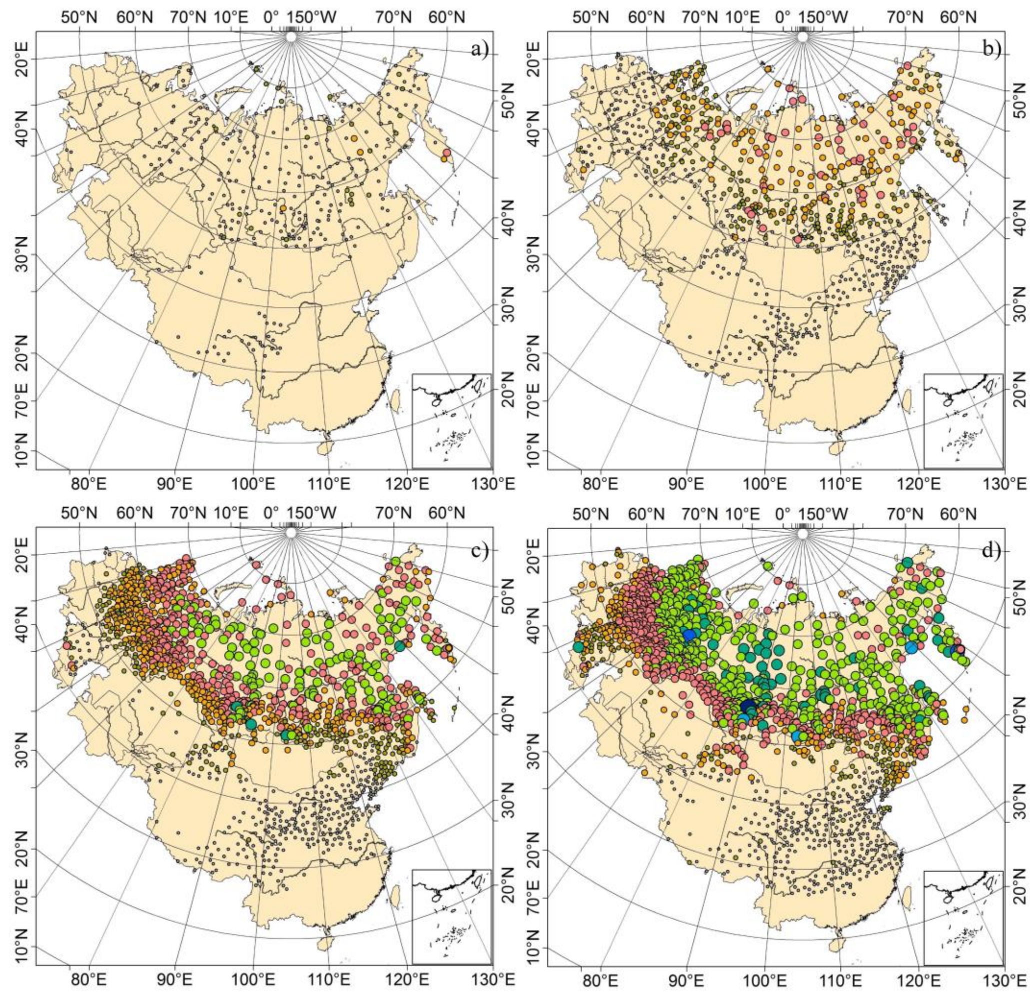


Figure 2. Annual mean snow depth (a) and maximum snow depth (b) across the Eurasian continent (cm) during 1966-2012.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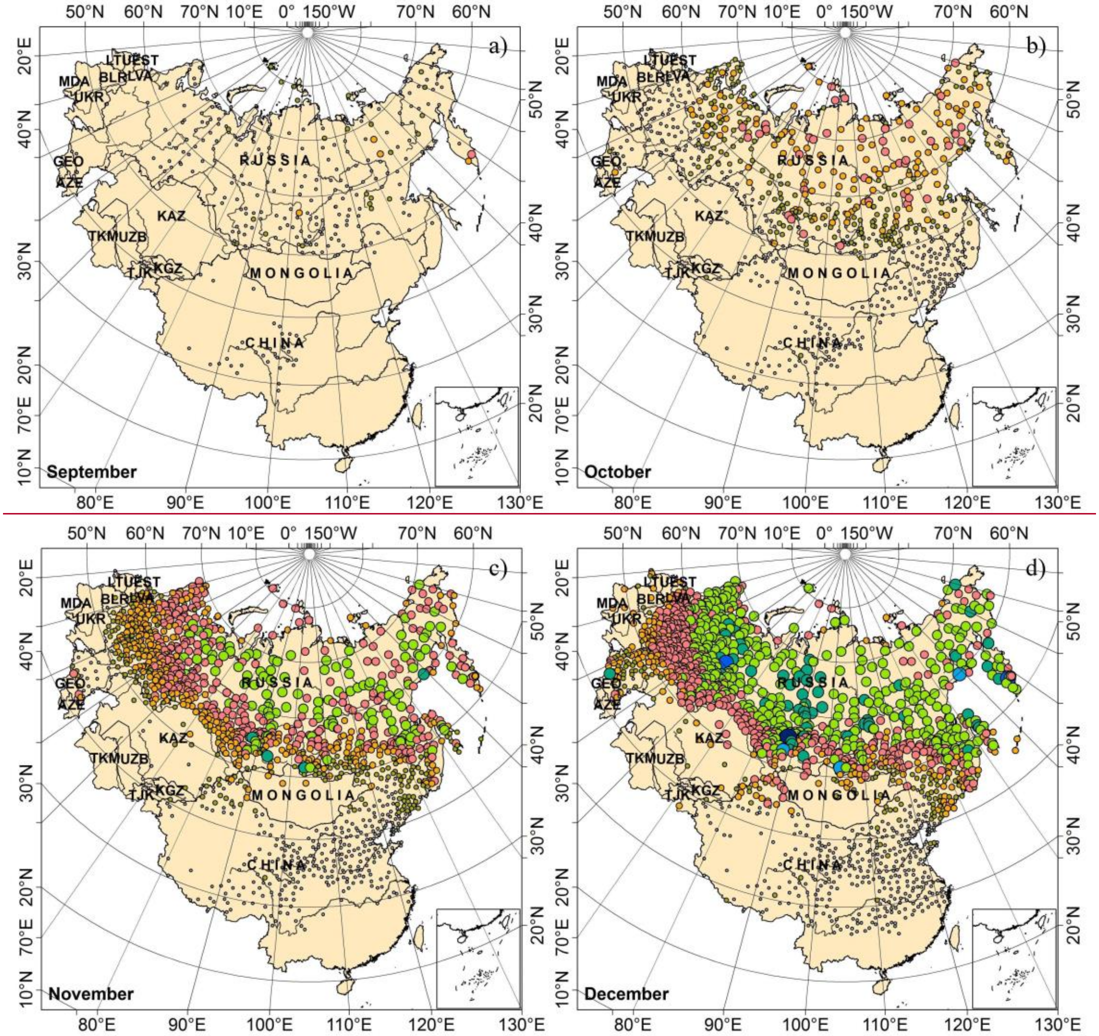
a)
September
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October
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RUSSIA
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LTU
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BLR
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50°N
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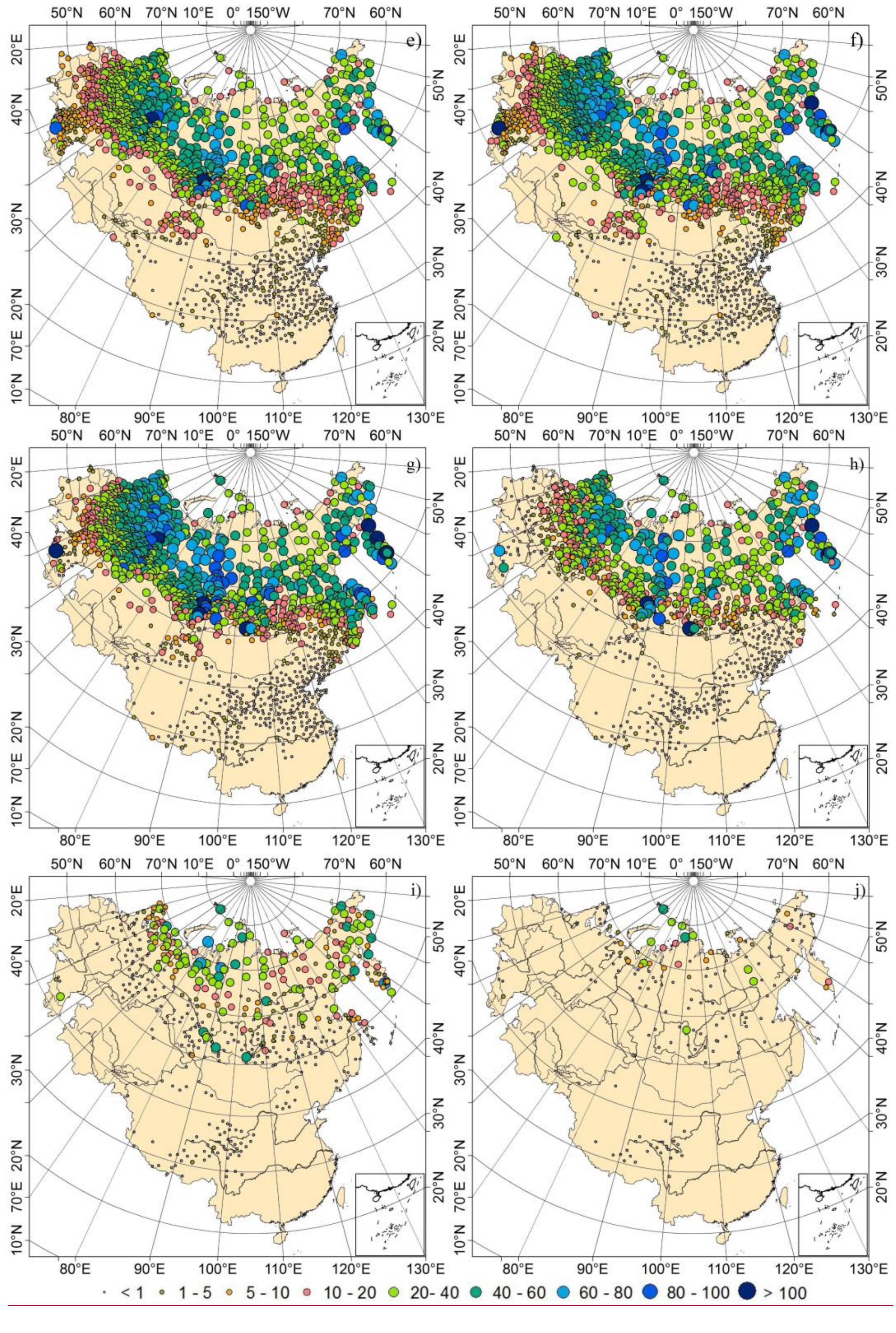

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j)
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50°N
40°N
30°N
20°N
80°E 90°E 100°E 110°E 120°E 130°E
< 1
1 - 5
5 - 10
10 - 20
20- 40
40 - 60
60 - 80
80 - 100
> 100

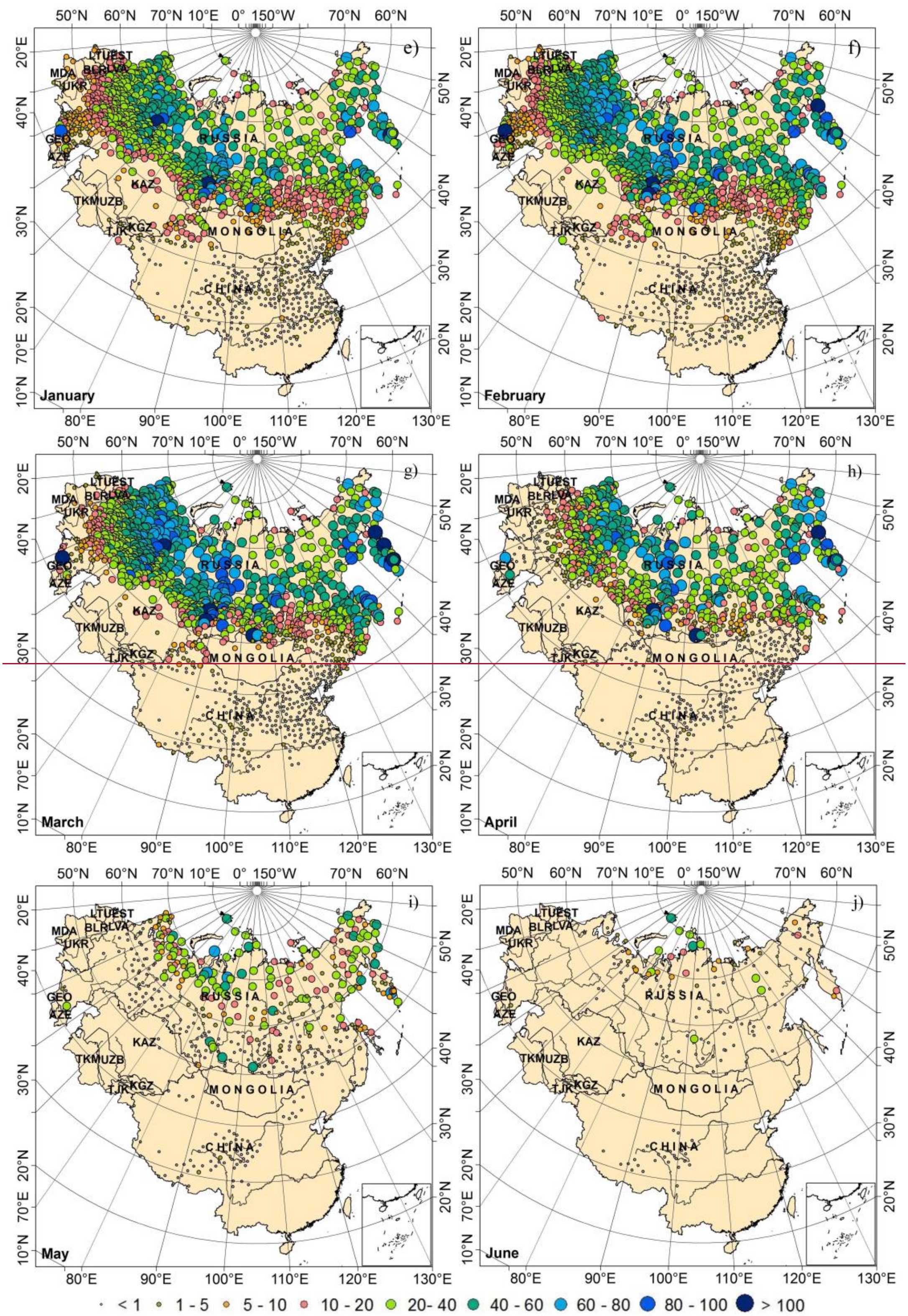


Figure 3. Monthly mean snow depth (from September to June) (cm) across the Eurasian continent (cm) during 1966-2012. (a) September, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, (h) April, (i) May, (j) June.

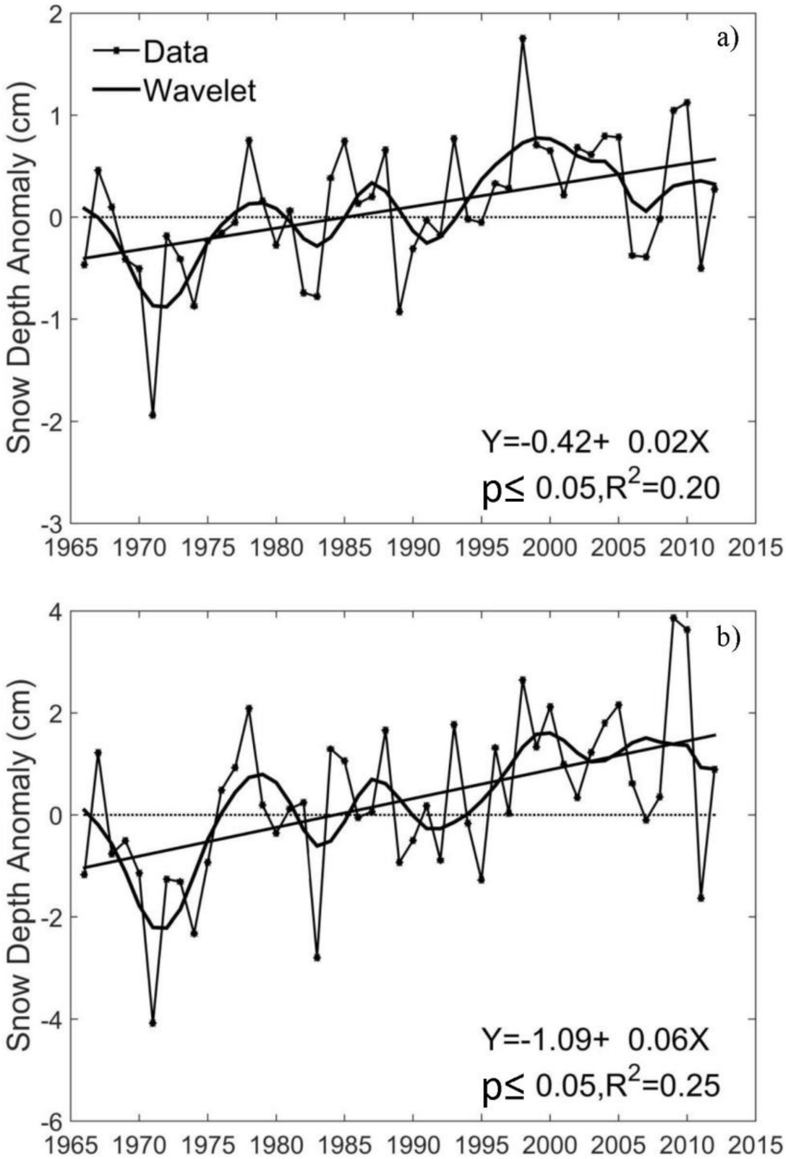
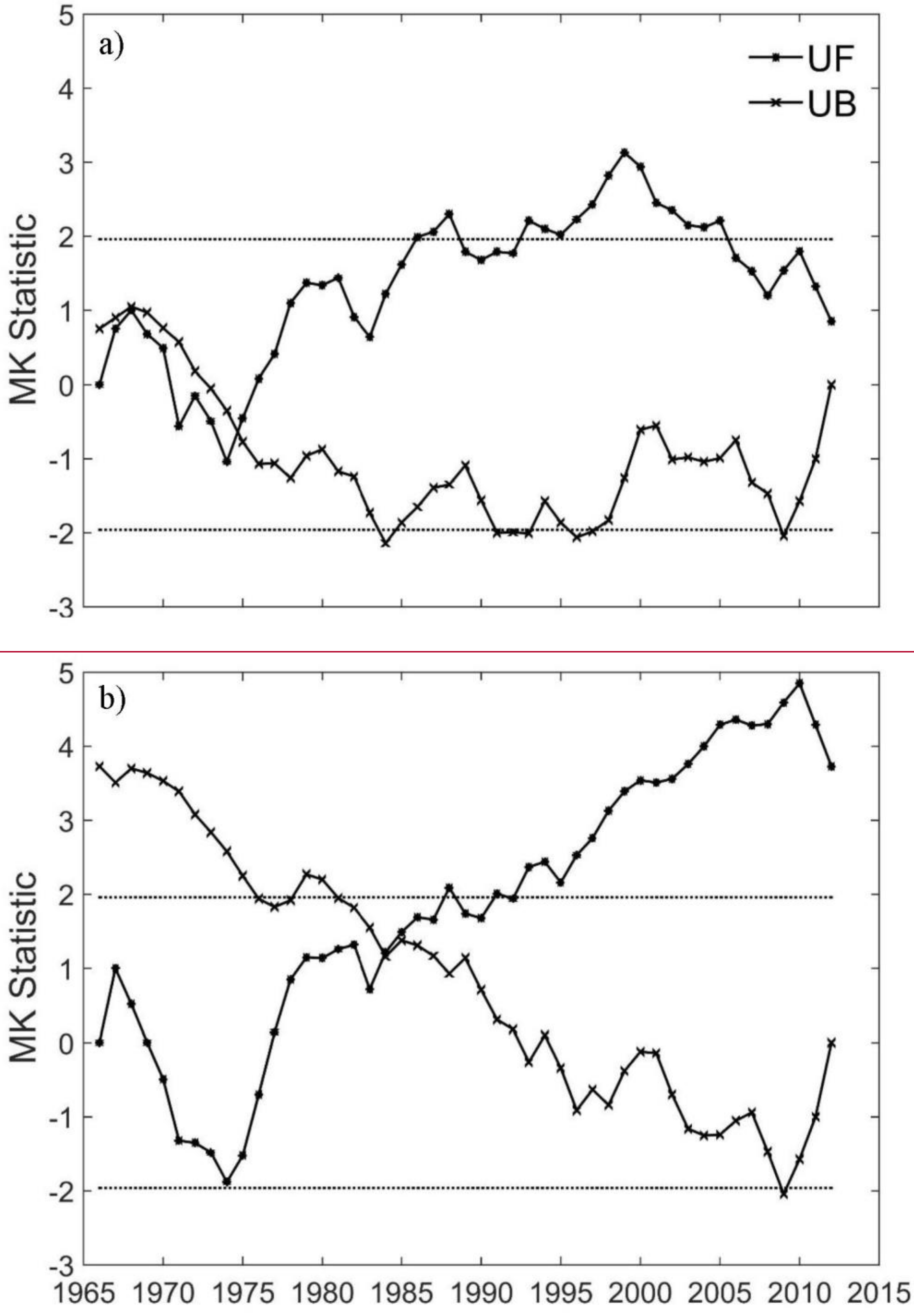


Figure 4. Composite of inter-annual variation of annual mean snow depth (a) and maximum snow depth (b) from 1966 through 2012 with respect to the 1971-2000 mean across the Eurasian continent. The line with dots is the anomaly of snow depth; the thick curve represents the smoothed curve using wavelet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



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

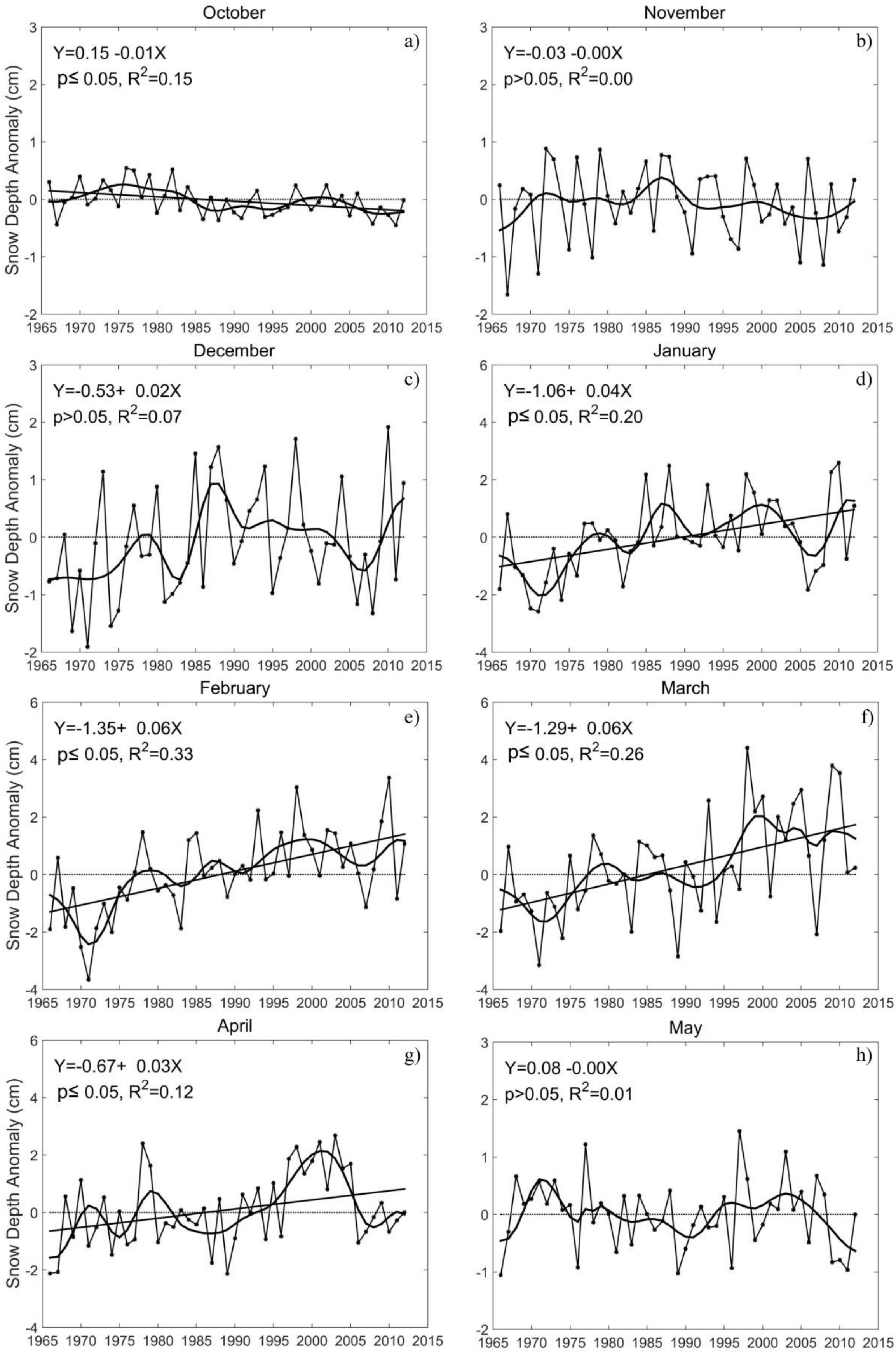
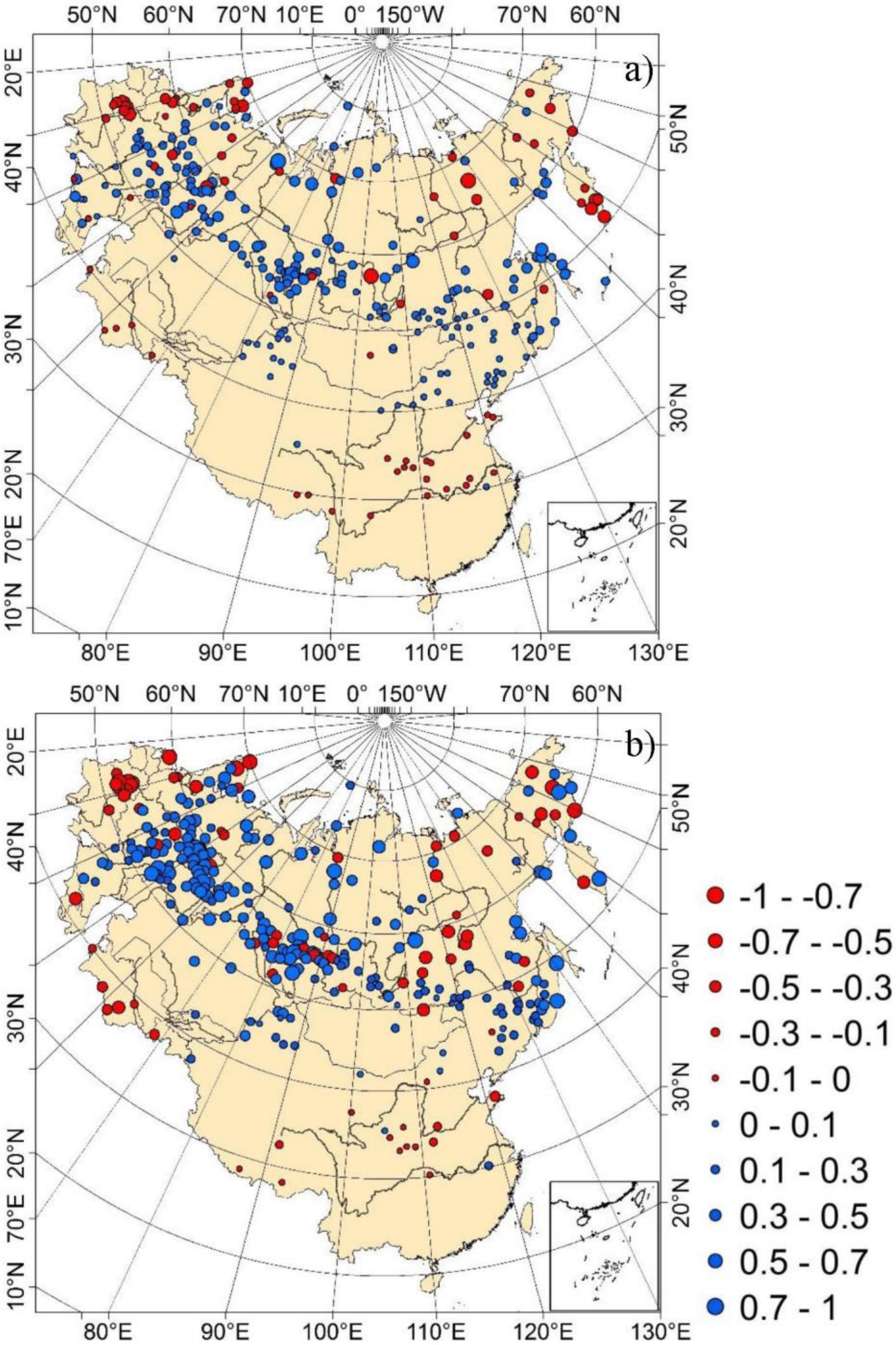
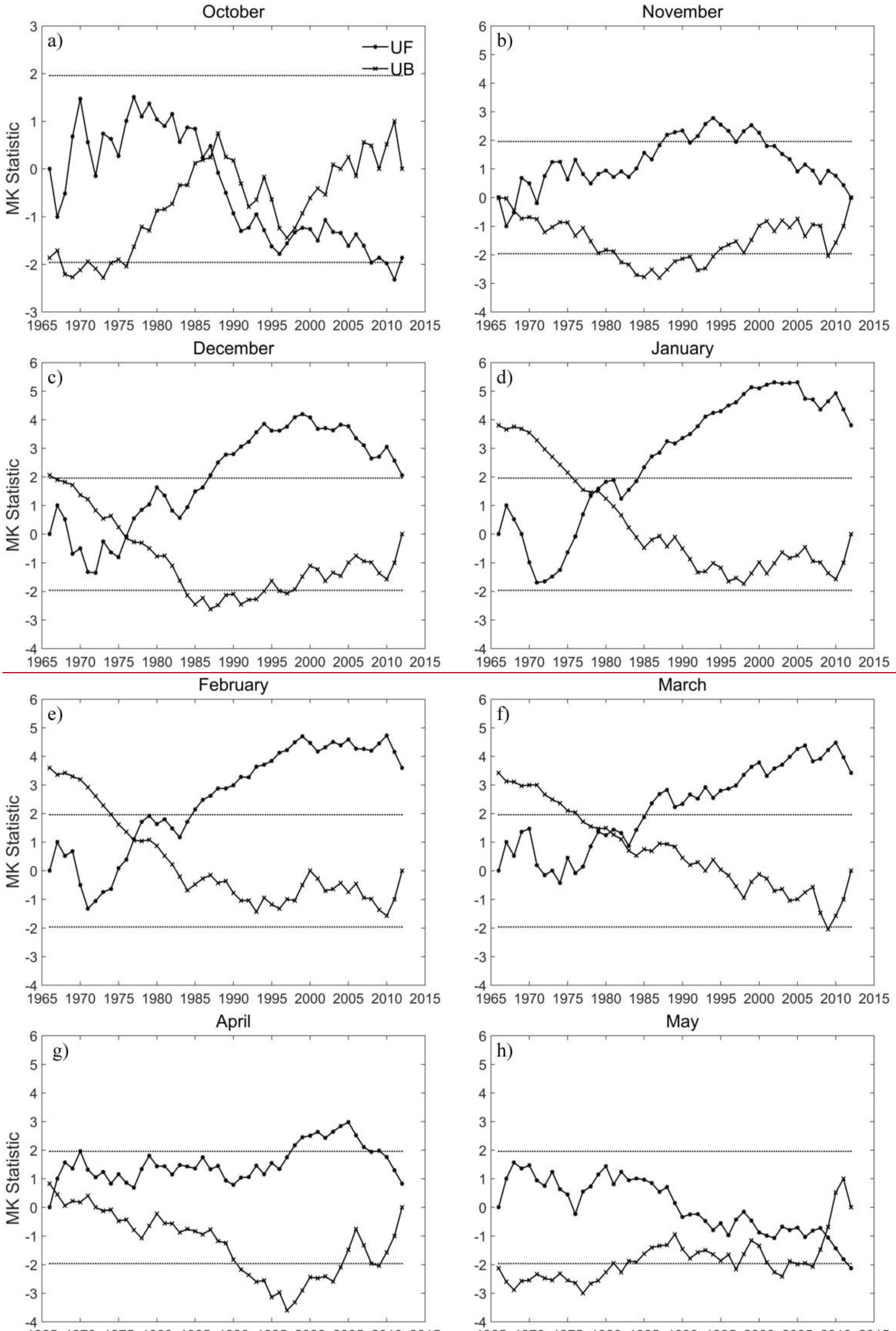


Figure ~~6~~5. Composites of inter-annual variation of monthly mean snow depth (from October to May) from 1966 through 2012 with respect to the 1971-2000 mean across the Eurasian continent. (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May. The line with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





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

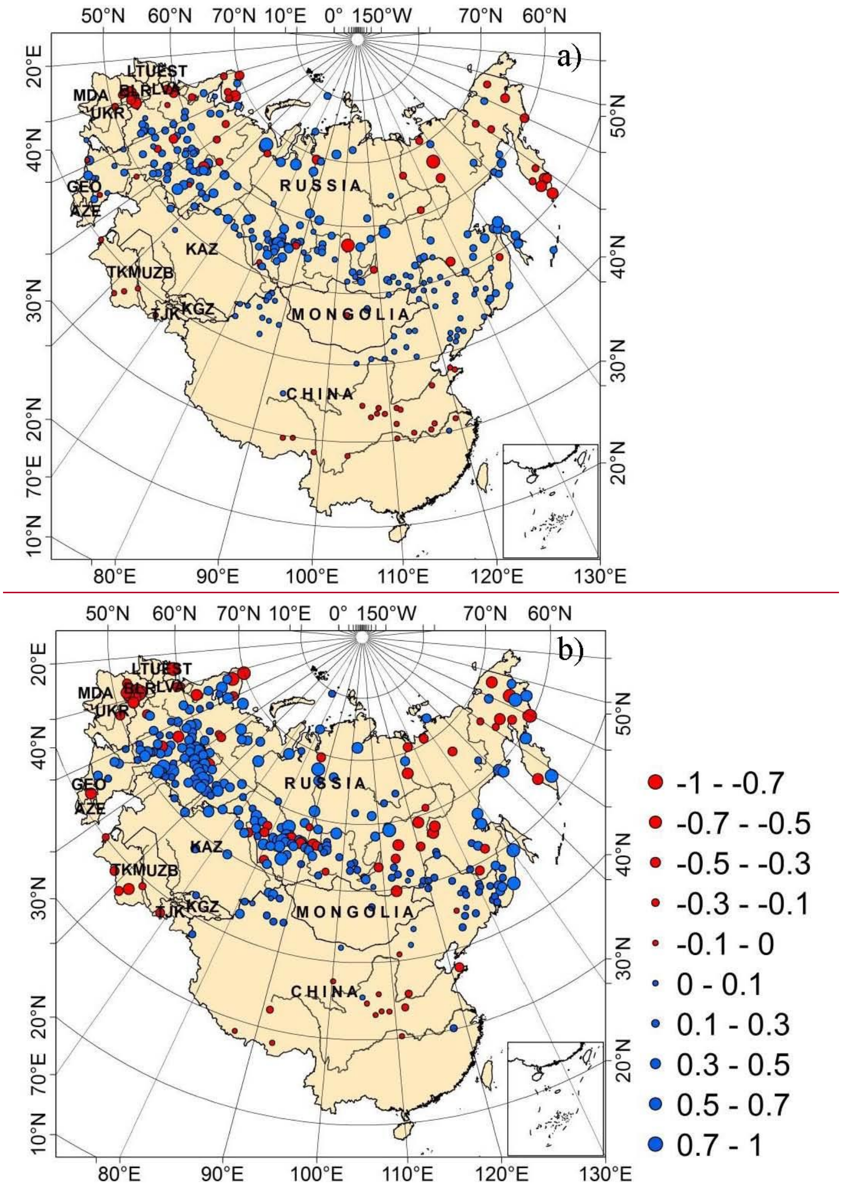
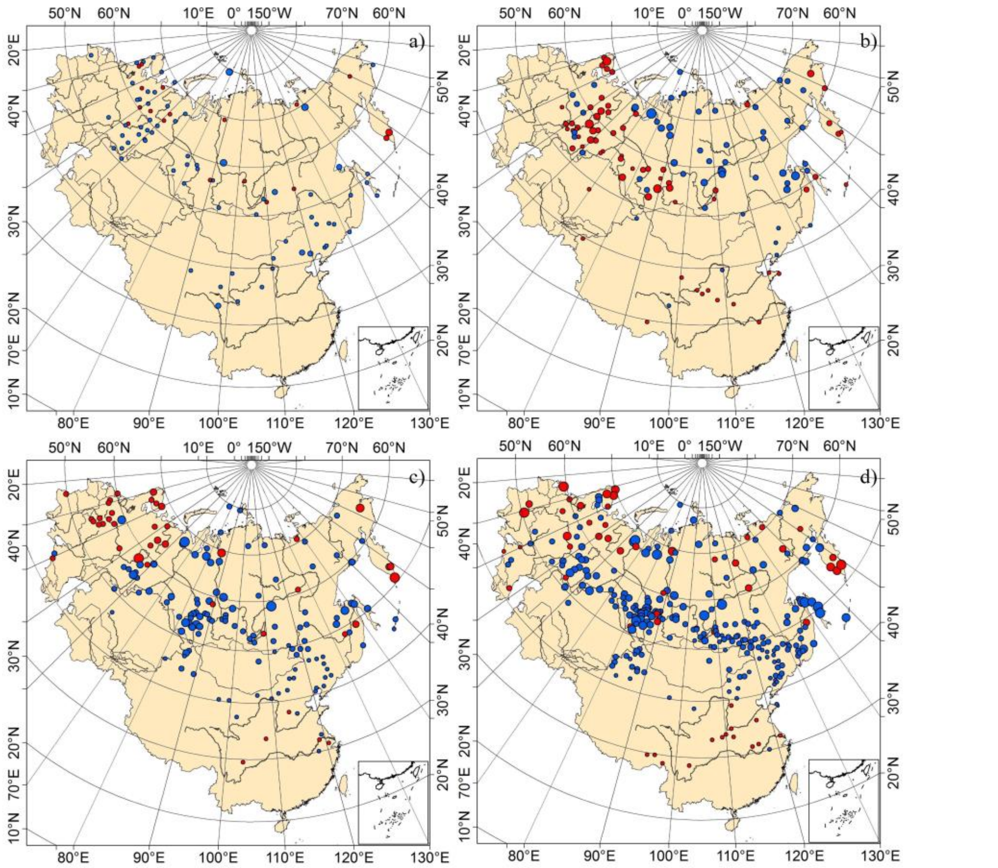


Figure ~~8~~6. Spatial distribution of linear trend coefficients (cm yr^{-1}) of annual mean snow depth (a) and maximum snow depth (b) for each station in 1966-2012. The rate of change was at the 95% level. Red circles represent a decreasing trend, and blue circles represent an increasing trend.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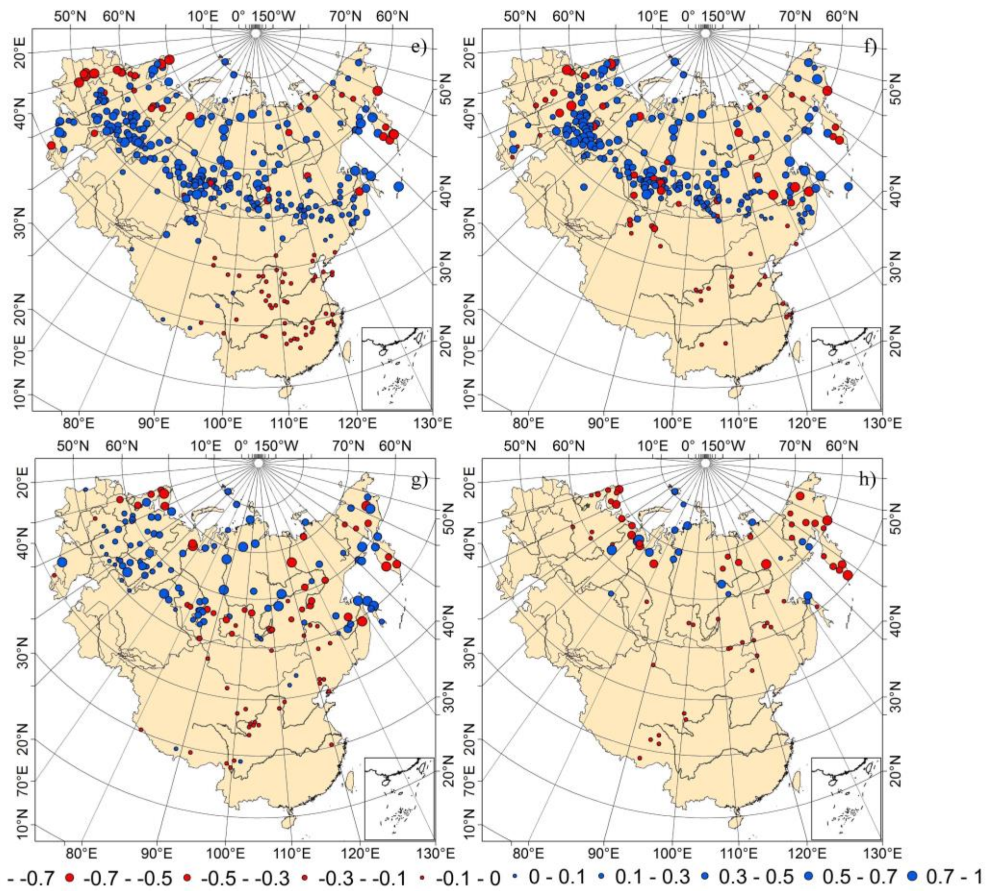
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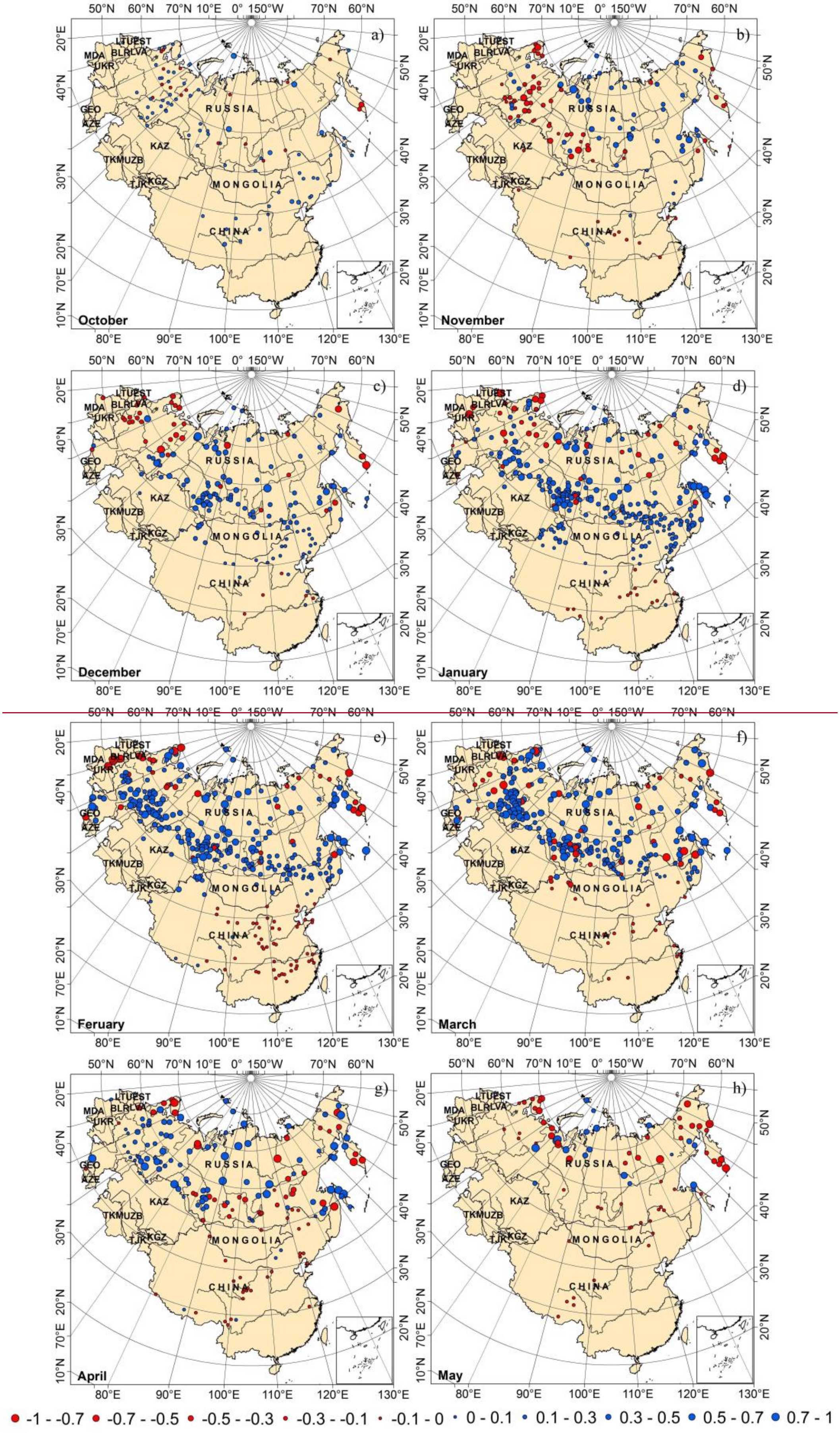
20°E 40°N 30°N 20°N 70°E 10°N
50°N 40°N 30°N 20°N
80°E 90°E 100°E 110°E 120°E 130°E
-1 - -0.7
-0.7 - -0.5
-0.5 - -0.3
-0.3 - -0.1
-0.1 - 0
0 - 0.1
0.1 - 0.3
0.3 - 0.5
0.5 - 0.7
0.7 - 1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BLR LVA
MDA
UKR
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AZE
TKM UZB
TJK KGZ
50°N 60°N 70°N 10°E 0° 150°W 70°N 60°N
80°E 90°E 100°E 110°E 120°E 130°E
-1 - -0.7
-0.7 - -0.5
-0.5 - -0.3
-0.3 - -0.1
-0.1 - 0
0 - 0.1
0.1 - 0.3
0.3 - 0.5
0.5 - 0.7
0.7 - 1

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

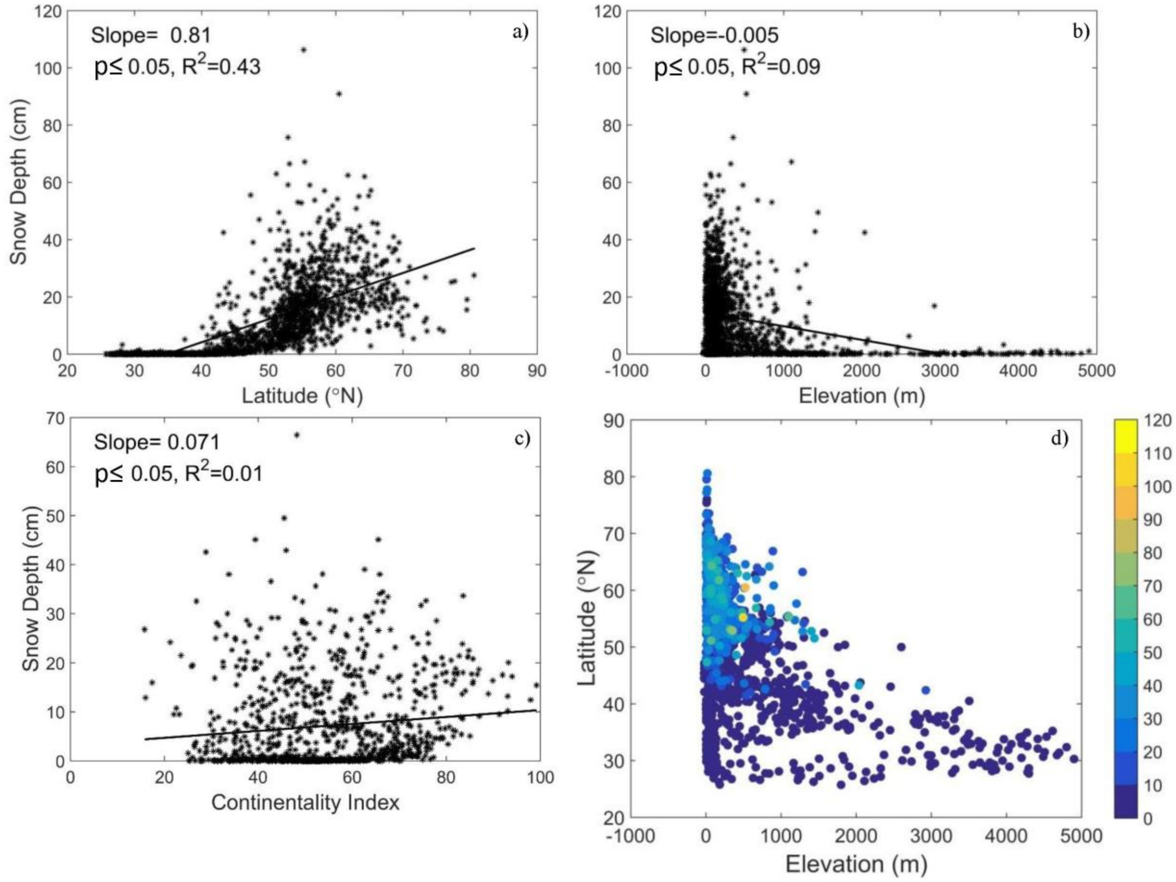


Figure ~~10~~8. The relationship between annual mean snow depth and latitude (a), elevation (b) and continentality (c) for all stations across the Eurasian continent during 1966-2012. Asterisks show the mean snow depth of each station; the thick line is a linear regression trend; the different colors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

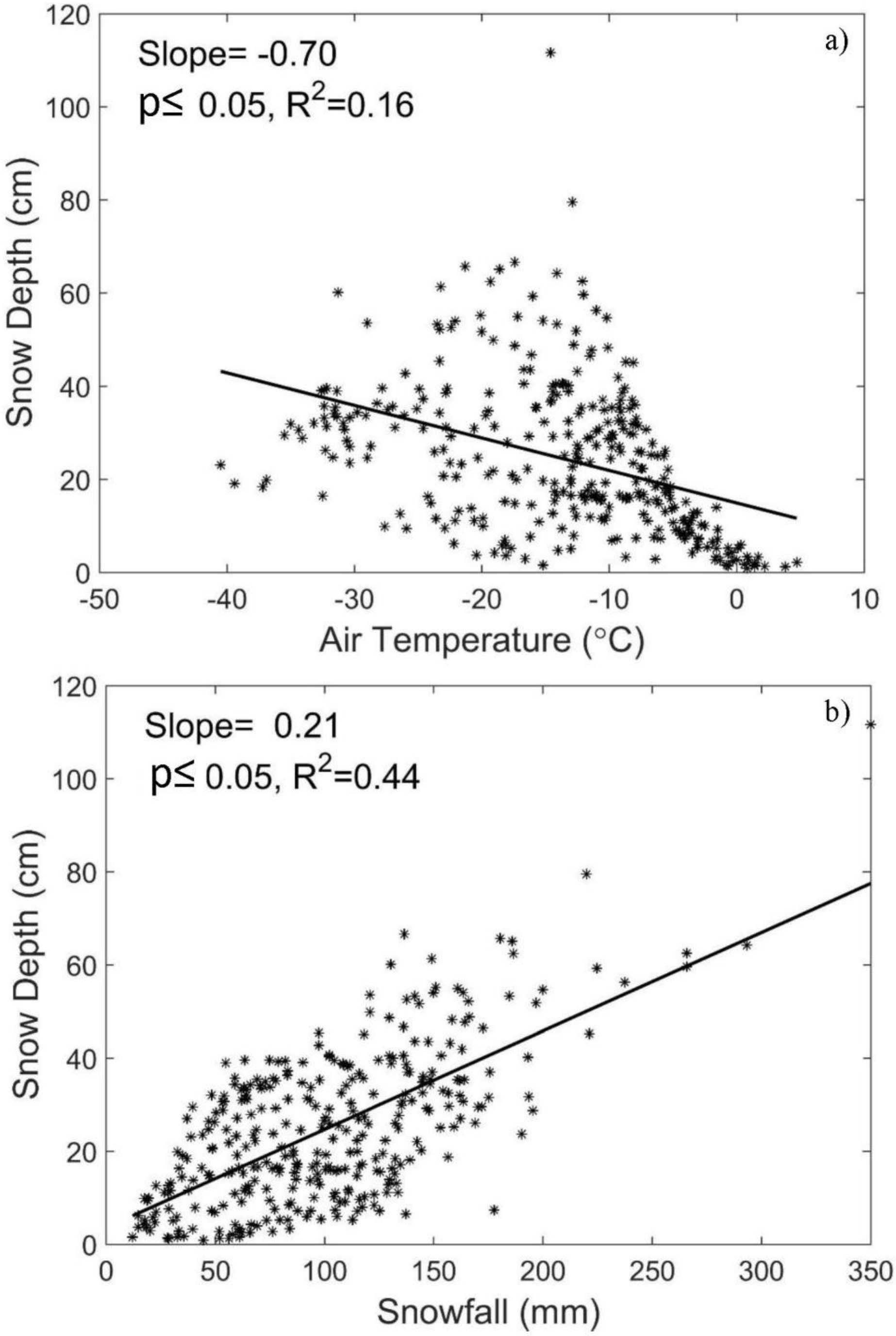


Figure ~~11~~9. The relationships among annual mean snow depth, air temperature and snowfall for 386 stations from November through March during 1966-2009 over the USSR. The thick line is a linear regression trend.

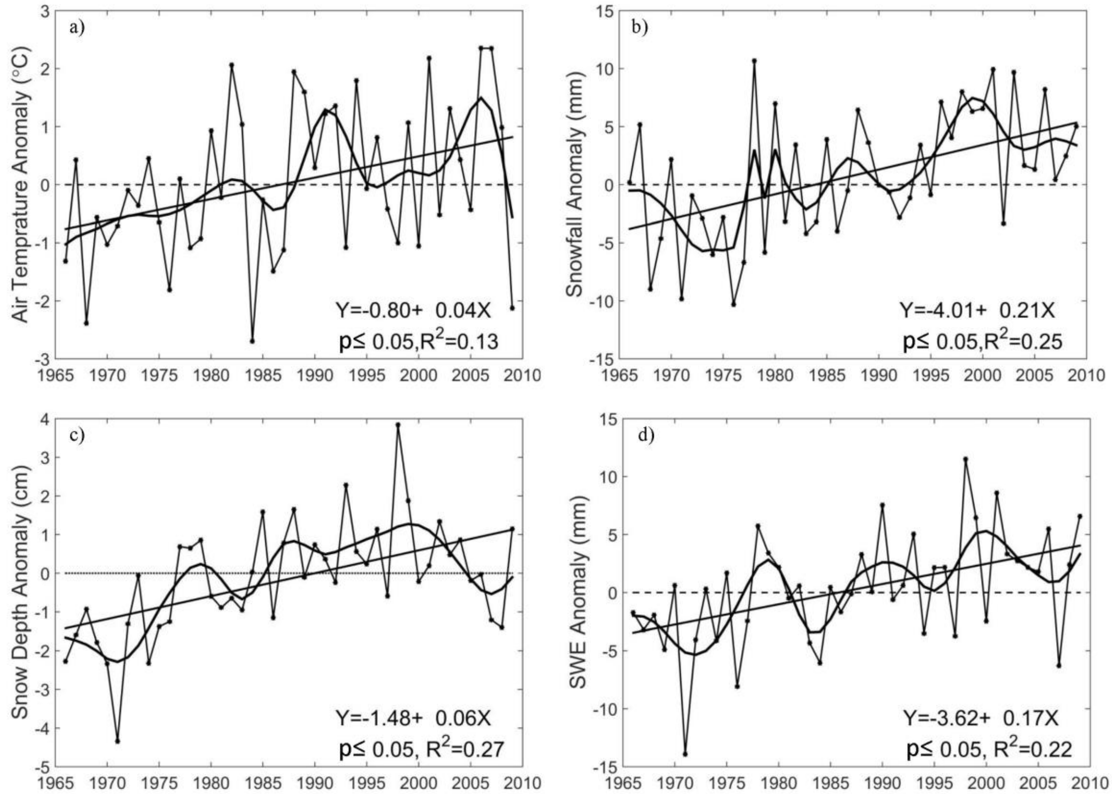
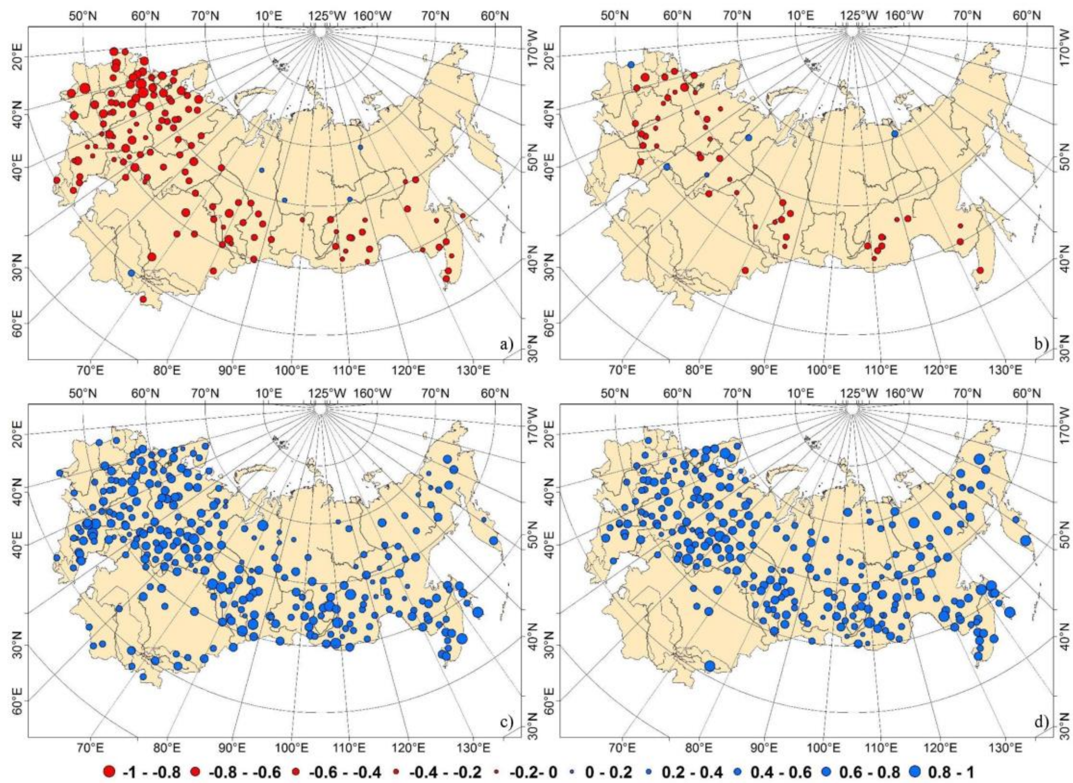


Figure ~~12~~10. Composite of inter-annual variation of annual mean air temperature (a), annual snowfall (b), annual snow depth (c) and snow water equivalent (d) from November through March during 1966-2009 with respect to the 1971-2000 mean across the former USSR. The line with dots is the composite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



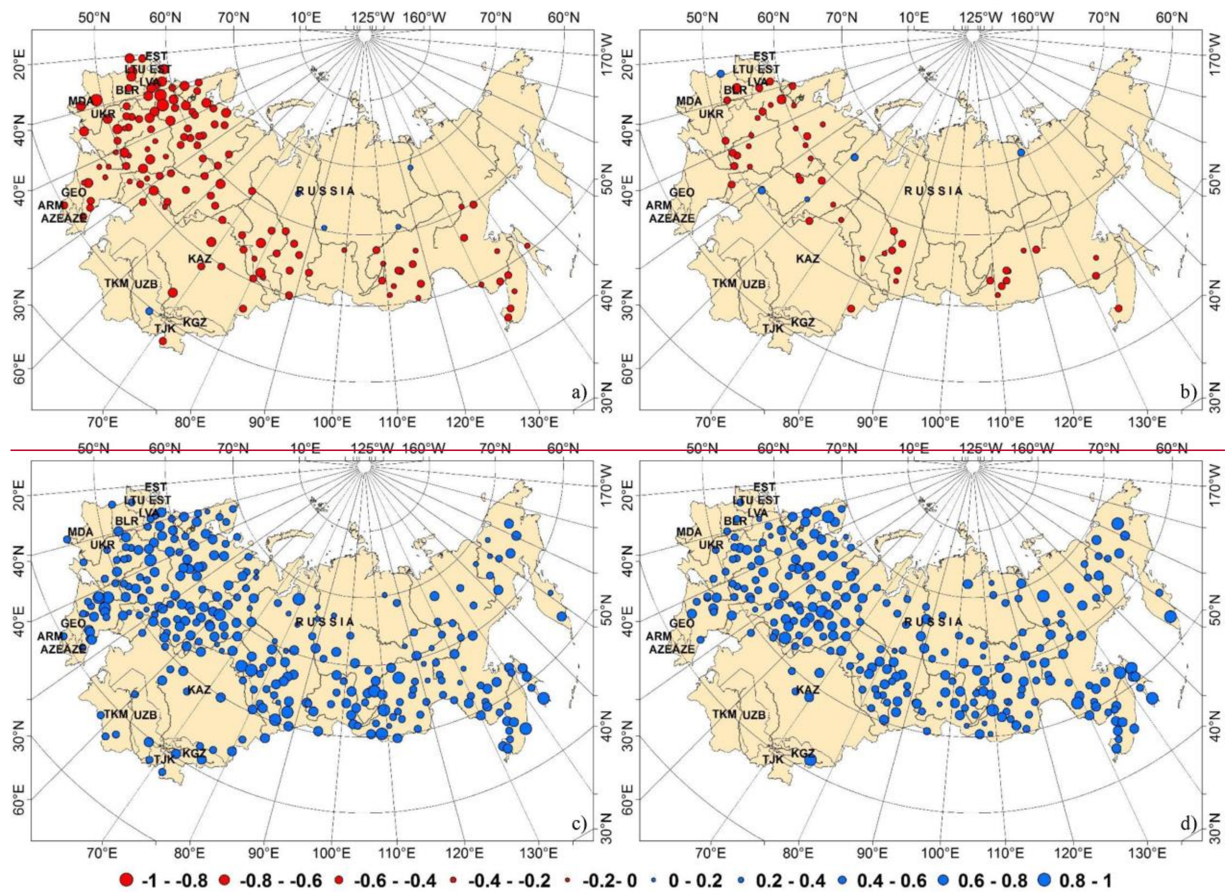


Figure ~~13~~11. Spatial distributions of partial correlation coefficients of snow depth and air temperature (a), snow depth and snowfall (b), SWE and air temperature (c), SWE and snowfall from November through March during

1966-2009. The coefficients reaching to 0.05 ~~confident level~~confidence level are displayed. Red circles represent a negative relationship, and blue circles indicate a positive relationship.