Replies to the comments of Anonymous Referee #1

Authors' replies are in BLUE color.

Interactive comment on "Variability in snow cover phenology in China from 1952 to 2010" by C. Q. Ke et al.

Anonymous Referee #1

Received and published: 18 May 2015

CONTENTS

The paper presents the climatology of snow several snow variables (snow cover days, onset and end date of snow cover), their spatiotemporal evolution, extreme years and trends from 1952-2010 in China for a prey large number of stations. The relation to temperature variables and climate patterns (Arctic Oscillation, AO) is also discussed.

A good relation between temperature indices and snow pack is found (shortening of snow season), for some regions also with the AO. Trends are not as clear as on the northern hemispheric scale.

RECOMMENDATION

The paper gives a good overview of snow climatology of China with a lot of snow stations included. It also discusses the spatiotemporal evolution of several snow variables and analyses the relation with temperature and a major climate pattern. By discussing first the climatology of the mean, then the extremes and finally the trends gives the paper a good structure in my view. It is worth to be published but some major clarifications and "more consistency" in the presentation is needed before final acceptance.

Replies: We have read your comments carefully. Thanks for your detail comments, and we have made amendments to the article according to your recommendations. You can see detail replies below.

MAJOR COMMENTS

Abstract L18-19: "the AO has the maximum impact" not the "AO index". An index has no impact, it is the process behind the index.

Replies: We change the 'AO index' to 'AO'.

2.2 Methods: There is no validation of the gridding procedure applied to your SCD, SCOD and SCED data (Fig. 2, 4 and 7). Please provide some results on how good the procedure works (e.g. by doing some kind of cross-validation).

Replies: We add a new Table to illustrate this point, and also provide some description in the revised manuscript.

Table 1 Prediction errors of cross validation for the spatial interpolation with the universal kriging method

Item (Figure)	Mean error	Average standard error	Root mean squared error	Root mean squared standardized error
SCD (Fig3a)	-0.0078	9.3710	10.3351	1.1729
CV (Fig3b)	0.0027	70.9203	56.7797	0.8236
SCD in 1957 (Fig5a)	-0.0001	10.1066	11.6712	1.1430
SCD in 2002 (Fig5b)	0.0170	5.7430	7.9122	1.2862
SCD in 2008 (Fig5c)	0.0008	6.8352	7.3988	1.0627
SCED in 1957 (Fig5d)	0.0050	14.7432	14.8384	1.0112
SCED in 1997 (Fig5e)	0.0026	16.9098	19.5960	1.1420
SCOD in 2006 (Fig5f)	-0.0035	15.4075	16.2315	1.0396
SCOD (Fig8a)	0.0037	13.8313	15.3312	1.1001
SCED (Fig8b)	-0.0038	17.1397	19.9136	1.1376

3.1.2: L13-15: Is there an explanation on why the winter on the Tibetan Plateau is so scare of snow? My first guess is, that it is too cold and dry in order to produce enough snow. Can this be shown in your data?

Replies: Yes, your guess is right. Mean temperature and precipitation in winter for Dangxiong station are -7.73 °C and 7.92 mm, respectively, and these for Qingshuihe station are -15.8 °C and 16.3 mm. Therefore it is too cold and dry in order to produce enough snow (Hu and Liang, 2014), and we also cite reference to support this.

3.1.2: L24: you speak of a nation-wide “snowstorm”. Do you mean one event or an annual anomaly here? Please be precise here. Normally the word “snowstorm” is used for one certain event of a few days length.

Replies: We change the ‘snowstorm’ to ‘SCD anomaly’.

Fig. 5 and elsewhere in text: you use the terms advanced and postponed. Wouldn't it be better to used "earlier" and "later" everywhere? Especially "advanced" is a strange word to be used here in my view.

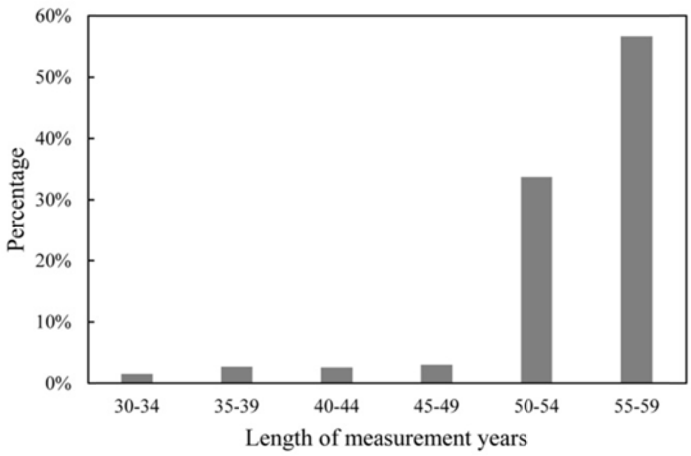
Replies: We change the 'advanced' and 'postponed' to 'earlier' and 'later' everywhere in text, respectively.

Section 4.2: In my view you could omit one of the analyses with MAT or TBZD. The two seem to have the same effect. I would shorten 4.2 to one sentence at the end of section 4.1. Very similar results are found for MAT.

Replies: We change the section 4.2 to one sentence 'Very similar results are found for MAT' at the end of section 4.1 as you suggested.

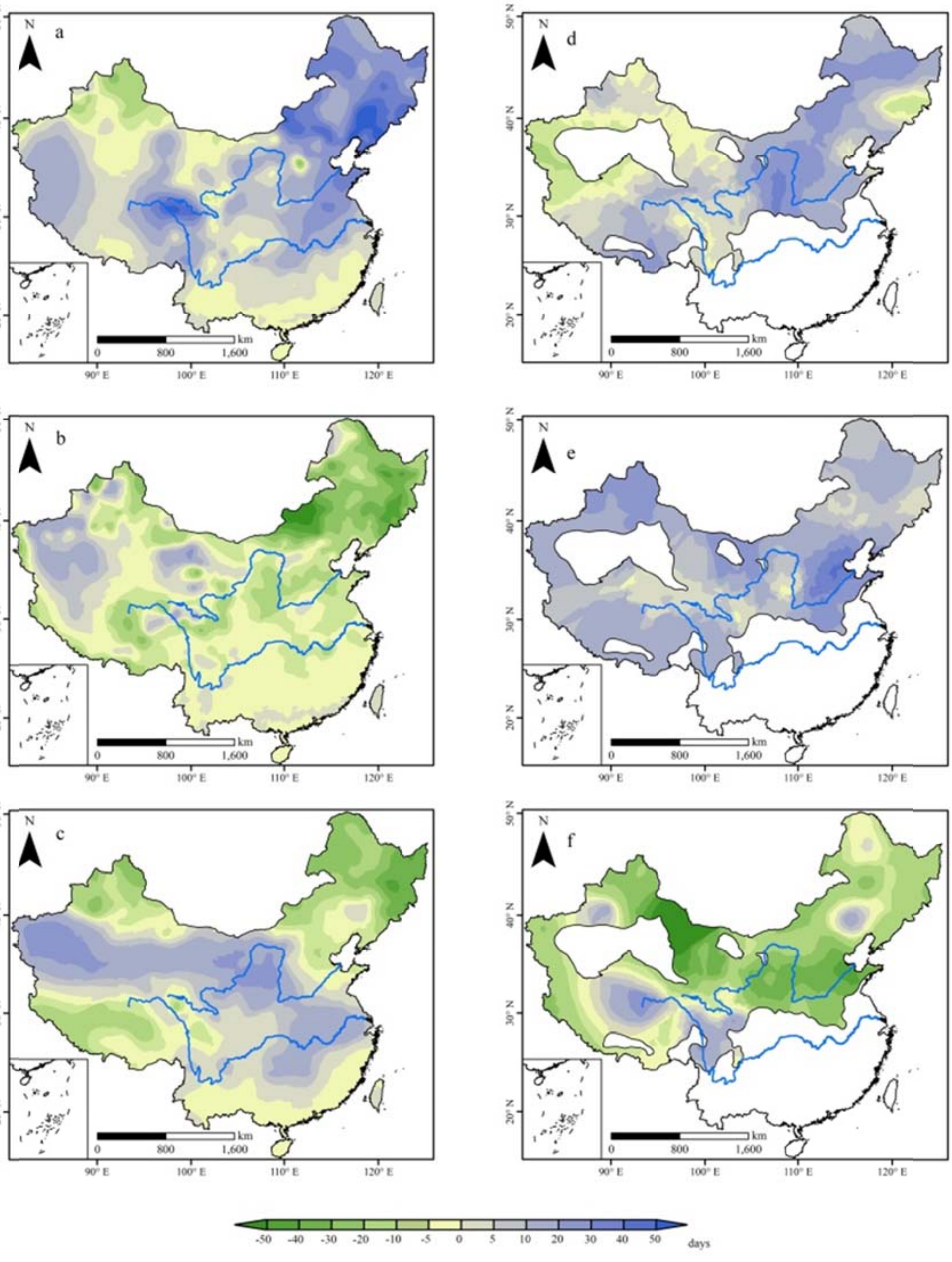
An additional table with the length of measurements for the different stations and probably a figure with the distribution of the lengths of the snow series would be very helpful in my view.

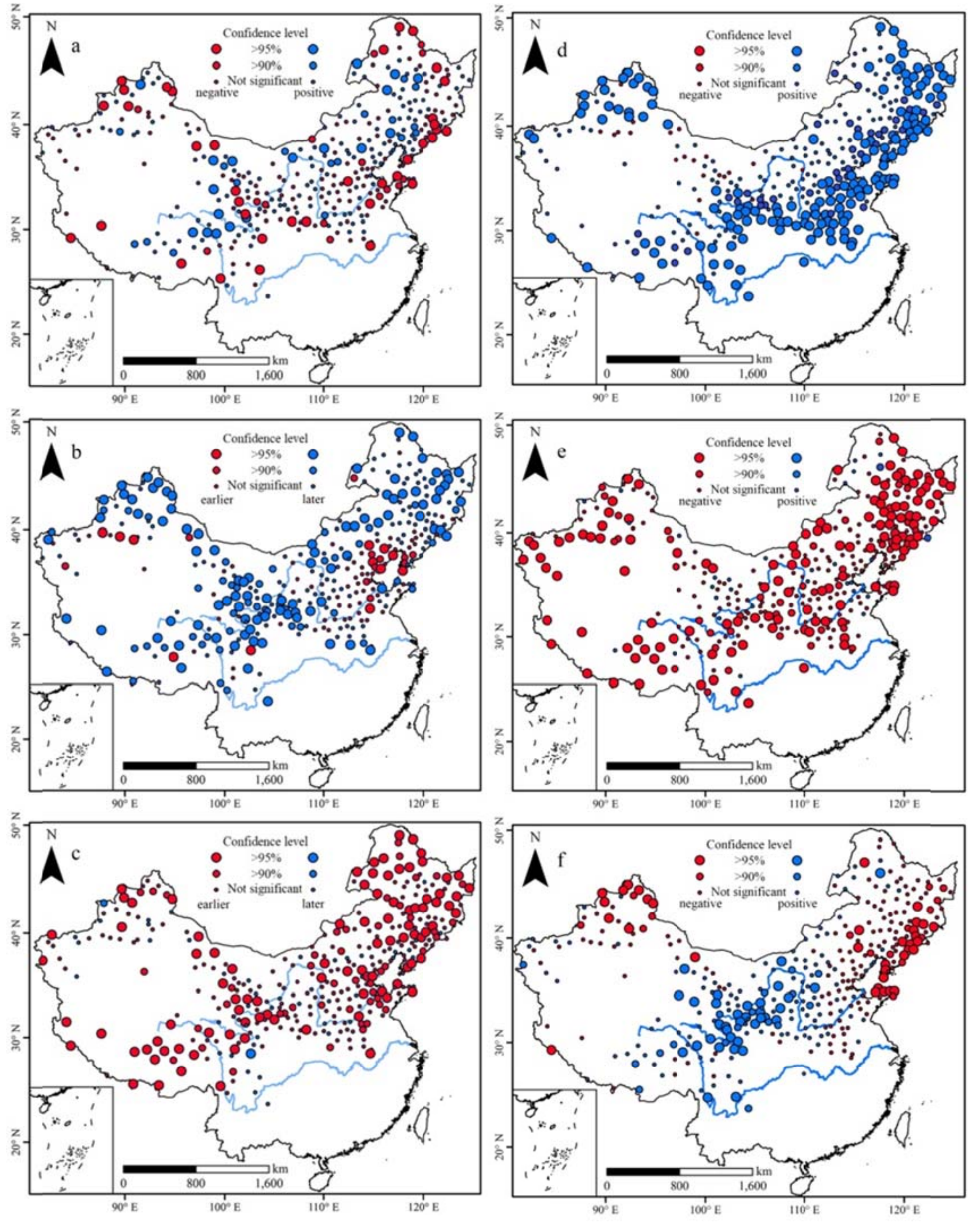
Replies: We add a figure to show this.



The colour tables you use in Fig. 4 and 5 are not optimal and not intuitive. Fig. 4: I suggest to use a scale that goes from green or brown to blue. Blue is often associated with lots of snow, brown and green with no snow. Fig. 5: Panel a: positive trends should be blue, negative ones red. Panel c: earlier should be red, later blue. Panel d: Use blue for positive correlation. Use earlier instead of advanced in Fig. 5 and text everywhere!

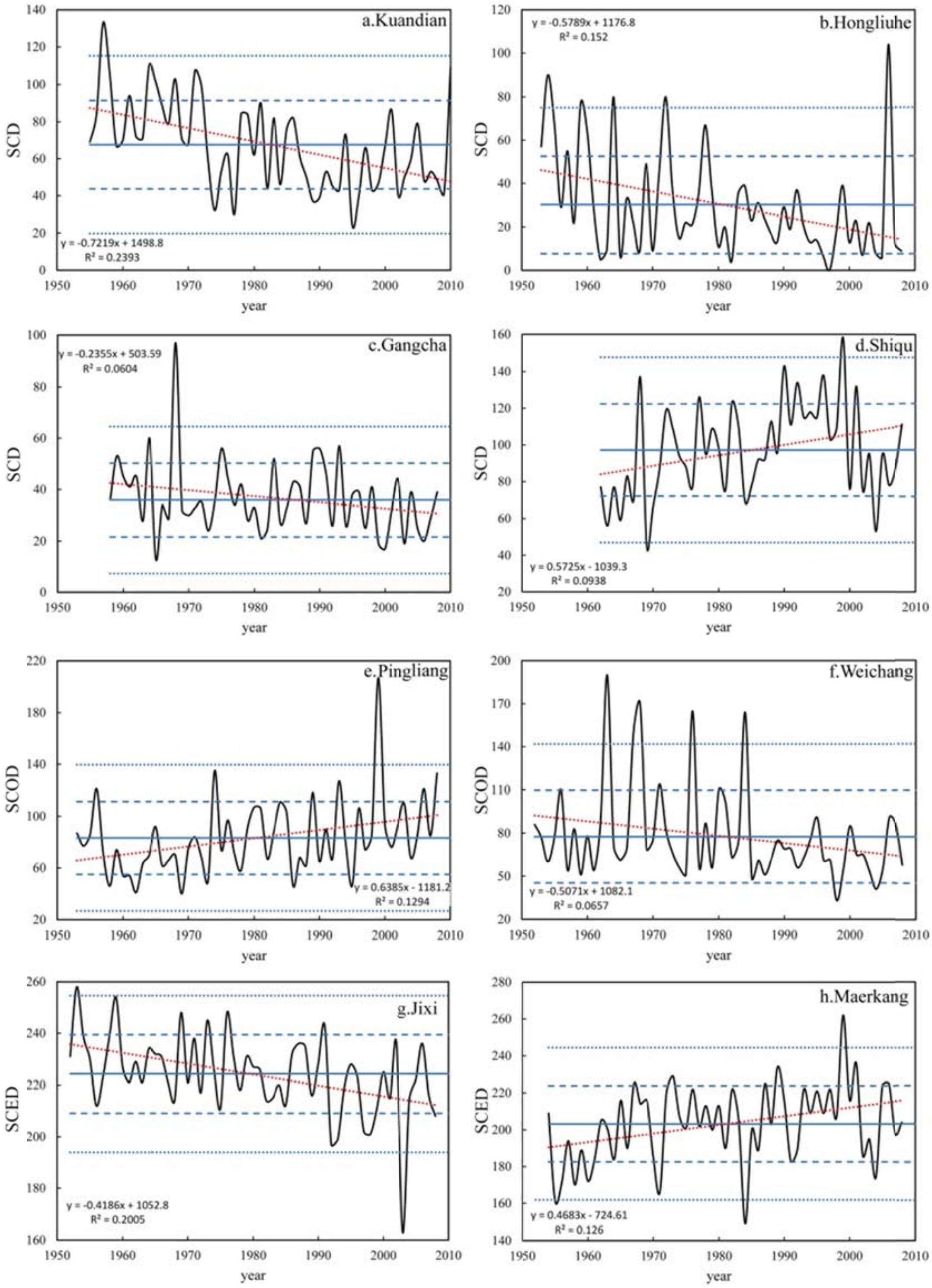
Replies: According to your suggestions, we change the colour tables in all figures, and use 'earlier' instead of 'advanced', 'later' instead of 'postponed' everywhere in text.


a
b
c
d
e
f
N
50° N
40° N
30° N
20° N
90° E
100° E
110° E
120° E
0
800
1,600
km
-50
-40
-30
-20
-10
-5
0
5
10
20
30
40
50
days

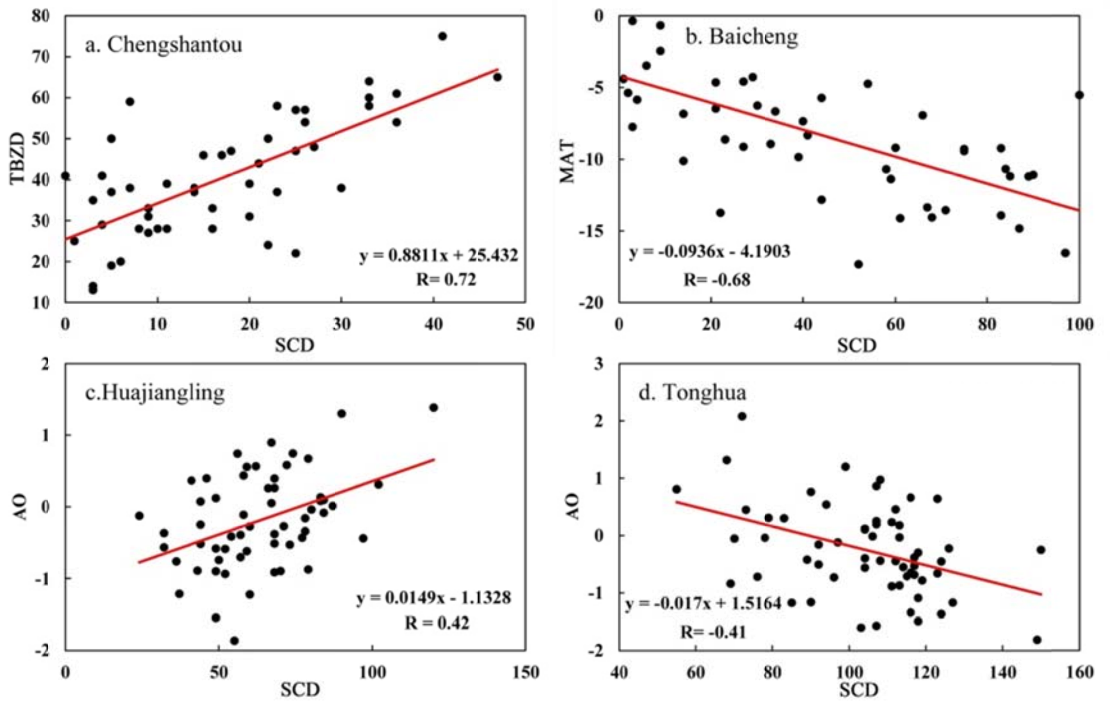


Use consistent panel labelling in all Figs., i.e. top left a, top left b etc: : :(as in Fig. 6) or left column down (a,b,c) as in Fig. 5. Do not mix them as in the current version.

Replies: We use consistent panel labeling in all figures in the revised manuscript.



a.Kuandian
y = -0.7219x + 1498.8
R² = 0.2393
b.Hongliuhe
y = -0.5789x + 1176.8
R² = 0.152
c.Gangcha
y = -0.2355x + 503.59
R² = 0.0604
d.Shiqu
y = 0.5725x - 1039.3
R² = 0.0938
e.Pingliang
y = 0.6385x - 1181.2
R² = 0.1294
f.Weichang
y = -0.5071x + 1082.1
R² = 0.0657
g.Jixi
y = -0.4186x + 1052.8
R² = 0.2005
h.Maerkang
y = 0.4683x - 724.61
R² = 0.126
SCD
SCOD
SCED
year



The data in Fig. 6f looks very suspicious. Can you explain the strong changes in variability when comparing the 1962-1985 period with the one after 1985? (station relocation, other inhomogeneity?)

Replies: We check some reference, and explain as: the strong change of SCOD in Weichang is resulted from station relocation and urbanization.

MINOR COMMENTS

P 4473 L9: Decreases in snow pack have also been found for the European Alps in the last 20 years of the 20th century (e.g. Scherrer et al. (2004)). But: very long series of snow pack suggest large decadal variability and overall weak long term trends only (cf. Scherrer et al., 2013).

Replies: We add the sentences above and cite the two references in the revised manuscript.

P 4474 L23: Another study confirming the large influence of large scale atmospheric circulation: Scherrer and Appenzeller (2006).

Replies: We cite and add the reference.

P 4476 L14: change to “to identify possible breakpoints”

Replies: We change them as suggested.

P 4477 L19: change to “of climate series”

Replies: We change them as suggested.

P 4478 L 19: explain what you mean with annual periodicity and no annual periodicity

Replies: We explain as following:

with annual periodicity, every winter there is definitely snow.

without annual periodicity, not every winter there is snow, especially there is no snow in a warm winter.

We add the sentences mentioned above in the revised manuscript.

P 4480 L10-11: You could also add Scherrer et al. (2004) here.

Replies: We cite and add the reference.

Fig. 3: Can you give numbers for the seasons winter, Autumn and spring also. Please put a box around the legend or place it outside the figure.

Replies: We give numbers for each season beside the circle.

Fig. 6: Are the curves somehow smoothed? If so, I would prefer a direct connection between the years and no smoothing on the edges.

Replies: The curves are original, not smoothed.

REFERENCES

Scherrer SC, Appenzeller C. 2006. Swiss Alpine snow pack variability: major patterns and links to local climate and large-scale flow. Climate Research 32(3): 187–199. http://www.int-res.com/articles/cr_oa/c032p187.pdf

Scherrer SC, Wüthrich C, Croci-Maspoli M, Weingartner R, Appenzeller C (2013) Snow variability in the Swiss Alps 1864-2009. Int. J. Clim, 33(15), 3162–3173. doi: 10.1002/joc.3653.

Replies to the comments of Anonymous Referee #2

Authors' replies are in BLUE color.

Interactive comment on "Variability in snow cover phenology in China from 1952 to 2010" by C. Q. Ke et al.

Anonymous Referee #2

Received and published: 25 May 2015

This manuscript presents the spatio-temporal snow cover data of China on the timing (snow cover onset and end dates: SCOD and SCED) and duration (snow cover days: SCD) and analyses their relationships with air temperature and arctic oscillation. While substantial datasets were used, the data were not well interpreted and analysed, and no significant conclusions were drawn. The results and conclusions are even suspicious considering the way they treated the data. I suggest to reject and resubmit.

Replies: We do not agree with the referee.

We analyzed the climatology of several snow variables (snow cover days, onset and end date of snow cover), their spatiotemporal evolution, extreme years and trends from 1952-2010 in China for a large number of stations. Temperature variable and climate pattern (Arctic Oscillation, AO) are used to explain the results. Trends in some places differ with the overall shortening of the snow period in the Northern Hemisphere. This conclusion is different from previous research works reported in literature.

We believe that our works are significant and we have reasonably explained the results and have achieved solid conclusions.

Given this recommendation, I would only give some major comments.

1. The data. "According to the Specifications for Surface Meteorological Observations (China Meteorological Administration, 2003), an SCD is defined as a day when the snow cover in the area fulfils two requirements: at least half of the observation field is covered by snow, and the minimum snow depth is 1 cm. For any day with at least half of the observation field covered by snow but with snow depth of less than 1 cm, the snow depth is denoted as 0, i.e. a thin

SCD.” (P4475: Lines 19-24). “: : :in western China, station density is low, and the observation history is relatively short... If all stations with short time series are eliminated, and thin SCDs are not taken into account, the spatial representativeness of the dataset would be a problem. Therefore, a time series of at least 30 years is included in this study, including those thin SCDs.” (P4476: Lines 3-8).

In my opinion, however, including those thin SCDs is more problematic than excluding them. As far as I know, the snow cover observations are commonly conducted at 8:00 (Beijing time) in the morning, and most of the thin snow covers correspond to the snowing events in which snow exists only several hours. This is also the case for many SCDs with snow cover depths not less than 1 cm.

Replies: We do not agree with the referee’s argument to remove the ‘thin SCDs’ for consideration. The thin SCD mainly exist in western China, especially in the Tibetan Plateau. We can agree that thin SCD is not needed when investigating snow climatology with snow depth data, however it has to be considered when studying snow climatology with the SCDs, especially in the Tibetan Plateau. Many previous studies did the same.

For example, An et al. (2009) compared the difference between using thin SCD and without using thin SCD , based on the weather station data from 1951 to 2005 for the Tibet, and suggested that thin SCDs in the Tibet should be considered, since thin SCD accounts for more than **40% (very high proportion)** in the most stations, especially in the beginning and end of snow season. SCD in Tibet features bimodal, frequent snowfall occurs in seasonal transition period, i.e. summer and autumn (September, October), winter and spring (April, May). During these periods, although there are many snowfall events, temperature is relatively high. Therefore snow cover does not exist longer, resulting in many thin SCDs.

Ma et al. (2012) and Xi et al. (2009) also considered thin SCDs in their studies. He and Li (2011) also considered thin SCDs when they compared snow cover days from remote sensing and weather stations. We are citing these references to explain why we considered thin SCDs in the version.

An, D., Li, D. L., Yuan, Y. and Hui, Y.: Contrast between snow cover data of different definitions, J. Glaciol. Geocrol., 31(6), 1019-1027, 2009.

He, L. and Li, D.: Classification of snow cover days and comparing with satellite remote sensing data in west China, J. Glaciol. Geocrol., 33(2), 237-245, 2011.

Ma, L. and Qin, D.: Temporal-spatial characteristics of observed key parameters of snow cover in China during 1957-2009, Sci. Cold Arid Reg., 4, 384-393, 2012.

Xi, Y., Li, D. and Wang, W.: Study of the temporal-spatial characteristics of snow covers days in Hetao and its vicinity, J. Glaciol. Geocrol., 31, 446-456, 2009.

Except for several small regions, there have been not much snow in China during recent three decades. In this sense, there have been very few snow covers, but several snowfalls per year in a considerably large area of China (south, central and north China, and even a large area of western China) in recent _30 years. Therefore, for these areas, it may make more sense to conduct statistics of precipitation phase rather than the SCDs.

Replies: The referee did not provide any data, figures or references to indicate that "Except for several small regions, there have been not much snow in China during recent three decades".

Even if the referee's point is correct, it does not mean that there is less snow in China in the recent three decades and there is no need to study snow any more.

Our analysis indicates that there are three major stable snow regions with more than 60 annual mean SCDs: Northeast China, North Xinjiang, and the Tibetan Plateau, and the longest annual mean SCDs are 169 days (Fig.3). Among the 352 stations with more than 10 annual mean SCDs, there are 54 stations (15%) with a significant negative trend, and 35 stations (10%) with a significant positive trend (both at the 90% level), while 75% of stations show no significant trends. We also cite some relevant researches to compare with or validate our results. Several extreme snowfall events occurred in the past decades (Fig.5).

We agree referee's view that precipitation phase is important, but cannot deny the significance of SCDs, our results mentioned above are enough to show the significance of climatology study on SCD. There are many studies focusing on SCD in China or other countries, some are cited in our manuscript and listed in the references, we do not list them here again.

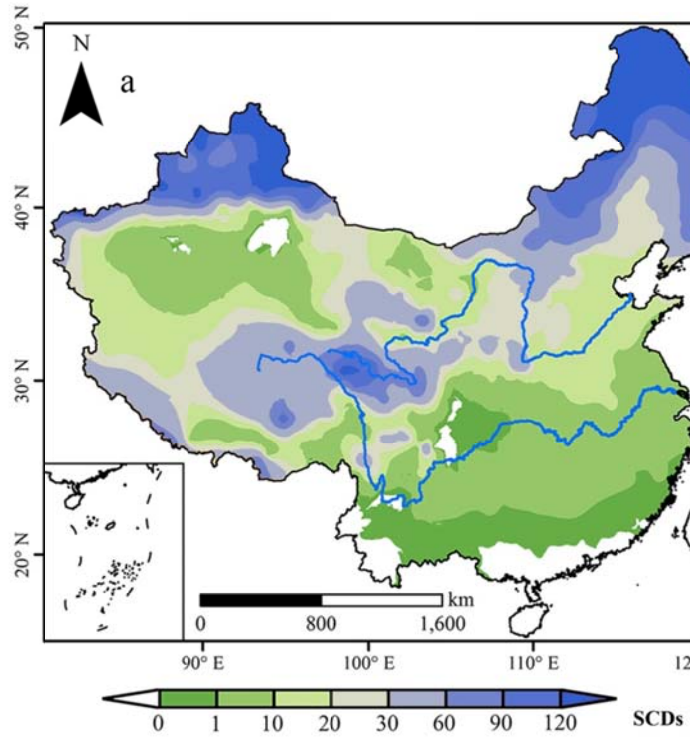


Fig.3 Annual mean snow cover days (SCDs)

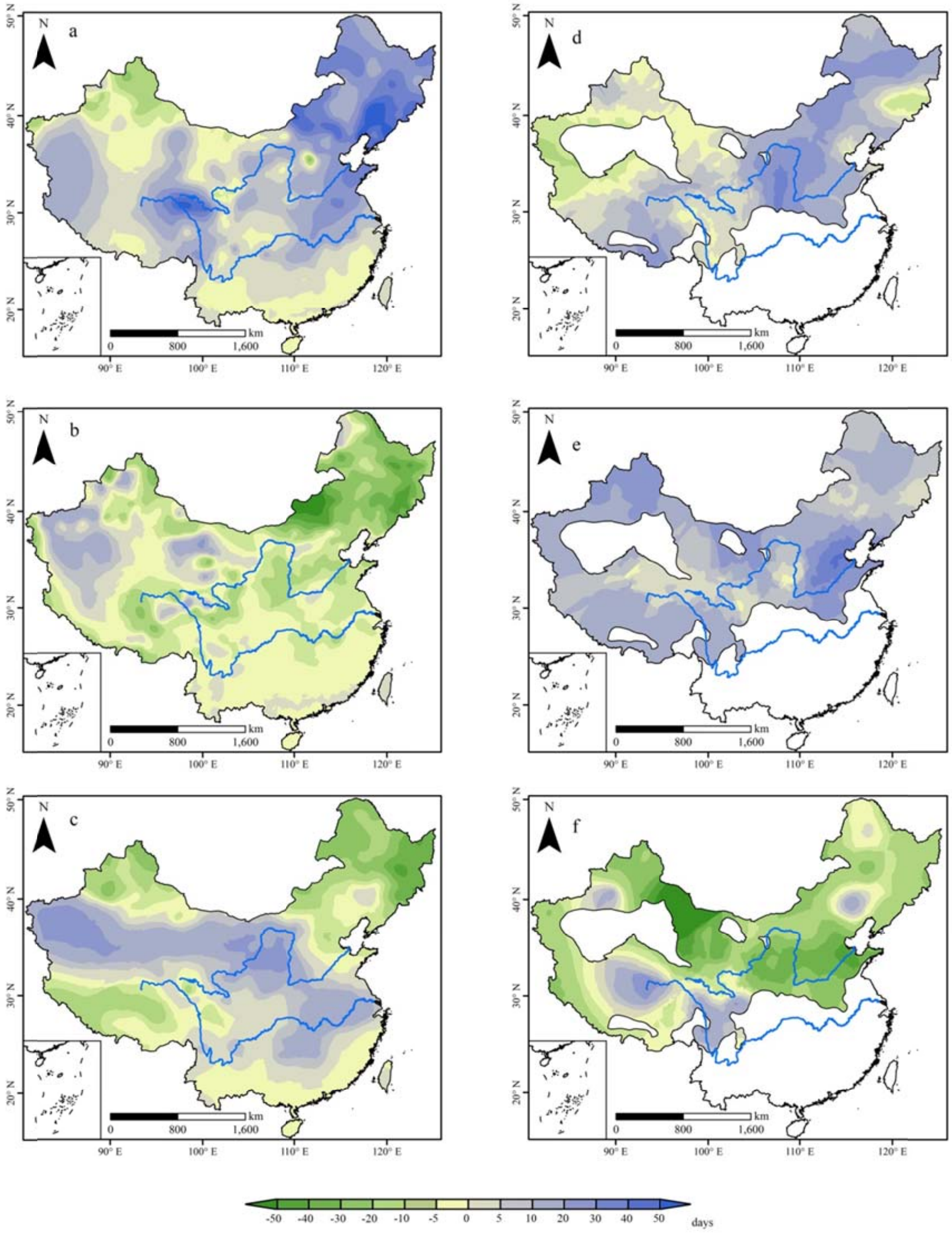


Fig.5 SCD anomalies in 1957 (a), 2002 (b), 2008 (c), snow cover onset date (SCOD) in 2006 (d), and snow cover end date (SCED) in 1957 (e), and 1997 (f).

2. Some basic information on the spatio-temporal distributions of snow cover water equivalent or snow cover depth should be provided. Readers need these information for judgements.

Replies: In this paper, we only investigate several snow variables (snow cover days, onset and end date of snow cover), their spatiotemporal evolution, extreme years and trends, and also their relations to temperature variables and climate patterns (Arctic Oscillation, AO). It already has 36 pages, including 4 tables and 8 figures, long and comprehensive enough, therefore we do not provide snow water equivalent or snow depth result. We do not see any problem to focus only on SCDs.

Choi, G., Robinson, D. A. and Kang, S.: Changing Northern Hemisphere snow seasons, J. Climate, 23, 5305-5310, 2010.

Dong, A., Guo, H., Wang, L. and Liang, T.: A CEOF analysis on variation about yearly snow days in Northern Xinjiang in recent 40 years, Plateau Meteorol., 23, 936-940, 2004.

Marty, C.: Regime shift of snow days in Switzerland, Geophys. Res. Lett., 35, L12501, 2008.

Scherrer, S. C., Appenzeller, C. and Laternser, M.: Trends in Swiss Alpine snow days: The role of local- and large-scale climate variability, Geophys. Res. Lett., 31, L13215, 2004.

Xu, L., Li, D. and Hu, Z.: Relationship between the snow cover day and monsoon index in Tibetan Plateau, Plateau Meterol., 29, 1093-1101, 2010.

Ye, H. and Ellison, M.: Changes in transitional snowfall season length in northern Eurasia, Geophys. Res. Lett., 30, 1252, 2003.

3. Analysis. Analysis is lacking on the climatic and physical interpretations/processes of the statistical results throughout the manuscript.

Replies: We analyzed the climatology of several snow variables (snow cover days, onset and end date of snow cover), their spatiotemporal evolution, extreme years and trends from 1952-2010 in China for a large number of stations. The relationships among SCDs and temperature and Arctic Oscillation are the climatic and physical interpretation in our view. All statistic results are conducted significant test, we only think about the results passed 90% or 95% significant test, and explanation is given in the manuscript.

4. Definition and analysis of heavy-snow and light-snow years (Sections 3.1.2 and 3.2.1). A heavy-snow year or a light-snow year was determined in terms of the relative time duration of

SCDs of a region. This is logically problematic. Authors should know that, for a given station, a longer period of SCDs does not necessarily mean a year of more snowfall.

Replies: According to comments from you and other referees, we change a heavy-snow year or a light-snow year as “a year with positive (negative) SCD anomaly”.

5. Consistensy of data. As far as I know, for the Specifications for Surface Meteorological Observations of China, there have been several versions (1951?, 1980, 2003 and 2007?). There are some differences in the criteria between the versions (e.g. minimum snow depth of 0.5 cm in the 2007 version?). This should be addressed.

Replies: We find all “Specifications for Surface Meteorological Observations” in National Library of China and other special Libraries, some information is different from those provided by the referee, and details are as follow.

1 Central Meteorological Administration, Specifications for Surface Meteorological Observations (it was not published by a press, informal publishing), 1955.

2 Central Meteorological Administration, Specifications for Surface Meteorological Observations (it was not published by a press, informal publishing), 1961.

3 Central Meteorological Administration, Specifications for Surface Meteorological Observations, China Meteorological Press, Beijing, 1979.

4 China Meteorological Administration: Specifications for Surface Meteorological Observations, China Meteorological Press, Beijing, 2003.

5 China Meteorological Administration: Specifications for Surface Meteorological Observations, China Meteorological Press, Beijing, 2007.

It is possible that change and update of measuring instrument have an important effect on data. Snow measurement is very simple, unlike other climate variables needing high accurate instrument, with only an ordinary ruler and a snow volumenometer or a balance. After checking all Specifications mentioned above, we find out that there are no changes in the requirements. Actual measuring minimum snow depth is 0.5 cm in all Specifications including the 2007 version. Snow depth is recorded as an integral in the meteorological information database and the unit is centimeter, and it is rounded as the nearest whole centimeter, for example, 0.5---1.4 cm snow depth measurement is rounded up to 1 cm, 1.5---2.4 cm is rounded up to 2 cm, and so on. Therefore, the final recorded minimum snow depth in the meteorological information database is 1 cm.

Thank you very much for your comments. Here, we made an error in the requirements description. We change the sentences as "…fulfils requirement: at least half of the observation field is covered by snow. For any day with at least half of the observation field covered by snow, snow depth is recorded as a rounded up integral if it is more than or equal to 0.5 cm, and the snow depth is denoted as 0 if it is less than **0.5** cm, i.e. a thin SCD".

Moreover, in this paper we do not use snow depth data, one possible difference is thin SCD and normal SCD, but we considered thin SCDs when we analyze all data. In addition, we conducted data homogeneity test, and data provider, National Meteorological Information Center (Meteorological Data Services), has also implemented data quality control. The relevant description can be found in Lines 9-14 in page 4476.

6. The tilte. Authors used the word "phenology". However, except the SCDs, SCODs and SCEDs, they did not analyze any of the important snow properties such as density. I would suggest not to use the word.

Replies: Yes, we did not analyze any of the important snow properties such as density, as well as snow depth, snow water equivalent. Although other experts used this word when they conducted the similar research, we can change the title to "snow cover variability of China from 1952 to 2010 under climate change", if the referee would like.

Peng, S., Piao, S., Ciais, P., Friedlingstein, P., Zhou, L. and Wang, T.: Change in snow phenology and its potential feedback to temperature in the Northern Hemisphere over the last three decades, Environ. Res. Lett., 8, 014008, 2013.

Replies to the comments of Anonymous Referee #3

Authors' replies are in BLUE color.

Interactive comment on "Variability in snow cover phenology in China from 1952 to 2010" by C. Q. Ke et al.

Anonymous Referee #3

Received and published: 7 June 2015

The authors present a study on spatiotemporal variations and trends in snow cover days (SCD), snow cover onset date (SCOD), and snow cover end date (SCED) using observational data from 672 climate stations in China. The period of analysis is from 1952 to 2010.

Overall the manuscript contains a lot of valuable information and is well organized for the most part. However, I feel there is room for improvement. In the following, I have listed several recommendations and questions to the authors.

Replies: Thank you for your detail review, we will revise the paper according to your comments.

Major recommendations:

2.1 Data: The authors selected 672 stations for their analyses. How many climate stations are contained in the original dataset? This information should be added to the text. When using nearest neighbor interpolation to fill data gaps, was the correlation between the time series tested over common time periods? Especially in the western and northwestern regions with low station density, the nearest neighbor might show a quite different snowfall pattern.

Replies: There are 722 stations in the original dataset, this information is added to the revised manuscript.

In order to guarantee the quality of original data, we did not conducted the standard normal homogeneity test at the 90% confidence level, but at the 95% confidence level (much higher). In addition, we implement strict quality controls (such as inspection for logic, consistency, and uniformity) on the observational datasets in order to reduce errors.

"Time series gap filling is performed after all inhomogeneities are eliminated, using nearest neighbour interpolation", here "nearest neighbour interpolation" is used for time series gap filling for one station in a temporal domain, is not for spatial interpolation between different neighbor stations. Overall, these cases are very few, moreover, the time series needed to conduct interpolation are also implemented strict quality control to meet the data requirements.

However, the spatial distribution of SCD, SCOD, and SCED, and their calculated results, are spatially interpolated by applying the universal kriging method. We add a new Table to illustrate this point, and also provide some description in the revised manuscript. Overall, the interpolation results are correct and acceptable.

Table 1 Prediction errors of cross validation for the spatial interpolation with the universal kriging method

Item (Figure)	Mean error	Average standard error	Root mean squared error	Root mean squared standardized error
SCD (Fig3a)	-0.0078	9.3710	10.3351	1.1729
CV (Fig3b)	0.0027	70.9203	56.7797	0.8236
SCD in 1957 (Fig5a)	-0.0001	10.1066	11.6712	1.1430
SCD in 2002 (Fig5b)	0.0170	5.7430	7.9122	1.2862
SCD in 2008 (Fig5c)	0.0008	6.8352	7.3988	1.0627
SCED in 1957 (Fig5d)	0.0050	14.7432	14.8384	1.0112
SCED in 1997 (Fig5e)	0.0026	16.9098	19.5960	1.1420
SCOD in 2006 (Fig5f)	-0.0035	15.4075	16.2315	1.0396
SCOD (Fig8a)	0.0037	13.8313	15.3312	1.1001
SCED (Fig8b)	-0.0038	17.1397	19.9136	1.1376

2.2 Methods: In this chapter, the authors need to provide information about the correlation analysis. What correlation coefficients have been calculated? If the authors calculated Pearson Product-Moment Correlation Coefficients, were the data tested for normal distribution? How was the significance testing done?

Replies: We added a paragraph to provide the correlation analysis in Section 2.2 in the revised manuscript.

Yes, 'Pearson Product-Moment Correlation Coefficients' have been calculated by us. We tested the data for normal distribution, "The standard normal homogeneity test

(Alexandersson and Moberg, 1997) at the 95% confidence level is applied to the daily SCD and temperature series data in order to identify possible breakpoints." in the second paragraph of Section 2.1. Among 722 stations, 672 stations with annual mean SCDs greater than 1.0 (day), passed the standard normal homogeneity test and other strict checks, finally were used for analysis.

3 Results: Fig. 2: What is the time period covered? It needs to be the time period covered by all climate stations used (1980/81 to 2009/10). If not, and the result is based on means over different time periods, comparability is a problem.

Replies: Fig. 2 is based on means over different time periods, we replaced a new map over same time period (1980/81 to 2009/10).

The results of the correlation analysis reported in the subchapters 4.1, 4.2, and 4.3 of the Discussion chapter should be in the Results chapter.

Replies: In the result section, we investigate means, extremes and trends of SCD, SCOD and SCED. In the discussion section, we investigate the potential reasons of SCD variation, the SCD relationships with TBZD, MAT and AO. In our opinion, this structure is OK, if the referee insists on moving the discussion chapter to the result one, we can move and merge two chapters to one section.

Minor recommendations:

Page 4474, row 6: Please omit this part of the sentence "China is the main large snow cover distribution area in the middle latitudes and the Northern Hemisphere [: : :]". There are vast areas covered by snow in other regions of the middle latitudes and the Northern Hemisphere as well.

Replies: We deleted some words and changed as "China has large spatiotemporal differences in the SCD".

Page 4475, row 20: "[: : :] a SCD is defined [: : :]" instead of "[: : :] an SCD is defined [: : :]"

Page 4479, rows 22-23: "The Tarim Basin is located inland, with relatively little precipitation, thus snowfall there is extremely rare (Li, 1993).” Snowfall is not rare in the mountains surrounding the Taklamakan desert. Please correct this.

Replies: Here, according to the pronunciation of the first letter of ‘SCD’, it should be ‘an SCD’, which is edited by a language expert. If the referee insists on changing it, we can do it.

We change the sentence “The Tarim Basin is located inland, with relatively little precipitation, thus snowfall there is extremely rare (Li, 1993).” as “The Tarim Basin is located inland, with relatively little precipitation, thus snowfall there is extremely rare except for the surrounding mountains (Li, 1993).”

Page 4480, rows 17-20: The authors define heavy-snow and light-snow years based on the SCD anomaly using two requirements. However, more snow cover days do not necessarily coincide with more snowfall. Therefore, I recommend the authors to name it “year with a positive (negative) SCD anomaly”.

Replies: We renamed it as ‘a year with positive (negative) SCD anomaly’ according to the referee’s suggestion.

Fig. 1: Please add the symbol for the climate stations to the legend.

Replies: We added the symbol for climate stations to the legend in the revised manuscript.

My last comment is an idea beyond the scope of this paper. It is an idea for future research. The authors have already looked at the relationship between the Arctic Oscillation and SCD. I encourage the authors to also look at the Siberian High Intensity (SHI) defined as the mean sea level pressure averaged over the center of the anticyclone (40_N-60_N, 70_E-120_E) (Gong et al. 2001; Gong and Ho 2002) and its relationship with SCD.

Gong, D.-Y.; Ho, C.-H. (2002): The Siberian High and climate change over middle to high latitude Asia. Theoretical and Applied Climatology 72: 1-9.

Gong, D.-Y.; Wang, S.-W.; Zhu, J.-H. (2001): East Asian winter monsoon and Arctic Oscillation. Geophysical Research Letters 28: 2073-2076.

Replies: Thanks for very good suggestions. This paper is enough long, we do not supplement it this time. Next step, we will investigate the relationship between SCD and Siberian High Intensity (SHI). Furthermore, we cited the relevant references mentioned above in the following paper, and discussed the relationship between snow cover and Siberian High Intensity (SHI).

Jin Xin, Ke Chang-Qing*, Xu Yu-Yue, Li Xiu-Cang, Spatial and temporal variations of snow cover in the Loess Plateau, China. *International Journal of Climatology*, 2015, 35: 1721-1731, doi: 10.1002/joc.4086.

Variability in snow cover phenology in China from 1952 to 2010

Chang-Qing Ke[1,2], Xiu-Cang Li[3,4], Hongjie Xie[5], Xun Liu[1,2] and Cheng Kou[1,2]

1. Jiangsu Provincial Key Laboratory of Geographic Information Science and Technology, Nanjing University, Nanjing, 210023, China.
2. Key Laboratory for Satellite Mapping Technology and Applications of State Administration of Surveying, Mapping and Geoinformation of China, Nanjing University, Nanjing, 210023, China.
3. National Climate Center, China Meteorological Administration, Beijing 100081, China.
4. Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters， Faculty of Geography and Remote Sensing, Nanjing University of Information Science & Technology, Nanjing, 210044, China.
5. Department of Geological Sciences, University of Texas at San Antonio, Texas 78249, USA.

Correspondence to: C. Q. Ke (kecq@nju.edu.cn)

Tel: 0086-25-89685860

Fax: 0086-25-83592686

Abstract Daily snow observation data from 672 stations, particularly the 352 stations with over ten annual mean snow cover days (SCD), during 1952–2010 in China, are used in this study. We first examine spatiotemporal variations and trends of SCD, snow cover onset date (SCOD), and snow cover end date (SCED). We then investigate SCD relationships with number of days with temperature below 0°C (TBZD), mean air temperature (MAT), and Arctic Oscillation (AO) index, the latter two being constrained to the snow season of each snow year. The results indicate that ~~the heavy snow~~ years with positive SCD anomaly for the entire country include 1955, 1957, 1964, and 2010, and ~~light snow~~ years with negative SCD anomaly include 1953, 1965, 1999, 2002, and 2009. The reduced TBZD and increased MAT are the main reasons for the overall ~~delayed~~ late ~~of~~ SCOD and ~~advance of~~early SCED since 1952, although it is not necessary for one station to experience both significantly delayed SCOD and early SCED. This explains why only 15% of the stations show significant shortening of SCD, while 75% of the stations show no significant change in the SCD trends. This differs with the overall shortening of the snow period in the Northern Hemisphere previously reported. Our analyses indicate that the SCD distribution pattern and trends in China are very complex and are not controlled by any single climate variable examined (i.e. TBZD, MAT, or AO), but a combination of multiple variables. It is found that the AO ~~index~~ has the maximum impact on the SCD shortening trends in Shandong Peninsula, Changbai Mountains, and North Xinjiang, while the combined TBZD and MAT have the maximum impact on the SCD shortening trends in the Loess Plateau, Xiaoxingganling, and Sanjiang Plain.

Keywords: snow cover day; snow cover onset date; snow cover end date; spatiotemporal variation; trend; days with temperature below 0°C; ~~mean air temperature;~~ Arctic Oscillation

Abbreviations:

Snow Cover Day (SCD)

Snow Cover Onset Date (SCOD)

Snow Cover End Date (SCED)

Days with Temperature Below 0°C (TBZD)

Mean Air Temperature (MAT)

Arctic Oscillation (AO)

1 Introduction

Snow has a profound impact on the surficial and atmospheric thermal conditions, and is very sensitive to climatic and environmental changes, because of its high reflectivity, low thermal conductivity, and hydrological effects via snowmelt (Barnett et al., 1989; Groisman et al., 1994). The extent of snow cover in the Northern Hemisphere has decreased significantly over the past decades because of global warming (Robinson and Dewey 1990; Brown and Robinson 2011). Snow cover showed the largest decrease in the spring, and the decrease rate increased for higher latitudes in response to larger albedo feedback (Déry and Brown, 2007). In North America, snow depth in central Canada showed the greatest decrease (Dyer and Mote, 2006), and snowpack in the Rocky Mountains in the U.S. declined (Pederson et al., 2013). However, *in situ* data showed a significant increase in snow accumulation in winter but a shorter snowmelt season over Eurasia (Bulygina et al., 2009). Decreases in snow pack have also been found for the European Alps in the last 20 years of the 20th century (Scherrer et al., 2004), but a very long time series of snow pack suggests large decadal variability and overall weak long-term trends only (Scherrer et al., 2013). Meteorological data indicated that the snow cover over northwest China exhibited a weak upward trend in depth (Qin et al., 2006), but the spatiotemporal variations were large (Ke et al., 2009; Ma and Qin 2012). Simulation experiments using climate models indicated that, with continuing global warming, the snow variation in China would show more differences and uncertainties in space and time than ever before (Shi et al., 2011; Ji and Kang 2013). Spatiotemporal variations of snow cover are also manifested as snowstorms or blizzards, particularly, excessive snowfall over a short time duration (Bolsenga and Norton, 1992; Liang et al., 2008; Gao, 2009; Wang et al., 2013; Llasat et al., 2014).

Snow cover day (SCD) is an important index that represents the environmental features of climate (Ye and Ellison 2003; Scherrer et al., 2004), and is directly related to the radiation and heat balance of the Earth–atmosphere system. The SCD varies in space and time and contributes to climate change over short time scales (Zhang, 2005), especially in the Northern Hemisphere. Bulygina et al. (2009) investigated the linear trends of SCD observed at 820 stations from 1966 to 2007, and indicated that the duration of snow cover decreased in the northern regions of European Russia and in the mountainous regions of southern Siberia, while it increased in Yakutia and the Far East. Peng et al. (2013) analysed trends in the snow cover onset date (SCOD) and snow cover end date (SCED) in relation to temperature over the past 27 years (1980–2006) from over 636 meteorological stations in the Northern Hemisphere. They found that the SCED remained stable over North America, whereas over Eurasia it has advanced. Satellite snow data indicated that the average snow season duration over the Northern Hemisphere has decreased at a rate of 5.3 days per decade between 1972/73 and 2007/08, with a major change in the trend of snow duration in the late 1980s, especially in western Europe, central and East Asia, and mountainous regions in western United States (Choi et al., 2010).

~~China is the main large snow cover distribution area in the middle latitudes and the Northern Hemisphere, with~~ There are large spatiotemporal differences in the SCD in China (Wang and Li, 2012). Analysis of 40 meteorological stations from 1971 to 2010 indicated that the SCD had a significant decreasing trend in the western and south-eastern Tibetan Plateau, with the largest decline observed in Nielamu, reaching 9.2 days per decade (Tang et al., 2012). Data analysis also indicated that the SCD had a linear decreasing trend at most stations in the Hetao region and its vicinity (Xi et al., 2009). However, analysis of meteorological station data in Xinjiang showed that the SCD had a slight increasing trend, occurring mainly in 1960–1980 (Wang et al., 2009b). Li et al. (2009) analysed meteorological data from 80 stations in Heilongjiang Province, Northeast China. Their results showed that the snow cover duration shortened, because of both the delayed SCOD (by 1.9 days per decade) and advancing SCED (by 1.6 days per decade). The delay and advance took place mainly in the lower altitude plains.

The SCD is sensitive to local winter temperature and precipitation, latitude (Hantel et al., 2000; Wang et al., 2009a; Serquet et al., 2011; Morán-Tejeda et al., 2013), and altitudinal gradient and terrain roughness (Lehning et al., 2011; Ke and Liu, 2014). Essentially, the SCD variation is mainly attributed to large-scale atmospheric circulation or climatic forcing (Beniston, 1997; Scherrer and Appenzeller, 2006; Ma and Qin, 2012; Birsan and Dumitrescu, 2014), such as monsoons, El Niño/Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Arctic Oscillation (AO). Xu et al. (2010) investigated the relationship between the SCD and monsoon index in the Tibetan Plateau and indicated their great spatial differences. As an index of the dominant pattern of non-seasonal sea-level pressure variations, the AO shows a large impact on the winter weather patterns of the Northern Hemisphere (Thompson and Wallace, 1998; Thompson et al., 2000; Gong et al., 2001; Wu and Wang, 2002; Jeong and Ho, 2005). The inter-annual variation of winter extreme cold days in the northern part of eastern China is closely linked to the AO (Chen et al., 2013). Certainly, the AO plays an important role in the SCD variation. An increase in the SCD before 1990 and a decrease after 1990 have been reported in the Tibetan Plateau, and snow duration has positive correlations with the winter AO index (You et al., 2011), and a significant correlation between the AO and snowfall over the Tibetan Plateau on inter-decadal timescale was also reported by Lü et al. (2008).

The focus of this study is the variability in the snow cover phenology of China. A longer time series of daily observations of snow cover is used for these spatial and temporal analyses. We first characterize the spatial patterns of change in the SCD, SCOD, and SCED in different regions of China; we then examine the sensitivity of SCD to the number of day with temperature below 0°C (TBZD), the mean air temperature (MAT), and the Arctic Oscillation (AO) index during the snow season (between SCOD and SCED).

2 Data and methods

2.1 Data

We use daily snow cover and temperature data in China from 1 September, 1951 to 31 August, 2010, provided by the National Meteorological Information Centre of China Meteorological Administration (CMA). According to the Specifications for Surface Meteorological Observations (China Meteorological Administration, 2003), an SCD is defined as a day when the snow cover in the area ~~fulfils~~ meets ~~two~~ the following requirement: at least half of the observation field is covered by snow~~, and the minimum snow depth is 1 cm~~. For any day with at least half of the observation field covered by snow, snow depth is recorded as a rounded-up integer if it is more than or equal to 0.5 cm (measured with a ruler), and ~~but with snow depth of less than 1 cm,~~ the snow depth is denoted as 0 if it is less than 0.5 cm, i.e. a thin SCD. We define a snow year as the period from 1 September of the previous year to 31 August of the current year. For instance, September, October, and November 2009 are treated as the autumn season of snow year 2010, December 2009 and January and February 2010 as the winter season of snow year 2010, and March, April, and May 2010 as the spring season of snow year 2010.

Station density is high in eastern China, where the observational data for most stations are complete, with relatively long histories (as long as 59 years). Because of topography and climate conditions, the discontinuous nature of snowfall is obvious in western China, especially in the Tibetan Plateau, with patchy snow cover (Ke and Li, 1998), and many thin SCDs in these station records. At the same time, in western China, station density is low, and the observation history is relatively short, although two of the three major snow regions are located in western China. If all stations with short time series are eliminated, and thin SCDs are not taken into account, the spatial representativeness of the dataset would be a problem. Therefore, a time series of at least 30 years is included in this study, including those thin SCDs. Totally, there are 722 stations in the original dataset.

Since station relocation and changes in the ambient environment could cause inconsistencies in the recorded data, we implement strict quality controls (such as inspection for logic, consistency, and uniformity) on the observational datasets in order to reduce errors (Ren et al., 2005). The standard normal homogeneity test (Alexandersson and Moberg, 1997) at the 95% confidence level is applied to the daily SCD and temperature series data in order to identify all possible breakpoints. Time series gap filling is performed after all inhomogeneities are eliminated, using nearest neighbour interpolation. After being processed as mentioned above, the 672 stations with annual mean SCDs greater than 1.0 (day) are finally selected for subsequent investigation (Fig. 1).

~~We define a snow year as the period from 1 September of the previous year to 31 August of the current year. For instance, September, October, and November 2009 are treated as the autumn season of snow year 2010, December 2009 and January and February 2010 as the winter season of snow year 2010, and March, April, and May 2010 as the spring season of snow year 2010. Finally, 672 stations with annual mean SCDs greater than 1.0 (day) are selected for this study (Fig. 1), although the~~ The observation period for each station is different, varying between 59 years (1951/1952–2009/2010) and 30 years (1980/1981–2009/2010). Overall, 588 stations have observation records between 50 and 59 years, 47 stations between 40 and 49 years, and 37 stations between 30 and 39 years (Fig. 2). Most of the stations with observation records of less than 50 years are located in remote or high elevation areas. All 672 stations are used to analyse the spatiotemporal distribution of SCD in China, while only 352 stations with more than ten annual mean SCDs are used to study the changes of SCOD, SCED, and SCD relationships with TBZD, MAT, and the AO index.

The daily AO index constructed by projecting the daily (00Z) 1,000 mb height anomalies poleward of 20°N from http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml, is used in this paper. A positive (negative) AO index corresponds to low (high) pressure anomalies throughout the polar region and high (low) pressure anomalies across the subtropical and mid-latitudes (Peings et al., 2013). We average the daily AO indexes during the snow season (between SCOD and SCED) of each station as the AO index of the year. A time series of AO indexes of the snow seasons from 1952 to 2010, for each of the 352 stations, is then constructed.

A digital elevation model (DEM) according to the Shuttle Radar Topographic Mission (SRTM, http://srtm.csi.cgiar.org) of the National Aeronautics and Space Administration (NASA) with a resolution of 90 m and the administration map of China are used as the base map.

2.2 Methods

We apply the non-parametric Mann–Kendall (MK) test to analyse the trends of SCD, SCOD, and SCED. The MK test is an effective tool to extract the trends of time series, and is widely applied to the analysis of climate sequences series (Marty, 2008). The MK test is characterized as being more objective, since it is a non-parametric test. A positive standardized MK statistic value indicates an upward or increasing trend, while a negative value demonstrates a downward or decreasing trend. Confidence levels of 90% and 95% are taken as thresholds to classify the significance of positive and negative trends of SCD, SCOD, and SCED.

At the same time, if SCD, SCOD, or SCED at one climate station has significant MK trend (above 90%), its linear regression analysis is performed against time. The slopes of the regressions represent the changing trends and are expressed in days per decade. Linear regressions between the SCD and TBZD, MAT and AO for each station are also performed. The statistical significance of the slope for each of the linear regression is assessed by the Student's *t* test (two-tailed test of the Student *t* distribution), and only confidence levels above 90% are considered.

Correlation analysis is used to examine the SCD relationships with the TBZD, MAT, and the AO index, and the Pearson product-moment correlation coefficients (PPMCC) have been calculated. The PPMCC is a widely used estimator for describing the spatial dependence of rainfall processes, and it indicates the strength of the linear covariance between two variables (Habib et al., 2001; Ciach and Krajewski, 2006). The correlation coefficient can be defined as the covariance of the two variables (X, Y) divided by the product of their standard deviations, giving a value between +1 and −1 inclusive, where 1 is total positive correlation, 0 is no correlation, and −1 is total negative correlation. The statistical significance of the correlation coefficients is calculated using the Student's *t* test, and only confidence levels above 90% are considered significant in our analysis.

The spatial distribution of ~~tendency in the~~ SCD, SCOD, and SCED, and their calculated results, are spatially interpolated by applying the universal kriging method (assuming the data is normally distributed). The universal kriging model is capable of simultaneously treating multiple variables and their cross-covariance, and has been successfully applied to spatial data interpolation (Kyriakidis and Goodchild, 2006). All mean errors are near zero, all average standard errors are close to the corresponding root mean squared errors, and all root mean squared standardized errors are close to 1 (Table 1). These facts indicate that prediction errors are unbiased and valid, except for slightly overestimating the variability in the CV predictions and slightly underestimating the variability in predictions of the SCD in 2002. Overall, the interpolation results have fewer errors and are acceptable.

3 Results

3.1 Spatiotemporal variations of SCD

3.1.1 Spatial distribution of SCD

The analysis of observations from 672 stations indicates that there are three major stable snow regions with more than 60 annual mean SCDs: Northeast China, North Xinjiang, and the Tibetan Plateau, with Northeast China being the largest of the three (Fig. ~~2a~~3a). In the Daxingganling, Xiaoxingganling, and Changbai Mountains of Northeast China, there are more than 90 annual mean SCDs, corresponding to a relatively long snow season. The longest annual mean SCDs, 169 days, is at Arxan Station (in the Daxinganling Mountains) in Inner Mongolia. In North Xinjiang, the SCDs are relatively long in the Tianshan and Altun Mountains, followed by the Junggar Basin. The annual mean SCDs in the Himalayas, Nyainqentanglha, Tanggula Mountains, Bayan Har Mountains, Anemaqen Mountains, and Qilian Mountains of the Tibetan Plateau are relatively long, although most of these areas have less than 60 annual SCDs. Although the Tibetan Plateau has a high elevation, a cold climate, and many glaciers, its mean SCD is not as large as that of the other two stable snow regions.

Areas with SCDs of 10–60 are called unstable snow areas with annual periodicity (there is definitely snow in every winter), including the peripheral parts of the three major stable snow regions, and the Loess Plateau, Northeast Plain, North China Plain, Shandong Peninsula, and areas in north of the Qinling-Huaihe line (along the Qinling

Mountains and Huaihe River to the east). Areas with SCDs of 1–10 are called unstable snow areas without annual periodicity (the mountainous areas are excluded, not in every winter there is snow, especially in a warm winter), including the Tarim Basin, Qaidam Basin, Badain Jaran Desert, the peripheral parts of Sichuan Basin, the northeast part of the Yungui Plateau, and the middle and lower Yangtze River Plain. Areas with occasional snow and mean annual SCD of less than 1.0 (day) are distributed north of the Sichuan Basin and in the belt along Kunming, the Nanling Mountains, and Fuzhou (approximate latitude of 25°N). Because of the latitude or local climate and terrain, there is no snow in the Taklimakan Desert, Turpan Basin, the Yangtze River Valley in the Sichuan Basin, the southern parts of Yunnan, Guangxi, Guangdong and Fujian, and on the Hainan Island.

The spatial distribution pattern of SCDs based on longer time series climate data in this study is similar to previous studies (Li and Mi, 1983; Li, 1990; Liu et al., 2012; Wang et al., 2009a; Wang and Li, 2012). The snow distribution is closely linked to latitude and elevation, and is generally consistent with the climate zones (Lehning et al., 2011; Ke and Liu, 2014). The higher the latitude, the lower the temperature and the more SCDs there are. Therefore, there are relatively more SCDs in Northeast China and North Xinjiang, and fewer SCDs to the south (Fig. ~~2a~~3a). In the Tibetan Plateau, located in south-western China, the elevation is higher than eastern areas at the same latitude, and the SCDs are greater than in eastern China (Tang et al., 2012). The amount of precipitation also plays a critical role in determining the SCD (Hantel et al., 2000). In the north-eastern coastal areas of China, which are affected considerably by the ocean, there is much precipitation. In North Xinjiang, which has a typical continental (inland) climate, the precipitation is less than in Northeast China, and there are more SCDs in the north of Northeast China than in North Xinjiang (Dong et al., 2004; Wang et al., 2009b). Moreover, the local topography has a relatively large impact on the SCD (Lehning et al., 2011). The Tarim Basin is located inland, with relatively little precipitation, thus snowfall there is extremely rare exception for the surrounding mountains (Li, 1993). The Sichuan Basin is surrounded by high mountains, and therefore situated in the precipitation shadow in winter, resulting in fewer SCDs (Li and Mi, 1983; Li, 1990).

The three major stable snow regions, Northeast China, North Xinjiang, and the eastern Tibetan Plateau, have smaller coefficients of variation (CV) in the SCD (Fig. ~~2b~~3b). Nevertheless, the SCD in arid or semi-arid areas, such as South Xinjiang, the northern and south-western Tibetan Plateau, and central and western Inner Mongolia have large fluctuations because there is little precipitation during the cold seasons, and certainly little snowfall and large CVs of SCD. In particular, the Taklimakan Desert in the Tarim Basin is an extremely arid region, with only occasional snowfall. Therefore, it has a very large range of SCD fluctuations. Additionally, the middle and lower Yangtze River Plain also has large SCD fluctuations because of warm-temperate or sub-tropic climate with short winter and little snowfall. Generally, the smaller the SCD, the larger the CV (Wang et al., 2009a). This is consistent with other climate variables, such as precipitation (Yang et al., 2015).

3.1.2 Temporal variations of SCD

Seasonal variation of SCD is primarily controlled by temperature and precipitation (Hantel et al., 2000; Scherrer et al., 2004; Liu et al., 2012). In North Xinjiang and Northeast China, snow is primarily concentrated in the winter (Fig. ~~3~~4). In these regions, the SCD exhibits a 'single-peak' distribution. In the Tibetan Plateau, however, the seasonal variation of SCD is slightly different, i.e. more snow in the spring and autumn combined than in the winter. The mean temperature and precipitation in winter at Dangxiong station are -7.73° C and 7.92 mm, respectively. Those at Qingshuihe station are -15.8° C and 16.3 mm, respectively. It is too cold and dry to produce enough snow in the Tibetan Plateau (Hu and Liang, 2014)

The temporal variation of SCD shows very large differences from one year to another. We define a year with a positive (negative) SCD anomaly~~heavy-snow or light-snow years based on the SCD anomaly~~ in the following way: for a given year, if 70% of the stations have a positive (negative) anomaly and 30% of the stations have an SCD larger (smaller) than the mean +/− one standard deviation (1SD), it is regarded as a year with a positive (negative) SCD anomaly~~as a heavy-snow (light-snow) year~~. The ~~heavy-snow~~ years with a positive SCD anomaly in China are 1955, 1957, 1964, and 2010 (Table ~~1~~2). Moreover, the stations with SCDs larger than the mean + 2SD account for 29% of all stations in 1955 and 1957, and they are considered as ~~extremely heavy-snow~~ years with an extreme positive SCD anomaly. In 1957, there was an almost nationwide positive SCD anomaly ~~snowstorm~~ except for North Xinjiang (Fig. ~~4a~~5a). This 1957 event had a great impact on agriculture, natural ecology, and social-economic systems, and resulted in a tremendous disaster (Hao et al., 2002). The year 2010 was also a ~~heavy snow~~ year with a positive SCD anomaly in China. At the same time, blizzards occurred in North America and Europe (including Spain) (Llasat et al., 2014). Globally, an unusual cold weather pattern caused by high pressure (the AO) brought cold, moist air from the north. Many parts of the Northern Hemisphere experienced heavy snowfall and record-low temperatures, leading to, among other things, a number of deaths, widespread transport disruption, and power failures (http://en.wikipedia.org/wiki/Winter_of_2009–10_in_Europe, http://en.wikipedia.org /wiki/February_9–10,_2010_North_American_blizzard). The blizzards across the Texas and Oklahoma panhandles in 1957 (Bolsenga and Norton, 1992; Changnon and Changnon, 2006) and across the east coast in 2010 were also recorded as the biggest snowstorms of the United States from 1888 to the present (http://www.crh.noaa.gov/mkx/?n=biggestsnowstorms-us).

~~Light snow y~~Years with a negative SCD anomaly include 1953, 1965, 1999, 2002, and 2009 (Table ~~1~~2). If there is too little snowfall in a specific year, a drought is possible. Drought resulting from little snowfall in the cold season is a slow process and can sometimes cause disasters. For example, East China displayed an apparent negative SCD anomaly in 2002 (Fig. ~~4b~~5b), and had very little snowfall, leading to an extreme winter drought in Northeast China, where snowfall is the primary form of winter precipitation (Fang et al., 2014).

Because of different atmospheric circulation backgrounds, vapour sources, and topographic conditions in different regions of China, there are great differences in the

SCD even in one year. For example, in 2008, there were more SCDs and longer snow duration in the Yangtze River Basin, North China, and the Tianshan Mountains in Xinjiang (Fig. ~~4c~~5c), especially in the Yangtze River Basin, where large snowfall is normally not observed. However, four episodes of severe and persistent snow, extreme low temperatures, and freezing weather occurred in early 2008, leading to a large-scale catastrophe in this region where there were no mitigation measures for this type of a disaster (Gao, 2009). As reported by the Ministry of Civil Affairs of China, the 2008 snow disaster killed 107 people and caused losses of US$15.45 billion. Both the SCDs and scale of economic damage broke records from the past five decades (Wang et al., 2008). On the contrary, in the same year (2008), there was no snow disaster in North Xinjiang, the Tibetan Plateau, and Pan-Bohai Bay region. Moreover, Northeast China had an apparent negative SCD anomaly (Fig. ~~4c~~5c).

There are big differences in the temporal variations of SCD even in the three major stable snow regions. If we redefine ~~the SCD anomaly for heavy snow or light snow years~~ a year with a positive (negative) SCD anomaly, using the much higher standard that 80% of stations should have a positive (negative) anomaly and 40% of stations should have an SCD larger (smaller) than the mean +/- 1SD, it is found that 1957, 1973, and 2010 are ~~heavy snow~~ years with a positive SCD anomaly in Northeast China (Helongjiang, Jilin and eastern Inner Mongolia), while 1959, 1963, 1967, 1998, 2002, and 2008 are ~~light snow~~ years with a negative SCD anomaly there (Table ~~2~~3, Fig. ~~4a~~5a–c). ~~Heavy snow years~~ Years with a positive SCD anomaly in North Xinjiang include 1959, 1960, 1977, 1980, 1988, 1994, and 2010, and ~~light snow~~ years with a negative SCD anomaly include 1974, 1995, and 2008 (Table ~~2~~3, Fig. ~~4c~~5c). North Xinjiang is one of the regions prone to catastrophe, where frequent heavy snowfall greatly affects the development of animal husbandry (Hao et al., 2002).

~~Heavy snow y~~ Years with a positive SCD anomaly in the Tibetan Plateau include 1983 and 1990, whereas ~~light snow~~ years with a negative SCD anomaly include 1965, 1969, and 2010 (Table ~~2~~3). The climate in the Tibetan Plateau is affected by the Indian monsoon from the south, westerlies from the west, and the East Asian monsoon from the east (Yao et al., 2012). Therefore, there is a regional difference in the SCDs within the Tibetan Plateau, and even a difference in the spatiotemporal distribution of snow disasters (Wang et al., 2013). Our results differ from the conclusions drawn by Dong et al. (2001), as they only used data from 26 stations, covering only a short period (1967–1996).

3.1.3 SCD trends

Changing trends of annual SCDs are examined, as shown in Figure ~~5~~6, and summarized in Table ~~3~~4. Among the 352 stations, there are 54 stations (15%) with a significant negative trend, and 35 stations (10%) with a significant positive trend (both at the 90% level), while 75% of stations show no significant trends. The SCD exhibits a significant downward trend in the Shandong Peninsula, and insignificant downward trends in the North China Plain, the Loess Plateau, the Xiaoxingganling, the Changbai Mountains, North Xinjiang, Northeast Qinghai, and the south-western Tibetan Plateau (Fig. ~~5a~~6a). Some station records indicate a decreasing rate of 1.3–7.2 days per decade, for example, the SCD decreased by 40 days from 1955 to 2010 at the Kuandian station in Northeast China, 30 days from 1954 to 2010 at the Hongliuhe station in Xinjiang, and 15 days from 1958 to 2010 at the Gangcha station on the Tibetan Plateau (Fig. ~~6a~~7a–c).

The SCDs in the Bayan Har Mountains, the Anemaqen Mountains, the Inner Mongolia Plateau, and Daxingganling, exhibit a significant upward trend (Fig. ~~5a~~6a). For example, for the Shiqu station on the eastern border of the Tibetan Plateau, the SCD increased 26 days from 1960 to 2010 (Fig. ~~6d~~7d). The coexistence of negative and positive trends in the SCD change was also reported by Bulygina et al. (2009) and Wang and Li (2012).

3.2 Spatiotemporal variations of SCOD

3.2.1 SCOD variations

The SCOD is closely related to both latitude and elevation (Fig. ~~7a~~8a). For example, snowfall begins in September on the Tibetan Plateau, in early or middle October on the Daxingganling, and in middle or late October on the Altai Mountains of Xinjiang. The SCOD also varies from one year to another (Table ~~1~~2). Using the definition of a year with a positive (negative) SCD anomaly~~SCD anomaly in terms of heavy snow or light snow years~~, as introduced before (i.e. 70% stations with positive (negative) SCOD anomaly and 30% stations with SCOD larger (smaller) than the mean +/− 1SD), we consider a given year as a ~~delayed~~ late (early) SCOD year. Only two years, 1996 and 2006, can be considered as ~~delayed~~ late SCOD years on a large scale

(Table ~~1~~2), especially in 2006, in East China and the Tibetan Plateau (Fig.~~5d~~6d), while not any single year can be considered as an early SCOD year.

3.2.2 SCOD trends

There are 136 stations (39%) with a significant trend of delayed SCOD, and 23 stations (7%) with a significant trend of early SCOD (both at the 90% level), while 54% of the stations show no significant trends (Table ~~3~~4). The ~~delaying of~~ SCOD ~~is significant~~ in Northeast China, the central and eastern Tibetan Plateau, the upper reach of the Yellow River, North Gansu, and North Xinjiang exhibits a significant trend towards later SCOD (Fig. ~~5b~~6b). These significantly ~~delayed~~ late trends dominate the major snow areas of China. In particular, the ~~delaying of~~ late SCOD in Northeast China is consistent with a previous study (Li et al., 2009). The SCOD in the Pan-Bohai Bay region and the Tianshan Mountains exhibits a trend towards earlier SCOD. However, this trend is only significant in the Liaoxi corridor and the Tianshan Mountains. For example, the SCOD at Pingliang station in Gansu Province shows a ~~delaying~~ late rate of 5.2 days per decade from 1952 to 2010, but the SCOD at Weichang station in Hebei Province shows an ~~advancing~~ early rate of 5.2 days per decade from 1952 to 2010 (Fig. ~~6e~~7e–f).

3.3 Spatiotemporal variations of SCED

3.3.1 SCED variations

The pattern of SCED is similar to that of SCOD (Fig. ~~7b~~8b), i.e. places with early snowfall normally show late snowmelt, while places with late snowfall normally show early snowmelt. Like the SCOD, temporal variations of SCED are large (Table ~~1~~2). Using the same standard for defining the SCOD anomaly, we judge a given year as a ~~delayed~~ late ~~or~~ (early) SCED year. It is ~~obvious~~ evident that 1957 was a typical year whose SCED was ~~delayed~~late, which was also the reason for the great SCDs (Table ~~1~~2, Fig. ~~4e~~5e). The SCEDs in 1997 and 2004 were very early. For example, in 1997, the SCED was early for almost all of China except for the Tibetan Plateau, western Tianshan, and western Liaoning. In general, the early SCED ~~was~~ is dominant and more evident than the ~~delayed~~ late SCED (Table ~~1~~2, Fig. ~~4f~~5f).

3.3.2 SCED trends

For the SCED, there are 138 stations (39%) with a significant ~~advancing~~ early trend (at the 90% level), while 60% of stations show no significant trends (Table ~~3~~4). Major snow areas in China all show early SCED, significant for Northeast China and the Tibetan Plateau (Fig. ~~5c~~6c). The tendency of ~~delayed~~ late SCED is limited, with only two stations showing a significant trend. For example, the SCED at Jixi station in Northeast China ~~advanced~~ shows an early ~~at a~~ rate of 4.4 days per decade from 1952 to 2010, while the SCED at Maerkang station in Sichuan Province ~~delayed~~ shows ~~was~~ a late ~~at a~~ rate of 4.2 days per decade from 1954 to 2010 (Fig. ~~6g~~7g–h).

4 Discussion

In the context of global warming, 136 stations (~39%) show significant ~~delaying~~

late SCOD, and 138 stations (~39%) show significant ~~advancing~~ early SCED, all at the 90% confidence level. It is not necessary for one station to show both significant late SCOD and ~~advancing~~ early SCED. This explains why only 15% of stations show a significantly negative SCD trend, while 75% of stations show no significant change in the SCD trends. The latter is inconsistent with the overall shortening of the snow period in the Northern Hemisphere reported by Choi et al. (2010). One reason could be the different time periods used in the two studies, 1972–2007 in Choi et al. (2010) as compared with 1952–2010 in this study. Below, we discuss the possible connections between the spatiotemporal variations of snow cover and the warming climate and changing AO.

4.1 Relationship with TBZD

The number of days with temperature below 0°C (TBZD) plays an important role in the SCD. There are 330 stations (94% of all stations) showing positive correlations between TBZD and SCD, with 193 of them (55%) having significantly positive correlations (Table ~~3~~4, Fig. ~~5d~~6d). For example, there is a significantly positive correlation between SCD and TBZD at Chengshantou station (Fig. ~~8a~~9a). Therefore, generally speaking, the smaller the TBZD, the shorter the SCD.

For the SCOD, there are 287 stations with negative correlations with TBZD, accounting for 82% of 352 stations, whereas only 63 stations (18%) show positive correlations (Table ~~3~~4). This means that for smaller TBZD, the SCOD is ~~more delayed~~ later. For the SCED, there are 318 stations with positive correlations, accounting for

90% of 352 stations, whereas only 34 stations (10%) have negative correlations (Table 3). This means that for smaller TBZD, the SCED is earlier. Very similar results are found for MAT (Table ~~3~~4, Fig. 6e)~~.~~, and Fig. 9b shows a typical example.

~~4.2 Relationship with MAT~~

~~We calculate the correlation coefficient between SCD and MAT during the snow season for each of the 352 stations (Table 3). There are 320 stations with negative correlations (91%), but only 32 stations (9%) have positive correlations. Among them, 171 stations (49%) show significantly negative correlations. For example, the SCD and MAT at Baicheng station significantly negatively correlated (Fig. 8b). The negative correlations are dominant, and exist in almost all snow areas (Fig. 5e). That is, the SCD has a close relationship with the MAT, clearly indicating that the higher the MAT because of global warming during the snow season, the shorter the SCD.~~

4.~~3~~ 2 Relationship with AO

Although the AO index showed a strong positive trend in the past decades (Thompson et al., 2000), its impact on the SCD in China is spatially distinctive. Positive correlations (47% of stations) are found in central China, i.e. the eastern Tibetan Plateau, the upper reach of the Yangtze River, and the upper and middle reaches of the Yellow River (Huajiangling station as an example, Fig. ~~8c~~9c), while negative correlations (53% of stations) exist in North Xinjiang, the Changbaishan Mountain (Tonghua station as an example, Fig. ~~8d~~9d), and the coasts of Liaoning and the Shandong Peninsula (Fig. ~~5f~~6f).

5 Conclusion

This study examines the snow cover change based on 672 stations in 1952–2010 in China. Specifically, the 352 stations with more than ten annual mean SCDs are used to study the changing trends of SCD, SCOD, and SCED, and SCD relationships with TBZD, MAT, and AO index during snow seasons. Some important results are summarized below.

Northeast China, North Xinjiang, and the Tibetan Plateau are the three major snow regions, with Northeast China being the largest. In North Xinjiang and in central and north-eastern China, the SCDs are concentrated in the winter season. On the Tibetan Plateau, however, snowfall is more frequent in the spring and fall. In China, the overall inter-annual variability of SCD is large. The ~~heavy snow~~ years with a positive SCD anomaly in China include 1955, 1957, 1964, and 2010, while the ~~light snow~~ years with a negative SCD anomaly are 1953, 1965, 1999, 2002, and 2009. Only 15% of stations show a significantly negative SCD trend, while 75% of stations show no significant SCD trends. This differs from the overall shortening of the snow period in the Northern Hemisphere previously reported. One reason could be the different time periods used in the two studies, 1972–2007 in the work of Choi et al. (2010) compared with 1952–2010 in this study. Our analyses indicate that the SCD distribution pattern and trends in China are very complex and are not controlled by any single climate variable examined (i.e. TBZD, MAT, or AO), but a combination of multiple variables. However, it seems that the AO index has the most impact on the SCD shortening trends in the Shandong

Peninsula, Changbai Mountains, and North Xinjiang; the combination of smaller TBZD and increasing MAT has the largest impact on the SCD shortening trends on the Loess Plateau, Xiaoxingganling, and the Sanjiang Plain.

It is found that significantly ~~delayed~~ late SCOD occurs in Northeast China, the central and eastern Tibetan Plateau, the upper reach of the Yellow River, North Gansu, and North Xinjiang; significantly early SCED occurs in Northeast China and the Tibetan Plateau. Both the SCOD and SCED are closely related to the TBZD and MAT, and are mostly controlled by local latitude and elevation. Owing to global warming since 1950s, the reduced TBZD and increased MAT are the main reasons for overall ~~delayed~~ late SCOD and early SCED, although it is not necessary for one station to experience both significantly ~~delayed~~ late SCOD and early SCED. This explains why only 15% of stations show significantly negative SCD trends, while 75% of stations show no significant SCD trends.

Long-duration, consistent records of snow are rare in China because of many challenges associated with taking accurate and representative measurements, especially in western China. The density of stations and the choice of metric also vary with time and locality. Therefore, more accurate and reliable observation data are needed to further analyse the spatiotemporal distribution and features of snow cover phenology. Atmospheric circulation causes variability in the snow cover phenology, and these effects also require deeper investigation.

Acknowledgments

This work is financially supported by the Program for National Nature Science Foundation of China (No. 41371391), and the Program for the Specialized Research Fund for the Doctoral Program of Higher Education of China (No. 20120091110017). This work is also partially supported by Collaborative Innovation Center of Novel Software Technology and Industrialization. We would like to thank the National Climate Center of China (NCC) in Beijing for providing valuable climate datasets. We thank the three anonymous reviewers and the editor for valuable comments and suggestions that greatly improved the quality of this paper.

References

An, D., Li, D., Yuan, Y. and Hui, Y.: Contrast between snow cover data of different definitions, J. Glaciol. Geocrol., 31(6), 1019-1027, 2009.

Alexandersson, H. and Moberg, A.: Homogenization of Swedish temperature data Part 1: homogeneity test for linear trends, Int. J. Climatol., 17, 25-34, 1997.

Barnett, T. P., Dumenil, L. and Latif, M.: The effect of Eurasian snow cover on regional and global climate variations, J. Atmos. Sci., 46, 661-685, 1989.

Beniston, M: Variations of snow depth and duration in the Swiss Alps over the last 50 years: Links to changes in large-scale climatic forcings, Clim. Change, 36, 281-300, 1997.

~~Biggs, E. M. and Atkinson, P. M.: A comparison of gauge and radar precipitation data for simulating an extreme hydrological event in the Severn Uplands, UK, Hydrol. Process., 2, 795-810, 2011.~~

Birsan, M. V. and Dumitrescu, A.: Snow variability in Romania in connection to large-scale atmospheric circulation, Int. J. Climatol., 34, 134-144, 2014.

Bolsenga, S. J., and Norton, D. C.: Maximum snowfall at long-term stations in the U.S./Canadian Great Lakes, Nat. Hazards, 5, 221-232, 1992.

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

Bulygina, O. N., Razuvaev, V. N. and Korshunova, N. N.: Changes in snow cover over Northern Eurasia in the last few decades, Environ. Res. Lett., 4, 045026, 2009.

Changnon, S. A. and Changnon, D.: A spatial and temporal analysis of damaging snowstorms in the United States, Nat. Hazards, 37, 373-389, 2006.

Chen, S., Chen, W. and Wei, K.: Recent trends in winter temperature extremes in eastern China and their relationship with the Arctic Oscillation and ENSO, Adv. Atmos. Sci., 30, 1712-1724, 2013.

China Meteorological Administration: Specifications for Surface Meteorological Observations, Beijing, China Meteorological Press, 1-62, 2003.

Choi, G., Robinson, D. A. and Kang, S.: Changing Northern Hemisphere snow seasons, J. Climate, 23, 5305-5310, 2010.

Ciach, G. J. and Krajewski, W. F.: Analysis and modeling of spatial correlation structure in small-scale rainfall in Central Oklahoma, Adv. Water Resour., 29(10), 1450–1463, 2006.

Déry, S. J. and Brown, R. D.: Recent Northern Hemisphere snow cover extent trends and implications for the snow-albedo feedback, Geophys. Res. Lett., 34, L22504, 2007.

Dong, A., Guo, H., Wang, L. and Liang, T.: A CEOF analysis on variation about yearly snow days in Northern Xinjiang in recent 40 years, Plateau Meteorol., 23, 936-940, 2004.

Dong, W., Wei, Z. and Fan, J.: Climatic character analysis of snow disasters in east Qinghai-Xizang Plateau livestock farm, Plateau Meteorol., 20, 402-406, 2001.

Dyer, J. L. and Mote, T. L.: Spatial variability and trends in observed snow depth over North America, Geophys. Res. Lett., 33, L16503, 2006

Fang, S., Qi, Y., Han, G., Zhou, G. and Cammarano, D.: Meteorological drought trend in winter and spring from 1961 to 2010 and its possible impacts on wheat in wheat planting area of China, Sci. Agricul. Sin., 47, 1754-1763, 2014

Gao, H.: China's snow disaster in 2008, who is the principal player? Int. J. Climatol., 29, 2191-2196, 2009.

Gong, D. Y., Wang, S. W. and Zhu, J. H.: East Asian winter monsoon and Arctic oscillation, Geophys. Res. Lett., 28, 2073-2076, 2001.

Groisman, P. Y., Karl, T. R. and Knight, R. W.: Observed impact of snow cover on the heat-balance and the rise of continental spring temperatures, Science, 263, 198-200, 1994.

Habib, E., Krajewski, W. F. and Ciach, G. J.: Estimation of rainfall interstation correlation, J. Hydrometeorol., 2(6), 621–629, 2001.

Hantel, M., Ehrendorfer, M. and Haslinger, A.: Climate sensitivity of snow cover duration in Austria, Int. J. Climatol., 20, 615-640, 2000.

Hao, L., Wang, J., Man, S. and Yang, C.: Spatio-temporal change of snow disaster and analysis of vulnerability of animal husbandry in China, J. Nat. Disaster, 11, 42-48, 2002.

He, L. and Li, D.: Classification of snow cover days and comparing with satellite remote sensing data in west China, J. Glaciol. Geocrol., 33(2), 237-245, 2011.

Hu, H. and Liang, L.: Temporal and spatial variations of snowfall in the east of Qinghai-Tibet Plateau in the last 50 years, Acta Geogr. Sin., 69, 1002-1012, 2014.

Jeong, J. H. and Ho, C. H.: Changes in occurrence of cold surges over East Asia in association with Arctic oscillation, Geophys. Res. Lett., 32, L14704, 2005.

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

Ke, C. Q. and Li, P. J.: Spatial and temporal characteristics of snow cover over the Tibetan plateau, Acta Geogr. Sin., 53, 209-215, 1998.

Ke, C. Q. and Liu, X.: MODIS-observed spatial and temporal variation in snow cover in Xinjiang, China, Clim. Res., 59, 15-26, 2014.

Ke, C. Q., Yu, T., Yu, K., Tang, G. D. and King, L.: Snowfall trends and variability in Qinghai, China, Theor. Appl. Climatol., 98, 251-258, 2009.

~~Kuhlman, K. L. and Igúzquiza, E. P.: Universal cokriging of hydraulic heads accounting for boundary conditions, J. Hydrol., 384, 14-25, 2010.~~

Kyriakidis, P. C. and Goodchild, M. F.: On the prediction error variance of three common spatial interpolation schemes, Int. J. Geogr. Info. Science, 20(8), 823-855, 2006.

Lehning, M., Grünewald, T. and Schirmer, M.: Mountain snow distribution governed by an altitudinal gradient and terrain roughness, Geophys. Res. Lett., 38, L19504, 2011.

Li, D., Liu, Y., Yu, H. and Li, Y.: Spatial-temporal variation of the snow cover in Heilongjiang Province in 1951-2006, J. Glaciol. Geocrol., 31, 1011-1018, 2009.

Li, J. and Wang, J.: A modified zonal index and its physical sense, Geophys. Res. Lett., 30, 1632, 2003.

Li, L. Y. and Ke, C. Q.: Analysis of spatiotemporal snow cover variations in Northeast China based on moderate-resolution-imaging spectroradiometer data, J. Appl. Remote Sens., 8, 084695, doi: 10.1117/1.JRS.8.084695. 2014.

Li, P. J.: Dynamic characteristic of snow cover in western China, Acta Meteorol. Sin., 48, 505-515, 1993.

Li, P. J.: A preliminary study of snow mass variations over past 30 years in China, Acta Geogr. Sin., 48, 433-437, 1990.

Li, P. J. and Mi, D.: Distribution of snow cover in China, J. Glaciol. Geocrol., 5, 9-18, 1983.

Liang, T. G., Huang, X. D., Wu, C. X., Liu, X. Y., Li, W. L., Guo, Z. G. and Ren, J. Z.: An application of MODIS data to snow cover monitoring in a pastoral area: A case study in Northern Xinjiang, China, Remote Sens. Environ., 112, 1514-1526, 2008.

Liu, Y., Ren, G. and Yu, H.: Climatology of Snow in China, Sci. Geogr. Sin., 32, 1176-1185, 2012.

Llasat, M. C., Turco, M., Quintana-Seguí, P. and Llasat-Botija, M.: The snow storm of 8 March 2010 in Catalonia (Spain): a paradigmatic wet-snow event with a high societal impact, Nat. Hazards Earth Syst. Sci., 14, 427-441, 2014.

Lü, J. M., Ju, J. H., Kim, S. J., Ren, J. Z. and Zhu, Y. X.: Arctic Oscillation and the autumn/winter snow depth over the Tibetan Plateau, J. Geophys. Res., 113, D14117, 2008.

Ma, L. and Qin, D.: Temporal-spatial characteristics of observed key parameters of snow cover in China during 1957-2009, Sci. Cold Arid Reg., 4, 384-393, 2012.

Marty, C.: Regime shift of snow days in Switzerland, Geophys. Res. Lett., 35, L12501, 2008.

Morán-Tejeda, E., López-Moreno, J. I. and Beniston, M.: The changing roles of temperature and precipitation on snowpack variability in Switzerland as a function of altitude, Geophys. Res. Lett., 40, 2131-2136, 2013.

Pederson, G. T., Betancourt, J. L. and Gregory, J. M.: Regional patterns and proximal causes of the recent snowpack decline in the Rocky Mountains, U.S., Geophys. Res. Lett., 40, 1811-1816, 2013.

Peings, Y., Brun, B., Mauvais, V. and Douville, H.: How stationary is the relationship between Siberian snow and Arctic Oscillation over the 20th century, Geophys. Res. Lett., 40, 183-188, 2013.

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

Peng, S., Piao, S., Ciais, P., Friedlingstein, P., Zhou, L. and Wang, T.: Change in snow phenology and its potential feedback to temperature in the Northern Hemisphere over the last three decades, Environ. Res. Lett., 8, 014008, 2013.

Qin, D., Liu, S. and Li, P.: Snow cover distribution, variability, and response to climate change in western China, J. Climate, 19, 1820-1833, 2006.

Ren, G. Y., Guo, J., Xu, M. Z., Chu, Z. Y., Zhang, L., Zou, X. K., Li, Q. X. and Liu, X. N.: Climate changes of China's mainland over the past half century, Acta. Meteorol. Sin., 63, 942-956, 2005.

Robinson, D. A. and Dewey, K. F.: Recent secular variations in the extent of northern hemisphere snow cover, Geophys. Res. Lett., 17, 1557-1560, 1990.

Scherrer, S. C., Appenzeller, C. and Laternser, M.: Trends in Swiss Alpine snow days: The role of local- and large-scale climate variability, Geophys. Res. Lett., 31, L13215, 2004.

Scherrer, S. C. and Appenzeller, C.: Swiss Alpine snow pack variability: major patterns and links to local climate and large-scale flow, Clim. Res., 32(3), 187-199, 2006.

Scherrer, S. C., Wüthrich, C., Croci-Maspoli, M., Weingartner, R. and Appenzeller, C.: Snow variability in the Swiss Alps 1864-2009, Int. J. Clim., 33(15), 3162–3173, 2013, doi: 10.1002/joc.3653.

Serquet, G., Marty, C., Dulex, J-P. and Rebetez, M.: Seasonal trends and temperature dependence of the snowfall/precipitation-day ratio in Switzerland, Geophys. Res. Lett., 38, L07703, 2011.

Shi, Y., Gao, X., Wu, J. and Giorgi, F.: Changes in snow cover over China in the 21st century as simulated by a high resolution regional climate model, Environ. Res. Lett., 6, 045401, 2011.

Tang, X., Yan, X., Ni, M. and Lu, Y.: Changes of the snow cover days on Tibet Plateau in last 40 years, Acta. Geogr. Sin., 67, 951-959, 2012.

Thompson, D. W. J. and Wallace, J. M.: The Arctic oscillation signature in the wintertime geopotential height and temperature fields, Geophys. Res. Lett., 25, 1297-1300, 1998.

Thompson, D. W. J., Wallace, J. M. and Hegerl, G. C.: Annular modes in the extratropical circulation, part II: Trends, J. Climate, 13, 1018-1036, 2000.

Wang, C. and Li, D.: Spatial-temporal variations of the snow cover days and the maximum depth of snow cover in China during recent 50 years, J. Glaciol. Geocrol., 34, 247-256, 2012.

Wang, C., Wang, Z. and Cui, Y.: Snow cover of China during the last 40 years: Spatial distribution and interannual variation, J. Glaciol. Geocrol., 31, 301-310, 2009a.

Wang, J. and Hao, X.: Responses of snowmelt runoff to climatic change in an inland river basin, Northwestern China, over the past 50 years, Hydrol. Earth Syst. Sci., 14, 1979-1987, 2010.

Wang, L. et al.: Characteristics of the extreme low-temperature, heavy snowstorm and freezing disasters in January 2008 in China, Meteorol. Mon., 34, 95-100, 2008.

Wang, Q., Zhang, C., Liu, J. and Liu, W.: The changing tendency on the depth and days of snow cover in Northern Xinjiang, Adv. Clim. Change Res., 5, 39-43, 2009b.

Wang, W., Liang, T., Huang, X., Feng, Q., Xie, H., Liu, X., Chen, M. and Wang, X.: Early warning of snow-caused disasters in pastoral areas on the Tibetan Plateau, Nat. Hazards Earth Syst. Sci., 13, 1411-1425, 2013.

Wu, B. Y. and Wang, J.: Winter Arctic oscillation, Siberian high and East Asian winter monsoon, Geophys. Res. Lett., 29, 1897, 2002.

Xi, Y., Li, D. and Wang, W.: Study of the temporal-spatial characteristics of snow covers days in Hetao and its vicinity, J. Glaciol. Geocrol., 31, 446-456, 2009.

Xu, L., Li, D. and Hu, Z.: Relationship between the snow cover day and monsoon index in Tibetan Plateau, Plateau Meterol., 29, 1093-1101, 2010.

Yang, H., Yang, D., Hu, Q. and Lv, H.: Spatial variability of the trends in climatic variables across China during 1961-2010, Theor. Appl. Climatol., 2015 (in press).

Yao, T. et al.: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings, Nature Clim. Change, 2, 663-667, 2012.

Ye, H. and Ellison, M.: Changes in transitional snowfall season length in northern Eurasia, Geophys. Res. Lett., 30, 1252, 2003.

You, Q., Kang, S., Ren, G., Fraedrich, K., Pepin, N., Yan, Y. and Ma, L.: Observed changes in snow depth and number of snow days in the eastern and central Tibetan Plateau, Clim. Res., 46, 171-183, 2011.

Zhang, T.: Influence of the seasonal snow cover on the ground thermal regime: An overview, Rev. Geophys., 43, 1-23, 2005.

Table Captions

Table 1. Prediction errors of cross validation for the spatial interpolation with the universal kriging method

Item (Figure)	Mean error	Average standard error	Root mean squared error	Root mean squared standardized error
SCD (Fig.3a)	-0.0078	9.3710	10.3351	1.1729
CV (Fig.3b)	0.0027	70.9203	56.7797	0.8236
SCD in 1957 (Fig.5a)	-0.0001	10.1066	11.6712	1.1430
SCD in 2002 (Fig.5b)	0.0170	5.7430	7.9122	1.2862
SCD in 2008 (Fig.5c)	0.0008	6.8352	7.3988	1.0627
SCED in 1957 (Fig.5d)	0.0050	14.7432	14.8384	1.0112
SCED in 1997 (Fig.5e)	0.0026	16.9098	19.5960	1.1420
SCOD in 2006 (Fig.5f)	-0.0035	15.4075	16.2315	1.0396
SCOD (Fig.8a)	0.0037	13.8313	15.3312	1.1001
SCED (Fig.8b)	-0.0038	17.1397	19.9136	1.1376

Table 2. Percentage (%) of stations with anomalies (P for positive and N for negative) of snow cover day (SCD), snow cover onset date (SCOD), and snow cover end date (SCED), and percentage (%) of stations with anomalies of SCD, SCOD, and SCED larger (smaller) than the mean +/- one or two standard deviations (1SD or 2SD), with the bold number denoting years with a positive (negative) SCD anomaly ~~extremely heavy snow or light snow years for the SCD~~, and ~~extremely delayed~~ late~~or (~~(early) ~~(for SCOD or SCED)~~ years for SCOD or SCED ~~, for~~ in China.

	SCD						SCOD						SCED					
Year	P	1SD	2SD	-2SD	-1SD	N	P	1SD	2SD	-2SD	-1SD	N	P	1SD	2SD	-2SD	-1SD	N
1952	33	5	0	12	31	67	67	39	21	2	12	33	57	17	2	11	16	43
1953	30	6	0	**3**	**34**	**70**	40	8	2	2	18	60	39	9	1	9	17	61
1954	59	29	11	0	8	41	36	8	4	1	17	64	57	12	0	0	9	43
1955	**80**	**48**	**29**	1	5	20	35	8	3	1	24	65	78	21	2	1	5	22
1956	48	11	0	0	4	52	70	20	2	0	8	30	62	23	1	2	12	38
1957	**85**	**64**	**29**	0	3	15	25	5	1	0	14	75	**85**	**35**	**5**	1	4	15
1958	45	15	4	0	14	55	46	17	0	0	19	54	51	16	3	3	17	49
1959	27	6	1	4	23	73	55	27	9	1	17	45	57	22	3	1	5	43
1960	37	12	2	0	15	63	47	10	2	2	13	53	60	25	5	4	17	40
1961	34	7	1	1	19	66	24	9	2	1	28	76	29	6	1	9	28	71
1962	40	10	3	0	10	60	43	13	4	2	10	57	60	18	3	0	11	40
1963	24	5	1	1	25	76	33	13	5	1	26	67	52	14	0	8	16	48
1964	**77**	**39**	**11**	0	1	23	30	3	1	4	23	70	66	17	1	0	5	34
1965	25	8	0	**1**	**33**	**75**	56	18	5	1	9	44	56	14	2	3	16	44
1966	27	7	1	0	12	73	46	20	5	0	12	54	69	12	1	1	4	31
1967	32	7	1	3	23	68	39	10	3	1	14	61	44	4	0	3	11	56
1968	59	28	11	3	8	41	37	9	1	0	13	63	33	13	0	4	27	67
1969	45	21	8	4	21	55	45	13	1	3	19	55	68	21	1	1	7	32
1970	44	14	1	2	10	56	37	10	3	2	26	63	64	18	3	0	6	36
1971	52	12	1	1	11	48	38	14	4	1	17	63	54	8	1	1	9	46
1972	56	24	11	0	7	44	38	10	3	1	20	62	45	16	4	1	9	55
1973	49	19	2	1	7	51	37	10	1	1	22	63	44	9	1	1	8	56
1974	34	9	0	3	23	66	55	30	6	1	10	45	54	12	1	1	9	46
1975	40	9	3	1	14	60	26	7	2	1	21	74	42	14	3	3	17	58
1976	35	11	3	1	22	65	58	24	11	0	5	42	76	29	5	1	3	24
1977	45	20	3	0	9	55	29	5	1	0	24	71	55	14	3	2	12	45
1978	58	21	8	0	2	42	45	13	2	2	12	55	53	10	1	0	8	47

1979	41	9	1	0	7	59	43	10	1	0	18	57	78	25	2	0	4	22
1980	39	11	1	0	5	61	43	9	1	1	16	57	82	28	2	0	3	18
1981	42	12	2	0	12	58	48	21	4	2	17	52	44	13	1	2	14	56
1982	39	11	1	1	15	61	25	9	2	0	29	75	58	24	6	6	16	42
1983	48	19	6	0	15	52	45	14	1	1	11	55	65	25	2	1	10	35
1984	27	10	2	1	28	73	69	33	16	0	5	31	46	8	1	2	13	54
1985	68	25	3	0	3	32	31	8	1	1	23	69	48	9	2	1	8	52
1986	49	14	2	0	13	51	33	5	1	1	19	67	61	17	3	4	12	39
1987	66	22	4	0	4	34	39	6	1	2	15	61	62	26	3	1	8	38
1988	56	16	1	0	2	44	23	6	1	3	29	77	71	25	0	1	7	29
1989	48	19	4	0	11	52	70	28	7	1	6	30	43	5	1	3	17	57
1990	56	19	2	0	6	44	50	9	1	0	8	50	49	11	1	2	10	51
1991	33	4	0	2	10	67	60	24	5	0	3	40	73	26	3	1	4	27
1992	52	14	3	1	7	48	55	17	5	0	4	45	52	14	1	5	18	48
1993	59	18	2	1	4	41	45	9	1	0	16	55	48	17	2	2	21	52
1994	59	18	2	0	4	41	27	6	2	1	25	73	41	11	0	3	17	59
1995	34	10	3	3	19	66	58	23	3	1	15	42	48	8	1	8	20	52
1996	26	7	2	2	22	74	**72**	**30**	**4**	0	4	28	56	10	1	2	14	44
1997	35	3	0	1	18	65	46	16	3	2	12	54	18	4	2	**9**	**50**	**82**
1998	33	7	2	3	17	67	39	12	3	1	19	61	32	11	1	7	25	68
1999	24	4	1	**1**	**35**	**76**	59	23	12	1	7	41	51	13	2	7	16	49
2000	63	16	4	0	5	37	60	18	2	0	9	40	37	6	0	4	22	63
2001	67	28	7	0	5	33	38	15	1	1	22	62	42	17	1	3	15	58
2002	17	2	0	**5**	**31**	**83**	57	21	4	1	5	43	32	6	0	12	30	68
2003	58	28	4	1	8	42	35	5	1	0	20	65	52	9	1	6	18	48
2004	33	3	1	0	17	67	43	12	2	1	25	57	30	7	1	**12**	**35**	**70**
2005	61	20	1	0	4	39	47	15	2	0	12	53	35	4	0	2	19	65
2006	49	11	2	0	8	51	**72**	**32**	**7**	0	5	28	59	15	0	1	10	41
2007	28	5	1	0	23	72	68	24	5	1	5	32	28	3	1	9	28	72
2008	46	21	5	3	19	54	69	27	6	0	8	31	42	9	1	4	23	58
2009	23	5	0	**1**	**32**	**77**	73	23	9	0	4	27	29	4	0	3	25	71
2010	**75**	**40**	**11**	0	9	25	41	10	1	1	21	59	73	19	1	1	7	27

Table 3. The same as Table ~~1~~2, but only for the years with a positive (negative) SCD anomaly~~SCD~~ and only for the three major stable snow regions: Northeast China (78 stations), North Xinjiang (21 stations) and the Tibetan Plateau (63 stations).

	Northeast China						North Xinjiang						Tibetan Plateau					
Year	P	1SD	2SD	-2SD	-1SD	N	P	1SD	2SD	-2SD	-1SD	N	P	1SD	2SD	-2SD	-1SD	N
1957	**98**	**20**	**54**	0	0	2	20	0	0	30	0	80	77	12	42	4	0	23
1959	1	0	0	**58**	**14**	**99**	**89**	**0**	**44**	0	0	11	45	3	15	5	0	55
1960	42	1	15	24	0	58	**100**	**26**	**58**	0	0	0	22	0	0	29	2	78
1963	13	0	0	**35**	**5**	**87**	24	0	0	19	5	76	22	0	0	27	0	78
1965	68	1	23	13	1	32	24	0	0	38	0	76	13	0	4	**42**	**4**	**87**
1967	20	0	0	**43**	**13**	**80**	75	0	20	10	0	25	26	0	7	14	0	74
1969	23	0	3	26	14	77	75	0	30	5	0	25	3	0	0	**47**	**5**	**97**
1973	**90**	**4**	**55**	0	0	10	38	0	0	5	10	62	34	2	10	20	0	66
1974	53	0	17	18	3	47	5	0	0	**33**	**19**	**95**	40	0	3	11	2	60
1977	74	5	26	5	0	26	**95**	**0**	**71**	5	0	5	40	6	17	6	0	60
1980	62	1	16	8	0	38	**95**	**5**	**57**	0	0	5	43	2	10	3	0	57
1983	63	3	19	3	0	37	24	0	0	24	0	76	**95**	**24**	**38**	0	0	5
1988	71	0	23	3	0	29	**100**	**10**	**62**	0	0	0	51	5	16	2	0	49
1990	39	0	0	13	1	61	33	0	5	19	0	67	**81**	**3**	**38**	0	0	19
1994	95	1	26	0	0	5	**95**	**0**	**48**	0	0	5	44	2	11	10	0	56
1995	32	0	1	13	4	68	10	0	0	**29**	**19**	**90**	76	10	31	0	0	24
1998	5	0	0	**49**	**13**	**95**	62	0	5	5	10	38	77	11	24	2	0	23
2002	4	0	0	**43**	**21**	**96**	24	0	0	19	5	76	20	0	2	13	0	80
2008	6	0	0	**38**	**12**	**94**	5	0	0	**48**	**5**	**95**	61	2	7	11	2	39
2010	**92**	**17**	**50**	3	0	8	**100**	**10**	**55**	0	0	0	14	0	5	**49**	**2**	**86**

Table 4. Number of stations with SCD, SCOD, and SCED trends, number of stations with relationships of SCD, SCOD, and SCED, respectively, with TBZD, number of stations with relationship between SCD and MAT, and number of stations with relationship between SCD and AO. All of them have two significance levels, the 90% and 95%.

		SCD			SCOD			SCED		
		95%	90%	I*	95%	90%	I*	95%	90%	I*
Trend	P	18	35	136	93	136	124	1	2	43
	N	38	54	127	13	23	69	92	138	169
TBZD	P	156	193	137	0	2	63	85	115	203
	N	0	0	22	64	93	194	0	2	32
MAT	P	0	2	30						
	N	129	171	149						
AO	P	35	87	77						
	N	33	82	106						

(Note: Positive (P) or Negative (N) trends or relations, I* for insignificant)

Figure Captions

Figure 1. Locations of weather stations and major basins, mountains and plains mentioned in the paper, overlying the digital elevation model for China.

Figure 2. Percentage of weather stations with different measurement lengths.

Figure 3. Annual mean snow cover days (SCDs) from 1980/81 to 2009/10 (a), and their coefficients of variation (CV) (b).

Figure 4. Seasonal variation of SCDs; the number in the centre denotes annual mean SCDs, the blue colour in the circle the SCDs for winter season, the yellow colour for spring, and the red colour for autumn.

Figure 5. SCD anomalies in 1957 (a), 2002 (b) ~~,~~and 2008 (c), anomaly of snow cover onset date (SCOD) in 2006 (d), and anomalies of snow cover end date (SCED) in 1957 (e)~~,~~ and 1997 (f).

Figure 6. Trends of annual mean SCDs (a), SCOD (b), and SCED (c) from the 352 stations of more than ten annual mean SCDs with Mann–Kendall test, and relationships among the SCD and day with temperature below 0°C (TBZD) (d), mean air temperature (MAT) (e), and Arctic Oscillation (AO) index (f).

Figure 7. SCD variations in Kuandian (40°43′ N, 124°47′E, 260.1 m) (a), Hongliuhe (41°32′ N, 94°40′E, 1573.8 m) (b), Gangcha (37°20′ N, 100°08′E, 3301.5 m) (c) and Shiqu (32°59′ N, 98°06′E, 4533.0 m) (d), SCOD in Pingliang (35°33′ N, 106°40′E,

1412.0 m) (e) and Weichang (41°56′ N, 117°45′E, 842.8 m) (f), and SCED in Jixi (45°18′ N, 130°56′E, 280.8 m) (g) and Maerkang (31°54′ N, 102°54′E, 2664.4 m) (h). (The unit on the Y-axis in the figures e, f, g, h denotes the Julian day using 1st September as reference)

Figure 8. Spatial distribution of SCOD (a) and SCED (b) based on the stations with an average of more than ten SCDs.

Figure 9. SCD relationships with TBZD for Chengshantou (37°24′ N, 122°41′E, 47.7 m) (a), MAT for Baicheng (41°47′ N, 81°54′E, 1229.2 m) (b), and AO index for Huajialing (35°23′ N, 105°00′E, 2450.6 m) (c), and Tonghua (41°41′ N, 125°54′E, 402.9 m) (d).

Figure 1

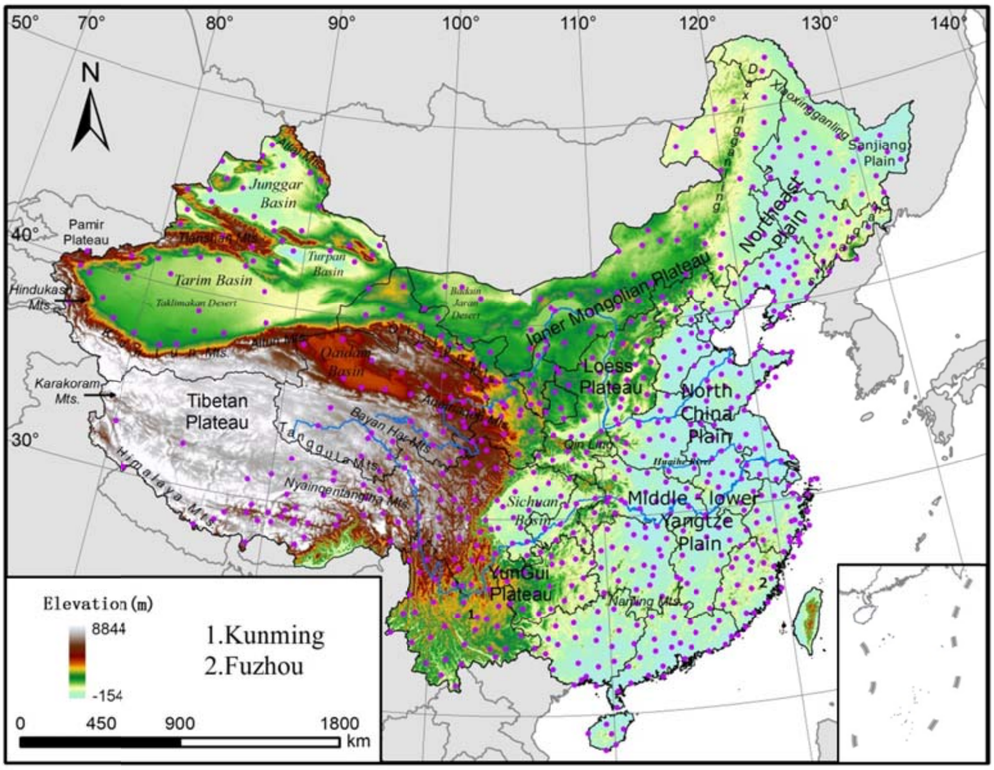


Figure 2

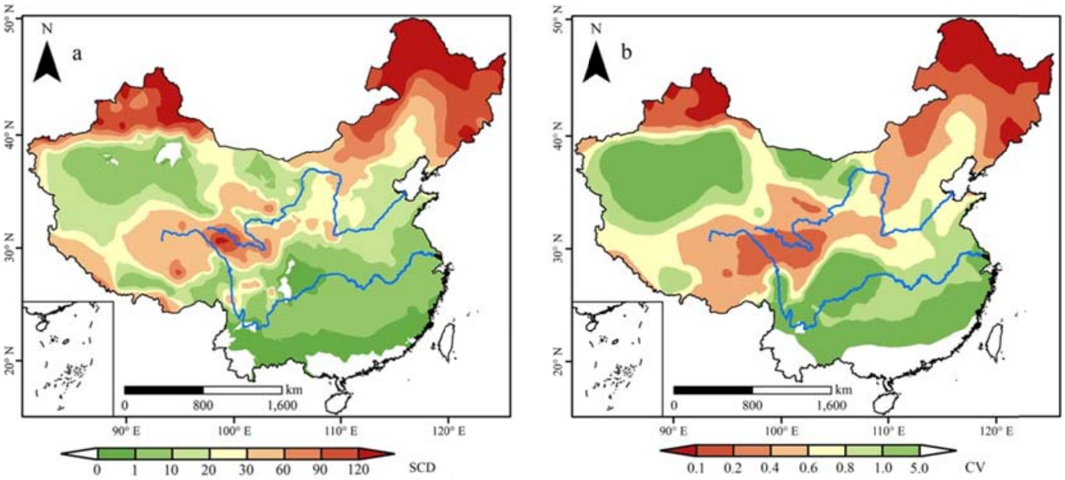
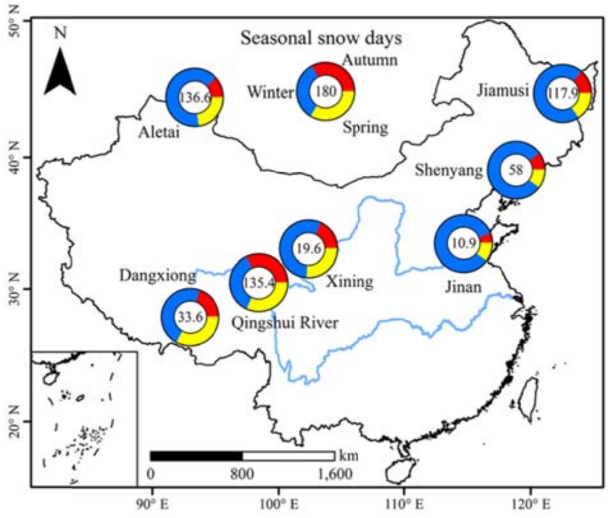


Figure 3



Seasonal snow days
N
Autumn
Winter
180
Spring
136.6
Aletai
Jiamusi
117.9
Shenyang
58
19.6
Xining
10.9
Jinan
Dangxiong
135.4
33.6
Qingshui River
km
0
800
1,600
50° N
40° N
30° N
20° N
90° E
100° E
110° E
120° E

Figure 4

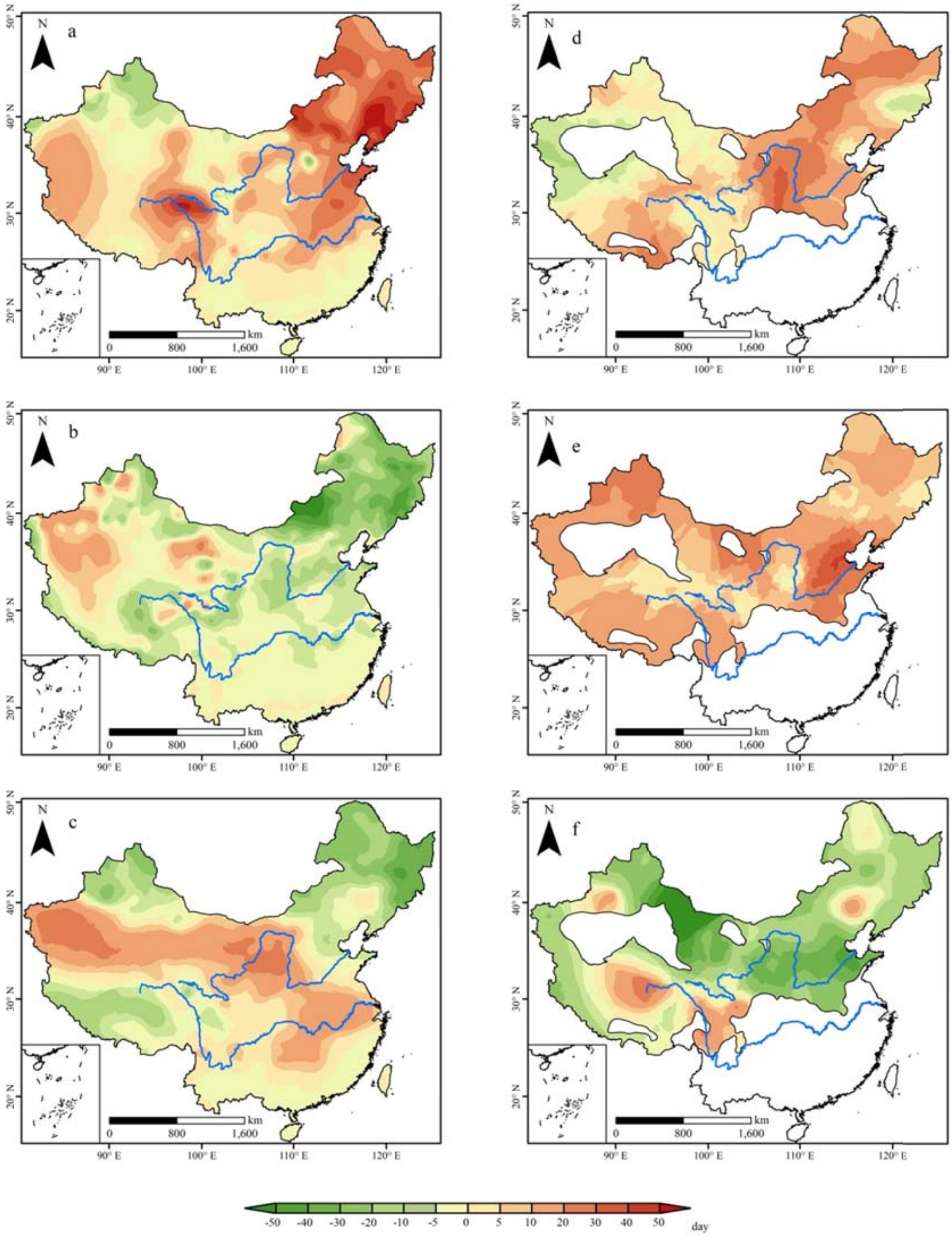

a
b
c
d
e
f
N
km
0
800
1,600
50° N
40° N
30° N
20° N
90° E
100° E
110° E
120° E
-50
-40
-30
-20
-10
-5
0
5
10
20
30
40
50
day

Figure 5

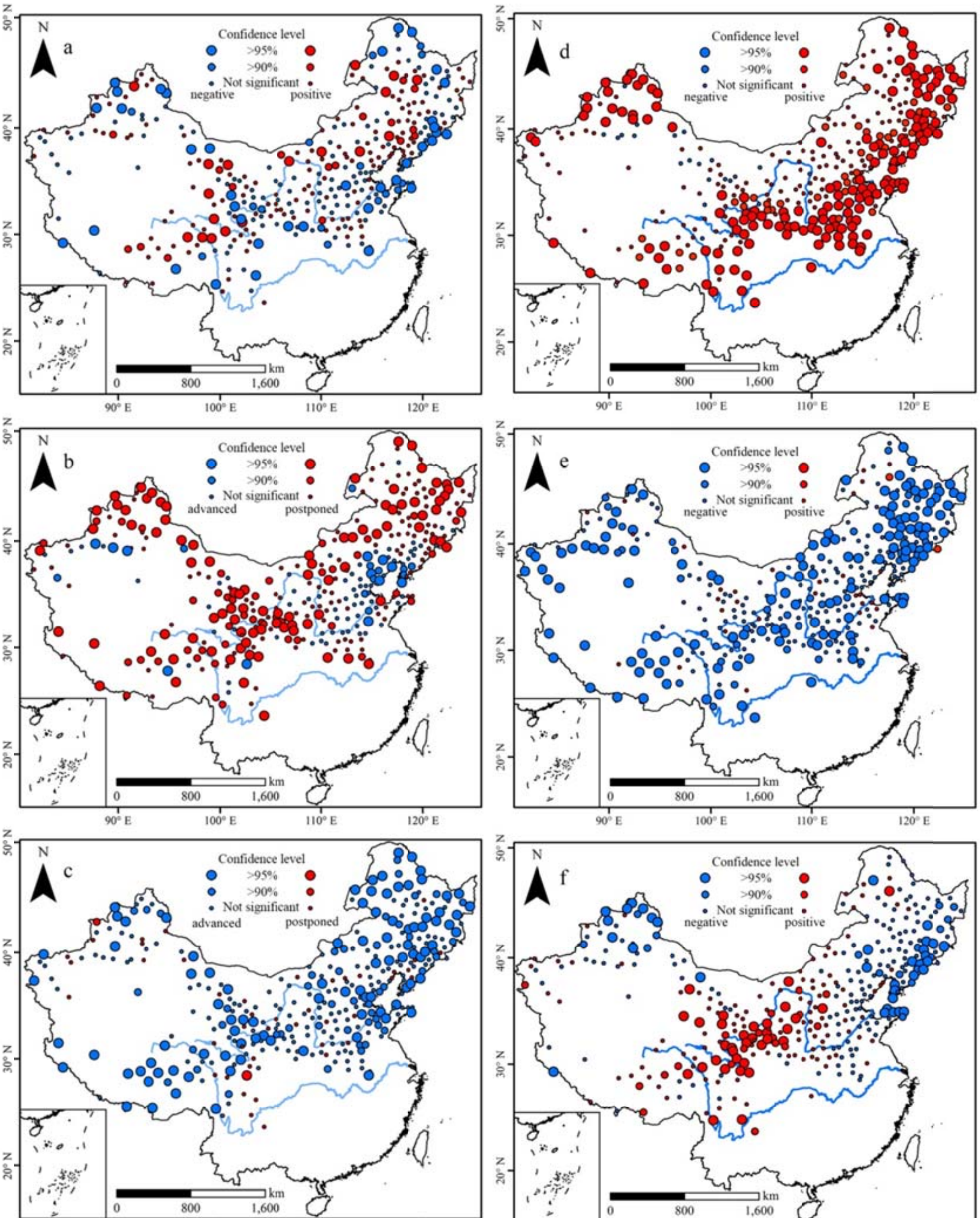
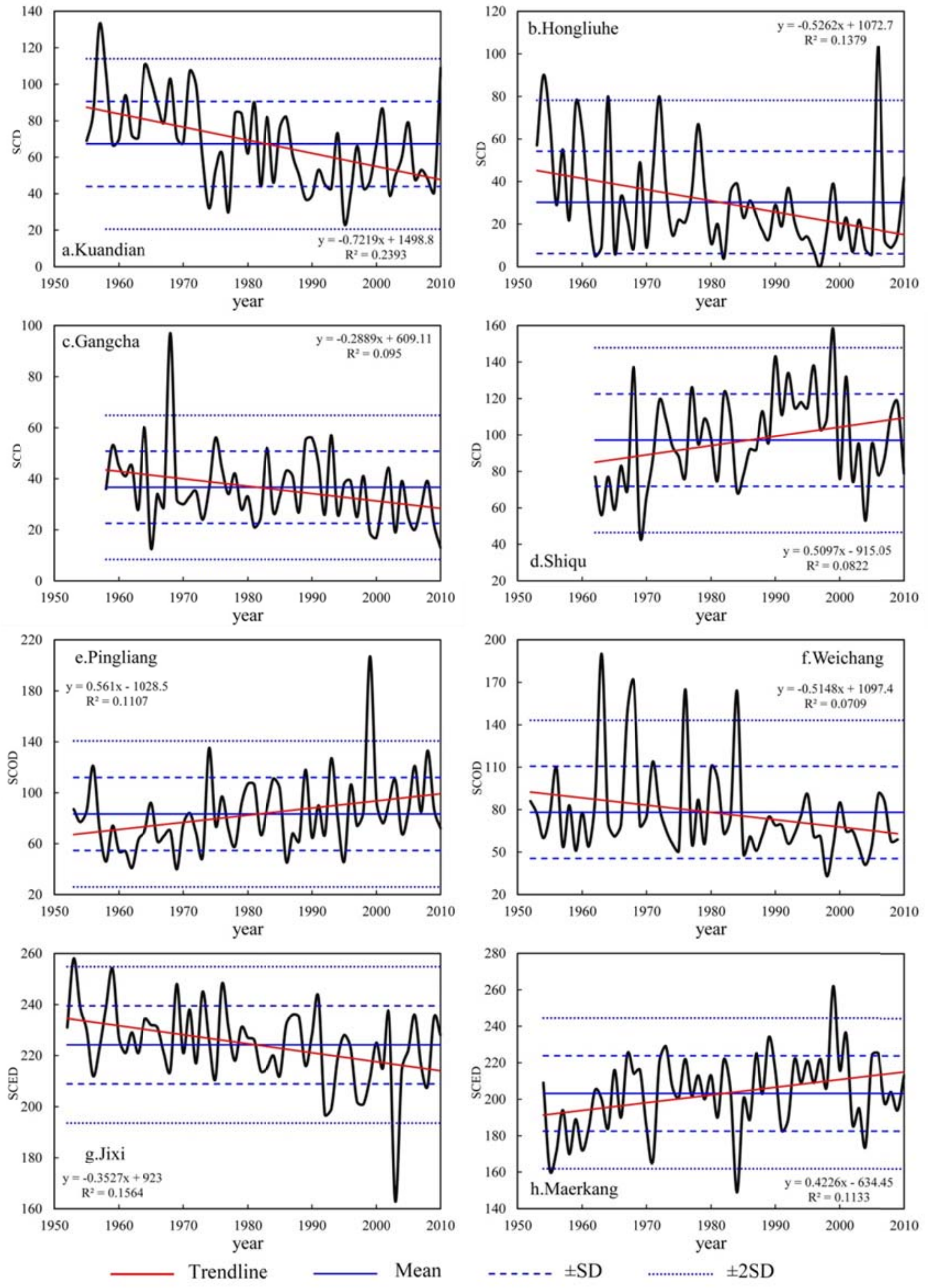

a
b
c
d
e
f
N
Confidence level
>95%
>90%
Not significant
negative
positive
advanced
postponed
0 800 1,600 km
90° E
100° E
110° E
120° E
20° N
30° N
40° N
50° N

Figure 6



a.Kuandian
y = -0.7219x + 1498.8
R² = 0.2393
SCD
year
b.Hongliuhe
y = -0.5262x + 1072.7
R² = 0.1379
c.Gangcha
y = -0.2889x + 609.11
R² = 0.095
d.Shiqu
y = 0.5097x - 915.05
R² = 0.0822
e.Pingliang
y = 0.561x - 1028.5
R² = 0.1107
SCOD
f.Weichang
y = -0.5148x + 1097.4
R² = 0.0709
g.Jixi
y = -0.3527x + 923
R² = 0.1564
SCED
h.Maerkang
y = 0.4226x - 634.45
R² = 0.1133
Trendline
Mean
±SD
±2SD

Figure 7

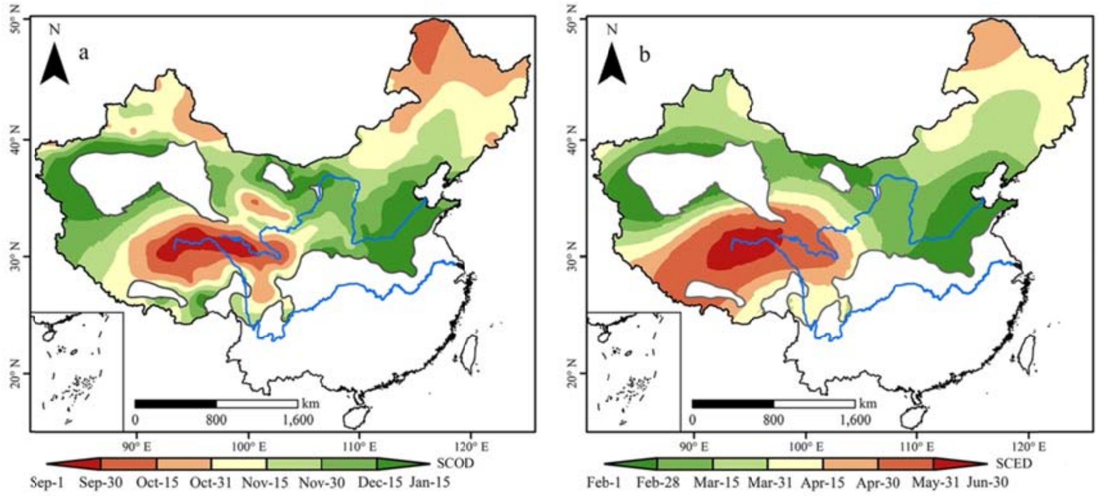


Figure 8