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Interactive comment on "Snow cover variations across China from 1951–2018" *by* Xiaodong Huang et al.

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Interactive comment on "Snow cover variations across China from 1951–2018" by Xiaodong Huang et al. Anonymous Referee 1 Received and published: 2 September 2020 In this paper the authors' document trends in China snow cover from surface observations of daily snow depth over the period 1951-2018. The paper results are consistent with previous publications showing mainly increasing snow depth and snow cover above 40N, with decreasing snow cover south of 40N. The main merit of the paper is the period of record (1951-2018) which currently represents the most up-to-date (and longest) assessment of snow cover trends in China. The introduction is well-written and comprehensive, but would be improved with more focus and synthesis of the Chinese snow cover literature, and a clearer discussion and presentation of the study rationale. The data and methods sections are mostly well written, although the methods section could use some additional explanation in a few places (see detailed comments). The trend results are presented clearly, but there is considerable potential to streamline the presentation. The Structural equation modeling component of the analysis is not compelling; it currently lacks a clear rationale and is based on inappropriate air temperature and precipitation variables. The updated trend results presented in the paper are of strong interest to the cryospheric community. However, the paper provides little explanation of the mechanisms responsible for the trends, which is a major weakness.

Author's response: Firstly, on behalf of all authors, we appreciate your careful review and also great comments for this manuscript. Please accept our respect and gratitude to you for your pertinent suggestion and responsible review. Base on your comments, the revised manuscript has made the following changes: 1) The Introduction section was revised based on your comments. Currently various available data for monitoring snow cover observations are referred to, including their advantages and limitation. More literatures focus on snow cover variation in China are cited and discussed. And what issues of snow cover change in China still need to resolve was put forward. 2) We have added more principles description of methods used in the article. Only the climate data in the cold season was re-analyzed in the revised manuscript. We definitely found more interesting results this time. 3) The results of the breakpoint analysis were discussed separately. 4) The structure of the article was re-organized, the results were partially condensed and more discussion has been added in order to explain the mechanisms responsible for the trends of snow cover in China. Include an enhance correlation analysis between climate and snow cover, snow cover spatiotemporal pattern based on EOFs analysis, as well as the oscillation cycle based on Morlet wavelet.

Detailed comments: 1. Comments from Referees: Suggested wording change for first line of Abstract: "Snow cover changes over China from 1951 to 2018 are documented based on an analysis of in situ daily snow depth observations from 730 meteorological stations. The snow cover indicators analyzed included snow depth (SD), snow covered days (SCDs), and snow phenology."

Author's response: Changed as you suggested. Thank you.

Author's changes in manuscript: In Abstract: "Snow cover changes over China from 1951 to 2018 are documented based on an analysis of in situ daily snow depth observations from 730 meteorological stations. The snow cover indicators analyzed included snow depth (SD), snow covered days (SCDs), and snow phenology."

2. Comments from Referees: The Introduction is well written and comprehensive, but it needs to focus more on China snow cover. I think you could delete the first two paragraphs and replace this with a focussed discussion of the various advantages and disadvantages of the currently available data for monitoring snow cover changes over China. In this regard, your statement that in situ snow depth observations provide the most reliable dataset for analyzing snow cover changes "with a high degree of credibility" will need to acknowledge the strong local scale processes influencing point snow depths, the poor spatial distribution of stations in some regions of China, and the low-elevation bias in the station network. A summary table of China snow cover trend results from previous studies would be a useful addition to the Introduction given the sensitivity of trend results to the specific period of data analysed. The recent findings by Ma et al. (2020) of the role of changes in winter snow-free periods in snow cover duration trends should be included in the discussion as they help explain why snow cover duration can increase under warming temperatures. A concise synthesis of previous results and identification of knowledge gaps is important for providing a clearer rationale for this particularly study. For example, the SEM analysis presented in subsection 3.2 appears to be an innovative aspect of the paper that needs to be incorporated in the study rationale.

Author's response: We completely agree with the comment. In the revised manuscript, more focus on previous studies on China snow cover was added in the introduction section. The limitation of the poor spatial distribution of stations in the west of China was discussed. Due to many of literature focus on the snow cover change in regional scale in China, especially the data and methods are different, only a few of literatures refer to throughout the China snow at present. It is difficult to compare different conclusions in the form of tables. Therefore, we have set aside a section in discussion section to compare with previous studies, include the latest literature. The SEM analysis are indeed added little to the paper. After discussion, the authors decided to delete the part of the SEM analysis results. Thank you very much for your great advice. Author's changes in manuscript: In Introduction section: "Limited by the coarse spatial resolution from passive microwave remote sensing data and severely cloud obscured from optical remote sensing data, in situ snow observations provide the most reliable dataset for analyzing the changes in snow cover with a high degree of credibility. Moreover, snow parameters are calculated from meteorological station data, which have great advantages in the process of long time series research. However, in situ observations from climate station is insufficient for representing at a regional scale due to spatial discontinuities, irregularities and inhomogeneities in the distribution. Most stations distributed in the flat and open area, and rare distribution in west China, especially the Tibetan Plateau. The stations are lacking in inner and mountain areas in plateau, greatly limits the observation integrity and representation of space. Nevertheless, the sparse station network still provides the long-term of high-quality ground observation data."

3. Comments from Referees: What is your definition of "stable" snow cover? Are TP, NX and NC highlighted in Figure 1 because they are the only areas in China with a stable snow cover? Is this also the reason that only these three regions are summarized in the results? The issue of ephemeral vs stable snow cover deserves some discussion particularly in light of the Ma et al. (2020) paper. Related to this, your statistical analyses are carried out at all stations in China not just those with a stable snow cover. How robust are the statistical methods in ephemeral snow cover areas with frequent zero snow cover years and undefined start and end dates to the snow season?

Author's response: The stable snow cover area means the area with the mean annual snow-covered days bigger than 60d during the snow season. The stable snow cover only distributes in TP, NX, and NC (Huang et al. 2016; 2017). In this study, the stations are distributed throughout the China are used to access the snow cover changes during the period of 1951 to 2018. The TP, NX and NC highlighted and discussed in this study, the main reason is that the snow in these three regions has more significance in regional climate, hydrology and ecology compare to other regions. We agree the ephemeral snow also play important role in climate change, thus in the revised manuscript, the summary and description are as inclined as possible to the whole of China, not only the TP, NX and NC, but also the ephemeral snow areas. To ensure consistent statistical results between the stable and ephemeral snow areas, strict statistics of snow cover indices was adopted. For example, to avoid the impact of ephemeral snow in snow phenology computations, SOD was defined as the first date of the first three continuous snow records, and SED was defined as the last day of the date of the last three continuous snow records in a hydrological year (from 1st July to 30th June of the next year). If the rules are not met, such as in ephemeral snow cover areas with zero or less than three continuous snow records in snow cover years, the statistics of the year will be abandoned.

4. Comments from Referees: In Section 2.2 the use of an annual period seems strange given the snow season is confined to a much shorter cold season. It is also not clear how annual maxima of air temperature and precipitation would assist in diagnosing changes in snow cover. From energy and mass balance considerations variables like freezing degree-days, total solid precipitation and the solid-fraction of total annual precipitation would be expected to have more relevance for explaining variability and change in snow cover.

Author's response: We completely agree with the comment. It is thoughtless to use annual period meteorological data to explain the cause of snow cover variation. In the revised paper, we only choose the temperature and precipitation in the cold season to analyze the response of snow cover to climate change. We think the maximum temperature in the clod season may accelerate the snow melting, especially in snow melt season, which may cause the snow depth to become shallower and the end date get earlier. To correspond to the snow season, the temperature and precipitation in clod season are selected this time. Thank you for your advice. Author's changes in manuscript: In 2.2 Meteorological data section "The dataset time series is from 1901 to 2017. In this study, the monthly mean temperature (Tmp-mean), minimum temperature (Tmn-min), maximum temperature (Tmx-max), and precipitation in the cold season (October to March of the following year) from 1951 to 2017 in the dataset were used to explore the spatiotemporal heterogeneity of snow cover variation."

5. Comments from Referees: Section 3.1: Can you provide a line or two of text prior to eqns. 3 to 6 to explain what these equations are being derived for? I suggest you add a new section "3.2 Change-point analysis". Overall I find section 3.1 a bit confusing and statements in the Results section further increase my confusion e.g. page 9 line 4 "The results of the M-K trend test are the same as those of the slope method".

Author's Response: Thank you for the comments. More explanation was added to those equations, and a new section for the breakpoint test was added. The M-K trend test was deleted, the method only employed for the breakpoint test. And the slope method was employed to analyze the trend of snow cover at each station as well as the overall snow cover trend from 1951 to 2018 in China, respectively.

Author's changes in manuscript: In "3.2 Breakpoint test" section "The Mann-Kendall (M-K) test is recommended by the World Meteorological Organization and is frequently used to analyze the trends of changes in meteorological and hydrological elements (Milan, 2013). M-K test can not only check the variation overall trend of the sequence but also specify the breakpoint starts. First, for a time series x with n samples, a sequential column Sk was constructed. Under the assumption of random independence of time series, a sequence of statistic UF was defined. Then, in reverse order according to time series x, the above process was repeated to calculate UB. The method is realized by the following formula: where Sk is the cumulative count of the number of values at the time i great than at time j. E(Sk) and var(Sk) are mean and variance values of Sk. UF is the standardized value of S, while UB is obtained by inverting the sequence of UF. ”

6. Comments from Referees: Section 3.2: Please provide some introductory text to your current section 3.2 on why you proposing to employ SEM? What are the hypotheses you are testing and why is SEM the best method? In your statement that “seven factors were screened out”, I think you mean that seven factors were retained for analysis. As mentioned previously, the use of annual maxima in this analysis is difficult to justify for understanding snow cover variability. I think you would learn more about snow cover variability by defining the regional snow cover response regions from EOF analysis, then looking at the corresponding regional time series of snow season air temperature, total precipitation, and precipitation solid fraction.

Author’s Response: Thank you for the comments and suggestions. The comments for SEM was responded in Author’s response 2. Based on your suggestion, the EOFs was employed in the revised manuscript to reveal the spatiotemporal pattern of snow cover, further proved that temperature is the main driving factor of snow cover variation in time and space. Author’s changes in manuscript: Please see section 5.3 Spatiotemporal pattern and driving factors of snow cover variation.

7. Comments from Referees: Include slope units in Table 2. Why is the China average not included as in Table 3? The same applies to the trend result tables for other snow cover variables. Author’s response: Revised as you suggested. Thank you very much.

8. Comments from Referees: Can you explain how the anomaly time series in Figure 4 is obtained? There should be an error bar for each annual mean, and the error will influence the linear fit through the points. Can you also provide a brief explanation how to interpret the UF and UB curves in Figures 4b and 4d. Wouldn’t the confidence interval in the trend get narrower as the length of the time series increases?

Author's response: In M-K analysis, only the interannual variation of the mean value can be used to test the breakpoint. Figure 4a was intended to show the overall trend of average snow depth. The UF and UB interannual variation curves are the key results for revealing the snow cover variation. The borderlines in the figure mean the UF and UB equal to ± 1.96, the trend reaches to significant level ($P < 0.05$). The confidence interval is constant, don't get narrower as the length of the time series increases. In the revised manuscript, the means of UF and UB were explained in the methodology section, and the UF curves for each snow indices were also introduced. Thank you for the comments.

Author's changes in manuscript: In section "4.2.2 Breakpoint test" Figure 6 shows the trend of different snow cover indexes changing with time during the period from 1951 to 2018 in China. From the perspective of time variation trend, each snow cover index has its own characteristics over time, which does not change linearly, but shows an increasing or decreasing trend of fluctuation and oscillation. The overall trend of snow depth is increasing, but the change has roughly experienced the process of first increasing, then decreasing, and then increasing again. The trend of SDoverall changes in 1961 and 1997, and increase significantly after 2010. The trend of SDmax changes in 1958 and 2007, however, the overall increase was not significant. SDDs represents the length of the snow season, while SCDs represents the number of days the surface is covered by snow. During the period of 1951 to 2018, the SCDs has experienced three processes of increasing first, then decreasing, and then increasing, with the overall increasing trend but not significant. While the SDDs first increase before 1999 and then decrease, and reduction significantly after 2015, indicating that the shortening of snow season in recent years is a well-established fact. The change of SOD is relatively complex. The SOD experienced several trends of postponing or advancing, and the overall trend was delayed but not significant. SED showed a trend of delay until 1998, but then getting earlier, and advance significantly after 2014. Table 3 summarized the breakpoints of six snow cover indices detected by a moving t test. The results indicate that the spatiotemporal variations in snow cover show obvious regional differences.

Specially, there is no significant breakpoint in the Tibetan Plateau. Furthermore, the snow phenology changes in the Tibetan Plateau are greater than those elsewhere. The abrupt change years of snow cover in different regions were almost different. However, almost all the abrupt change occurred around the 2000s, indicating that snow cover had changed significantly in the 20th century in China since 1951.

9. Comments from Referees: What is responsible for the break points shown in Table 3? Are they linked to changes in atmospheric circulation?

Author's response: If the UF and UB curves intersect between the borderlines ($u_{0.05} = \pm 1.96$), the point of intersection corresponds to the time at which the breakpoint transition begins. However, the breakpoints of the meteorological sequence can be further judged by combining the M-K and moving t tests. When t is greater than $t_{0.05}$, the year corresponding to t represents a breakpoint. Our study found that the long-term trend of snow cover variation is mainly due to warming climate in the cold season, and the short-term anomaly of snow cover is related to extreme weather, such as the abnormal increase of snow depth in negative temperature anomaly.

10. Comments from Referees: Section 4.4: The results of the SEM analysis are not very convincing and add little to the paper. The analysis may be more instructive using air temperature and precipitation variables that are more closely linked to snow cover variability.

Author's response: We completely agree with the comment. The SEM analysis is indeed added little to the paper. After discussion, the authors decided to delete the part of the SEM analysis results. Instead with an enhanced correlation analysis between climate and snow cover variation in the Discussion section. Thank you for the comments.

11. Comments from Referees: I think your Results section could be significantly shortened if you presented all the snow cover variables together instead of separately. I think this would also help interpreting and explaining the results. At the moment the

results are presented in a rather descriptive way following the same format for each variable, which is not very interesting from the readers point of view.

Author's response: In the revised version, the structure of the article was re-organized based on the comments. Thank you so much. Author's changes in manuscript: The catalog in the revised manuscript is the following: 1 Introduction 2 Dataset 2.1 Snow depth records 2.2 Meteorological data 3 Methodology 3.1 Trend analysis 3.2 Breakpoint test 4 Results 4.1 Spatiotemporal characteristics of snow cover in situ observation 4.1.1 Snow depth 4.1.2 SCDs 4.1.3 Snow phenology 4.2 Snow cover trends across China 4.3 Breakpoint 5 Discussion 5.1 Compared with previous study 5.2 Snow cover related to climate change 5.3 Spatiotemporal pattern and diving factors of snow cover variation 5.4 Dose the oscillation cycle exists in snow cover varation? 6 Conclusion

12. Comments from Referees: The conclusions are largely descriptive and it is hard to find any new insights into snow cover variability and change in China in this paper. As it stands, the only significant contribution of the paper is to extend the period of previous trend analyses. I see several areas where the authors could make potential new contributions: - document the snow response regions of China from EOF analysis of station annual series of SDmax and SCD series - determine the roles of regionally-averaged (over the identified snow response regions) snow season air temperature, total precipitation, and total snowfall in the observed snow cover series. - find physical explanations for break points e.g. atmospheric circulation changes, increased snowfall in winter storms, fewer snow-free periods (e.g. Ma et al. 2020). - find physical mechanisms for the decrease in snow season gaps documented by Ma et al. (2020)

Author's response: The conclusion section was rewrote based on your suggestions. The main conclusions of this study are summarized, and the prospect of future research is put forward according to the new findings in this study. Thank you.

Author's changes in manuscript: In section "6 Conclusion" "While ground measurements are the most accurate way for plot-scale snow information, the results reported in the current study would bear high uncertainties in poorly monitored areas, especially in the Tibetan Plateau, in which stations are much less when compared to eastern China. Here, long-term snow cover variations were assessed using in situ observations across mainland China from 1951 to 2018. The variation of snow cover has obvious regional deference. Snow depth tends to increase northward of 40°N, but decrease southward of 40°N, the overall snow depth increases significantly in China, where the greatest contribution came from the increase in north China. SCDs in Northeast China and northern Xinjiang both show increasing trends, especially in Northeast China, where the increase is significant. The snow season tends to shorten throughout mainland China, jointly resulting from later snow onset and earlier snow melting, which mainly due to the warming climate in clod season. Furthermore, the snow phenology changes in the Tibetan Plateau are greater than those elsewhere. China began warming persistently after 1980s and warmed significantly after the 1990s since 1951. With climate warming, snow depth, and its phenology change severely, and temperate is highly related to the change of snow cover. However, the temperature significantly negatively correlated with snow depth, the snow depth increased significantly in north China mainly possible due to the increase in temperature strengthen the south-north airflow exchange and water vapor circulation, thus increase of snowfall events in northern China and alpine areas. After the 2000s, the warming gradually slowed down, the unusually low-temperature years finally led to a significant trend of increasing snow depth. In addition, the abrupt change of variation occurred around the 2000s, indicating that snow cover had changed significantly in the 20th century in China since 1951. Furthermore, the snow cover varies interannual, the snow depth fluctuates, and changes periodically with the increase of temperature. The long-term trend of increasing snow depth is caused by warming in the cold season, and the short-term anomaly of snow depth is related to extreme weather, such as the abnormal increase of snow depth in negative temperature anomaly. The change of snow phenology is mainly caused by the warming climate in the cold season. This study also shows that the influence of the temperature effect on snow cover is more important than precipitation obviously.

With climate change, especially climate warming, snow depth, and its phenology will change severely, which will dominate by the temperature rise in the future. The large-scale fluctuation of snow cover must be the result of climate change, and the analysis of abnormal events in the weather system is a way to further reveal the interannual variation and regional differences of snow cover. However, this study also found that the abrupt change of snow cover occurred mainly around 2000, but the temperature warming gradually slowed down after 2000 in China. What causes the abrupt change of snow cover needs to be further explained in combination with extreme weather, atmospheric circulation, etc."

New reference cited in the revised manuscript: Bryant, E.: Climate process change, UK: Cambridge Univ. Press, 1997. China Meteorological Administration. Specifications for surface meteorological observations. China Meteorological Press, Beijing, 61-63, 2003. Dyer, J. L. and Mote, T.: Spatial variability and trends in observed snow depth over North America, Geophys. Res. Lett., 33, L16503, 2006. Kim, K. Y., and North, G. R.: EOF-based linear prediction algorithm theory, J. Climate, 11, 2046-3056, 1998. Li, D., Wang. C.: Research progress of snow cover and its influence on China climate, Trans. Atmos. Sci., 34, 627-636, 2011. Liu, Y., Peng, G., Chen, X., Yang, Y.: Climatic and environmental changes in Shangri-La in next 50 years according to wavelet analysis and multiple VAR regression prediction modeling, Res. Sci., 38, 1754-1767, http://doi.org/10.18402/resci.2016.09.13, 2016. Ma., N., Yu, K., Zhang, Y., Zhai, J., Zhang, Y., Zhang H.: Ground observed climatology and trend in snow cover phenology across China with consideration of snow-free breaks, Clim. Dyn., 55, 2867-2887, https://doi.org/10.1007/s00382-020-05422-z, 2020. Notarnicola C., Hotspots of snow cover changes in global mountain regions over 2000–2018, Remote Sens. Environ., 243, 111781, 2020. Peng, S., Piao, S., Ciais, P., Fang, J.: Change in winter snow depth and its impacts on vegetation in China, Global Change Biol., 16, 3004-3013, https://doi.org/ 10.1111/j.1365-2486.2010.02210.x, 2010. Percival, D. B., Walden, A. T.: Wavelet Methods for Time Series Analysis (Cambridge Series in Statistical and Probabilistic Mathematics), UK:

Cambridge Univ. Press, 2000. Soon, W., Connolly, R., Connolly, M., O'Neill, P., Zheng, J., Ge, Q., Hao, Z., Yan, H.: Comparing the current and early 20th century warm periods in China, Earth-Sci. Rev., https://doi.org/10.1016/j.earscirev.2018.05.013, 2018. Sun, Y, Zhang, T, Liu, Y, Zhao, W., Huang, X.: Assessing snow phenology over the large part of Eurasia using satellite observations from 2000 to 2016, Remote Sens., 12, 2060, http://doi.org/10.3390/rs12122060, 2020. Zhang, X., Wang, K., Boehrer, B.: Variability in observed snow depth over China from 1960 to 2014, Int. J. Climatol., 1-9, https://doi.org/10.1002/joc.6625, 2020. Zhou, C. and Wang, K.: Quantifying the sensitivity of precipitation to the long-term warming trend and interannual–decadal variation of surface air temperature over China, J. Clim., 30(10), 3687–3703. https://doi.org/10.1175/JCLI-D-16- 0515.1, 2017.

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