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Discussions

Interactive comment on "Spatio-temporal dynamics of snow cover based on multi-source remote sensing data in China" *by* Xiaodong Huang et al.

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The Huang et al paper used the combined MODIS snow cover and passive microwave snow depth data to produce a daily cloudless snow cover and 500 m snow depth (not daily based on the eqn 1), to analyze the snow cover day, snow cover area, and snow depth variation for China for the period of 2000-2014. They found the overall annual number of snow covered days increased (except in summer), average snow covered area did not change much (summer and winter decreased, spring and fall increased), and snow depth decreased (except in spring). They also analyze their spatial distribution of these changes and found snow cover significantly increased in south china and northeast China, but decreased in Xinjiang. Overall, I found the paper has some good

Printer-friendly version

Discussion paper

results and may be publishable with carefully addressing my comments below. One of my major comments is the English writing that needs to be carefully edited throughout the paper. The second one is the lack of discussion of their results with other published results, (such as the recent published Ke et al., 2016); without discussion, we do not know how this result differing from or similar as the known literature. The third one is the possible reason behind to all of the variation and changes. I know the last one is hard and I do not expect a thorough explanation, but some qualitative discussions are needed.

Response: Firstly, on behalf of all authors, we want to thank you for your affirmation for our work, and also your great help and suggestions for this manuscript. We are sorry the inconvenience caused to you about our English writing. The editorial changes for language usage throughout were made by a native English scientific editor in this version. In addition, based on your suggestion, a discussion section was added in the manuscript. We compared the Ke's as well as others results with our conclusions in discussion, and the possible reason behind the snow variation was also discussed. Thank you again for the great suggestion.

Author's changes in manuscript: Please see our responses to the above comments in revised manuscript.

Below are some general comments: Abstract: the abstract writing is not very clear and needs to rewrite and more organized and more clarification. For example, in Line 15-19, they talked about the snow covered days and snow cover area, but these two contents are mixed in several sentences; snow depth is also mentioned here, but later in line 20-21, snow depth is mentioned again. I also confused in the line 15, they said snow depth increased, but 20-21, snow depth was decreased except in spring. Unless the increase in spring is much larger than the decreased in other seasons, it is not possible to see the annual snow depth was increased as stated in line 15. If this is the case, then authors should make this statement clear, not let readers to figure it out. Also the last sentence in the abstract, authors should say all regions with increase together, then all regions with decrease together, not as did here. Also it is not clear in the last sentence, snow cover means snow cover area, days, or depth?

Response: We rewrote the Abstract based on your suggestion. Thanks.

Author's changes in manuscript: Abstract. By combining optical remote sensing snow cover products with passive microwave remote sensing snow depth (SD) data, we produced a MODIS cloudless binary snow cover product and a 500 m spatial resolution downscaling snow depth product. The temporal and spatial variations of snow cover from December 2000 to November 2014 in China were analyzed. The results indicate that over the past 14 years, 1) the perennial average annual snow-covered area (SCA) in China has been 11.3% over the entire year and 27% during the winter. The average SCA during the summer and winter decreased, whereas the average SCA during the spring and fall increased, and the overall average annual SCA did not change significantly. 2) The snow-covered days (SCDs) during the winter, spring, and fall all increased, whereas they decreased during the summer, and the annual SCDs increased. 3) The average SD during the winter, summer, and fall decreased, the average SD during the spring increased, and the overall average SD increased over the past decade. 4) The spatial distributions of the areas of increase and decrease average annual SD were highly consistent with those of the annual SCDs, and were also consistent with the variations in each season. 5) The regional differences in the variation of snow cover in China were significant. The SCD and SD increased significantly in South and Northeast China, decreased significantly in northern Xinjiang Province. The SCD and SD increased on the southwest edge and in the southeast part of the Tibetan Plateau, whereas it decreased in the north and northwest regions.

1. Introduction: the part should be more focused on the topic of study and does not need to include everything that does not link to the topic of snow cover change in China. From 52 to 92, authors list many snow cover studies, I don't think it make sense, you should only mention the most relevant and should discuss in the end of the paper that how your results differ from, similar with or extent those studies, so your study is not

just a study, but a significant addition to the current literature.

Response: We revised introduction part based on your comments, Thanks. First, the references focused on the snow cover change in China were moved in discussion part, which as a basis to compare with our results. Second, the origin introduction of the study area was also moved in Introduction, to emphasis the important of this study. Author's changes in manuscript: 1 Introduction. Snow cover is closely related to human lives, and it has both positive and negative effects (Liang et al., 2004). High and mid-latitude regions contain abundant snow cover and glacial resources, which are the source regions for many rivers (Zhang et al., 2002). Snowmelt runoff can make up more than 50% of the total discharge of many drainage basins (Seidel and Martinec, 2004). Snow cover is an important resource for industrial, agricultural, and domestic water use. Especially in arid and semi-arid regions, the development of agricultural irrigation and animal husbandry relies on the melting of snow cover (Pulliainen, 2006; Li, 2001). Winter water deficiencies can easily cause droughts (Cezar Kongoli et al., 2012). On the other hand, flood disasters caused by melting snow cover and snow disasters such as avalanches, glacial landslides, and snowdrifts are also common (Gao et al., 2008; Liu et al., 2011; Shen et al., 2013). Rising temperatures due to global warming rapidly change the snow cover conditions in seasonal snow-covered regions, which has led to accelerated melting of most ice sheets and permanent snow covers (Yao et al., 2012), increasing snowline elevations (Chen, 2014), decreasing wetland areas, and the reallocation of precipitation, which has further led to frequent floods and snow disasters (Lee et al., 2013; Wang et al., 2013). Global warming is an indisputable fact. Rising temperature will strongly affect alpine and polar snow cover (IPCC, 2013). The variation of global and regional snow covers greatly affects the use of snow resources by humanity, and the feedback mechanism of albedo further affects climate (Bloch, 1964; Robinson, 1997; Nolin and Stoeve, 1997). Several studies have indicated that the snow cover in the alpine regions in China affect the atmospheric circulation and weather systems in East Asia and further affect the climate in China (Qian et al., 2003; Zhao et al., 2007). Alpine snow cover has important implications for hydrology, climate, and the ecological environment (Chen and Liu, 2000; Hahn and Shula, 1976). China is large, and its snow-covered regions are widely distributed geographically. North Xinjiang, Northeast China-Inner Mongolia, and the Tibetan Plateau are the 3 major regions with seasonal snow cover in China (Wang et al., 2009). They are also the major pasturing regions. Winter and spring snowfalls are the major water resources in north Xinjiang and the Tibetan Plateau (Pei et al., 2008; Chen et al., 1991; Wang et al., 2014). Heavy snowfall can also cause severe snow disasters and large numbers of livestock deaths (Liu et al., 2008; Chen et al., 1996). Floods caused by melting snow cover also frequently occur in the spring, severely limit the development of grassland animal husbandry and affect the safety of human lives (Shen et al., 2013). Therefore, accurate acquisition of snow-covered area (SCA) and SD information is significant for understanding climate change and the hydrological cycle, conducting water resource surveys, and preventing and forecasting snow disasters in China. Recent studies of the distribution and variation of snow cover in China have progressed greatly, but they have mainly focused on the Tibetan Plateau, Xinjiang, and Northeast China (Chen and Li, 2011). Furthermore, the results from different snow cover datasets are slightly different, and the snow cover variations in different regions are also different. MODIS data, which have high spatial and temporal resolution, have been widely used in the remote sensing fields of ecology, atmospheric science, and hydrology. However, clouds strongly interfere with optical sensors. Hence, we cannot directly use snow cover products acquired by optical sensors to effectively quantify SCA. Passive microwaves can penetrate clouds and are not affected by weather. However, the coarse resolution of passive microwave products greatly limits the accuracy of regional snow cover monitoring. Therefore, cloud removal and downscaling are effective approaches for enhancing the accuracy of snow cover monitoring using optical and passive microwave products, respectively. This study used the MODIS daily snow cover product and passive microwave SD data to produce a daily cloudless SCA product and a downscaled SD product with a 500 m spatial resolution. The integrated daily snow products are used to analyze the temporal and spatial variations of the snow cover in China from December 2000 to November

2014 and quantitatively evaluate the variation of SCA, snow-covered days (SCDs), and average SD to provide a basis for further understanding the interaction between climate and snow cover under the background of globe warming in China.

2.1 study area: you include "why your study is important" here, but you do not need to repeat here again and it should be in the introduction. It is clear based on the figure 1, you should basically talk more about the elevation distribution, a little bit about the population distribution and economy, etc: : :

Response: Did as you suggested. We moved this paragraph in the introduction, and rewrote the study area based on your suggestion. Thanks a lot. Author's changes in manuscript: 2.1 Study area. China has a large area and a large population. Its relief is high in the west and low in the east. Mountains, plateaus, and hills account for approximately 67% of the land area, and basins and plains account for approximately 33%. The mountains are mostly oriented east-west and northeast-southwest, including the Altun Mountains, Tianshan, Kunlun, Karakoram, Himalaya, Yinshan, Qinling, Nanling, Daxing'anling, Changbaishan, Taihang, Wuyi, Taiwan, and Hengduan. The Tibetan Plateau, which has an average elevation of more than 4000 m, is located to the west and is known as the "Roof of the World". Mount Everest is 8844.43 m tall and is the highest mountain in the world. To the north and east, Inner Mongolia, the Xinjiang area, the Loess Plateau, the Sichuan Basin, and the Yunnan-Guizhou Plateau are second-stage terrains of China. The region from east of the Daxing'anling-Taihang-Wushan-Wuling-Xuefeng Mountains to the shoreline mostly contains third-stage terrains composed of plains and hills with an average elevation of less than 1000 m. The multi-year stable snow cover is mainly distributed in the Tibetan Plateau, Northeast China and Inner Mongolia, and northern Xinjiang and covers a total area of 4,200,000 km2. This snow cover forms the major reservoirs for the seasonal snow-cover water resources in China (Li et al., 1983).

3. Results: The current organization is very confusing and not easy to follow. You should reorganize the content into: snow covered days, snow covered area, snow

depth. One at a time, not mixing them together.

Response: We re-organized the Results as you suggested. The SCA, SCD, and the SD were separated as three parts of results in the revised manuscript. We fully agreed with your suggestion, thanks a lot. Author's changes in manuscript: The structure of the revised manuscript is as follows: 1 Introduction 2 Materials and Methods 2.1 Study area 2.2 Remote sensing snow products 2.3 Cloud removal and downscaling algorithms 2.4 Analysis of the snow cover variation 3 Results 3.1 Snow-Covered Area 3.2 Snow-Covered Days 3.3 Snow Depth 4 Discussion 5 Conclusion

4. You need a discussion section, to put your results in the big picture of literature, how your results differ from, similar as, or extent in certain degree of the current literature. You also need to include a paragraph on the possible explanations to the observed change, difference, or extension.

Response: A discussion section was added this time. Author's changes in manuscript: 4 Discussions Snow cover is widely distributed in China. Researchers have conducted numerous studies on the variation of the snow cover in China using remote-sensing snow cover data from various satellites. By combining the MODIS Terra and Aqua snow cover data, Liu et al. (2012) studied the spatial stability of the three major snow-covered regions in China for 2001–2010 and analyzed the characteristics of the seasonal and annual snow cover variations. The results indicated that the snow cover stabilities in the three major snow-covered regions were in the order of Xingjiang > Northeast China-Inner Mongolia > Tibetan Plateau. The stable SCA in China did not change significantly. Wang et al. (2012) used combined MODIS and AMSR-E data to obtain a cloudless snow cover product and analyzed the temporal and spatial distributions of the snow cover in the arid regions in China for 2002–2009. The results indicated that the SCA in the stable snow-covered regions did not change significantly, whereas the unstable snow-covered regions had large annual variations in the SCA. The results of this study indicated that the average annual SCA did not change significantly. The stable snow-covered regions in China ($60 < SCD \leq 350$) were primarily located in Northeast China-Inner Mongolia, north Xinjiang, and the high mountains in the Tibetan Plateau, and the stable snow area did not change significantly during 2001-2014. Che et al. (2005) used the SD data that were inverted from SSM/I passive microwave data to analyze the snow cover distribution and variations in China for 1993–2002. The results indicated that the snow cover reservoir in China did not increase or decrease significantly over that ten-year period. The winter snow cover reservoir was mainly located in the three major stable snow-covered regions of Xinjiang, the Tibetan Plateau, and Northeast China. Dai et al. (2010) indicated that the number of SCDs and the SD in China increased between 1978 and 2005. The western Tibetan Plateau was a sensitive region with an abnormal variation in SCDs, whereas north Xinjiang, the mountainous regions in Northeast China and the east-central Tibetan Plateau were sensitive regions with abnormal SD variations. Dou et al. (2010) used the MODIS snow cover product to study the Tianshan Mountains in China, and indicated that the SCA in the Tianshan Mountains increased slightly; the increase was especially significant in the winter. Furthermore, the snow cover decreased in the regions at with elevation of $\geq$ 4000 m and increased in the regions with elevation of < 4000 m. This study found similar results, but the significant increase in SCDs was observed in the spring, not in the winter. Wang et al. (2015) used the MODIS cloudless synthesized snow cover product to further study the Tibetan Plateau and showed that the maximum SCDs and the perennial SCA in the plateau region decreased, the SCA increased, and the variations in temperature and precipitation significantly affected the plateau snow cover. The study by Basang et al. (2012) on the variation of snow cover in Tibet indicated that from 1980 to 2009, the SCDs and maximum SD in Tibet decreased. The decrease was very significant after the start of the 21th century. The variations were slightly different in different seasons, and the results observed by different remote-sensing satellites were also different. The NOAA data showed that the snow cover decreased during the winter and summer and increased during the spring and fall. The MODIS data showed that the snow cover decreased during the summer, spring, and winter, and only increased during the fall. Our study showed that over the past 14 years, the SCDs and SD decreased primarily in the hinterlands of the Tibetan Plateau, and increased in the southwest and southeast margins of the Tibetan Plateau. Studies based on long time series of observations by ground stations have indicated that the number of SCDs and the SD in Northeast China increased every year (Chen and Li, 2011; Yan et al., 2015; Ke et al., 2016), which is consistent with our results for Northeast China over the past 14 years. The response of snow cover to global climate change has always been a popular topic among researchers in China and abroad. Aided by high-temporal-resolution optical and passive microwave remote-sensing data, researchers can simply and rapidly monitor the dynamic changes of snow cover over long periods of time. Previous studies have indicated that low-elevation regions were susceptible to the influence of precipitation, whereas high-elevation regions were more susceptible to the influence of temperature (Xu et al., 2007). As temperatures rise, precipitation increases, which leads to accelerations of snow melting rates in high-elevation regions and a decrease in the SCA. However, this pattern causes more moisture to participate in the atmospheric water cycle, which increases the precipitation in low-elevation regions and further increases the SCA. Thus, the snow cover increased significantly in South and Northeast China, and increased on the southwest margin and in the southeast region of the Tibetan Plateau, whereas the SCA in the north and northwest parts of the Tibetan Plateau generally decreased. However, Hu et al. (2013) indicated that the snow cover in north Xinjiang exhibited a good negative correlation with temperature but an insignificant correlation with precipitation. Therefore, the snow cover in Xinjiang has decreased overall with global warming.

The paper needs a thorough English edits and I only catch a few below and will do a detailed comments after the first revision. Line13, change “for December : : :” to “from the period of December: : :” L14, change “the snow cover” to “snow cover” L15, change “indicated” to “indicate” L140, by Dr. Huang, should be replace by “by Huang et al. 2014”, L147, change “continent” to “land” L151-157, the equation is not clear, SDsp, what sp means here? The equation only give the annual snow depth for each snow pixel, right? Then make it clear here. figures 4-8, captions, remove the "analysis result maps of the"

Response: Revised based on your comments. Thank you. Author's changes in manuscript: SDsp is the sub-pixel daily SD with a 500 m spatial resolution, SD is the daily SD with a 25 km spatial resolution, SDYi is the average number of SCDs for each MODIS pixel in year i, and SDTi is the sum of the total SCDs for each SD pixel in year i. Other responses to your comments please see the revised manuscript.

New references updated are as follows: Che, T., Dai, L.Y., Zheng, X.M., Li, X.F., Zhao, K.: Estimation of snow depth from MWRI and AMSR-E data in forest regions of Northeast China. Remote Sens. Environ, 183, 334-349, 2016. Dai, L., Che, T., Ding, Y.: Inter-Calibrating SMMR, SSM/I and SSMI/S Data to Improve the Consistency of Snow-Depth Products in China. Remote Sens, 7, 7212-7230, 2015. Dai, L.Y., Che, T., Wang, J., Zhang, P.: Snow depth and snow water equivalent estimation from AMSR-E data based on a priori snow characteristics in Xinjiang, China. Remote Sens. Environ, 127, 14-29, 2012. Hall, D. K., Riggs, G. A., Salomonson, V. V., Digirolamo, N. E., & Bayr, K. J.: MODIS snow-cover products. Remote Sens. Environ, 83(1): 181-194, 2002. Qian, Y. F., Zheng, Y. Q., Zhang, Y., Miao, M. Q.: Responses of China's summer monsoon climate to snow anomaly over the Tibetan Plateau. Int. J. of Climatol., 23, 593-613, 2003. Zhao, P., Zhou, Z. J., Liu, J. P.: Variability of the Tibetan spring snow and its associations with the hemispheric extropical circulation and East Asian summer monsoon rainfall: An observational investigation. J. Climate, 20, 3942-3955, 2007. Ke, C. Q., Li, X. C., Xie, H. J., Ma, D. H., Liu, X., Kou, C.: Variability in snow cover phenology in China from 1952 to 2010. Hydrol. Earth Syst. Sci., 20, 755-770, 2016.

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/tc-2016-124/tc-2016-124-AC1-supplement.pdf

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