Interactive comment on "Spatio-temporal dynamics of snow cover based on multi-source remote sensing data in China" by Xiaodong Huang et al. Anonymous Referee #1

Received and published: 25 July 2016

(1) Comments from Referees: 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 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.

Author's 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:

(2) Comments from Referees: 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?

Author's 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 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 mean snow-covered area (SCA) in China was 11.3% annually and 27% in winter season, with the mean SCA decreasing in summer and winter seasons, in increasing in spring and fall seasons, and no much change annually; (2) the snow-covered days (SCDs) showed increasing in winter, spring, and fall, and annually, whereas decreasing in summer; (3) the average SD decreased in winter, summer, and fall, while increased in spring and annually; (4) the spatial distributions of SD and SCD were highly correlated seasonally and annually; and (5) the regional differences in the variation of snow cover in China were significant. Overall, 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.

(3) Comments from Referees: 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.

Author's 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, and 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 were 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.

(4) Comments from Referees: 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: : :

Author's 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, with mountains, plateaus, and hills accounting for ~67% of the land area, and basins and plains for ~33% (Figure 1). 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 southwest and is known as the “Roof of the World”. Mount Everest is 8844.43 m in height 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 covering a total area of ~4,200,000 km2. This snow cover forms the major freshwater reservoirs for most part of China (Li et al., 1983).

(5) Comments from Referees: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.

Author's 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

(6) Comments from Referees: 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.

Author's Response: A discussion section was added this time.

Author's changes in manuscript:

4 Discussions

Snow cover is widely distributed in China. The results of this study indicated that the average annual SCA did not change significantly. The relative stable snow-covered regions ($60 < SCD \leqslant 350$) in China 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. 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. Same results also found for the relative stable snow-covered regions, whereas the unstable snow-covered regions (SCDs < 60) had large annual variations in the SCA (Wang et al. 2012). Dou et al. (2010) used the MODIS snow cover product to study the Tianshan Mountains in China, and indicated that the snow cover 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 ≥ 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.

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. 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. 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. 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.

(7) Comments from Referees: 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"

Author's Response: Revised based on your comments. Thank you.

Author's changes in manuscript: SD_{sp} is the sub-pixel daily SD with a 500 m spatial resolution, *SD* is the daily SD with a 25 km spatial resolution, SDY_i is the average number of SCDs for each MODIS pixel in year *i*, and SDT_i is the sum of the total SCDs for each SD pixel in year i. Other responses to your comments please see the revised manuscript.

Interactive comment on "Spatio-temporal dynamics of snow cover based on multi-source remote sensing data in China" by Xiaodong Huang et al. Anonymous Referee #2

Received and published: 8 August 2016

(1) Comments from Referees: In this manuscript, a synthesized snow cover product was produced first, which combined optical and passive remote sensing snow cover products. Cloud removal method and downscaling method were developed to retain the advantage of both optical and passive remote sending product, i.e., fine spatial resolution and cloudless, respectively. Then, based on the product, spatiotemporal dynamics of snow cover in China over the past 14 years were carefully analyzed. As a good data is the foundation of a reliable analysis. This synthesized snow cover product is considered of high quality, due to reasonable cloud removal and downscaling method. Also the analyses are well-organized, the results are quite specific. So, this manuscript is considered quite suitable to this journal. But still, some minor revisions are needed.

1. The descriptions of sentences need to be more carefully considered, especially some improper prepositions. In addition, some confused words or sentences are listed below: a) Line 31: "Middle-latitude". Usually we say middle latitude, or mid-latitude, but merely middle-latitude. b) Line 155: "SDi is the 25-km spatial resolution snow depth value in year i". This definition is not clear to me, as I cannot tell if SDi should be a daily result or annual mean result. c) Line 194: "Because some remote sensing data were lost". This sentence is quite confusing, especially with the word "lost". d) Line 268: "(December-February next year". There should be a ")" after "(" .

Author's Response: We are sorry the inconvenience caused to you about our English writing. Some confusing sentences you mentioned were revised. In additional, editorial changes for language usage throughout were also made by a native English scientific editor.

Author's changes in manuscript:

a) High and mid-latitude regions contain abundant snow cover and glacial resources, and they are the source regions for many rivers.
b) where SD_{sp} is the sub-pixel daily SD with a 500 m spatial resolution, *SD* is the daily SD with a 25 km spatial resolution, SDY_i is the average number of SCDs for each MODIS

pixel in year i, and SDT_i is the sum of the total SCDs for each SD pixel in year i.

c) Considering the accuracy of the MODIS snow product (Wang et al., 2015), we classified regions with more than 350 SCDs as permanent snow-covered regions.

d) We used the M-K method to analyze the variation in the number of snow-covered days in the different seasons of winter (December–February next year), spring (March–May), summer (June–August), and fall (September–November) in the grid cells.

(2) Comments from Referees: 2. Some detailed problems in figures. a) Resolution of figures (dpi) should be enhanced, especially the maps. b) In figure titles, when it refers to "average annual", it is suggested to add time duration. Take Figure 3 for example, it is advised to be: ". . . annual average snow depth in China from 2001to 2014".

Author's Response: The resolution of each figure was enhanced by 400 dpi, hope can meet the Journal's requirement. And the time duration of each figure title was also added based on your comments. Thank you so much.

Author's changes in manuscript:

a) Resolution of figures was enhanced with 400 dpi.

b) The time duration added for each figures.

(3) Comments from Referees: 3. There are some strange "missing" words or blanks throughout the manuscript. a) Line 173, Line 177: "at a given significance level " b) Line 233: "(<0) "

Author's Response: The missing words or blanks throughout the manuscript were modified.

Author's changes in manuscript:

a) At a given significance level α, if $|S| \geq S\alpha_{/2}$, the trend of the series is significant; otherwise, it is insignificant.

b) At a given significance level α, we looked up the critical $Z\alpha_{/2}$ in the normal distribution table.

(4) Comments from Referees: 4. There are some leap years during the study period, but it seems that you assumed every year to be 365 days. Explanations are needed.

Author's Response: Among them, the 2004, 2008 and 2012 are leap years. The average SCA refers the mean of 366 days.

Author's changes in manuscript: Fig. 2 summarizes the average annual SCA between 2001 and 2014. Leap years occurred in 2004, 2008 and 2012, so the average SCA refers to the mean of 366 days for these years.

(5) Comments from Referees:5. As you speak highly of the M-K method in analyzing the variation and trend of snow cover data, why you used Sen's median method "to test the accuracy of this result" (Line 230)? Do you have any explanations?

Author's Response: The M-K method can test the variation and trend of the snow cover, but can't examine the slope of the variation of the snow cover. We are sorry about the wrong statement of "to test the accuracy of this result" in the manuscript. The purpose of the Sen's median method used in the paper was to calculate the slope of the variation in the SCD.

Author's changes in manuscript: The results of the M-K variation analysis showed that the annual number of SCDs in South China increased significantly. To further analyze the trend of the SCDs in China over the past 14 years, we calculated the slope of the variation in the annual SCDs using Sen's median method.

(6) Comments from Referees: 6. The long time series of snow depth in China you used in WESTDC have been updated based on the following publications: a) Che, T., Dai, L.Y., Zheng, X.M., Li, X.F., Zhao, K., 2016. Estimation of snow depth from MWRI and AMSR-E data in forest regions of Northeast China. Remote Sensing of Environment 183, 334-349. b) Dai, L., Che, T., Ding, Y., 2015. Inter-Calibrating SMMR, SSM/I and SSMI/S Data to Improve the Consistency of Snow-Depth Products in China. Remote Sensing 7, 7212. c) Dai, L.Y., Che, T., Wang, J., Zhang, P., 2012. Snow depth and snow water equivalent estimation from AMSR-E data based on a priori snow characteristics in Xinjiang, China. Remote Sensing of Environment 127, 14-29.

Author's Response: Updated as your suggestion, thanks a lot.

Author's changes in 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.

Spatio-temporal dynamics of snow cover based on multi-source remote sensing data in China

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Abstract. ~~Through~~ 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~~ snow depth product. The temporal and spatial variations of snow cover from December 2000 to November 2014 in China were analyzed. The results indicate~~d~~ that, over the past 14 years, (1) the mean snow-covered area (SCA) in China was 11.3% annually and 27% in winter season, with the mean SCA decreasing in summer and winter seasons, in increasing in spring and fall seasons,~~The average the summer and winter decreased, whereas the average the spring and fall increased~~ and no much change annually; (2) the snow-covered days (SCDs) showed increasing in winter, spring, and fall, and annually, whereas decreasing in summer; (3) ~~The~~ the average SD decreased in~~the~~ winter, summer, and fall ~~decreased~~, while increased in ~~the average~~ spring and annually; ~~increased~~ (4) ~~The~~ the spatial distributions of SD and SCD were highly correlated seasonally and annually; and ~~the increase and decrease average highly consistent with of the annual~~. (5) ~~The~~ the regional differences in the variation of snow cover in China were significant. Overall, 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

Snow cover is closely related to human lives, and it has ~~two sides~~both positive and negative effects (Liang et al., 2004). High and mid~~dle~~-latitude regions contain abundant snow cover and glacial resources, ~~and they~~which are the source regions for many rivers (Zhang et al., 2002). ~~The fraction of~~ ~~s~~Snowmelt runoff can ~~be~~ make up more than 50% ~~in~~ 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 ~~mainly~~ relies on the melting of snow cover (Pulliainen, 2006; Li, 2001). Winter water ~~deficiency~~ deficiencies can easily cause~~s~~ droughts (Cezar Kongoli et al., 2012). On the other hand, flood disasters caused by melting snow cover ~~melting~~ and snow disasters ~~of~~ such as avalanches, glacial landslides, and snowdrifts are also ~~occur frequently~~common (Gao et al., 2008; Liu et al., 2011;

Shen et al., 2013).

~~Under the background of global warming, the r~~Rising temperatures due to global warming rapidly changes~~s~~ the snow cover conditions in seasonal snow-covered regions, ~~leading~~ 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 le~~a~~d to frequent floods and snow disasters (Lee et al., 2013; Wang et al., 2013). Global warming is an indisputable fact, and rising t~~T~~emperature ~~rise~~ 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 ~~S~~studies have indicated that the snow cover~~s~~ in the alpine regions in China affect~~ed~~ the atmospheric circulation and weather systems in East Asia and further affect~~ed~~ 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 ~~broad~~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 ~~disasters~~ caused by melting snow cover also frequently occur in the spring, severely limit~~ing~~ 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 ~~snow depth~~SD information ~~has important research~~is ~~significance~~ significant for understanding ~~the~~ climate change and the hydrological cycle, conducting water resource surveys, and preventing and forecasting snow disasters in China.

~~In summary, r~~Recent studies of the ~~snow cover~~ distribution and variation of snow cover in China have ~~greatly~~ progressed greatly, but they ~~are~~ have mainly focused on the Tibetan Plateau, Xinjiang, and Northeast China (Chen and Li, 2011). Furthermore, the results ~~observed by~~from different snow cover datasets ~~were~~ are slightly different, and the snow cover variations in different regions ~~were~~ are also different. ~~With high spatial and temporal resolution,~~ 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, ~~optical sensors are~~clouds ~~-~~ strongly interfere~~d~~ with ~~by clouds~~optical sensors. Hence, we cannot directly use ~~the~~ snow cover products acquired by optical sensors to effectively ~~count snow-covered area~~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 ~~snow depth~~SD data to produce a daily cloudless ~~snow-covered area~~SCA product and a downscaled SD product with a 500-m spatial resolution. The integrated daily snow products were used to analyze the temporal and spatial variations ~~characteristics~~ of the snow cover in China ~~in the past 14 years~~ from December 2000 to November 2014 and quantitatively evaluate the variation of SCA, snow-covered days (SCDs), and average SD to provide a ~~the~~ basis for further understanding ~~of~~ the ~~mechanism of~~ interaction between climate and snow cover under the background of globe warming in China.

2 Materials and Methods

2.1 Study area

China has a large area and a large population, with mountains, plateaus, and hills accounting for ~67% of the land area, and basins and plains for ~33% (Figure 1). 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 southwest and is known as the "Roof of the World". Mount Everest is 8844.43 m in height 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 covering a total area of ~4,200,000 km^2. This snow cover forms the major freshwater reservoirs for most part of China (Li et al., 1983).

[37]

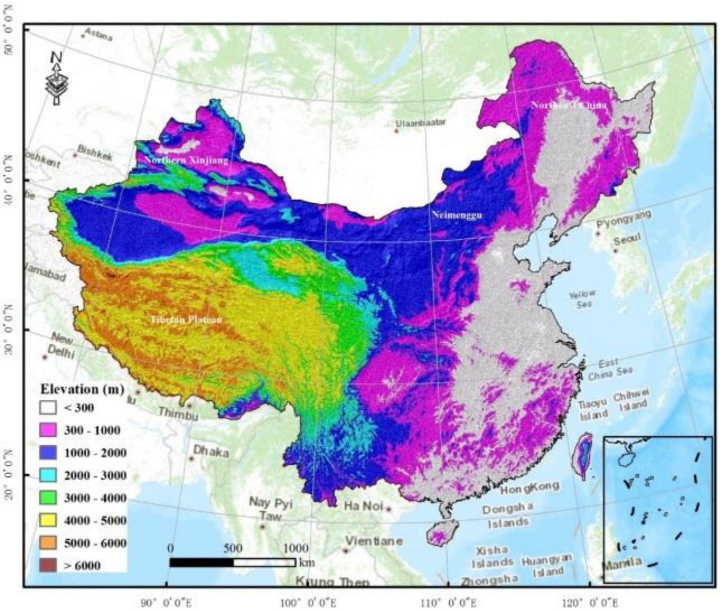

Figure 1: Schematic diagram of the study region.

2.2 Remote sensing snow products

The ~~snow depth~~SD data used in this study were from the 'Environmental and Ecological Science Data Center for West China' (http://westdc.westgis.ac.cn), which is a database with a long time series of ~~snow depth~~SD in China (1979–2014) (Che et al., 2008; 2016; Dai et al., 2012; 2015). It is a daily ~~snow~~

~~depth~~SD database that was ~~inversed~~ inverted using the brightness and temperature data of the ~~passive microwave remote sensing~~Scanning Multichannel Radiometer (SMMR) (1978–1987), Special Sensor Microwave/Imager (SSM/I) (1987–2007), and Special Sensor Microwave Imager/Sounder (SSMI/S) (2008–2014) passive microwave remote sensing instruments. This product is saved in text format. The unit of ~~snow depth~~SD is cm, and the spatial resolution is 25 km. ~~Currently, t~~The database is widely acknowledged and used (Dai et al., 2010; Wang et al., 2013; Bai et al., 2015). The ~~snow-covered area~~SCA product includes the MOD10A1 and MYD10A1 binary snow cover products of the MODIS/Terra and MODIS/Aqua daily V005 version covering China (Hall et al. 2002). The data were taken from the National Snow and Ice Data Center (NSIDC). The spatial resolution is 500 m, and the time period is from December 2000 to November 2014.

2.3 Cloud removal and downscaling algorithms

Following the MODIS cloud removal algorithm developed by Huang et al., (2014), ~~the~~ daily cloudless binary snow cover data were produced for December 2000 to November 2014. The cloud removal algorithm can be summarized in 3 steps: (1) daily snow cover product synthesis: the ~~two snow products of~~ MOD10A1 and MYD10A1 snow products were combined using the maximum SCA fusion method in accordance with the different acquisition times of the Terra and Aqua satellites and the characteristics of cloud movement; (2) adjacent day analysis: the cloud pixels on a given day were replaced with the pixel values on the previous and following days ~~before and after~~ under ~~the~~ cloudless conditions; and (3) combination with the passive microwave ~~snow depth~~SD product: the long time series ~~snow depth~~SD database of China was used to ~~determine~~ identify cloud pixels, completely ~~reclassified~~ reclassify the residual cloud pixels to land or snow pixels, and produce~~d~~ the MODIS daily cloudless binary snow cover images. Based on the downscaling algorithm for the AMSR-E snow water equivalent product by Mhawej et al. (2014), we ~~conducted~~ applied a downscaling algorithm to~~on~~ the passive microwave ~~snow depth~~SD product and built the 500-~~ ~~m spatial resolution ~~snow depth~~SD data ~~in~~ of China ~~from~~for December 2000 to November 2014. The ~~calculation~~ equation is as follows:

$$\begin{cases} \text{if MODIS} = 0 \\ SD_{sp} = 0 \\ \text{else} \\ \text{SDsp} = \frac{SD \times SDY_i \times 2500}{SDT_i}, \end{cases} \tag{1}$$

where SD_{sp} is the sub-pixel daily ~~snow depth~~SD with a 500 m spatial resolution, $SD_{\cancel{i}}$ is the daily ~~snow depth~~SD with a 25 km spatial resolution, SDY_i is the average number of SCDs for each MODIS pixel in year i, and SDT_i is the sum of the total SCDs for each SD pixel in year i.

2.4 Analysis of the snow cover variation

The Mann-Kendall (M-K) method is a nonparametric test method widely used in the analysis of long time series of data (Helsel and Hirsch, 1992). This method monitors the variation of monotonic nonlinear data. It has no requirement for the data distribution, and it can avoid the interference of a few anomalies (Mcbean and Motiee, 2008). This study used the M-K method to analyze the trend and significance level of the SCDs and SD in China at ~~a~~ the pixel scale. For a series $X_\mathrm{i} = (X_1, X_2, \ldots, X_n)$ with n samples, the test process is as follows:

$$Z = \frac{S}{\sqrt{VAR(S)}} \tag{2}$$

where:

$$S = \sum_{i=1}^{n} \sum_{j=i+1}^{n} sgn(X_j - X_i) \tag{3}$$

$$\mathrm{sgn}(X_j - X_i) = \begin{cases} +1, if\,(X_j - X_i) > 0 \\ 0, if\,(X_j - X_i) = 0 \\ -1, if\,(X_j - X_i) < 0 \end{cases} \tag{4}$$

$$\mathrm{VAR}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \tag{5}$$

where n is the year count (n = 14), m is the number of nodes (repetitive data groups) in the series, and t_i is the node width (the number of repetitive data points in the ith repetitive data group).

When n ≤ 10, we directly used the statistic S for the two-sided trend test. S > 0 represents an increase, S = 0 represents no variation, and S < 0 represents a decrease. At a given significance level α, if $|S| \geq S\alpha/_2$, the ~~series~~ trend of the series is significant; otherwise, it is insignificant.

When n > 10, the statistic S approaches the standardized normal distribution. We used the test statistic Z for the two-sided trend test. Z > 0 represents an increase, Z = 0 represents no variation, and Z < 0 represents a decrease. At a given significance level α, we looked up the critical $Z\alpha/_2$ in the normal distribution table. If $|Z| > Z\alpha/_2$, the series trend is significant; if $|Z| \leq Z\alpha/_2$, the trend is insignificant.

Sen's median method was also used to analyze the slope of the variation ~~of~~ in the annual SCDs. This method calculates the ~~slope~~ median slope of n(n-1)/2 pairs of combinations in a series of length n. The ~~calculation~~ equation is:

$$\beta = \mathrm{Median}\left(\frac{x_i - x_j}{i-j}\right), i > j \tag{6}$$

where $\beta > 0$ represents an increase in the trend, and $\beta < 0$ represents a decrease in the trend.

3 Results

3.1 Snow-Covered Area

Fig. ~~1~~ 2 summarizes the ~~annual~~ average annual SCA between ~~in~~ 2001 and ~~-~~ 2014. Leap years occurred in 2004, 2008 and 2012, so the average SCA refers to the mean of 366 days for these years. The results indicated that the average annual ~~snow-covered area~~SCA in China in 2001–2014 constituted 11.3% of the ~~whole~~ entire study region. ~~In the past 14 years, t~~The ~~annual~~ average annual SCA ~~slightly~~ varied slightly over the past 14 years, but ~~it~~ did not ~~show a significant~~ increase or decrease significantly.

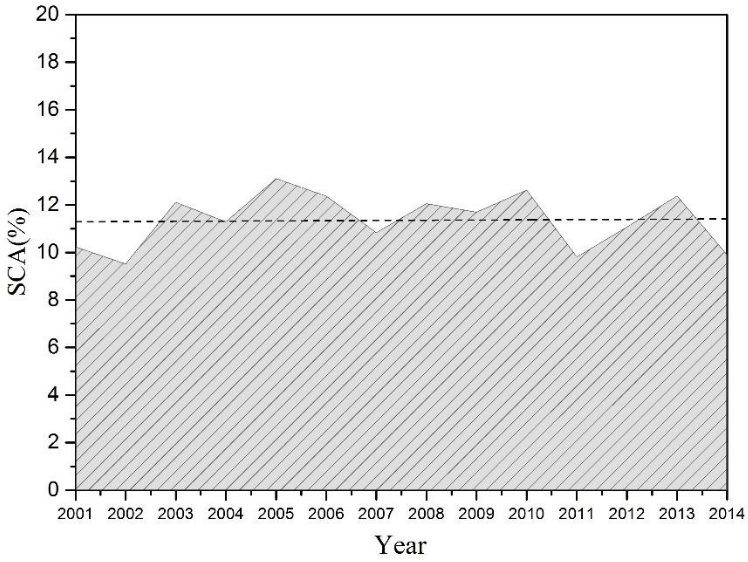

Figure ~~1~~2: ~~nnua~~l ~~average~~ Average annual SCA~~snow-covered area~~ in China between 2001 and 2014.

Fig. ~~2~~ 3 summarizes the average SCA during ~~in~~ each season in China from December 2000 to November 2014. The results indicated that ~~in~~ over the past 14 years, the average SCA in China was approximately 27.0% ~~in~~ during the winter, 10.7% ~~in~~ during the spring, 6.8% ~~in~~ during the fall, and 1.2% ~~in~~ during the summer. The average SCA during the winter and summer decreased and the average SCA in spring and fall increased.

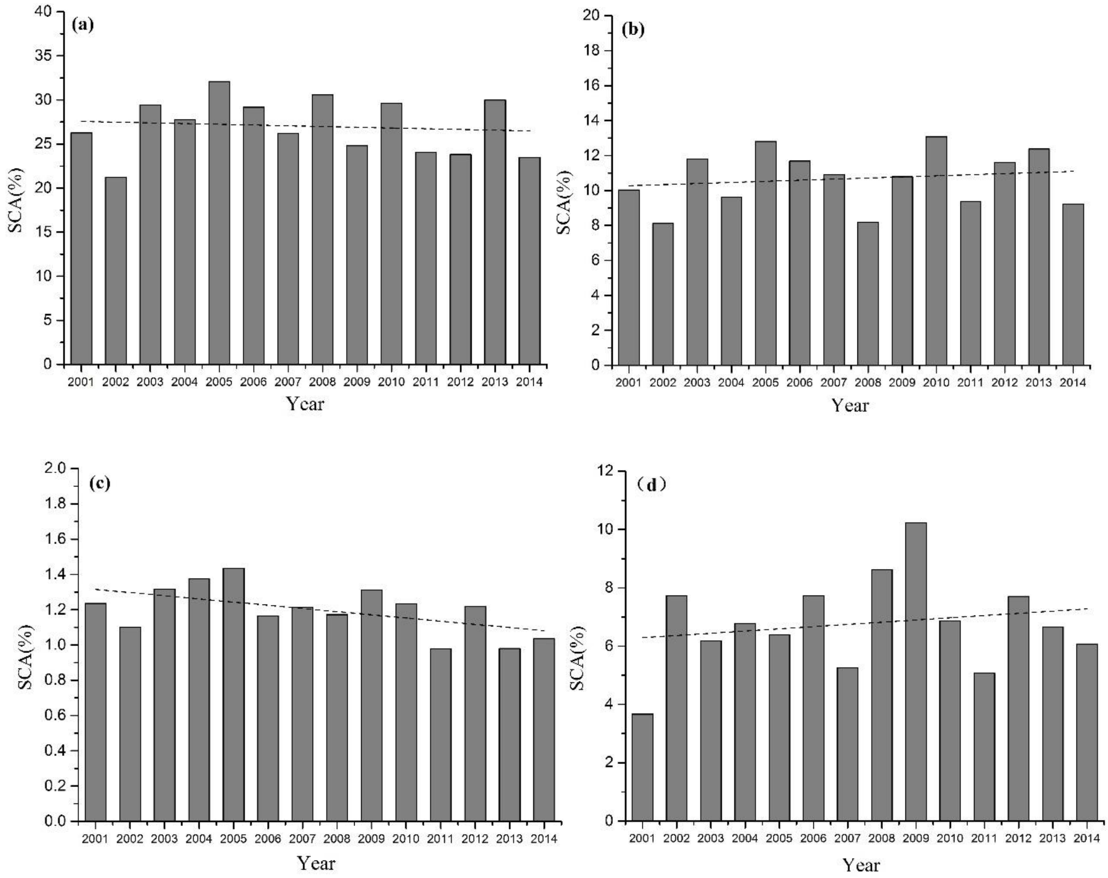

Figure ~~2~~3: Histograms of the average SCA in each season in China from December 2000 to November 2014. (a), (b), (c), and (d) are the average SCA in winter, spring, summer, and fall, respectively.

3.2 Snow-Covered Days

Fig. ~~3~~ 4 shows the spatial distribution of the ~~annual~~ average annual number of ~~snow-covered day~~SCDs ~~in the 14 years~~ from December 2000 to November 2014. ~~As shown in this figure, t~~The transient snow-covered regions with less than 10 annual SCDs ~~annually~~ were distributed primarily in ~~most of the regions in~~ East and South China, the Tarim Basin in Xinjiang, the Badian Jaran Desert in Inner Mongolia, and the Qaidam Basin in the Tibetan Plateau. The unstable snow-covered regions (10 < SCD ≤ 60) were ~~distributed~~ primarily located~~in most of the regions~~ to the north of the Hengduan, Qinling - Taihang and Changbai Mountains in China, in the North China Plain, in some hilly areas in Southeast China, and most regions in the north and west parts of China. The relatively stable snow-covered regions~~ in China~~ (60 < SCD ≤ 350) were ~~distributed~~ primarily located in Northeast China-Inner Mongolia, north Xinjiang, and the high mountains ~~in~~ of the Tibetan Plateau. Considering the accuracy of the MODIS snow product~~some remote sensing data were~~ (Wang et al., 2015), we classified regions with more than 350 ~~snow-covered day~~SCDs as permanent snow-covered regions~~.~~; they~~The~~

~~permanent snow-covered regions~~ were mainly ~~distributed~~ located in the Tienshan Mountains in Xinjiang, the Qilian, Kunlun, Nyainqentanglha, and the Himalaya in the Tibetan Plateau.

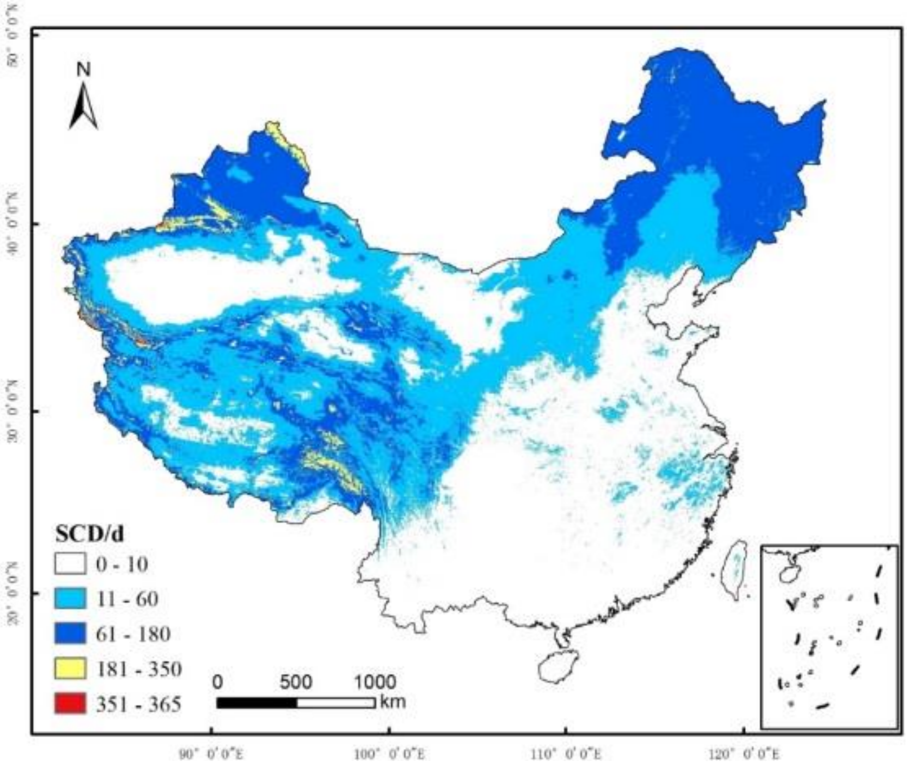

Figure ~~3~~4: Spatial distribution ~~map~~ of the average annual number of snow-covered days during 2001-2014 in China.

The M-K method was used to analyze the variation in the annual number of SCD in China form December 2000 to November 2014 (Fig. ~~4~~5). ~~As shown in the figure, t~~The number of SCDs in China decreased by ~~in~~ 29.2% ~~of the area in China in~~over the past 14 years ($Z < 0$), ~~among~~ for which 6.5% of the area decreased significantly ($p < 0.05$). These regions were ~~mainly distributed~~ primarily located in the Tienshan Mountains in Xinjiang and most of ~~the regions in~~ the Tibetan Plateau. The regions with increasing numbers of SCDs ~~constituted~~ represented 34.5% of ~~the whole~~ China ~~area~~ ($Z > 0$), ~~among~~ of which 10.8% of the area increased significantly ($p < 0.05$). These regions were mainly ~~distributed~~ located in the Great Khingan Mountains, Lesser Khinan Mountains, and Changbai Mountains in the northeast part of the country and ~~in~~ most regions ~~in~~ of South China.

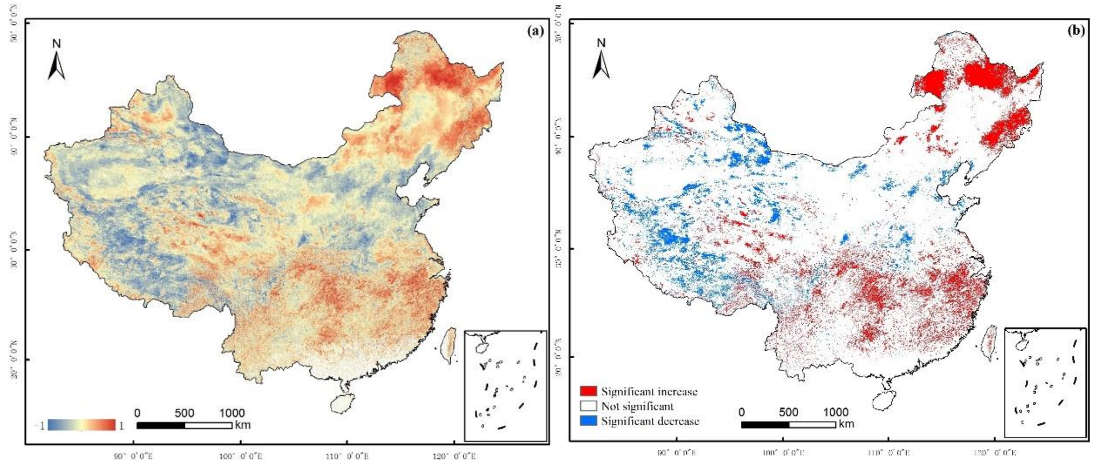

Figure ~~4~~5: Variation in the average annual SCDs in China based on the Mann-Kendall method from 2001-2014. (a) ~~The v~~Variation in the annual SCDs; (b) ~~the~~ significance of the variation in the annual SCDs.

The M-K method was also used to analyze the variation in SCDs ~~in~~ during the ~~different seasons of~~ winter (December–February ~~next year~~), spring (March–May), summer (June–August), and fall (September–November) in the grid cells (Fig. ~~5~~6). The results indicated that ~~in~~ over the past 14 years, the regions with significantly decreased numbers of winter SCDs ~~in China constituted~~represented 5.7% of the ~~whole~~ area of China ~~area~~, whereas the areas with significant increases ~~constituted~~ made up 7.2% of the study region (Fig. ~~5~~6(a)). The regions with significantly decreased spring SCDs ~~in China~~ constituted 4.0% of ~~the whole~~ China ~~area~~, whereas the regions with significant increases ~~constituted~~ represented 6.2% (Fig. ~~5~~6(b)). The regions with significantly decreased summer SCDs ~~in China constituted~~made up 3% of ~~the whole~~ China ~~area~~, whereas the regions with significant increases constituted 2.9% (Fig. ~~5~~6(c)). The regions with significantly decreased fall SCDs ~~in China~~ constituted 1.8% of ~~the whole~~ China ~~area~~, whereas the regions with significant increases constituted 5.7% (Fig. ~~5~~6(d)). The results indicated that ~~in~~ over the past 14 years, the summer SCDs ~~in China~~ decreased, whereas the SCDs ~~in~~ during the winter, spring, and fall ~~seasons~~ all increased. The spatial distributions of the increases and decreases in SCDs ~~in~~ during each season ~~in China~~ were highly consistent. Specifically, the winter SCDs in South China increased, the SCDs in Northeast China increased during ~~in~~ all of the seasons ~~increased~~, and the SCDs in the Xinjiang regions mainly decreased. The SCDs ~~in~~ on the southwest margin of the Tibetan Plateau and the southeast region increased, whereas those in the north and northwest mainly decreased.

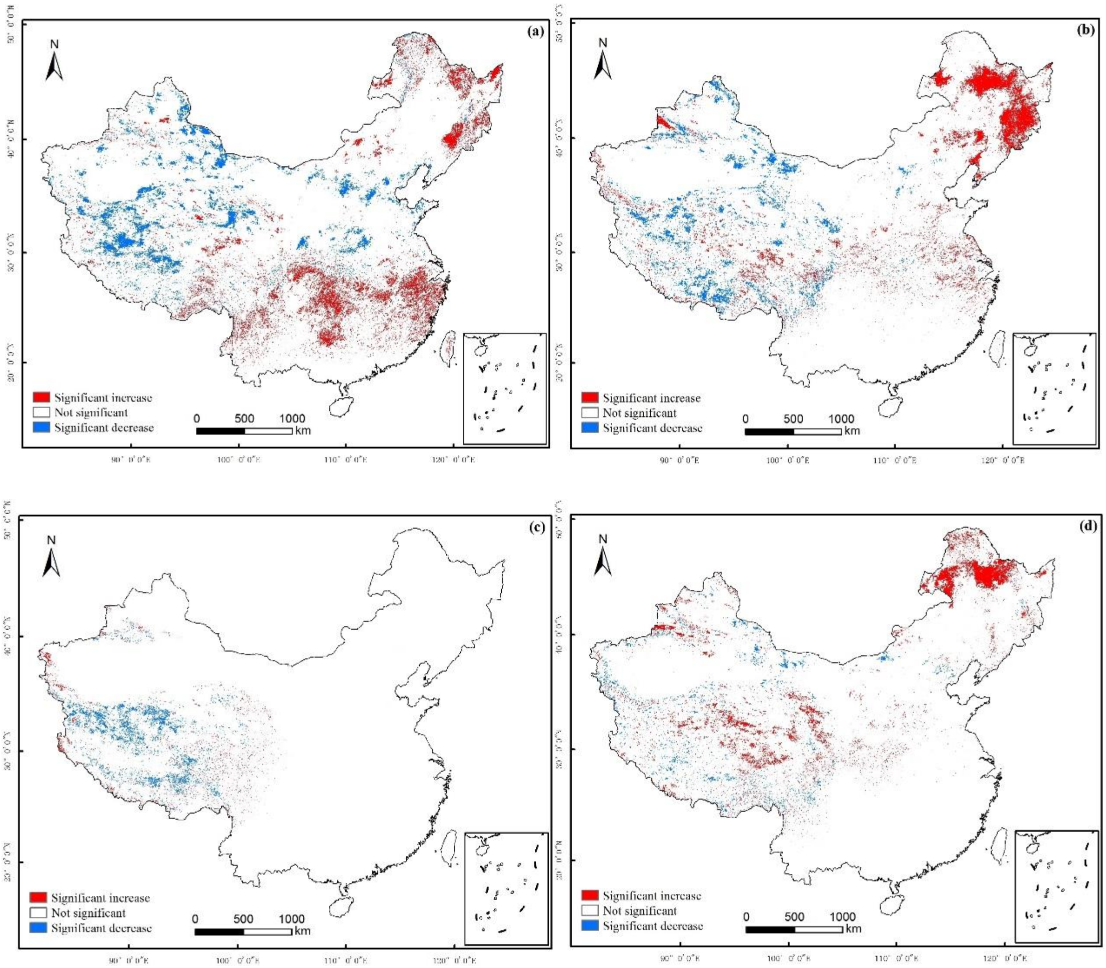

Figure ~~5~~6: ~~Analysis result maps of the v~~Variation in the number of ~~snow-covered day~~SCDs ~~in~~ during each season in China based on the Mann-Kendall method from 2001to 2014. (a), (b), (c) and (d) ~~are~~ show the significance of the variation in the number of ~~snow-covered day~~SCDs ~~in~~ during the winter, spring, summer, and fall, respectively.

The results of the M-K variation analysis ~~results~~ showed that the annual number of ~~snow-covered day~~SCDs in South China increased significantly. To further analyze the trend of the SCDs in China over the past 14 years, we calculated the slope of the variation in the annual SCDs using Sen's median method (Fig. ~~6~~7). The results indicated that the annual number of SCDs decreased ~~in~~ over approximately 22.1% of ~~the area in~~ China ($\beta < 0$), and ~~it~~ increased ~~in~~ over 23.5% of ~~the area~~China ($\beta > 0$). ~~Among these, t~~The rate of decrease in the annual SCDs was less than 2 d/year ~~in~~ over 18.5% of the area, which was sparsely distributed in Xinjiang, the Tibetan Plateau, and North China. The rate of decrease in some regions ~~in~~ of the Tibetan Plateau ~~was more than~~exceeded 6 d/year. The rate of increase in the annual SCDs was less than 2 d/year in 18.3% of the area, which was mainly distributed in South China, Northeast China, central northern Xinjiang, and the southeast Tibetan Plateau. The regions with rates of increase of more than 6 d/year were sparsely distributed in Northeast China and the southeast Tibetan Plateau. The results from Sen's median method were highly consistent with the results from the Mann-Kendall method, especially in terms of the spatial distribution of the variations. Because the regions in Southeast China ~~regions~~ were mainly transient snow-covered regions, and the main relatively stable snow-covered regions were ~~Northeast China, the low elevation regions~~located in north Xinjiang, in Northeast China, and the Tibetan Plateau~~ were the main stable snow-covered regions~~, the variation in the number of SCDs indicated that the annual SCDs in China increased overall (Figs. ~~4~~ 5 and ~~6~~7). However, the decreases in the SCDs in the Tibetan Plateau and the Tienshan Mountains in Xinjiang, which ~~are at~~have high elevations, ~~the decreasing trend in was~~were significant.

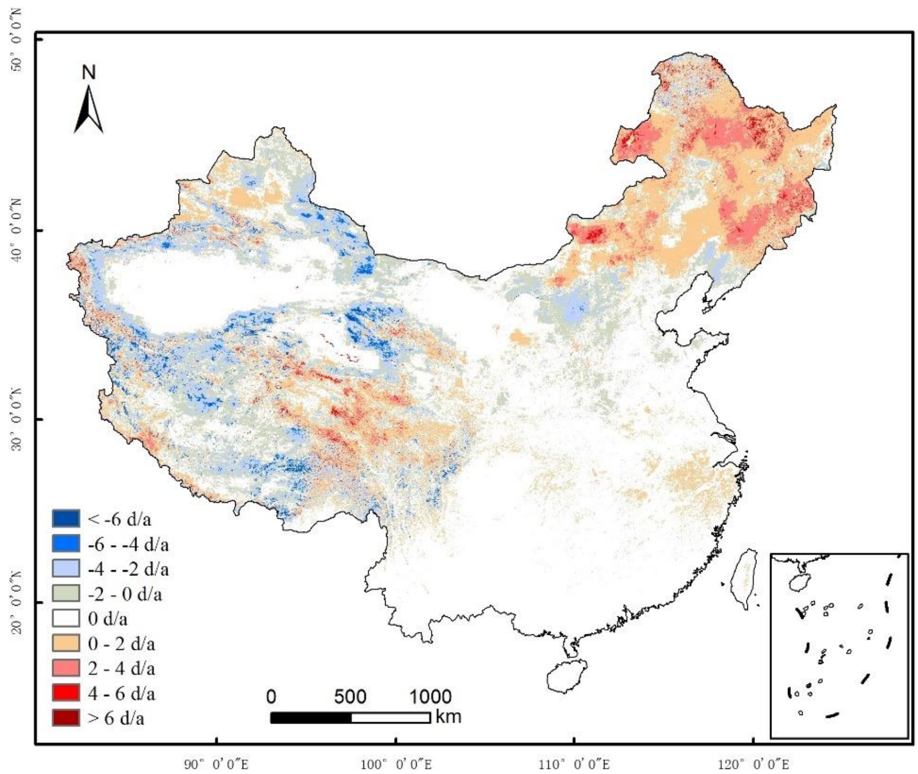

Figure ~~5~~7: Variation slope of the average annual number of SCD in China based on Sen's median method during the period of 2001-2014.

3.3 Snow Depth

~~Snow depth~~SD is a key factor that reflect~~ing~~ the ~~condition~~ variation of the surface snow cover ~~variation.~~ ~~It~~and has important hydrological, climate, and ecological significance. Fig. ~~6~~ 8 shows the spatial distribution of the average SD ~~for~~ from December 2000 to November 2014~~, which~~. The average SD was calculated by dividing the sum of the SD ~~are divided~~ by the total number of days. ~~As shown in this figure, t~~The spatial distributions of the average SD and SCDs in China were highly consistent. The regions with high values of the average SD ~~in China~~ were mainly distributed in the Great Khingan Mountains and Lesser Khinan Mountains in Northeast China, the Altai and Tienshan Mountains in Xinjiang, and the Kunlun and Nyainqentanglha Mountains in the Tibetan Plateau. The multi-year average SD ~~were more~~was greater than 7 cm. ~~Overall, e~~Except for ~~the special case of~~ the Tibetan Plateau, the ~~overall~~ SD generally ~~in China~~ increased with increasing latitude and elevation. However, because of the limited capability of passive microwave data to detect shallow snow and wet snow, the data did not capture any snowfall information in most regions in South China. Therefore, it is ~~very~~ necessary to combine optical and passive microwave data to improve the accuracy of snow cover monitoring.

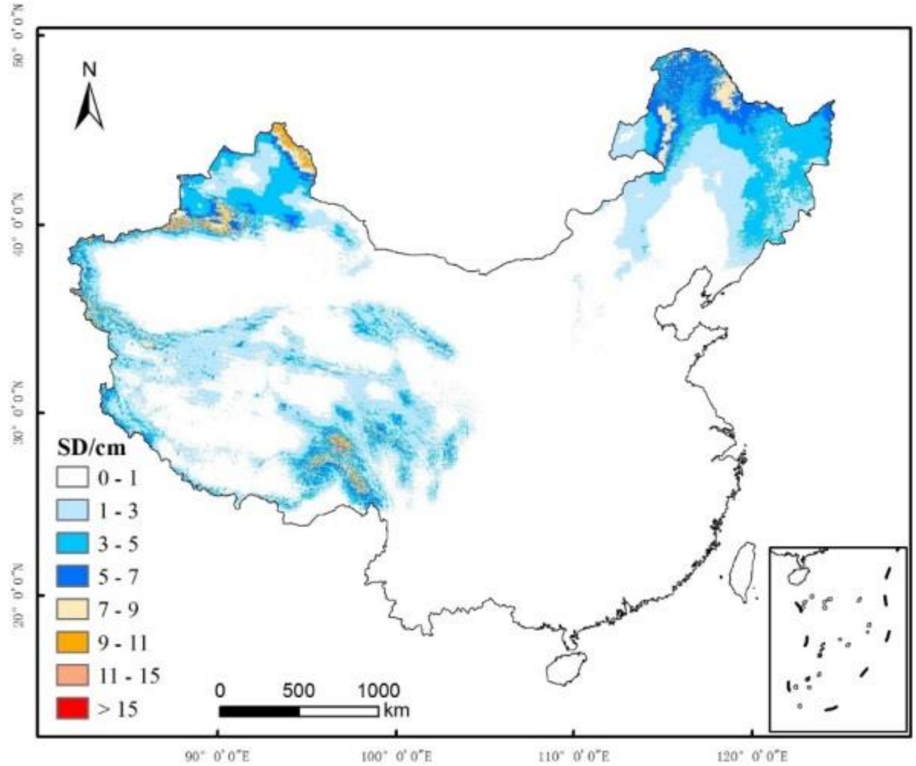

Figure ~~6~~8: Spatial distribution ~~map~~ of the ~~annual~~ average annual snow depth in China from December 2000 to November 2014.

Fig. ~~7~~ 9 summarizes the spatial variation ~~characteristics~~ of the ~~annual~~ average annual SD in China from December 2000 to November 2014. ~~It can be seen that t~~The variations in the SD and the SCDs were highly spatially consistent. The regions with decreasing ~~annual~~ average annual SD ~~constituted~~ covered 11% of ~~the area of~~ China, ~~among which~~and the ~~annual~~ average annual SD significantly decreased in 3.3% of the China ($p < 0.05$), ~~which was mainly distributed~~primarily in most regions ~~in~~ of north Xinjiang and the north Tibetan Plateau. ~~In~~ A total, ~~–~~ of 22.4% of the area showed an increase tendency, ~~among~~

~~which~~and significant increases were observed in 8.5% of the area ($p < 0.05$), which was mainly distributed in Northeast China, the Tienshan and Altai Mountains in Xinjiang, the south Tibetan Plateau, and the Kunlun Mountains.

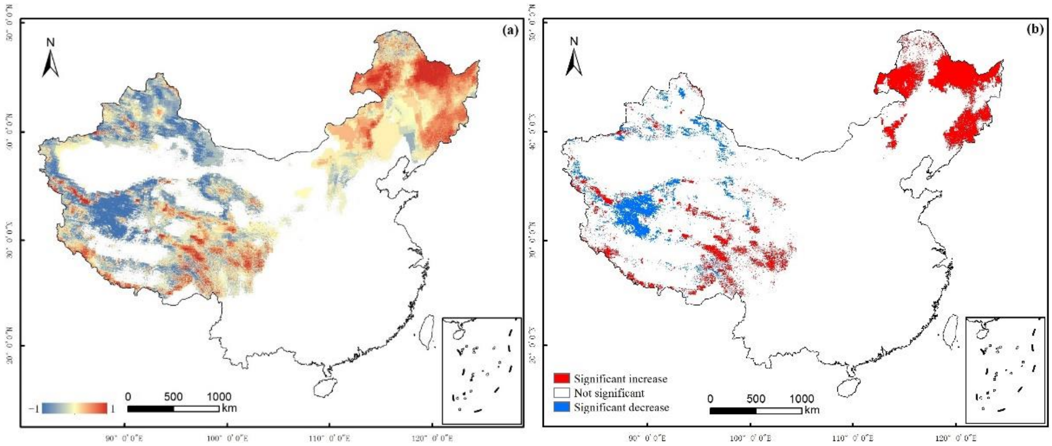

Figure ~~7~~9: Variation in the ~~annual~~ average annual ~~snow depth~~SD in China based on the Mann-Kendall method between 2001 and 2014. (a) Variation in the~~The~~ ~~annual~~ average annual ~~snow depth variation~~SD; (b)~~the~~ significance of the variation in the ~~annual~~ average annual ~~snow depth~~SD~~variation~~.

~~In~~ Over the past 14 years, the regions with significantly decreased winter SD ~~constituted~~ made up 10.6% ~~of the area~~ of China, whereas the regions with significant increases constituted 9.3% (Fig. ~~8~~10(a)). The regions with significantly decreased spring SD constituted 7.9% of the area of China, whereas the regions with significant increases ~~constituted~~ made up 9.8% (Fig. ~~8~~10(b)). The regions with significantly decreased summer SD ~~constituted~~ made up 1.9% of~~the area of~~ China, whereas the regions with significant increases constituted 0.9% (Fig. ~~8~~10(c)). The regions with significantly decreased fall SD ~~constituted~~ represented 7.8% of the area of China, whereas the regions with significant increases only ~~constituted~~ made up 1.8% (Fig. ~~8~~10(d)). ~~Overall, t~~The regions with significantly increased and decreased average SD ~~in~~ during the winter and spring ~~in China~~ were ~~essentially the same~~similar. The regions with increased SD were mainly concentrated in Northeast China and the high mountains ~~in~~ of the Tibetan Plateau, whereas the regions with decreased SD were ~~distributed~~ primarily located in the hinterlands of Xinjiang and the Tibetan Plateau. The ~~snow depth~~SD during the ~~in~~ fall and summer mainly decreased, and the regions with decreasing ~~snow depth~~SD were mainly distributed in Xinjiang and the Tibetan Plateau.

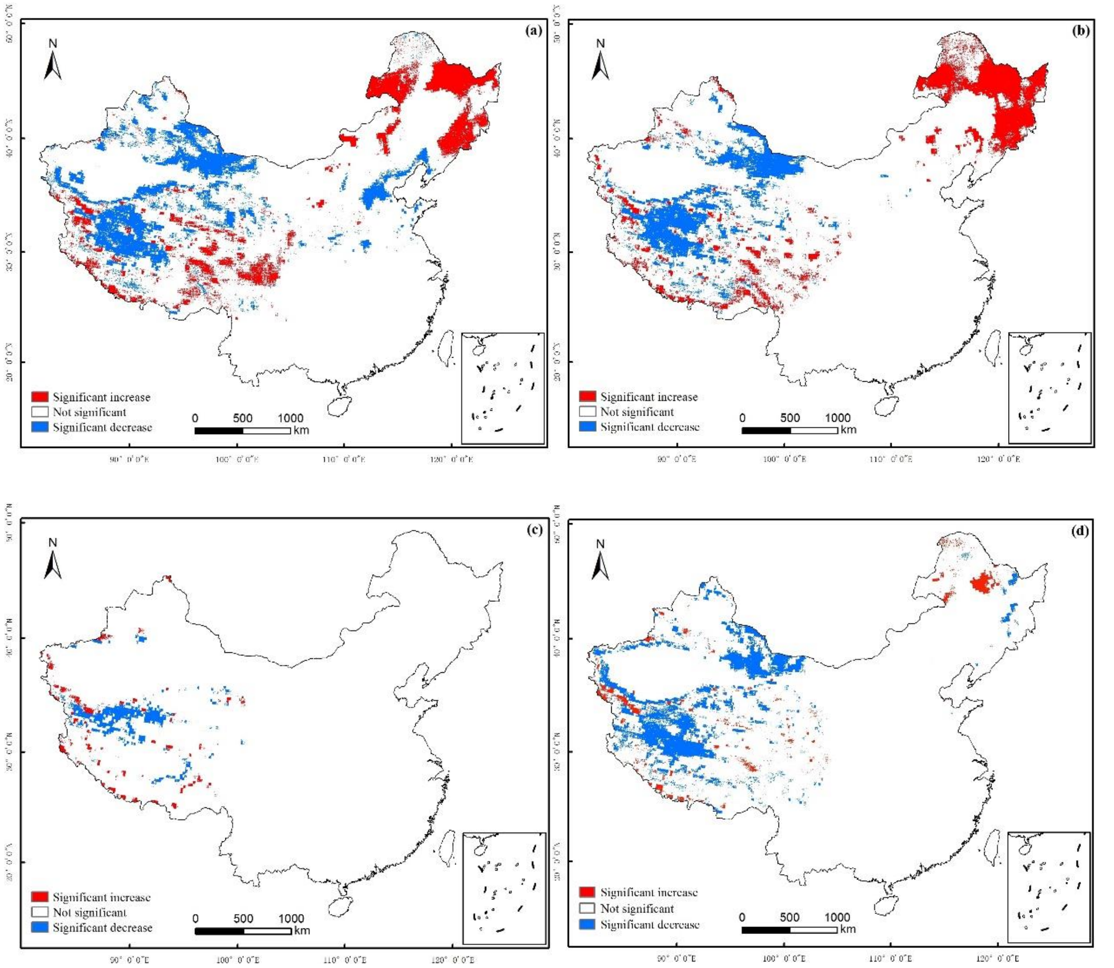

Figure ~~8~~10: Variation in the average SD during ~~in~~ each season in China based on the M-K method from 2001to 2014. (a), (b), (c), and (d) ~~are~~ show the significance of the variations ~~in~~ during the winter, spring, summer, and fall, respectively.

4 Discussion

Snow cover is widely distributed in China. The results of this study indicated that the average annual SCA did not change significantly. The relative stable snow-covered regions ($60 < SCD \leq 350$) in China 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. 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. Same results also found for the relative stable snow-covered regions, whereas the unstable snow-covered regions (SCDs < 60) had large annual variations in the SCA (Wang et al. 2012). Dou et al. (2010) used the MODIS snow cover product to study the Tianshan Mountains in China, and indicated that the snow cover 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 ≥ 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.

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. 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. 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. 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.

5 Conclusion

~~The distribution of SCA in China is broad. Snow cover has very important effects on the climate in China and the production activities of humans. Global climate change rapidly changes the snow cover conditions in China. The deficiencies of optical remote-sensing products and passive microwave products greatly affect the accuracy of snow cover monitoring. Therefore, this study first used the MODIS daily binary snow cover products MOD10A1 and MYD10A1 to produce a daily cloudless~~

~~snow cover product in China from December 2000 to November 2014. We then combined the daily cloudless snow cover product with the long time series of snow depth data in China, and we obtained a snow depth product with a 500-m spatial resolution after downscaling. We used the synthesized product to systematically~~In this study, we used the daily cloudless snow cover and snow depth products both at 500 m pixel size to investigate the variations~~ dynamics~~ of the ~~snow ~~snow-covered area (SCA), snow covered days (SCDs) and snow depth (SD) in China from December 2000 to November 2014. The important results are summarized below:

(1) The perennial average annual SCA in China was 11.3% over the entire year and 27.0% during the winter for2001–2014. The average SCA decreased during the winter and summer, and increased during the spring and fall. The average annual SCA varied slightly, but did not increase or decrease significantly.

(2) The transient snow cover in China was mainly ~~occurred~~ located in East and Southeast China and some regions ~~in~~ of Xinjiang and Inner Mongolia, whereas the unstable snow-covered regions were distributed in most of the northern and western regions in China. The stable snow-covered regions were mainly ~~distributed~~ located in Northeast China-Inner Mongolia, north Xinjiang, and the Tibetan Plateau. The west Tienshan Mountains in Xinjiang and the mountainous areas of~~in~~ the Tibetan Plateau were the main regions~~ in China~~ with permanent snow cover.

(3) The summer SCDs in China decreased, whereas the SCDs increased duirng the winter, spring, and fall. Specifically, the winter SCDs in South China increased, the SCDs in Northeast China increased during all of the seasons, and the SCDs in the Xinjiang regions mainly decreased. Overall, the SCDs increased during 2001-2014 in China.

(4) The spatial distribution of the variation in the average SD was highly consistent with that ~~in~~ of the SCDs. ~~Furthermore, t~~The spatial distributions of the amounts of increase and decrease in the snow cover ~~in~~ during each season were also highly consistent. However, the regional differences in the increases in the ~~annual~~ average annual SCDs and average SD were significant. The regions with increasing SCDs and SD were mainly ~~distributed~~ located in Northeast China, whereas the Tibetan Plateau and Xinjiang were the main regions with decrease.

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41471291).

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