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

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Abstract. Through combining optical remote sensing snow cover products with passive microwave remote-sensing snow depth data, we produced a MODIS cloudless binary snow cover product and a 500-m spatial resolution snow depth product for December 2000 to November 2014. We used the synthesized products to analyze the temporal and spatial variation of the snow cover in China. The results indicated that in the past 14 years, the overall annual number of snow-covered days and average snow depth in China increased. The annual average snow-covered area did not change significantly, and the number of snow-covered days in summer in China decreased. The number of snow-covered days in the winter, spring, and fall seasons all increased. The average snow-covered area in the summer and winter seasons decreased, whereas the average snow-covered area in the spring and fall seasons increased. The average snow depth in the winter, summer, and fall seasons decreased. Only the average snow depth in spring increased. The spatial distribution of the increase and decrease in the annual average snow depth was highly consistent with that of the annual number of snow-covered days. The spatial distributions of the variation of the number of snow-covered days and the average snow depth of each season were also highly consistent. The regional differences in the snow cover variation in China were significant. The snow cover increased significantly in South and Northeast China, decreased significantly in Xinjiang, increased in the southwest edge and southeast of the Tibetan Plateau, and mainly decreased in the north and northwest regions of the plateau.

1 Introduction

Snow cover is closely related to human lives, and it has two sides (Liang et al., 2004). High and middle-latitude regions contain abundant snow cover and glacial resources, and they are the source regions for many rivers (Zhang et al., 2002). The fraction of snowmelt runoff can be more than 50% in 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 easily causes droughts (Cezar Kongoli et al., 2012). On the other hand, flood disasters caused by snow cover melting and snow disasters of avalanches, glacial landslides, and snowdrifts also occur frequently (Gao et al., 2008; Liu et al., 2011; Shen et al., 2013).

Under the background of global warming, the rising temperature rapidly changes the snow cover conditions in seasonal snow-covered regions, leading to accelerated melting of most ice sheets and permanent snow covers (Yao et al., 2012), increasing snowline elevation (Chen, 2014), decreasing wetland area, and reallocation of precipitation, which further lead to frequent floods and snow disasters (Lee et al., 2013; Wang et al., 2013). Global warming is an indisputable fact. Temperature 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). Studies have indicated that the snow covers in the alpine regions in China affected the atmospheric circulation and weather systems in East Asia and further affected the climate in China. Alpine snow cover has important implications for hydrology, climate, and the ecological environment (Chen and Liu, 2000; Hahn and Shula, 1976).

The response of snow cover to global climate change has always been a hot 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 change of snow cover over long time series. Snow cover is widely distributed in China. Researchers have conducted numerous studies on the variation in the snow cover in China using remote-sensing snow cover data from various satellites. 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 in 2001–2010 and analyzed the characteristics of the seasonal and annual snow cover variation. The results indicated that the snow cover stabilities in the three major snow-covered regions were Xingjiang > Northeast China-Inner Mongolia > Tibetan Plateau. The stable snow-covered area in China did not change significantly. Che et al. (2005) used the snow depth data inversed from SSM/I passive microwave data to analyze the snow cover distribution and variation in China for 1993–2002. The results indicated that the snow cover reservoir in China did not significantly increase or decrease in that ten-year period. The winter snow cover reservoir was mainly distributed in the three major stable snow-covered regions of Xinjiang, the Tibetan Plateau, and Northeast China. The study by Dai et al. (2010) indicated that in the 28 years of 1978–2005, the number of snow-covered days and the snow depth in China increased. The western Tibetan Plateau was a sensitive region with an abnormal variation in the number of snow-covered days, whereas north Xinjiang, the mountainous regions in Northeast China and the east-central Tibetan Plateau were sensitive regions with abnormal snow depth variation. Wang et al. (2012) used combined MODIS and AMSR-E data to obtain a cloudless snow cover product, and they analyzed the temporal and spatial distribution characteristics of the snow covers in the arid regions in China for 2002–2009. The study indicated that the snow-covered area in the stable snow-covered regions did not change significantly, whereas the annual variation in the snow-covered area of the unstable snow-covered regions was large. Dou et al. (2010) used the MODIS snow cover product to study the Tianshan Mountains in China, and they indicated that the snow-covered area in the Tianshan Mountains slightly increased; the increase

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was especially significant in winter. Furthermore, the snow cover decreased in the regions at ≥ 4000 m elevation and increased in the regions at < 4000 m elevation. The study by Basang et al. (2012) on the snow cover variation in Tibet indicated that in the nearly 30 year period of 1980–2009, the number of snow-covered days and maximum snow depth in Tibet decreased overall. The decrease was very significant after entering the 21th century. The variations in different seasons were slightly different, and the results observed by remote-sensing by different satellites were also different. The NOAA data showed that the snow cover decreased in winter and summer and increased in spring and fall. The MODIS data showed that the snow cover in the summer, spring, and winter seasons all decreased, and only the snow cover in fall increased. Wang et al. (2014) used the MODIS cloudless synthesized snow cover product to further study the Tibetan Plateau, and they showed that the maximum number of snow-covered days and the perennial snow cover in the plateau region decreased, the snow-covered area increased, and the variation in temperature and precipitation significantly affected the plateau snow cover. The study by Zhang et al. (2010) of Northeast China in 2000–2009 indicated that the average snow depth in Northeast China decreased. However, studies based on long time series of observations by ground stations indicated that the number of snow-covered days and the snow depth in Northeast China increased every year (Chen and Li, 2011; Yan et al., 2015).

In summary, recent studies of the snow cover distribution and variation in China have greatly progressed, but they are mainly focused on the Tibetan Plateau, Xinjiang, and Northeast China (Chen and Li, 2011). Furthermore, the results observed by different snow cover datasets were slightly different, and the snow cover variations in different regions were also different. With high spatial and temporal resolution, MODIS data have been widely used in the remote sensing fields of ecology, atmospheric science, and hydrology. However, optical sensors are strongly interfered with by clouds. Hence, we cannot directly use the snow cover products acquired by optical sensors to effectively count snow-covered area. 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 data to produce a daily cloudless snow-covered area product and a downscaled snow depth product with 500-m spatial resolution. We studied the temporal and spatial variation characteristics of the snow cover in China in the past 14 years from December 2000 to November 2014. We quantitatively analyzed the temporal and spatial variation characteristics of the number of snow-covered days, average snow depth, and snow-covered area. We revealed the variation of the snow cover in China under the background of climate change, and we provided the basis for further understanding of the mechanism of interaction between climate change and the temporal and spatial variation of the snow cover in China.

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2 Materials and Methods

2.1 Study area

China is broad, 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 (Fig. 1). Winter and spring snowfalls are the major water resource in north Xinjiang and the Tibetan Plateau (Pei et al., 2008; Chen et al., 1991; Wang et al., 2014). Large snowfall amounts can also cause severe snow disasters and large numbers of livestock deaths (Liu et al., 2008; Chen et al., 1996). Flood disasters caused by melting snow cover also frequently occur in spring, severely limiting the development of grassland animal husbandry and the safety of human lives (Shen et al., 2013). Therefore, accurate acquisition of snow-covered area and snow depth information has important research significance for understanding the climate change and hydrological cycle, conducting water resource surveys, and preventing and forecasting snow disasters in China.

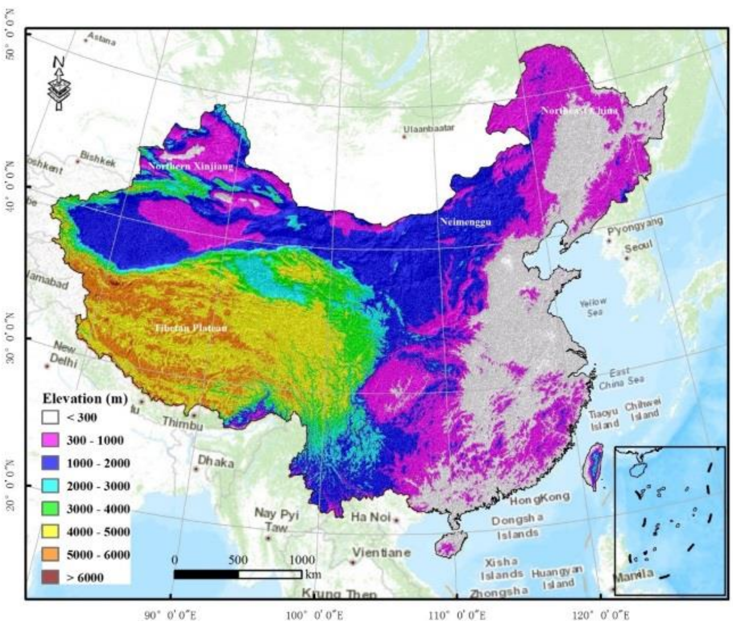

Figure 1: Schematic diagram of the study region

2.2 Remote sensing snow products

The snow depth data used in this study were from the 'Environmental and Ecological Science Data Center for West China' (http://westdc.westgis.ac.cn), a database with a long time series of snow depth in China (1979–2014) developed by Dr. Che (Che, 2008). It is a daily snow depth database inversed using the brightness and temperature data of the passive microwave remote sensing SMMR (1978–1987), SSM/I (1987–2007), and SSMI/S (2008–2014). This product is saved in text format. The unit of snow depth is cm, and the spatial resolution is 25 km. Currently, the database is widely acknowledged and used (Dai et al., 2010; Wang et al., 2013; Bai et al., 2015). The snow-covered area product includes the MOD10A1 and MYD10A1 binary snow cover products of the MODIS/Terra and MODIS/Aqua daily V005 version covering China. The data were from 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 Dr. Huang, we produced the daily cloudless binary snow cover data for December 2000 to November 2014 (Huang et al., 2014). The cloud removal algorithm can be summarized in 3 steps: (1) daily snow cover product synthesis: we combined the two products of MODIS/Terra and MODIS/Aqua; (2) adjacent day analysis: we replaced the cloud pixel on a given day with the pixel values on the days before and after under the cloudless condition; and (3) combination with the passive microwave snow depth product: we used the long time series snow depth database of China to determine cloud pixels, completely reclassified the residual cloud pixels to continent or snow-cover pixels, and produced 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 a downscaling calculation on the passive microwave snow depth product and built the 500-m spatial resolution snow depth data in China from December 2000 to November 2014. The calculation equation is as following Eq. (1):

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

where SD_{sp} is the 500-m spatial resolution snow depth value, SD_i is the 25-km spatial resolution snow depth value in year i, SDY_i is the 500-m spatial resolution annual number of snow-covered days in year i calculated from the MODIS binary snow cover product, and SDT_i is the sum of the annual number of

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snow-covered days of the 2500 MODIS pixels within a 25-km range 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 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 number of snow-covered days and snow depth in the study region at a pixel scale. For a series $X_i = (X_1, X_2, \ldots, X_n)$ with n samples, the test process is as follows:

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

where:

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

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

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

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 , if $|S| \geq S\alpha_{/2}$, the series trend 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 , 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.

We also used Sen's median method to analyze the slope of the variation of the annual number of snow-covered days. This method calculates the slope median of n(n-1)/2 pairs of combinations in a series of length n. The calculation equation is

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

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where β > 0 represents an increase in the trend, and β < 0 represents a decrease in the trend.

3 Results and discussion

3.1 The spatial distribution of the snow cover in China

Fig. 2 shows the spatial distribution of the annual average number of snow-covered days in the 14 years from December 2000 to November 2014. As shown in this figure, the transient snow-covered regions with less than 10 snow-covered days annually were mainly distributed 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 ($10 < SCD \leq 60$) were mainly distributed in most of the regions to the north of the Hengduan, Qinling - Taihang and Changbai Mountains in China, the North China Plain, some hilly areas in South China, and most regions in the north and west. The stable snow-covered regions in China ($60 < SCD \leq 350$) were mainly distributed in Northeast China-Inner Mongolia, north Xinjiang, and the high mountains in the Tibetan Plateau. Because some remote sensing data were lost (Wang et al., 2014), we classified regions with more than 350 snow-covered days as permanent snow-covered regions. The permanent snow-covered regions were mainly distributed in the Tienshan Mountains in Xinjiang and the Qilian, Kunlun, Tanggula, and Nyainqentanglha Mountains and the Himalayas in the Tibetan Plateau.

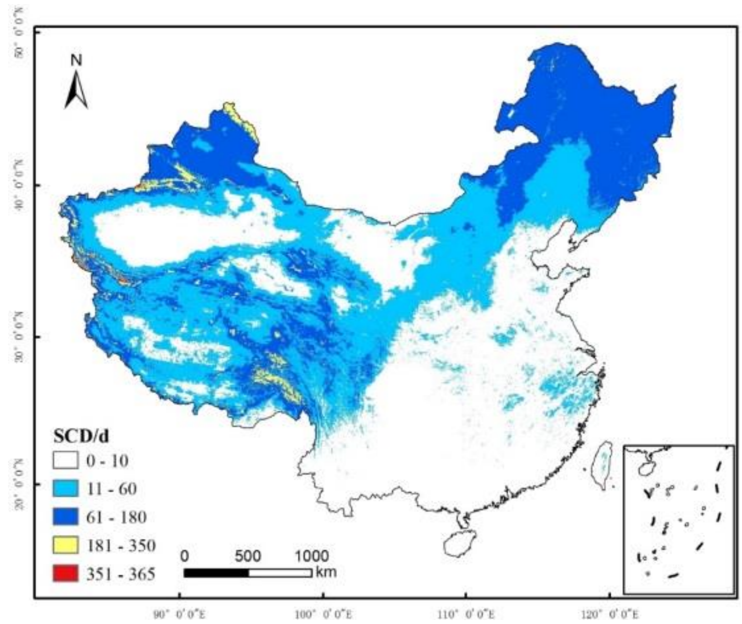

Figure 2: Spatial distribution map of the average annual number of snow-covered days in China

Fig. 3 shows the spatial distribution of the average snow depth (SD) for December 2000 to November 2014, which calculated by snow depth sum are divided by total number of days. As shown in this figure, the spatial distributions of the average snow depth and number of snow-covered days in China were highly consistent. The regions with high values of average snow depth in China were mainly distributed in the Great Khingan Mountain and Lesser Khinan Mountain in Northeast China, the Altai and Tienshan Mountains in Xinjiang, and the Kunlun and Nyainqentanglha Mountains in the Tibetan Plateau. The multi-year average snow depth values were more than 7 cm. Overall, except for the special case of the Tibetan Plateau, the overall snow depth in China increased with increasing latitude and elevation, and the number of snow-covered days and snow depth also increased. 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.

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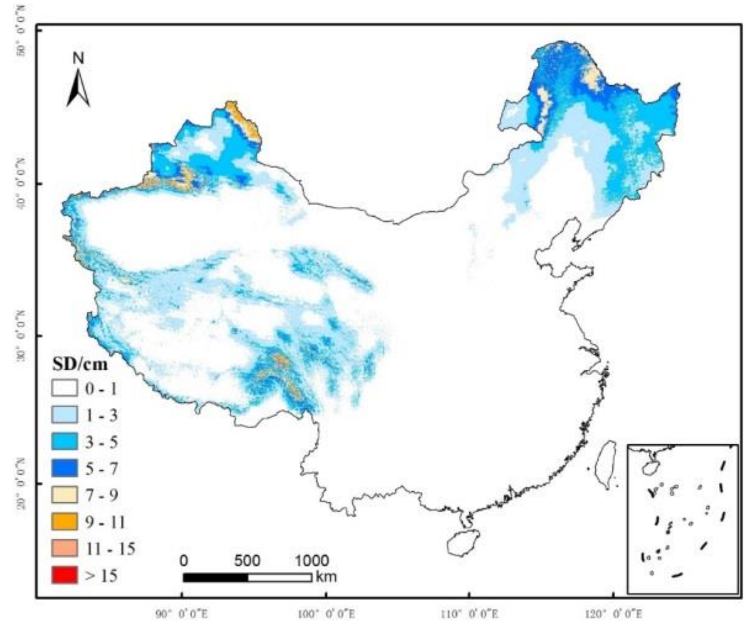

Figure 3: Spatial distribution map of the annual average snow depth in China

3.2 Analysis of the variation in the number of snow-covered days

We used the M-K method to analyze the variation in the annual number of snow-covered days in China for December 2000 to November 2014 (Fig. 4). As shown in the figure, the number of snow-covered days decreased in 29.2% of the area in China in the past 14 years ($Z < 0$), among which 6.5% of the area decreased significantly ($p < 0.05$). These regions were mainly distributed in the Tienshan Mountains in Xinjiang and most of the regions in the Tibetan Plateau. The regions with increasing number of snow-covered days constituted 34.5% of the whole China area ($Z > 0$), among which 10.8% of the area increased significantly ($p < 0.05$). These regions were mainly distributed in the Great Khingan Mountain, Lesser Khinan Mountain, and Changbai Mountains in the northeast and in most regions in South China.

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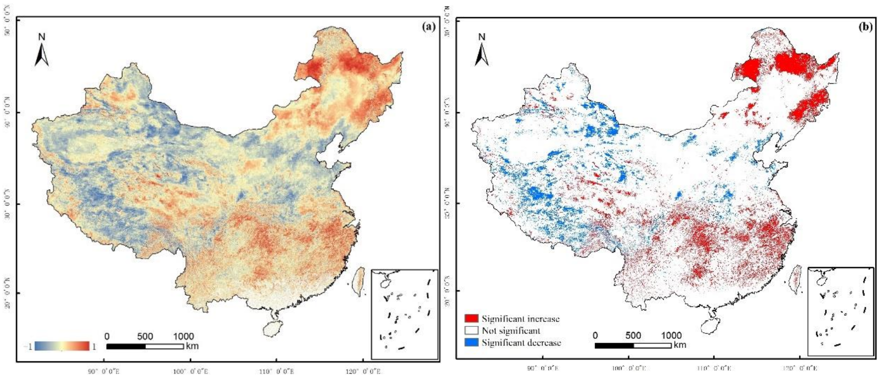

Figure 4: Analysis result map for the variation in the average annual number of snow-covered days in China based on the Mann-Kendall method. (a) The variation in the annual number of snow-covered days; (b) the significance of the variation in the annual number of snow-covered days.

The M-K variation analysis results showed that the annual number of snow-covered days in South China increased significantly. To test the accuracy of this result, we calculated the slope of the variation in the annual number of snow-covered days using Sen's median method (Fig. 5). The results indicated that the annual number of snow-covered days decreased in approximately 22.1% of the area in China (< 0), and it increased in 23.5% of the area (> 0). Among these, the rate of decrease in the annual number of snow-covered days was less than 2 d/year in 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 the Tibetan Plateau was more than 6 d/year. The rate of increase in the number of snow-covered days 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 variation. Because the Southeast China regions were mainly transient snow-covered regions and because Northeast China, the low elevation regions in north Xinjiang, and the Tibetan Plateau were the main stable snow-covered regions, the variation in the number of snow-covered days indicated that the annual number of snow-covered days in China increased overall (Figs. 4 and 5). However, in the Tibetan Plateau and the Tienshan Mountains in Xinjiang, which are at high elevation, the decreasing trend in the number of snow-covered days was

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significant.

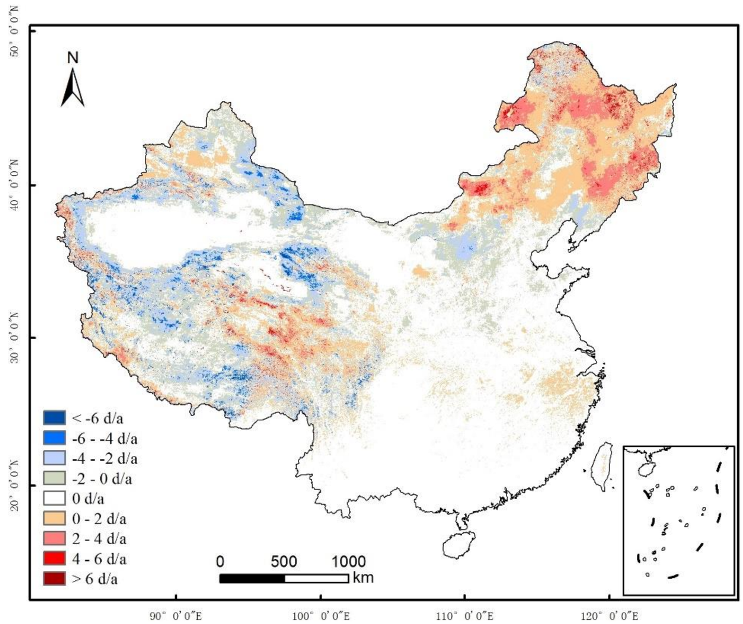

Figure 5: Analysis result map of the variation slope of the average annual number of snow-covered days in China based on Sen's median method

3.3 Analysis of the variation in snow depth

Snow depth is a key factor reflecting the condition of surface snow cover variation. It has important hydrological, climate, and ecological significance. Fig. 6 summarizes the spatial variation characteristics of the annual average snow depth in China from December 2000 to November 2014. It can be seen that the variations in the snow depth and the number of snow-covered days were highly spatially consistent. The regions with decreasing annual average snow depth constituted 11% of the area of China, among which the annual average snow depth significantly decreased in 3.3% of the area ($p < 0.05$), which was mainly distributed in most regions in north Xinjiang and the north Tibetan Plateau. In total, 22.4% of the area showed an increase, among which significant increases were observed in 8.5% of the area ($p < 0.05$), mainly distributed in Northeast China, the Tienshan and Altai Mountains in Xinjiang, the south Tibetan Plateau, and the Kunlun Mountains.

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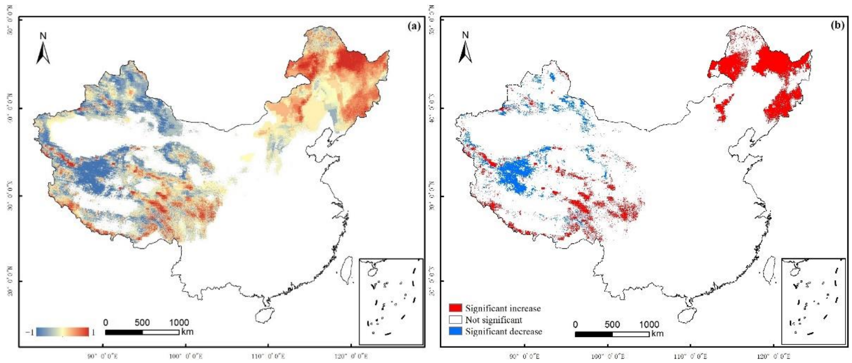

Figure 6: Analysis result map of the variation in the annual average snow depth in China based on the Mann-Kendall method. (a) The annual average snow depth variation; (b) the significance of the annual average snow depth variation.

3.4 Analysis of the snow cover variation in China

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 (Fig. 7). The results indicated that in the past 14 years, the regions with significantly decreased winter snow-covered days in China constituted 5.7% of the whole China area, whereas the areas with significant increases constituted 7.2% of the study region (Fig. 7(a)). The regions with significantly decreased spring snow-covered days in China constituted 4.0% of the whole China area, whereas the regions with significant increases constituted 6.2% (Fig. 7(b)). The regions with significantly decreased summer snow-covered days in China constituted 3% of the whole China area, whereas the regions with significant increases constituted 2.9% (Fig. 7(c)). The regions with significantly decreased fall snow-covered days in China constituted 1.8% of the whole China area, whereas the regions with significant increases constituted 5.7% (Fig. 7(d)). The results indicated that in the past 14 years, the summer snow-covered days in China decreased, whereas the numbers of snow-covered days in the winter, spring, and fall seasons all increased. The spatial distributions of the increases and decreases in the number of snow-covered days in each season in China were highly consistent. Specifically, the winter snow-covered days in South China increased, the number of snow-covered days in Northeast China in all the seasons increased, and the number of snow-covered days in the Xinjiang regions mainly decreased. The number of snow-covered days in the southwest

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margin of the Tibetan Plateau and the southeast region increased, whereas those in the north and northwest mainly decreased.

Previous studies 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 temperature rises, precipitation increases, leading to acceleration in snow melting rates in high-elevation regions and a decrease in snow-covered area. However, more moisture participates in the atmospheric water cycle process because of this pattern, which increases the precipitation in low-elevation regions and further increases the snow-covered area. Thus, the snow cover in South and Northeast China increased significantly, and the snow cover in the southwest margin and southeast region of the Tibetan Plateau increased, whereas that in the north and northwest of the Tibetan Plateau mainly 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, with global warming, the snow cover in Xinjiang decreased overall.

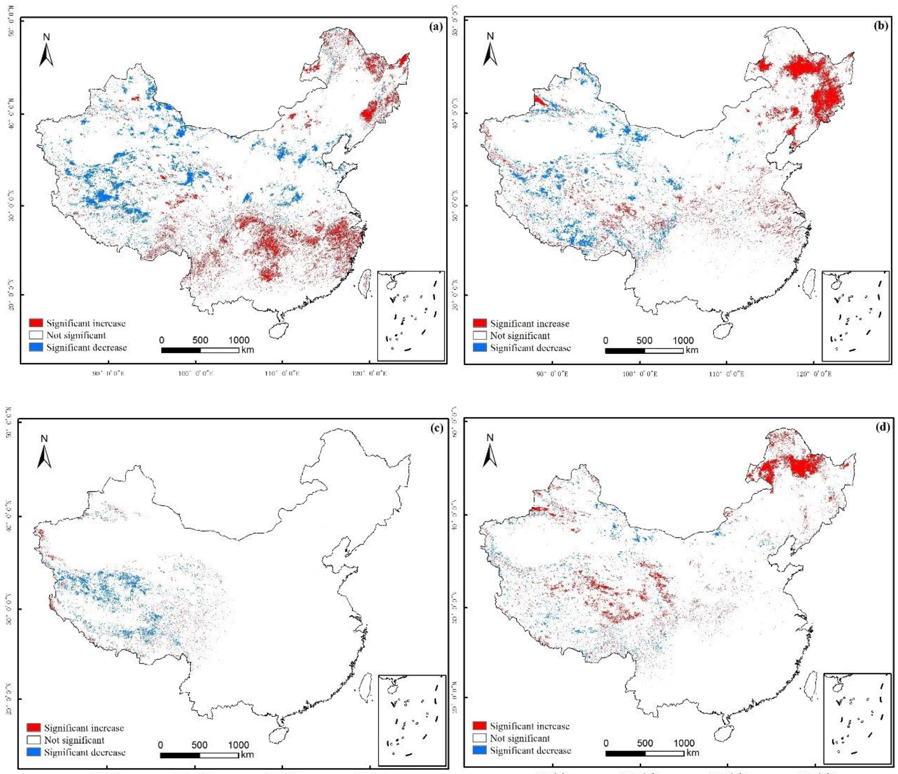

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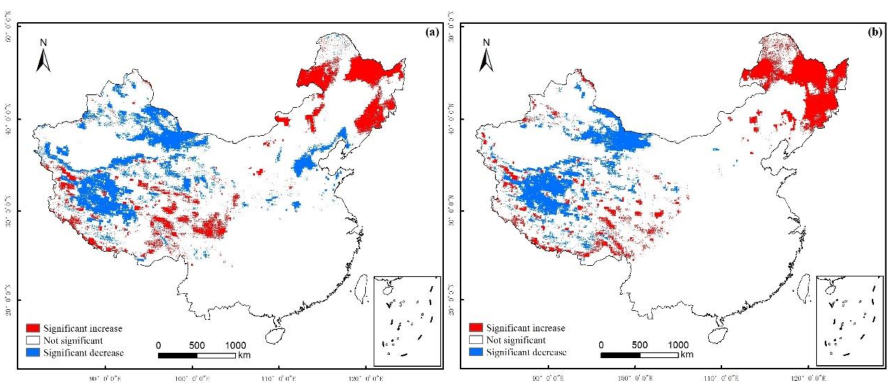
Figure 7: Analysis result maps of the variation in the number of snow-covered days in each season in China based on the Mann-Kendall method. (a), (b), (c) and (d) are the significance of the variation in the number of snow-covered days in winter, spring, summer, and fall, respectively.

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



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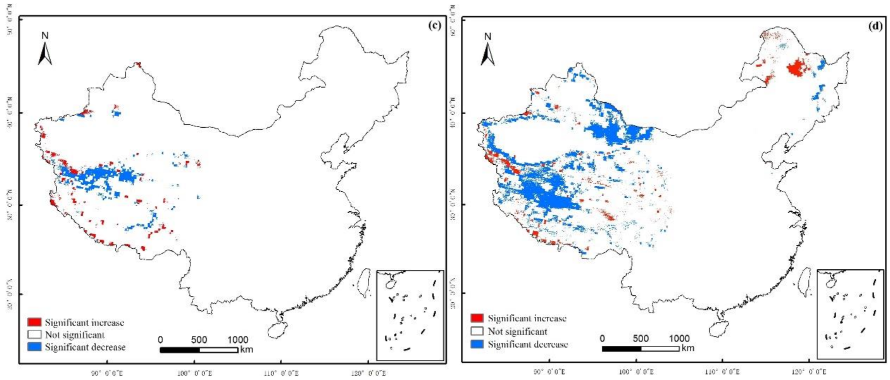

Figure 8: Analysis result maps of the variation in the average snow depth in each season in China based on the M-K method. (a), (b), (c), and (d) are the significance of the variation in the average snow depth in winter, spring, summer, and fall, respectively.

Fig. 9 summarizes the annual average snow-covered area in 2001-2014. The results indicated that the average annual snow-covered area in China in 2001–2014 constituted 11.3% of the whole study region. In the past 14 years, the annual average snow-covered area slightly varied, but it did not show a significant increase or decrease.

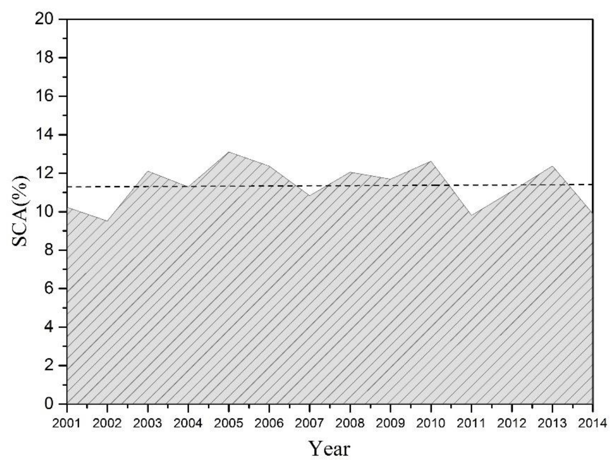

Figure 9: Variation map of the annual average snow-covered area in China in 2001–2014.

Fig. 10 summarizes the average fractional snow cover in each season in China from December 2000 to November 2014. The results indicated that in the past 14 years, the average snow-covered area

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in China was approximately 27.0% in winter, 10.7% in spring, 6.8% in fall, and 1.2% in summer. The average winter snow-covered area in China slightly decreased, the average summer snow-covered area decreased significantly, and the average snow-covered area in spring and fall slightly increased.

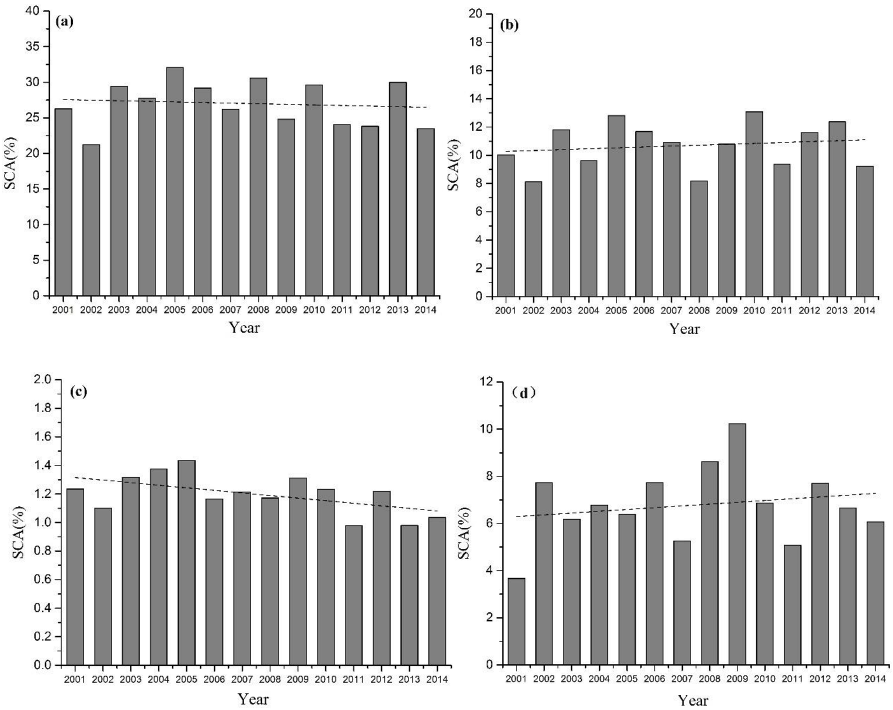

Figure 10: Histograms of the average fractional snow cover in each season in China from December 2000 to November 2014. (a), (b), (c), and (d) are the average fractional snow cover in winter, spring, summer, and fall, respectively.

4 Conclusion

The snow-covered area 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 investigate the variation dynamics of the snow cover in China from December 2000 to November 2014. We reached the following conclusions:

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

(2) The snow-covered area decreased in 29.2% of the area in China, and the regions with increased snow cover constituted 34.5% of the area of China. The regions with decreasing annual average snow depth constituted 10.9% of China, whereas average snow depth increased in 22.4% of China.

(3) The spatial distribution of the variation in the average snow depth was highly consistent with that in the number of snow-covered days. Furthermore, the spatial distributions of the amounts of increase and decrease in the snow cover in each season were also highly consistent. However, the regional differences in the increase in the annual average number of snow-covered days and average snow depth were significant. The regions with increasing snow were mainly distributed in Northeast China, whereas the Tibetan Plateau and Xinjiang were the main regions with decreasing snow cover.

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