Variation in the snow cover on the Qilian Mountains and its causes in the early 21st century

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ABSTRACT
Based on MODIS data, we analyzed the spatial distribution and the intra- and inter-annual variations of the snow cover in the Qilian Mountains. In addition to discussing regional climate, we discussed the reasons for the snow cover pattern variations. The spatial distribution of the snow cover in the Qilian Mountains is uneven, and the snow cover in the west is significantly greater than that in the east. The difference in the intra-annual variations of the snow cover at different altitudes is large, and the general seasonal cycle exhibits two maxima and one minimum. The snow cover and precipitation in the Qilian Mountains were consistently increasing from 2000 to 2005, but they generally decreased from 2008 to 2013. The influences of temperature, wind speeds and precipitations on snow cover variation at different altitudes vary greatly, with the snow cover being more sensitive to precipitation in the winter, while temperature and precipitation are the major factors that affect the snow cover in the spring.

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1. Introduction
Snow cover is an important component of the global landscape, and also as a main component of the cryosphere, snow cover has important influence on the surface radiation balance, energy balance and water-resource allocation, and thereby plays a very important role in the global and regional climate system (Yang et al. 2012). Snow cover has an effect on the climate of the local area through its reflectivity and the conversion between energy and water (Tang et al. 2012). The significance of snow cover is particularly important in the arid areas of the northwestern China, as the melted water from ice and snow in the high mountains is a vital living source for local ecosystem. The distribution and reserves of snow cover directly dominate the regional hydrological cycle. The inter-annual variation of snow cover in arid areas in the winter is relatively large and its duration is long, which may cause various disasters in agricultural and rural areas (Chen 2010; Lou et al. 2013). Therefore, it is essential to obtain general information of regional snow cover, such as the variation of snow-covered area and the duration of the snow cover in days.

The snow cover is very sensitive to climate change (Dang et al. 2012), and many studies have been conducted on the variations in the snow cover in the area of the Qilian Mountains. Chen et al. (1990) and Chen and Chen (1991) inverted the parameters of the snow cover of the Qilian
Mountains through the AVHRR data, acquired the temporal and spatial distribution features of the snow cover, and analyzed the climate of the snow cover resources. Guo et al. (2003) analyzed the snow cover variation of the Qilian Mountains using satellite data and obtained the snow cover variation of 10 recent years using the AVHRR data of 1989–1998 from the National Oceanic and Atmospheric Administration (NOAA). Zhang et al. (2005) continuously monitored the snow cover areas from May to August in 1997–2004 through remote sensing data and analyzed the variation in the snow-line height of the Qilian Mountains and the association between the variation of the snow cover area and an artificial precipitation project, thus acquiring the variation of the snow cover of the Qilian Mountains in the summer. Wang et al. (2010) analyzed the temporal and spatial variations of the snow cover of the Qilian Mountains in the winter half of the year using data from 1996 to 2002 acquired by the NOAA and FY-1C/1D meteorological satellite data. Wang et al. (2009) analyzed the seasonal and inter-annual variations of snow cover and their possible reasons in the Qilian Mountains through observational data from 1960 to 2005. Han et al. (2011) analyzed the variation of the total area of glacier snow on the Qilian Mountains through remote sensing and meteorological data and also analyzed the association between the climatic conditions in the Shiyang River Basin and the variation of the snow cover area. Cai et al. (2009) studied the spatial distribution and intra-annual variation characteristics of the snow cover using MOD10A2 data and explored the effects of topography on the snow cover distribution and seasonal variations. Dang et al. (2012) analyzed the temporal and spatial variation of the snow cover area in the Heihe River Basin and discussed the effects of temperature and precipitation.

The findings from these previous studies show that variations in the snow cover on the east, middle and west sections of the Qilian Mountains all have their own characteristics and differ from each other. The distribution of snow cover is greatly influenced by the seasons and topography, but few studies have considered the temporal and spatial variations of snow cover with the seasons on the Qilian Mountains at different altitudes. Since 2000, global warming has gradually become significant. With an increasing trend of precipitation in northwestern China, the variation of snow cover under this circumstance has become a hot issue of coping with climate change, including the spring flood in the northwest, water resource adjustment and control and people’s living and production. This paper makes an analysis of the snow cover data of the Qilian Mountains with the help of remote sensing technology, and tries to reveal the intra-annual distribution and inter-annual variation of snow cover since 2000, thus providing basic data for research on regional eco-environmental variation.

2. Data and methods
2.1. Overview of the study area

The Qilian Mountains are located on the Northeast Border of the Qinghai-Xizang Plateau, across the two provinces of Gansu and Qinghai. The overall length of the area is 850 km, and its maximum width is approximately 300 km. Starting from Wushaoling in the east, until the Dangjin Mountain Pass in the west, close to the Hexi Corridor in the north and reaching the Qaidam Basin in the south, the Qilian Mountains are composed of many parallel mountain ranges and broad valleys that run from northwest to southeast, and the mountain height decreases from west to east. As one of the famous high mountain ranges in Northwest China, the mean altitude above sea level of the highest Lenglong Ridge in the east section of the Qilian Mountains is 4860 m, and the highest peak in the west section is Tuanjie Peak of Shule South Mountain, with an altitude of 5766 m and a mean altitude above sea level of 3700 m (figure 1). Its total area is 901,661 km². The vertical differentiation of the climate is large. The precipitation in the high mountains is 400–800 mm, and due to the low temperature and alpine cold, 15% of the precipitation falls in the form of snow each year. The area above 4500 m is covered with snow and glaciers year round, and the area above 5000 m has grown modern glaciers. MOD10A2 data products have high snow accuracy, which can eliminate the impact of clouds on classification accuracy in surface snow. Zhou et al. (2005) compared the
observations from 2000 to 2004 of the four snow cover loggers at the Grand River Watershed of southern US, using MOD10A2 snow image classification, and found the recognition rate of MOD10A2 snow products ranged from 84.5% to 95.9%. The ice and snow melt water on the mountains is an important supply source of many rivers (Yin et al. 2009; Chen et al. 2012).

2.2. Data sources

2.2.1. Remote sensing
The MODIS/Terra8 daily emerging snow data (MOD10A2) was downloaded from the US National Snow and Ice Data Center (http://nsidc.org/). This research is based on two data sets of MOD10A2, with orbit numbers h25v05 and h25v06. The time series is from 26 February 2000 to 27 December 2013, and the spatial resolution is 500 m. Previous studies (Zhou et al. 2005; Lei et al. 2011; Tahir et al. 2011) have shown that the MOD10A2 products of mountain areas have a higher snow recognition rate than other snow cover products, which can be applied to the research of a wide range of snow cover, especially to the research of the snow cover variation in mountainous areas.

2.2.2. Digital elevation model
The source of the digital elevation data is http://www.gscloud.cn/, and the resolution is 90 m.

2.2.3. Meteorological data
The daily temperature, wind speed and precipitation are collected from 12 meteorological stations located in the Qilian Mountain Area and on the edge of the Qilian Mountains from 1 January 2000 to 31 December 2013, to analyze the variations of temperature, wind speed and precipitation. The distribution of meteorological stations is shown in figure 1, and the source of the data is http://cdc.cma.gov.cn/.

2.3. Research methods
The MOD10A2 products are processed as follows: (1) process the image data with the projection, format conversion and montage, and set the data as a unified longitude—latitude projection; (2) edit the image obtained after processing with the vector boundary of the research area; (3) extract the pixels of the snow cover, and then create the MODIS snow cover image. Convert all pixel values of snow cover...
into 1 and the other pixel values to 0. Get access to the spatial distribution information of the snow cover frequency of the research area from 2000 to 2013 through an image overlay operation; (4) make statistics of the regional snow cover according to the different pixel values of the snow cover areas and other areas; (5) extract the snow cover areas at different altitudes based on the digital elevation data. The first step is implemented by the MODIS professional software of Modis Reprojection Tools (MRT), and the second, third, fourth and fifth steps are implemented through the software platforms of Environment for Visualizing Images (ENVI), and Interface Description Language (IDL).

Eight-day mean temperature and accumulated precipitation are calculated in accordance with the snow cover time series. Pearson correlation coefficients are calculated between the snow cover area and the temperature and precipitation of the same station, to allow a discussion of the effects of temperature and precipitation on the variation of the snow cover area.

3. Results and analysis

3.1. Spatial distribution characteristics of snow cover

The snow cover frequency of the Qilian Mountains (figure 2) is composed of the figures of snow cover from 2000 to 2013 through raster calculation. From the figure, we can see that snow cover frequency is high mainly in the Lenglong Ridge, Corridor South Mountain, Great Snow Mountain, Tuole South Mountain, Shule South Mountain, Yema South Mountain, Danghe South Mountain and Tuergen Daban Mountain, from east to west, and the snow cover frequencies of these areas at high altitudes are above 60%. Most of these areas are distributed on the north slopes of the mountains, while only distributed sporadically on the south slopes in high-altitude areas. The sub-high value areas are distributed around the high-value areas, which are mainly around the mountain ranges with a snow cover frequency of 40% to 60%. The snow cover frequency of the Datong Mountain and Tuolai Mountain in the middle of the Qilian Mountains and the surroundings of the high-value areas are between 20% and 40%. In general, the snow cover frequency in the west area of the Qilian Mountains is higher than that in the east area.

Comparing the snow cover frequency of the Qilian Mountains in the four seasons (figure 3) with its annual mean for 2000−2013 (figure 2), the frequencies in the spring and autumn are similar to the annual mean, but snow is somewhat more widely distributed in the autumn than in the spring. The high-value areas are mainly the Lenglong Ridge, Corridor South Mountain, Great Snow Mountain, Tuole South Mountain, Shule South Mountain, Yema South Mountain, Danghe South Mountain and Tuergen Daban Mountain, from east to west, and the snow cover frequencies of these areas at high altitudes are above 60%. The sub-high-value areas are distributed around the

![Figure 2. Spatial distribution of snow cover frequency in the Qilian Mountains from 2000 to 2013.](image-url)
high-value areas. The high-value areas of the snow cover frequency (above 60%) in the summer are mainly distributed in the west section of the Qilian Mountains and are the Corridor South Mountain, Great Snow Mountain, Shule South Mountain and Tuergen Daban Mountain. The high-value areas of the snow cover frequency in winter and summer are mainly the Yema South Mountain, Danghe South Mountain and Tuergen Daban Mountain in the west region and the Lenglong Ridge in the east region, while the snow cover frequency in the middle is relatively low. The snow cover in summer and winter is most prevalent in the west, and the snow cover frequency and evenness in winter are the highest of all of the seasons. The snow cover in the east section of the Qilian Mountains in the spring and autumn is mainly distributed on the North Slope, where snow is more frequent in the spring and autumn than in the winter.

3.2. Intra-annual variation characteristics of snow cover

The average seasonal cycle and maxima and minima of 8-day snow cover in the Qilian mountains in the years 2000–2013 are shown in figure 4. The highest value of the maximum snow cover area appears at the end of October, with a value of $1.42 \times 10^5$ km$^2$, and the second highest value appears in mid-January, with a value of $1.41 \times 10^5$ km$^2$. The highest value of the minimum snow cover area appears in early May, with a value of $1.86 \times 10^4$ km$^2$ and the highest value of the average snow cover area, $6.5 \times 10^4$ km$^2$, appears in mid-November. The lowest value of the maximum snow cover area appears in mid-July, only 9917 km$^2$. The lowest value of the minimum snow cover area appears in early August, only 728.5 km$^2$, and the lowest value of the average snow cover area, in mid-July, is 3894.16 km$^2$. In general, the specific procedure of intra-annual snow cover variation is as follows. Snow cover is established in mid-September, and it rapidly expands with accumulation from...
October to November. Two peaks arise in November and January, and the snow cover area starts to decrease in February. When spring comes, the snow cover melts. The snow cover area gradually decreases with the increase of snow melting in March and has a rapidly decreasing trend in May. The snow cover area decreases continuously until the end of July and achieves its lowest value in early August. It starts to increase in late August, and the periods of the highest and low values are relatively short. The snow cover area is smallest in the summer each year, autumn is the accumulation period, the variation in the winter is quite gentle, and spring is the melting period.

Based on the digital elevation data and remote sensing images of the snow cover, curves for the snow cover area and the average intra-annual variation of snow cover at various elevations were plotted (figures 5 and 6). The figure shows that the curves of the intra-annual variation of snow

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**Figure 5.** Seasonal cycle of the absolute snow cover area (in km²) at different altitudes in 300-m elevation bands.

**Figure 6.** The seasonal variation of the relative snow cover area (snow cover area in each altitude band divided by the total area of the same altitude band), which varies from 0% to 100%.
cover at different altitudes below 4800 m display the features of a double maximum and single minimum, among which the maxima below 3900 m occur in late January and mid-November and those between 3900 and 4800 m in early April and late October. The variation above 4800 m is relatively gentle. While the minimum below 3000 m appears in the period from late April to early October and the duration is the longest, the minimum between 3000 and 3900 m appears in the period from early June to October and the duration has decreased, and the minimum between 3900 and 4800 m appears in the period from July to September. The minimum above 4800 m is insignificant. Along with the increase of altitude, the occurrence time of the maximum is delayed in the first half of the year and advances in the second half of the year, and the time during which snow cover is close to its minimum decreases.

In the summer, precipitation mostly occurs in liquid form due to the high temperature, so there is almost no snow cover below 4500 m. The snow cover area above 4500 m is maintained at a relatively high level with a small variation from mid-April to mid-June. The snow cover area achieves its minimum value from the end of June to the end of August. Starting in early September, the snow cover starts to establish and rapidly increases with the decrease of the temperature and reaches its peak value by the end of October. The snow coverage rate falls after that, which leads to a smaller snow cover area in the winter compared to that in the spring and autumn. This is in accordance with the intra-annual variation of snow cover at high altitudes on the Qinghai-Tibet Plateau and its surrounding areas (Pu et al. 2007; Dang et al. 2012) and West Kunlun Mountain (Yan et al. 2014).

3.3. Inter-annual variation characteristics of snow cover

A time series of annual mean snow cover area in the Qilian Mountains is shown in figure 7. We can see that the annual snow cover first increases from 2000 to 2004 (trends formula: \( y = 4000x + 19620, R^2 = 0.6692 \)), and then decreases characteristic from 2005 to 2013 (trends formula: \( y = -1541.2x + 40828, R^2 = 0.5871 \)). A scatter plot of the highest and average values of snow cover shows that the correlation between the two is relatively high and the correlation coefficient \( R \) is 0.66, which is in accordance with the daily scale features and confirms that extreme snowfall events play an important role in the inter-annual variation of snow cover.

Seasonal means of snow cover area in the years 2000—2013 are shown in figure 8. As the snow cover in the summer is generally the permanent snow cover at high altitudes, it is relatively stable with an insignificant trend. The snow covers in the spring, autumn and winter all first increase and then decrease, fluctuating drastically. In the spring, the snow cover area has an increasing trend from 2000 to 2005 and a decreasing trend from 2005 to 2013. In the autumn, the snow cover area has an increasing trend from 2000 to 2004 and a decreasing trend from 2004 to 2013. In the winter, the snow cover area has an increasing trend from 2000 to 2006 and a decreasing trend from 2006 to 2013.

![Figure 7. Annual variation of SCA in the Qilian Mountains.](image-url)
4. Discussion

Temperature and precipitation are two important factors in determining the melting and accumulation of snow cover (Wei et al. 2005). Due to the low temperature and high wind speed in mountainous areas in the winter, the critical wind velocity of blown snow is satisfied, leading to the redistribution and sublimation of snow cover (Li et al. 2012). Therefore, this paper performed intra-annual and inter-annual analyses of the average value of the precipitation, temperature and wind speed at 12 automatic weather stations in the Qilian Mountain Area (figure 9). The average precipitation gradually increases at the beginning of May every year and decreases after the end of October. The annual precipitation has an increasing trend from 2000 to 2007 and a decreasing trend from 2007 to 2013. The average wind speed is relatively high in the spring and is less in the other seasons. The inter-annual variation of wind speed is small, between 2.1 and 2.5 m/s. The average temperature from the end of October to the end of March is below 0 °C. The temperature gradually increases at the beginning of April, reaches its highest value at the end of July, and then gradually decreases. The inter-annual variation of temperature is relatively smooth, between 1 °C and 2 °C.

The snow covers at different altitudes vary greatly due to the influence of temperature, wind speed and precipitation. For the areas below 4500 m, the snow cover area in each season has a significant negative association with temperature (table 1). The ablation of the snow cover in this area mainly occurs in the spring. The rise of temperature in the spring leads to the fast ablation of the snow cover, which is completed in the late spring and early summer. Because the temperature is relatively high in the summer, precipitation mostly falls in liquid form, so the association between summer precipitation and snow area is insignificant. Because of the lack of data from meteorological stations (e.g. temperature, precipitation and wind speed), we did not analyze the effects of temperature, precipitation and wind speed on snow cover variation above 4500 m.

Comparing the correlation coefficients between the snow cover areas in each season with the temperature, wind speed and precipitation, we see that the temperature and precipitation are the main causes for the variation of the snow cover in the spring; the temperature greatly affects the variation of the snow cover in the summer; and the snow cover is more sensitive to precipitation in the winter. From the perspective of the inter-annual variation of snow cover, the variation is consistent...
with that of precipitation from 2000 to 2005, with both exhibiting an increasing trend. Precipitation and the snow-covered area both have a decreasing trend from 2008 to 2013. Because the inter-annual variations of the wind speed and temperature are relatively small, their effects on the inter-annual variation of the snow cover area are relatively small.

5. Conclusions

The spatial distribution of the snow cover of the Qilian Mountains is very uneven, and the snow cover of the west section of the Qilian Mountains is significantly more extensive than that in the east section. Snow cover frequency is high in the Lenglong Ridge, Corridor South Mountain, Great Snow Mountain, Tuole South Mountain, Shule South Mountain, Yema South Mountain, Danghe South Mountain and Tuergen Daban Mountain, from east to west. The snow cover frequency of these areas at high altitudes is above 60%, and the areas are mainly distributed on the north slopes of the mountains. Moderately high values of snow cover frequency are mainly found in the surroundings of the mountain range. Considering the snow cover frequencies of the four seasons, the

Table 1. The inter-annual correlation of seasonal mean SCA with precipitation, wind speed and temperature in the Qilian Mountains.

| Snow area | Precipitation | Temperature | Wind speed |
|-----------|---------------|-------------|------------|
| Spring    | -0.502        | -0.563      | -0.164     |
| Summer    | -0.281        | -0.899      | 0.649      |
| Autumn    | -0.879        | -0.825      | -0.719     |
| Winter    | 0.687         | -0.299      | 0.271      |

Figure 9. Average seasonal cycles and annual time series of precipitation, temperature and wind speed in the Qilian Mountains.
snow cover in the summer and winter mainly occurs in the west section, and the frequency and evenness of snow cover is higher in winter than in the other seasons. The pattern is different in the east section, where the snow cover in the spring and autumn is mainly distributed on the north slope and is geographically more widely distributed than in the winter.

The snow cover of the Qilian Mountains starts to be established in early September. The snow cover area rapidly expands its accumulation from October to November and reaches two peak values in November and January. The snow cover area starts to decrease in February and reaches its lowest value in late July and early August. The inter-annual and seasonal variation curves of the snow cover vary greatly between different altitudes, and the annual variations all have two peaks, which occur in the spring and autumn. The periods of accumulation and ablation of snow cover differ at different altitudes; the higher the altitude, the earlier the accumulation of snow in the autumn and the later the ablation of snow cover in the spring.

The annual snow cover area of the Qilian Mountains first increased and then decreased as a whole from 2000 to 2013. Considering the inter-annual variation of the snow cover area of the Qilian Mountains in different seasons, the snow cover areas in the spring, autumn and winter fluctuate drastically from year to year, and the absolute variation is insignificant in summer, when the snow-covered area is much smaller than in the other seasons.

Through the analysis and discussion of the temporal–spatial distribution and variations of the snow cover of the Qilian Mountains and its association with precipitation, wind speed and temperature, we conclude that the snow cover at different altitudes varies greatly under the influence of temperature, wind speed and precipitation, and in the areas below the altitude of 4500 m, the snow cover area in each season has a significant negative association with temperature. Temperature and precipitation are the main factors that affect the snow cover variation in the spring. The temperature greatly affects the snow cover variation in the summer, while the snow cover variation in the winter is sensitive to precipitation. From the perspective of the inter-annual variation of the snow cover, the trends of snow cover and precipitation from 2000 to 2005 are consistently increasing, and the trend from 2008 to 2013 is decreasing. Because the inter-annual variations of the wind speed and temperature are relatively small, their effects on the inter-annual variation of the snow cover area are relatively small.

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