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MODIS/Terra observed seasonal variations of snow cover over the Tibetan Plateau

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[1] Seasonal variations of snow cover fraction (SFC) over the Tibet Plateau (TP) are examined using the data acquired from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra spacecraft. In this study, we first evaluate the accuracy of the MODIS high-resolution snow cover data by comparing the data with in-situ Chinese snow observations. Results show that overall accuracy of MODIS snow data is about 90% over the TP area. Statistical analysis is then performed over the MODIS snow data during 2000–2006. It is found that the most persistent snow cover is located in the southern and western edges of the TP within large mountain ridges and western part of Yarlung Zangbo valley. The higher SCFs are mostly concentrated in the regions where the elevation is higher than 6000 m. The duration for snow persistence varies in different elevation ranges and generally becomes longer with increases in the terrain elevation. **Citation:** Pu, Z., L. Xu, and V. V. Salomonson (2007), MODIS/Terra observed seasonal variations of snow cover over the Tibetan Plateau, *Geophys. Res. Lett.*, *34*, L06706, doi:10.1029/2007GL029262.

1. Introduction

[2] Compared with other regions in the middle latitudes, seasonal snow cover over the Tibetan Plateau (TP) is a unique feature in global snow maps. The TP, located at the south west of China, with an average elevation more than 4000 meters above sea level, is often called "the roof of the world." With the highest mountains in the world, snow cover can persist during all seasons over the high altitudes in the TP. In general, snow cover over the TP is a vital water source in western China. The largest rivers of China, such as the Yangtze River, Yellow River etc., have their headwaters there. In addition, snow cover is also a comprehensive indicator of the mean conditions of temperature and precipitation in the TP and its surrounding areas. Previous studies have shown that winter snow cover over the TP has a strong link with general circulation and monsoon systems over eastern and southern Asia during spring and summer [*Dickson*, 1984; *Yang*, 1996]. Snow cover variability also responded to the global warming, making it an important problem in regional climate studies [*Qin et al.*, 2006].

[3] Before the era of "satellite meteorology", traditional sources of snow observations were usually obtained from ground-based meteorological networks, in which only the presence or absence of snow along with snow depth is measured on a daily basis. Given the scarcity of ground-based, in-situ stations, it is difficult to adequately capture the spatial variability in snow cover particularly in remote, difficult to access regions such as the TP. At present, there are only 115 conventional ground-based stations managed by Chinese government over the TP. Most of these stations are located in the inhabited, lower-altitude river valleys, where elevations are usually below 4500 m. Therefore, complete and accurate snow cover information over the TP is difficult to obtain with the in-situ stations.

[4] On December 18 1999, the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) Terra satellite was launched with a complement of five instruments, one of which is Moderate Resolution Imaging Spectroradiometer (MODIS). Among all the comprehensive observations on cloud, ocean, and earth surface characteristics available from the Terra MODIS, the snow-cover product is available since February of 2000. With improved spatial resolution (500-m globally), high temporal frequency (daily), enhanced capability to separate snow and clouds [*Hall et al.*, 2002] due to more spectral bands (particularly in the short-wave infrared), as well as a consistently applied, automated snow-mapping algorithm (G. A. Riggs et al. (2003), MODIS snow products user guide for collection 4 data products, available at http://modis-snow-ice.gsfc.nasa.gov/sug_main.html, hereinafter referred to as Riggs et al., MODIS user guide, 2003), MODIS provides an excellent, advantageous opportunity to study the snow cover over large, relatively inaccessible regions such as the TP.

[5] In this study, we first evaluate accuracy of the MODIS/Terra snow cover data products over the TP by comparing the data with in-situ Chinese station snow observations. Then we perform statistical analyses based on the MODIS/Terra snow cover data from last 7 years (2000–2006) to get an indication of the monthly to seasonal variations of snow cover over the TP.

[6] We specifically define the area of the TP as the region covering about 3.6 million square kilometers with an elevation *higher* than 2000 m. This overall area occurs in a domain between 70–110°E longitude and 25–45°N latitude. Major mountain ridges in the region include the Himalaya Mountains in the southern edge of the TP, and the Karakoram and Kunlun mountains in the western and northern edges. The Pamir, Karakoram, Kunlun and Tianshan ridges are adjacent in the west part. The Qilian Mountain separates the Gobi desert from the TP in the north-eastern edge. Two large sub-regions, the Qaidam basin and Yarlung Zangbo valley, are located in the east-

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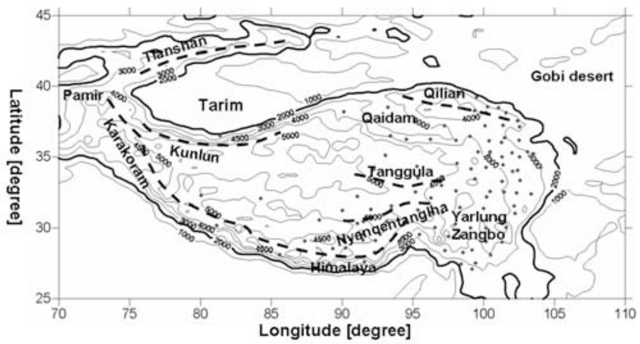

Figure 1. Map of the Tibetan Plateau area. The contour lines (interval: 1000 meter) show the elevation of topography in the area. Available in situ Chinese ground-based stations are shown as dots. The thick contour line represents the elevation at 2000 m.

northern and east-southern part of the TP, respectively (Figure 1).

2. Description of the MODIS Snow Data and In Situ Observations

2.1. MODIS Snow Data

[7] MODIS snow data used in this study were obtained from the National Snow and Ice Data Center. Because the MODIS 8-day composite snow data eliminates the cloud obscuration and thereby provides more consistent and cloud-free coverage than daily resolution data products, we have chosen to rely on analyses of the 8-day composite snow data product in this work.

[8] According to Riggs et al. (MODIS user guide, 2003), there are two types of 8-day composite snow data products available (MOD10A2 and MOD10C2). Specifically, MOD10A2 data are the 8-day composite snow cover observations at 500 m resolution. MOD10C2 data are the snow cover fraction (SCF) data at 0.05° resolution (so-called climate modeling grids or CMG grid) directly derived from the MOD10A2. In the MOD10A2, the MODIS snow cover algorithm labels each 500 m pixel as clear land, snow, cloud obscured, water, etc. When the data are converted to CMG grids, results are provided for each CMG grid based on the original MOD10A2 data and total numbers of the pixels. Therefore, fractional-snow cover or percent snow cover is available in the MOD10C2. Upon considering the characteristics of the data and amount of total data flow, in this study we use MOD10A2 products for data quality/accuracy evaluation and the MOD10C2, as directly derived using the MOD10A2 product, for analysis of the seasonal variations.

[9] The quality of MODIS snow data has been evaluated [e.g., *Hall et al.*, 2001; *Klein and Barnett*, 2003]. As determined by prototype MODIS data, annually averaged, estimated error for Northern Hemisphere snow-cover maps is approximately 8% in the absence of cloud. However, applying the cloud mask has to be carefully done; for example, there is a tendency to overestimate cloud cover [*Ackerman et al.*, 1998]. Therefore, confusion in identifying cloud over snow has been observed in high-elevation regions, e.g., the Sierra Nevada in California and Southern Alps of New Zealand [*Hall et al.*, 2002]. This problem has been partially taken care of in the most recent MODIS data products (Riggs et al., MODIS user guide, 2003). However, so far, evaluation of MODIS snow data has not yet been done for the TP area. In this study, we evaluate the accuracy of the MODIS high-resolution snow cover data by comparing the data with in-situ Chinese snow observations.

2.2. In Situ Snow Depth Observations

[10] The in-situ daily snow depth data are obtained from the China Meteorological Information Center, China Meteorological Administration. The data were collected from 115 ground-based operational meteorological stations over the TP. All data have been well quality controlled and verified manually. Figure 1 shows the geographic distribution of these ground stations. Based on the availability of the data, we obtained a 3-year in-situ snow data set over the TP for the time period from 01 April 2000 to 31 March 2003.

3. Evaluation of MODIS Snow Products

[11] Following *Klein and Barnett* [2003], MODIS snow cover data are compared with in-situ ground based snow observations. Since we use the 8-day composite snow products from MODIS, the evaluation is performed in 8-day periods during 01 April 2000 to 31 March 2003.

[12] Table 1 shows the confusion matrix comparing MOD10A2 snow data against in-situ observations. Following the definition of snow cover in MOD10A2, if snow is recorded any day at an in-situ ground station during eight-day period, we mark this station as snow covered. When MODIS snow mapping data agree with the in-situ snow cover, we say this is a correct hit. In Table 1, a1 and b2 represent the total numbers of correct snow hits and clear land (non-snow) hits, respectively. In the case when MODIS products indicate a clear-land event at a certain location but snow were present during eight-day period in the in-situ observations, the event is labeled as snow missing. The total number of snow missing is summed up as b1. When MODIS data indicate snow cover but in-situ observations are snow free, the event is labeled as false alarm. The total number of false alarms is represented by a2. Overall accuracy of snow detection rate is then defined as:

$$\text{Overall accuracy} = (\text{a1} + \text{b2})/(\text{a1} + \text{b1} + \text{a2} + \text{b2})$$

[13] Hence

$$\text{Snow missing rate(omission error)} = \text{b1}/(\text{a1} + \text{b1} + \text{a2} + \text{b2})$$

$$\text{False alarm rate(commission error)} = \text{a2}/(\text{a1} + \text{b1} + \text{a2} + \text{b2})$$

[14] The snow detection rate is defined as the ratio of snow cover detected by the MODIS sensor to the total snow cover events:

$$\text{Snow detection rate} = \text{a1}/(\text{a1} + \text{b1})$$

Table 1. Confusion Matrices for MODIS Data Against In Situ Observations

MODIS, In-Situ Observations	Snow	Non-Snow
Snow (Snow depth >0)	a1	b1
Non-snow (Snow depth = 0)	a2	b2

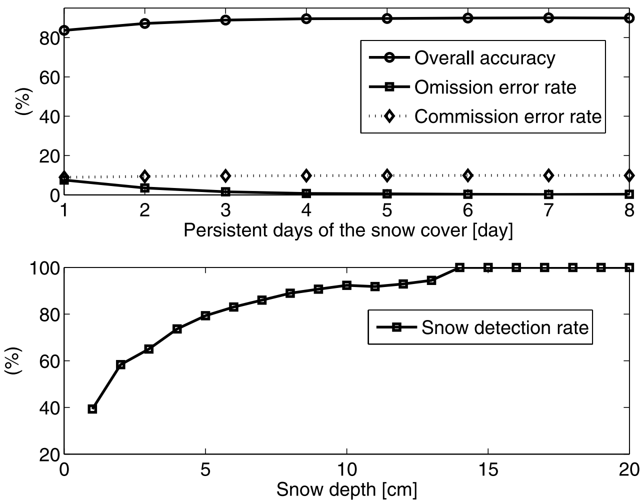

Figure 2. (top) Overall accuracy, rates of commission and omission errors of MODIS snow cover data products against in-situ station snow data, with respect to the snow cover persistent period in the 8-day period. (bottom) The MODIS snow detection rate respect to in situ mean snow depth (cm) in the 8-day period.

[15] At the same time we investigate the dependency of the MODIS snow cover detection as a function of the persistence of snow cover during an 8-day period. All the above parameters were calculated according to number of days with persistent snow cover within an 8-day period. Figure 2 (top) shows the overall accuracy of detection, rate of omission and commission errors as a function of the number of snow cover persistent days within an 8-day period. Figure 2 (top) indicates that the overall accuracy of MOD10A2 is in a range between 84–91% and monotonically increases with the number of persistent snow cover days. The averaged overall accuracy of MODIS snow detection is about 90%. Commission error rate is roughly 9% and stays constant with snow persistent days. *Hall et al.* [2002] commented that main reason for the commission error is the misidentifying clouds comprised of ice particles as snow. However, omission errors are dramatically decreased from 7% to near zero with increasing the snow cover persistent days going from 1 to 8, implying the MODIS snow detection rate strongly depends on the persistence of the snow cover. For snow cover persisting for only one day out of eight, the rate of omission error is over 7%; for any snow cover that persists longer than 3 days, the omission error is almost zero percent.

[16] The MODIS snow detection rate is also associated with snow depth observed at in-situ stations. Figure 2 (bottom) illustrates the percentage of snow detection as function of the snow depth over the in-situ ground stations. It shows very clearly that the snow depth clearly affects the snow detection rate. Specifically, for any snow cover with depth over 10 centimeters, the detection rate is over 95 percent. When snow depth increased over 14 centimeters, the detection rate is 100%. In contrast, when the snow depth is less than 5 centimeters, the detection rate is below 75%. The results suggest that the major omission errors are apparently caused by occasions when the depth of the snow is very small. Other investigations with in-situ data had corroborated this conclusion. For example, *Klein and Barnett* [2003] also found that the majority of the days when MODIS fails to map snow over the Upper Rio Grande River Basin were accompanied by the snow depth being less than 4 centimeters.

4. Seasonal Variations of Snow Cover Over the Tibetan Plateau

[17] The above evaluation indicated that the MODIS 8-day composite snow cover data is typically quite accurate over the TP. However, snow cover over a certain area is frequently, if not always, referred to the fraction of snow-covered land. Thus, it is quite reasonable to use the snow cover fraction (SCF) to examine the temporal variability of the snow cover over a certain area. Therefore, as mentioned in the previous section, the MOD10C2 data products, as directly derived from MOD10A2, are used to provide and analyze the snow cover spatial distribution and temporal variations over the TP.

[18] Figure 3 shows the annual cycle of SCF averaged over the areas and the standard deviation in the different elevation ranges as calculated from available data over the period from February of 2000 to September of 2006. Strong seasonal variations in SCF are found over the whole area of the TP (Figure 3a). From early of October to late of April, overall SCF's over the total area are greater than 25% with relatively large standard deviations reflecting the variability from year to year. The SCF, depending upon the elevation, peaks in January at the lower elevations and as late as in April above 6000m, and then progressively decreases and reaches minimum values (except above 6000m) of about ~1–5% in the July–August period. The interannual variability is relatively small during the summer months. At elevations above 6000m (Figure 3d), averaged SCFs are greater than about 60% in all seasons, with two maxima in SCF occurring in the spring and fall seasons and a relative minimum during early of December to later of January along with the typical minimum in the summer. The variability above 6000m during the winter may be principally caused by: (1) less frequent snow storms during the winter at these elevations; (2) the existence of the winter East Asia jet stream (EAJT) over the TP [*Moore*, 2004] and the accompanying downslope flow due to thermal-driven mountain-valley circulations; and (3) increased sublimation of the snow associated with the high winds over this area. The EAJT blows the snow and tends to transfer snow into the valleys and decrease the total SCF. Sublimation contributes largely to decreases in SCF during the winter, especial for the areas with thin snow cover [*Qin et al.*, 2006].

[19] The 8-day composite snow cover data are aggregated to obtain monthly mean SCF using a weighted average. Figure 4 shows the monthly mean SCF over the TP from January to December. Extremely spatial variability in monthly snow cover is exhibited due to the complex terrain. Specifically, higher SCFs correspond well with the huge mountains, including Himalaya, Karakoram, Pamirs, Kunlun and Nyainqentanglha Mountains. The most persistently snow-covered areas (over 50% of area coverage and 70% of the time) are concentrated in the Himalaya, Kunlun, Karakoram regions and the western part of the Yarlung Zangbo

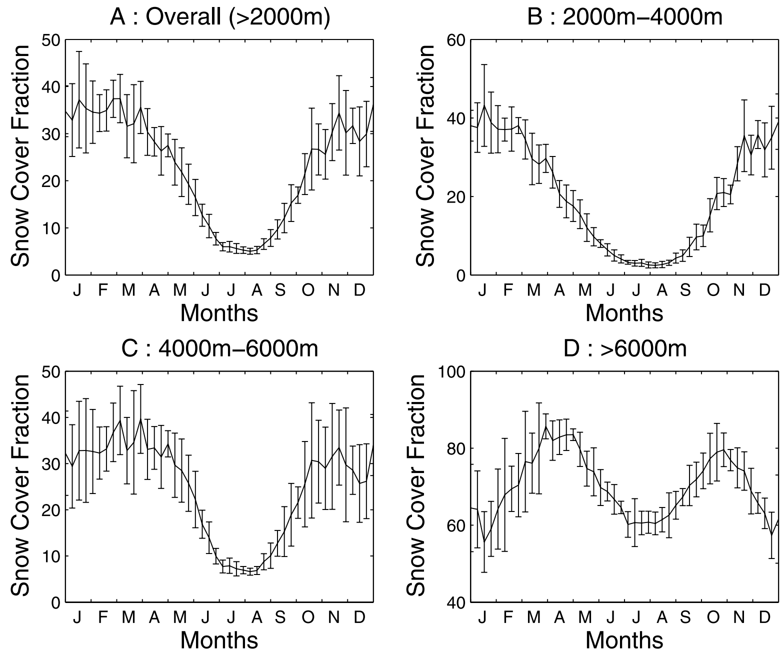

Figure 3. The annual cycle of snow cover fraction (SCF) averaged over the areas in different elevation ranges: (a) over the whole area of the TP (>2000m), (b) 2000–4000m; (c) 4000–6000m; and (d) beyond 6000m. The curve on each panel shows the averaged SCF over the period of 2000–2006. The error bars show the standard deviation, indicating the variations of snow cover from 2000–2006.

Valley. They especially occur in the combined areas of Karakoram and Kunlun mountains that are the most heavily glaciated regions in the world located outside of the Polar Regions. Warm and moist air comes from India Ocean and Arabian Sea and contributes to the larger SCF and persistence of snow cover occurring in this narrow region extending along the Himalayan and Karakoram mountains to the Pamirs. In the south-eastern part of the TP, SCF is also relatively higher as the moist air goes up along the Yarlung Zangbo valley from the southern region. In contrast, due to huge shielding from the Himalaya and Karakoram mountains, most of the interior of the TP has relatively less snow-cover persistence although the averaged elevation is beyond 4000 m. Table 2 shows the month mean SCFs in the different elevation ranges. The monthly mean SFCs in the areas between elevations of 3000–4000m are grater than in the areas at 4000–600m elevations from November to February, mainly because of the most areas between 4000–6000m elevations are located in the interior of the TP. Only in the major large mountains, such as Nyainqentanglha, is the frequency of snow cover relatively higher than nearby regions.

[20] The maximum SCF over the entire TP is roughly 33% in February (Table 2). From February to August, the mean for the total TP SCF decreases to 5.3%. With regard to elevation zone variability, the snow cover also starts to decrease after January in the areas between 2000–4000 m of elevation, after March between elevations of 4000–6000 m and after April in the regions above 6000m of elevation. Obviously, the snow persistence varies in different elevations as onset of snow melt is naturally postponed with increases in the terrain elevation.

[21] Time series of the mean SCF over the whole TP area during 2000–2006 are analyzed based on linear regression (figure not shown). The linear trend in mean SCF for whole period shows that the SCF is pretty flat over the TP area during 2000–2006, although a slight decrease (about −0.34% per year) is found. The decreasing linear trends in SCF might suggest a climate change over the region. However, with only 7 years of MODIS data, it is hard to arrive at any definitive conclusion regarding the time trend of the snow-cover fraction for this area. Clearly a longer time series of data is needed to attain any definitive conclusions.

5. Summary and Discussion

[22] Assessment of snow cover variability over the TP has been a challenging problem due to lack of conventional observations. MODIS/Terra satellite high resolution snow mapping products have provided an excellent opportunity to define details in the spatial and temporal snow cover distribution in the area.

[23] An evaluation of MODIS 8-day composite snow cover observations using available in-situ Chinese snow observations shows the overall accuracy is about 90%. Total error in these observations over the TP is about 10% and this compares favorably with previous studies showing global average errors of 8%. The omission error and snow detection rate depend on both the persistence of snow during eight-day periods and the snow depth; i.e. very shallow snow depths (<5 cm.) cause omission errors.

[24] Based on the MODIS snow cover data during 2000–2006, the snow cover distribution is spatially quite variable over the TP due to the complex terrain. The most persistently snow covered areas occur in the southern and western edges of the TP within large mountain ridges and western part of Yarlung Zangbo valley where there is a strong link

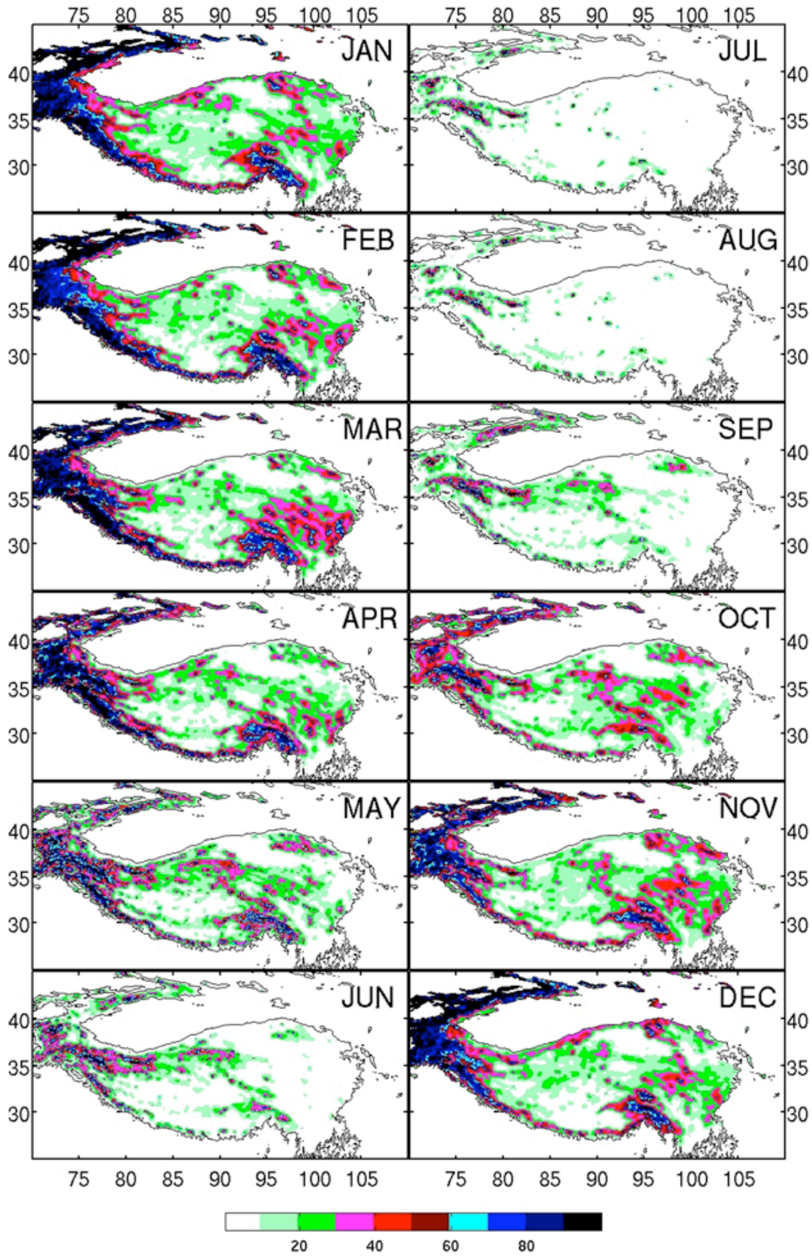

Figure 4. Monthly mean snow cover fraction over the Tibetan Plateau from January to December. The black contour line represents the elevation at 2000 m.

with the warm moist air that comes from southern Asia. In the interior of the TP, SCFs are relatively small and less persistent. The highest snow fractions, typically in the range between 49 and 76%, are mostly concentrated at elevations higher than 6000m. During the summer months (e.g. July and August), the Tibet Plateau retains approximately 5% snow cover made up of scattered, patches of snow. Maximum snow accumulation and melting times over the year

Table 2. Monthly Mean of Snow Cover Fraction in Different Elevations[a]

Elevation Range	Area Percentage Out of Whole Tibetan Plateau	JAN	FEB	MAR	APR	MAR	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2000–3000m	20.1	33.8	30.5	22.2	12.3	5.5	2.3	1.2	1.2	3.3	10.3	20.6	29.4
3000–4000m	21.2	41.3	40.6	37.4	30.0	20.4	8.9	4.4	4.1	9.8	22.9	35.1	37.6
4000–5000m	39.9	30.4	31.2	32.5	28.3	24.4	11.3	4.9	4.8	10.9	24.2	29.8	27.1
5000–6000m	18.5	28.3	32.2	37.5	37.0	36.2	23.6	11.1	11.7	22.0	32.8	31.7	26.3
>6000m	0.3	49.1	56.8	69.6	76.1	73.9	59.3	53.6	55.9	67.2	77.0	70.7	54.1
overall	100.0	33.1	33.3	32.5	27.2	22.1	11.4	5.3	5.3	11.4	22.8	29.5	29.7

[a]Monthly mean of snow cover fraction is given in percent.

vary, but generally are later as the elevations increase. In addition the larger interannual variabilities occur in the late fall and winter months. Lastly, there is an indication of a slight decrease in snow cover during 2000–2006, however, a longer time series of data needs to be examined to reach a definitive conclusion about temporal trends.

[25] **Acknowledgment.** Li Xu is supported by the NASA Earth and Space Sciences Fellowship Program.

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