Postprint: Vertical Distribution Heterogeneity of Snow Cover in the Tianshan Mountains, China

Authors: Zhang Bo

Date: 2022-06-07T00:00:00+00:00

Abstract

Based on MOD10A2 snow cover products and MOD11A2 land surface temperature data from 2001 to 2018, and employing fine-scale zonal statistics and correlation analysis methods, this study investigated the vertical distribution characteristics of snow cover and its response relationship with land surface temperature (LST) at different altitudes in the Tianshan Mountains of China. The results indicate that the snow cover percentage (SCP) in the Tianshan Mountains of China exhibits four distinct seasonal variation patterns with altitude across spring, summer, autumn, and winter. Below 4200 m altitude, SCP shows an increasing trend in autumn and winter and a decreasing trend in spring and summer, while above 4200 m altitude, it shows a decreasing trend in autumn and winter and an increasing trend in spring and summer. Except for winter, SCP and LST in spring, summer, and autumn all exhibit significant strong negative correlations.

Full Text

Heterogeneity of the Vertical Distribution of Snow Cover in Chinese Tianshan Mountains

ZHANG Bo[1,2,3], LI Xuemei[1,2,3], QIN Qiyong[1,2,3], LI Chao[1,2,3], SUN Tianyao[1,2,3]

[1]Faculty of Geomatics, Lanzhou Jiaotong University, Lanzhou 730070, Gansu, China
[2]Gansu Provincial Engineering Laboratory for National Geographic State Monitoring, Lanzhou 730070, Gansu, China
[3]National Local Joint Engineering Research Center of Technologies and Applications for National Geographic State Monitoring, Lanzhou 730070, Gansu, China

Abstract: Using MOD10A2 snow products and MOD11A2 land surface temperature (LST) data from 2001-2018, this study employs fine zonal statistical and correlation analysis methods to investigate the vertical distribution characteristics of snow cover and its response to LST across different altitudes in the Chinese Tianshan Mountains. Results indicate that snow cover percentage (SCP) exhibits four distinct seasonal variation patterns with altitude in spring, summer, autumn, and winter. Below 4200 m, SCP shows an increasing trend in autumn and winter and a decreasing trend in spring and summer; above 4200 m, the opposite pattern occurs. Except in winter, SCP shows a significant strong negative correlation with LST in spring, summer, and autumn.

Keywords: snow cover percentage; land surface temperature; vertical distribution; Chinese Tianshan Mountains

---

1.2 Data Sources

Snow cover data were obtained from the MOD10A2 product provided by the National Snow and Ice Data Center (NSIDC, http://nsidc.org/nasa/MODIS), with a temporal resolution of 8 days and spatial resolution of 500 m. Previous studies have demonstrated that MOD10A2 achieves snow identification accuracy of 87.5%-94.0% in Xinjiang and can effectively characterize spatiotemporal snow distribution patterns in the Chinese Tianshan Mountains. The study area comprises images from four tiles: h23v04, h23v05, h24v04, and h24v05. The Digital Elevation Model (DEM) was acquired from the Geospatial Data Cloud (http://www.gscloud.cn). Land surface temperature data were obtained from the MOD11A2 product via NASA' s Earthdata portal (https://earthdata.nasa.gov/), with a spatial resolution of 1 km. To match the snow cover data, daytime and nighttime datasets were averaged and resampled to 500 m resolution.

To validate the applicability of MOD11A2 LST data in the study area, daily mean air temperature measurements from three meteorological stations (Bayinbuluke, Baluntai, and Yiwu) were obtained from the China Meteorological Data Service Center (http://cdc.cma.gov.cn) for the period 2001-2018. Regression analysis between MOD11A2 LST and station-measured air temperature (365 data pairs per station) yielded correlation coefficients exceeding 0.9, confirming that the MOD11A2 product meets the requirements of this study. Detailed information on the meteorological stations is provided in Table 1 .

1.3 Research Methods

Snow Cover Percentage (SCP): SCP represents the percentage of snow-covered area relative to the total study area, calculated as:

$$SCP = \frac{S_{snow}}{S_{total}} \times 100\%$$

where S_{snow} is the snow-covered area within the statistical region (km^2) and S_{total} is the total study area (km^2).

Zonal Statistical Method: To investigate altitudinal differences in snow cover, the Chinese Tianshan Mountains were divided into elevation zones at 200 m intervals based on topographic characteristics. Six distinct altitude partitions were established for comparative analysis: $ $1000 m, 1000-2000 m, 2000-3200 m, 3200-4200 m, 4200-5000 m, and $ $5000 m.

2.1.1 Vertical Distribution Patterns of Monthly SCP

Figure 2 [Figure 2: see original paper] illustrates the vertical distribution of monthly mean SCP across different elevation bands from 2001-2018, with monthly values calculated as weighted averages based on the temporal span of snow cover observations.

Winter (January): SCP exhibits a distinct pattern, increasing from approximately 20% at low altitudes to 60-70% at 800-1200 m, then declining sharply above 1200 m. This pattern persists through December, February, and March, with SCP remaining at 60-70% in the 800-1200 m zone and showing minimal variation.

Spring (April): SCP increases rapidly from low altitudes to approximately 60-70% at 800-1200 m, then decreases. From May to June, SCP rises steadily across all zones, though the rate of increase diminishes with altitude. In June, SCP shows a gradual upward trend, peaking at 4800-5000 m before declining.

Summer (July-August): SCP remains largely unchanged at low altitudes but increases significantly above 2800 m, reaching maximum values at 4800-5000 m. The ascending trend accelerates above 3200 m, with all zones showing consistent patterns: rapid increase in the 3200-4200 m zone, decreasing ascent rates in the 4200-5000 m zone, and subsequent decline above 5000 m.

Autumn (September-October): SCP shows an upward trend from 600-800 m, peaking at 800-1200 m, then declining to minimum values at 2000-3200 m before rising again. The rate of increase accelerates above 3200 m, reaching peaks at 4800-5000 m. Notably, the 4200-5000 m zone exhibits higher ascent rates than the 3200-4200 m zone.

2.2 Spatiotemporal Variation Characteristics of LST in Chinese Tianshan Mountains

Figure 4 [Figure 4: see original paper] presents the vertical distribution of monthly mean LST across elevation bands, derived from 8-day MODIS LST data averaged for each month. In spring, LST curves show similar patterns, gradually decreasing from high to low altitudes. A temperature inversion occurs between 200-400 m, where LST initially decreases then increases. Summer LST below 5000 m remains relatively stable, while winter LST shows a gradual decline with altitude, reaching minimum values around -29°C.

2.1.2 Intra-Annual Variation of SCP in Different Altitude Zones

Figure 3 [Figure 3: see original paper] displays intra-annual SCP variation across altitude partitions from 2001–2018. Low-altitude zones (A and B) show SCP gradually increasing from January to peak in mid-January (40%), then declining sharply to minimum values by late May before stabilizing. Mid-altitude zones (C and D) exhibit continuous SCP increase from January to late July, reaching peaks exceeding 90%, followed by rapid ablation through August and stabilization at minimum values.

High-altitude zones (E and F) maintain SCP above 60% from January to July, with peaks exceeding 95% in late July. The vertical distribution patterns of SCP and LST show strong correspondence, with inverse temporal trends: SCP increases during LST decline (summer melt period) and decreases during LST rise (winter accumulation period). This inverse relationship demonstrates altitudinal heterogeneity in snow cover vertical distribution.

2.2.2 Intra-Annual Variation of LST in Different Altitude Zones

Figure 5 [Figure 5: see original paper] shows intra-annual LST variation across altitude partitions. All zones share common characteristics: lowest LST occurs in mid-to-late January (winter), while highest LST appears in July–August (summer). As altitude increases, mean LST decreases correspondingly. The LST variation pattern inversely matches SCP: rising LST corresponds to snowmelt, while falling LST corresponds to snow accumulation.

Zones A and B show relatively high LST year-round, with minima around -16°C and maxima near 20°C. Zones C and D exhibit greater seasonal amplitude, with winter minima around -24°C and summer maxima of 8–12°C. Zones E and F maintain the lowest temperatures, with winter minima below -29°C and summer maxima below 8°C. The inverse correlation between SCP and LST is evident across all zones, with correlation coefficients strengthening with altitude up to 4200 m, then weakening above this threshold.

2.3 Correlation Analysis Between SCP and LST

Correlation analysis reveals significant negative relationships between monthly SCP and LST across the Chinese Tianshan Mountains (Table 3). Correlation coefficients (r) range from -0.89 to -0.96 for most months, with the strongest negative correlations occurring in autumn ($r < -0.9$). Winter shows weaker correlations, likely due to abundant low-altitude snowfall, wind-blown snow effects, and temperature inversion phenomena.

Table 4 presents correlation coefficients between SCP and LST for different altitude zones. All zones show significant strong negative correlations ($r < -0.9$), with correlation strength first increasing then decreasing with altitude. The greatest influence of LST on SCP occurs in the 3200–4200 m zone (Zone D), where temperature is the primary control factor on snow distribution. Below

1000 m and above 4200 m, LST exhibits no clear altitude gradient effect, resulting in weaker correlations.

3 Discussion

The vertical distribution of SCP in Chinese Tianshan Mountains shows distinct seasonal patterns, with peaks occurring at 4800–5000 m across all seasons. This aligns with previous findings that SCP increases with altitude, particularly in permanent snow zones above 4200 m. However, this study reveals altitudinal heterogeneity: SCP variation patterns are inverse between high-altitude zones (E and F) and mid-to-low altitude zones (A–D) from October to April. Snow sublimation and wind-blown snow are critical factors reducing snow cover in high-altitude regions. Despite low year-round temperatures satisfying snow preservation conditions, precipitation becomes the decisive factor controlling snow area at high altitudes. Winter precipitation in high mountains is less than in summer, and prevailing westerly winds redistribute snow to valleys and lower altitudes, while dry, windy conditions accelerate sublimation, causing the inverse SCP pattern above 4200 m.

Except in winter, SCP demonstrates significant strong negative correlations with LST in spring, summer, and autumn. Poor winter correlations may relate to greater low-altitude snowfall, wind-blown snow effects, and high-altitude temperature inversion. The influence of LST on SCP varies by altitude: temperature is the dominant control factor within the 3200–4200 m threshold, but above this elevation, snow distribution becomes more complex due to wind redistribution and precipitation patterns. Limited observational data in mountainous regions pose challenges for identifying driving factors of high-altitude snow changes, warranting further investigation. Additionally, the 18-year study period is relatively short for robust interannual variability analysis; longer remote sensing time series will enable more comprehensive future research.

4 Conclusions

This study employed MOD10A2 snow products and MOD11A2 LST data from 2001–2018, applying fine zonal statistics and correlation analysis to investigate the heterogeneity of snow cover vertical distribution and its response to temperature in the Chinese Tianshan Mountains. Key findings include:

1) SCP exhibits four distinct seasonal patterns with altitude. Winter SCP varies dramatically, increasing below 800 m, decreasing between 800–1200 m, and rising significantly above 1200 m to peak at 4000–4200 m. Spring and autumn show similar trends, with gentle increase followed by consistent decrease. Summer SCP rises significantly above 2800 m, peaking at 4800–5000 m before declining rapidly. Each pattern shows unique characteristics across altitude zones, with peaks at 4800–5000 m and significant strong negative correlations between SCP and LST.

2) High-altitude zones (E and F) show inverse SCP distribution patterns compared to mid-to-low altitude zones (A–D), yet both exhibit altitude-dependent sensitivity. SCP is most sensitive in zones C and D (2000–4200 m) from May–September, while zones A, B, E, and F show minimal change and low sensitivity during April–October.

3) Seasonally, SCP and LST show significant strong negative correlations in spring, summer, and autumn (excluding winter). Spatially, the negative correlation strengthens with altitude up to 3200–4200 m, then weakens above 4200 m as LST influence diminishes.

References

[1] Yi Ying, Liu Shiyin, Zhu Yu, et al. Spatiotemporal variation of snow cover in the Yarkant River Basin during 2002–2018[J]. Arid Land Geography, 2021, 44(1): 15–26.

[2] Romanov P, Gutman G, Csiszar I, et al. Automated monitoring of snow cover over North America with multispectral satellite data[J]. Journal of Applied Meteorology, 2000, 39(11): 1866–1880.

[3] Sheng Guangwei, Xiao Pengfeng, Zhang Xueliang, et al. Difference of snow albedo between Tianshan and northern Xinjiang[J]. Arid Land Geography, 2019, 42(4): 774–781.

[4] Chen Y, Li W, Deng H, et al. Changes in Central Asia' s water tower: Past, present and future[J]. Scientific Reports, 2016, 6(1): 35458, doi: 10.1038/srep39364.

[5] Mu Zhenxia, Jiang Huifang. Response of snow melting law of Kunmalike River to climate change in Aksu River Basin, Xinjiang[J]. Journal of Glaciology and Geocryology, 2012, 34(6): 1284–1292.

[6] Tang Z G, Wang J, Li H Y, et al. Spatiotemporal changes of snow cover over the Tibetan Plateau based on cloud-removed moderate resolution imaging spectroradiometer fractional snow cover product from 2001 to 2011[J]. Journal of Applied Remote Sensing, 2013, 7(1): 3582, doi: 101117/1.JRS.7.073582.

[7] Chu Duo, Da Zhen, Laba Zhuoma, et al. Spatial distribution and topographic influence of snow cover in Tibet Plateau[J]. Journal of Geo-Information Science, 2017, 19(5): 635–645.

[8] Chen Wenqian, Ding Jianli, Ma Yonggang, et al. Spatial-temporal variability of snow cover in arid regions of Central Asia[J]. Advances in Water Science, 2018, 29(1): 11–19.

[9] Wei Renjuan, Peng Liang, Liang Chuan, et al. Analysis of snow coverage in Yarkant River Basin based on MODIS snow data[J]. Advanced Engineering Sciences, 2018, 50(6): 141–147.

[10] He Haidi, Li Zhongqin, Zhang Mingjun. Spatio-temporal variation analysis of snow cover area of Tianshan Mountains in China using MODIS data[J]. Arid Land Geography, 2018, 41(2): 367-374.

[11] Qin Yan, Ding Jianli, Zhao Qiudong, et al. Spatial-temporal variation of snow cover in the Tianshan Mountains from 2001 to 2015, and its relation to temperature and precipitation[J]. Journal of Glaciology and Geocryology, 2018, 40(2): 249-260.

[12] Wan Z. New refinements and validation of the MODIS land-surface temperature/emissivity products[J]. Remote Sensing of Environment, 2008, 112(1): 59-74.

[13] Huang Xiaodong, Zhang Xuetong, Li Xia, et al. Accuracy analysis and evaluation of MODIS snow products MOD10A1 and MOD10A2 in northern Xinjiang area[J]. Journal of Glaciology and Geocryology, 2007, 29(5): 722-729.

[14] Ma Yonggang, Huang Yue, Chen Xi, et al. Analyzing spatial-temporal variability of snow cover in Xinjiang[J]. Advances in Water Science, 2013, 24(4): 483-489.

[15] Tang Zhiguang, Wang Jian, Wang Xin, et al. Spatiotemporal variation of snow cover in Tianshan Mountains based on MODIS[J]. Remote Sensing Technology and Application, 2017, 32(3): 556-563.

[16] Ren Yanqun, Liu Hailong, Bao Anming, et al. Spatial and temporal characteristics of snow depth in the Tianshan Mountains derived from SSM/I and MODIS data[J]. Journal of Glaciology and Geocryology, 2015, 37(5): 1178-1187.

[17] Hou Xiaogang, Li Shuai, Zhang Xu, et al. Study on spatial and temporal distribution of snow cover in Tianshan Mountains of China based on daily cloudless snow cover product of MODIS[J]. Desert and Oasis Meteorology, 2017, 11(3): 9-16.

[18] Li H Y, Wang J, Hao X H. Role of blowing snow in snow processes in Qilian mountainous region[J]. Sciences in Cold and Arid Regions, 2014, 6(2): 124-130.

[19] Liu J P, Zhang W, Liu T. Monitoring recent changes in snow cover in Central Asia using improved MODIS snow cover products[J]. Journal of Arid Land, 2017, 9(5): 763-777.

[20] Sorg A, Bolch T, Stoffel M, et al. Climate change impacts on glaciers and runoff in Tien Shan (Central Asia)[J]. Nature Climate Change, 2012, 2(10): 725-731.

[21] Hu Ruji. Physical geography of the Tianshan Mountains in China[M]. Beijing: China Environmental Science Press, 2004: 10-29.

[22] Beniston M. Is snow in the Alps receding or disappearing?[J]. WIREs Climate Change, 2012, 3(4): 349-358.

[23] Tejeda E, López-Morán J I, Beniston M. The changing roles of temperature and precipitation on snowpack variability in Switzerland as a function of altitude[J]. Geophysical Research Letters, 2013, 40: 2131-2136.

[24] Pu Z, Xu L, Salomonson V V. MODIS/Terra observed seasonal variations of snow cover over the Tibetan Plateau[J]. Geophysical Research Letters, 2007, 34(6): 137-161.

[25] Aikemu Roukeyamu, Rusuli Yusufujiang. Analysis of snow cover distribution and its changes in the Ili River Valley[J]. Science of Surveying and Mapping, 2020, 45(6): 157-164.

[26] Bi Y B, Xie H J, Huang C L, et al. Snow cover variations and controlling factors at upper Heihe River Basin, northwestern China[J]. Remote Sensing, 2015, 7(6): 6741-6762.

[27] Guan Yanlong, Wang Ranghui, Li Cheng, et al. Spatial-temporal characteristics of land surface temperature in Tianshan Mountains area based on MODIS data[J]. Chinese Journal of Applied Ecology, 2015, 26(3): 681-688.

[28] Xu Yongming, Tan Zhihao, Shen Yan. The relationship between interannual variations of land surface temperature and climate factors in the Yangtze River Delta[J]. Remote Sensing for Natural Resources, 2010(1): 60-64.

[29] Li Xuemei, Gao Pei, Li Qian, et al. Multi-paths impact from climate change on snow cover in Tianshan mountainous area of China[J]. Climate Change Research, 2016, 12(4): 303-312.

[30] Dou Yan, Chen Xi, Bao Anming, et al. Study of the temporal and spatial distribution of the snow cover in the Tianshan Mountains, China[J]. Journal of Glaciology and Geocryology, 2010, 32(1): 28-34.

[31] Wei Wenshou, Yuan Yujiang, Yu Shulong, et al. Climate change in recent 235 years and trend prediction in Tianshan Mountainous area[J]. Journal of Desert Research, 2008, 28(5): 803-808.

Note: Figure translations are in progress. See original paper for figures.