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Snow cover dynamics in and around the Shangri-La County, southeast margin of the Tibetan Plateau, 1974–2012: the influence of climate change and local tourism activities

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The Shangri-La County and its surrounding areas lie within the Hengduan Mountains system at the southwestern margin of the Tibetan Plateau, and belong to the core zone of Three Parallel Rivers of Yunnan Protected Areas. There are numerous snow mountains of special ecological and cultural significance. The investigation of snow cover dynamics is important for understanding how snow cover responds in the context of climate change. In this study, the spatial and temporal dynamics of snow cover in the entire area were analysed using 28-scene Landsat images from 1974–2012. Snow cover variability of different altitudinal zones and orientations was also discussed. Then, we explored the relationship between snow cover dynamics and both climate change and local tourism activities. The results show that snow cover area in the Shangri-La region continued a clear decreasing trend in the last 40 years, declining from 4188 km² in 1974 to 901 km² in 2012. The decrease of snow cover generally occurred from low to high altitude and was most pronounced at altitudes of 4000–5000 metres, with a reduction of 2800 km² since 1974. Snow cover decreased more significantly in the northwest part of the area than in the southeast. The primary driving force for this decrease was attributed to the increase in air temperature (+0.22°C per decade in the area). Compared with a similar decreasing trend in the Meili Snow Mountains, a dramatic reduction of snow cover in the southeastern Yulong Snow Mountains is attributed partially to local tourism activities.

Keywords: snow cover; climate change; tourism activity; Meili Snow Mountains; Shangri-La County

Introduction

Snow is an important natural resource (for biodiversity, stream flows, soil water) (Liu et al. 2009; Mu et al. 2010; Thondhlana et al. 2012) and has social value (tourism, drinking water supply, hydropower, agriculture and mining) (Elsasser & Messerli 2001; Shackleton & Shackleton 2012; Vocciaa 2012; Apantaku et al. 2013; Næss 2013). Snow accumulation and melt are governed primarily by air temperature, precipitation and surface relief (Xu et al. 1994; Liston 1999; Vikhamar & Solberg 2003; Lopeza et al. 2008). The spatial and temporal trends of snow cover dynamics can be used as sensitive indicators of climate change (Blöschl 1999; IPCC 2007; Naustdalslid 2011). The Tibetan Plateau, the world's third pole (Qiu 2008), is the Earth's highest region and stores the largest volume of snow and glaciers outside the polar regions, and has a strong influence on regional and global climate (Manabe & Broccoli 1990; Yanai & Wu 2006; Wu et al. 2007). Moreover, many studies have found that the Tibetan Plateau is one of the most sensitive areas (Liu & Chen 2000) and has been characterized as a driving force and amplifier for global climate change (Pan & Li 1996). A significant temperature rise of 0.3°C per decade has been ongoing for 50 years on the Tibetan Plateau – approximately three times the global warming rate (Qiu 2008). Another 4°C warming will likely occur on this plateau during the next century. Snow and glacier

retreat, mainly attributed to continued and accelerated temperature increases (Lau et al. 2010), increased greatly during the last century, especially the last 10 years (Yao et al. 2004). This brought major consequences for climate, ecosystems and human well-being. From an ecological perspective, the margins of the plateau in transitional areas often react more quickly and strongly to climate effects (Neilson 1993; Kupfer & Cairns 1996; Beckage et al. 2008; Beier et al. 2012). According to glacier observation data, the magnitude of glacier retreated on the Tibetan Plateau increased from the inland to the margins, reaching a maximum on the southeast plateau (Yao et al. 2004). Monitoring in these areas can be especially informative and serves for trend detection of climate change in the broad inland of the plateau. It, therefore, is of great value to analyse the long-term snow cover extent dynamics on the southeastern margin of the Tibetan Plateau.

Shangri-La County is located within the Hengduan Mountains system on the southeastern margin of the Tibetan Plateau. The name of 'Shangri-La' was officially titled in 2001, which was from the novel 'Lost Horizon' by British author James Hilton. The mystical cultural and physical inspiration for Hilton's Shangri-La has been pursued as a great opportunity for tourism development in the area (Xu 2008). Well-known as the Tibetan customs, plateau landscape and snow mountains, it has become a centre for tourism activities. There are several important

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and famous snow mountains of the southeastern Tibetan Plateau concentrated in Shangri-La County and its surrounding areas, which are important natural and tourism resources. In this study, considering the distribution of snow mountains and scope of tourism activities, we took Shangri-La County and its surrounding areas as the study area and analysed spatial and temporal variability of snow cover. The area covers roughly 47,000 km², from longitude 98°32' to 100°21' East and latitude 26°49' to 29°17' North (Figure 1). This area is the core area of the Three Parallel Rivers of Yunnan Protected Areas, the Jinsha, Lancang and Nu rivers run roughly parallel from north to south through steep gorges, some of which reach 3000 metres deep and are bordered by glaciated peaks more than 6000 metres high, enriching their outstanding landscape diversity and biodiversity. Changes in snow cover have dramatic impacts on water resource supplies and ecosystem structure, as well as on tourism development. The objective of this study is to analyse the snow cover dynamics during 1974–2012 and to explore the potential relationship between snow cover

dynamics and both climate change and local tourism activities.

Data and methods

Data

Given extensive cloud coverage from May to August in the Shangri-La County and its surrounding areas, clear-sky, dry-season Landsat images in the winter half year (October to March) are most suitable for identifying snow-covered areas at regional scale. We used 28 scenes of Landsat Multispectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) images from 1974 to 2012, acquired from the United States Geological Survey and Global Land Cover Facility at the University of Maryland. Landsat MSS images consist of four spectral bands with 60 metre spatial resolution. Bands 2 to 5 of Landsat TM/ETM+ images that were used have spatial resolution 30 metres. Data and sensor types for each image are shown in Table 1.

Figure 1. Map of the study area including major geographic features and its location.

Table 1. Path, row, acquisition date of Landsat MSS/TM/ETM+ images in the Shangri-La region from 1974 to 2012.

No.	Path-row	Acquisition date	Sensor type	No.	Path-row	Acquisition date	Sensor type
1	p141r040	4 January 1974	MSS	15	p132r041	25 December 2000	ETM+
2	p141r041	4 January 1974	MSS	16	p133r040	19 December 2001	ETM+
3	p142r040	5 January 1974	MSS	17	p131r041	11 December 2006	TM
4	p142r041	5 January 1974	MSS	18	p132r040	13 November 2005	TM
5	p131r041	2 January 1989	TM	19	p132r041	26 November 2004	TM
6	p132r040	30 December 1993	TM	20	p133r040	4 November 2005	TM
7	p132r041	4 November 1990	TM	21	p132r040	24 November 2009	TM
8	p133r040	16 November 1992	TM	22	p131r041	27 December 2009	ETM+
9	p131r041	13 December 1995	TM	23	p132r041	5 December 2010	ETM+
10	p132r040	6 December 1996	TM	24	p133r040	23 November 2009	ETM+
11	p132r041	6 December 1996	TM	25	p131r041	9 March 2013	ETM+
12	p133r040	24 October 1996	TM	26	p132r040	27 January 2013	ETM+
13	p131r041	26 December 2000	TM	27	p132r041	22 November 2011	ETM+
14	p132r040	25 December 2000	ETM+	28	p133r040	15 November 2012	ETM+

Other data include: (1) ASTER Digital Elevation Models (DEMs) with 30 metre spatial resolution, released by the Ministry of Economy, Trade and Industry of Japan and National Aeronautics and Space Administration. These DEMs were used for identifying actual extent of snow covered area and snow cover variability in altitudinal zones, as well as for detecting altitude ranges of snowline change in typical snow mountains(Xiao et al. 2010); (2) Rivers and county boundaries were from the National Geomatics Center of China; (3) Mean monthly temperature and precipitation data in the winter half of the year during 1951–2012 from 17 long-term meteorological stations (Dari, Ganzi, Maerkang, Songpan, Litang, Deqin, Jiulong, Xichang, Lijiang, Tengchong, Chuxiong, Kunming, Lincang, Lancang, Simao, Mengzi and Wanyuan) were used for exploring the potential relationship between snow cover dynamics and climate change.

Snow cover mapping and topographical correction

Snow cover mapping used an algorithm based on the Normalized Difference Snow Index (NDSI) for Landsat TM/ETM+ images and Supervised Classification for Landsat MSS images.

Snow-cover mapping using SNOMAP algorithm for Landsat TM/ETM+

The SNOMAP algorithm (Riggs et al. 1994; Hall et al. 1995) based on the NDSI was originally designed for global snow cover mapping, using a normalized difference between Moderate Resolution Imaging Spectroradiometer (MODIS) Bands 4 and 6. The algorithm has been widely used for snow cover mapping at regional scale using Landsat TM/ETM+ Bands 2 and 5 (Crane & Anderson 1984; Dozier & Marks 1987; Dankers & De Jong 2004). The NDSI functions based on the fact that snow is highly reflective in the visible part of the spectrum and highly absorptive in the mid-infrared part of the spectrum; cloud reflectance remains high in those same parts of the

spectrum, allowing effective discrimination between snow cover and clouds. The algorithm was improved with several spectral tests. The reflectance of TM Band 4 must be >11% to distinguish snow from water bodies with weaker absorption in the near-infrared part of the spectrum. Another important modification was that the Normalized Difference Vegetation Index (NDVI) and NDSI were combined to enhance snow cover identification in densely forested areas (Klein et al. 1998). All thresholds of the above indices were proven effective with snow classification accuracy of >90% (Hall et al. 1998). The algorithm can be conducted that snow is mapped in the pixel if the Band 4 reflectance is >11% and the NDSI ≥ 0.4 , or if the Band 4 reflectance is >11%, $\text{NDVI} \geq 0.38$ and $0.1 \leq \text{NDSI} < 0.4$. The NDSI and NDVI for Land sat TM/ETM+ images are calculated using the following equations:

$$\text{NDSI} = \text{float}(\text{band2} - \text{band5}) / (\text{band2} + \text{band5}) \quad (1)$$

$$\text{NDVI} = \text{float}(\text{band4} - \text{band3}) / (\text{band4} + \text{band3}) \quad (2)$$

Snow-cover mapping using supervised classification for Landsat MSS

Supervised classification was performed for each calibrated Landsat MSS image using the Bayesian maximum likelihood (ML) classifier with all spectral bands and two classes, snow and non-snow. For each class, training areas were established by choosing one or more individual polygons to provide parameters for the Bayesian probability function calculation. This information was used by the ML classifier to assign each pixel to a particular class by their spectral values, rather than manual interpretation.

Based on the snow cover mapping, actual snow-covered area and snow coverage rate were calculated based on Equations 3 and 4, respectively (Lin et al. 2011). Topographic correction using DEMs was done to account for slopes for each pixel to calculate actual snow-covered surface area. Snow coverage rate indicated the actual area percentage that was snow-covered.

$$\text{Pixel surface area} = [\text{pixel resolution} / \cos(\text{pixel slope})]^2 \quad (3)$$

in which, corrected Landsat MSS images were resampled to spatial resolution 30 metres, and the pixel resolution of 30 metres is the same spatial resolution of DEMs and images.

$$\text{Snow coverage rate} = S_{\text{snow-covered}} / S_{\text{total}} \times 100\% \quad (4)$$

where $S_{\text{snow-covered}}$ is actual snow-covered area, S_{total} is the actual study area.

Results and discussion

Spatio-temporal variability of snow cover

Interannual variability of snow cover

Snow-cover fluctuations in the Shangri-La County and its surrounding areas during the past 40 years were investigated by comparing snow cover extent for the years 1974, 1990, 1995, 2000, 2005 and 2012 using Landsat images (Figure 2 (a–f)). The snow cover extent was 4188.45 km² in 1974 and only 901.55 km² in 2012, a difference of 78%, representing a decreasing trend of 88 km² per year from 1974 to 2012. Temporal trends of the annual average decrease of winter snow cover are significant, although the magnitude of these decreases varies considerably in different periods. During 1974–1990, the extent of snow cover in this area decreased by as much as 2874 km², at

a rate of 190 km² per year. There were reductions of 4.28% in snow coverage rate for the entire region (6.23% in 1974, 1.96% in 1990), especially in the eastern part of the area. The trend of snow cover shrinkage persisted but slowed from 1990 to 2012, at a rate of 20 km² per year, corresponding to about 412 km² snow cover shrinkage. The extremely large snow cover extent in 1974 may be the result of different spatial resolutions between Landsat MSS and TM images. There was 1841.91 km² of snow cover in 2000, the abrupt increase of snow cover in 2000 was closely linked to heavy precipitation in early December 2000, before the satellite passed by.

Snow cover variability in different altitudinal zones

Temperature and precipitation are the most important climatic factors for snow accumulation, as well as predictors of snow cover variability. The adiabatic gradient implies that temperatures decrease with height in mountains. In addition, topography enhances the uplift of moist air, triggering condensation and precipitation (Barry 2008). Temperature (precipitation) decreases (increases) with height (Morán-Tejeda et al. 2013). Altitude is thus one of most important geographic influences on snow cover distribution and variability at small spatial scales. Snow coverage rate generally increases with altitude and a decrease of snow cover also occurs from low to high altitude, which is consistent with our results. Figure 3 shows that snow

Figure 2. Dynamics of snow-covered areas in Shangri-La region in winter half year of 1974, 1990, 1995, 2000, 2005 and 2012. (a)–(f) show snow-covered areas in white colour, (g) indicates the variation tendency of snow-covered areas in unit of square kilometre.

Figure 3. Annual dynamics of snow coverage rate in different periods and altitudinal zones.

coverage rate at low altitudes declined earlier and faster than at high altitudes. In areas at altitude below 4000 metres, average snow coverage extent was approximately 200 km² and the coverage rate was less than 1%. Thus, interannual variability of snow cover in this altitudinal zones, which was most probably induced by temperature and precipitation fluctuations, contributed little in the Shangri-La County and its surrounding areas. However, snow cover extent at altitude ranges of 4000–4500 and 4500–5000 metres, which comprised 80% of snow in the region, decreased substantially over the last 40 years. The rate of decrease was 30 km² per year at 4000–4500 metres and 47 km² per year at 4500–5000 metres, corresponding to decadal decreases in snow

coverage rate of 2.6% and 8.5%, respectively. Snow cover extent at altitudes of 4000–5000 metres significantly decreased by about 2800 km² since 1974, the most pronounced impact on the decreasing trends of the entire area. At high altitudes, snow coverage extent decreased by 35 km² (9% of snow coverage rate) from 1974–2012 in the 5000–5500 metre zone. At altitudes over 5500 metres, there was a minor reduction of snow coverage rate, with that rate remaining nearly stable at 55%.

Snow cover variability in different orientations

Given an obvious district difference, we subdivided the study area into four orientations: NE (northeast), NW (northwest), SE (southeast) and SW (southwest), based on natural boundaries delineating similar climate and geographic characteristics in these orientations. Figure 4 shows that during 1974–2012, the decrease of snow cover extent was particularly pronounced in northern areas (NE and NW). In the NE, the snow coverage rate declined from 5.8 to 0.3%, and there was only 100 km² of snow cover left. There are many snow mountains with a complete vanishing of snow on peaks. The investigation results also represented that in the Shika Snow Mountains, south of Napahai wetland, permanent snow patches were disappearing and local people come up to the highest altitude of 4450 metres to herd sheep. Snow cover extent in the NW comprised 81% of the total (2012: 734 km²) and decreased about 1400 km² during 1974–2012, determining the decreasing trend in this area. In addition, the fluctuations of snow cover in different altitudinal zones in the NW were largely consistent with snow cover changes in the entire area. In the SE, snow cover continued to

Figure 4. Dynamics of snow coverage rate in four different orientations (northwest/northeast/southwest/southeast) in Shangri-La region. The legend 'Zoning scheme' shows the distribution of different regions. The legend 'Altitude range' indicates the line and symbol for snow coverage rate in different altitude range that applies to all four orientations.

decrease at various altitudes and there was an abrupt increase in 2012. In the SW, snow was located at lower altitudes and showed large fluctuations.

Relationship between snow cover dynamics and climate change

Snow cover variability is intimately associated with changes of air temperature and precipitation. Precipitation determines the overall amount of snow, but air temperature determines whether the precipitation falls as rain or snow and governs the rate of snow melt (Zhang et al. 2005). Data from 17 weather stations in and around the study area during 1951–2012 show that the rise in mean winter temperature reached 0.22°C per decade over the last 40 years, whereas mean winter precipitation slowly increased at 3.3 mm per decade with an average of 180 mm in winter (Figure 5 upper). Cumulative values of temperature and precipitation for 1951–2012 (Figure 5 bottom) are plotted rather than individual years, so each year reflects temperature and precipitation anomalies in previous years. The trend of winter temperatures was cooling during 1951–1985. An upward concavity signals that warming began after about 1985. There are also apparent fluctuations of short period over 1985–1995. Snow cover extent during 1974–2012 declined consistently, with increasing temperature during 1985–2012. The recent rise in temperatures had a significant influence on snow cover. The decrease of snow cover extent in the entire area or in different directional regions was greater at high altitudes than at low latitudes. This might be attributed to warming that was more pronounced at higher altitudes

than at lower sites, especially during winter and spring (Su et al. 2003). The dependency of snow on seasonal temperature made the snowpack at mid-altitudes highly vulnerable to climate warming.

Relationship between snow cover dynamics and local tourism activities

Apart from the influence of climate change, there has been a boom of snow mountain tourism, which has brought substantial income to the area and has expanded tremendously, with tourists increasing by 220% in the last 3 years. This activity likely also poses direct impacts on snow cover in these mountains. The Meili Snow Mountains in the NW of the study area and the Yulong Snow Mountains in the SE are the most popular attractions for snow mountain tourisms in the area. These two mountains have great religious importance to the Tibetans and Naxi people, respectively. However, none of the major peaks in the Meili Snow Mountains have ever been summited because of restrictions and dangerous conditions. Most tourists enjoy a distant view of Meili. In the Yulong Snow Mountains, the highest viewing deck is at 4680 metres and open all year around. People can climb or take the cableway up to the deck or closer to the peaks, at an altitude of 5596 metres. In the context of climate change, therefore, these two snow mountains, with obvious differences in geographic location and tourism patterns, are very suitable for addressing whether, how and to what extent snow mountain tourism activities affect snow cover. The results show that although snow cover continued to decrease and snowline altitude remained to

Figure 5. (a) Dynamics of temperature and precipitation (averaged from October to March in winter half year) over the seasons of 1951 ~ 2012; (b) Cumulative anomaly percentage of temperature and precipitation during 1951 ~ 2012, and snow cover dynamics during 1974 ~ 2012. The black solid and dotted lines in Figure 5 (a) refer to the trend lines of temperature and precipitation, respectively.

Figure 6. Dynamics of snow-covered areas in two typical snow mountains: (a) Yulong and (b) Meili Snow Mountains during 1974–2012. The legends on the right applies to both images.

rise over the last 40 years in both Yulong and Meili (Figures 6 and 7), snow cover extent in Meili decreased by 400 km² over the last 40 years – approximately eight times that of Yulong’s decrease. Similarly, local observations of snow cover changes in Meili demonstrated that snow retreated 1000 metres upward from the observed point in the last 20 years. The magnitudes of snow cover changes in Meili were much greater than those in Yulong, consistent with the trends of strong decrease of snow cover in the NW and slight decrease in the SE of the study area.

Thus, the decreases of snow cover in both mountains were fundamentally attributed to climate change.

Snow coverage rate with various orientations in Meili declined at a similar rate. In Yulong, the rate in the SE and NE orientations declined more quickly than other orientations (Figure 7), which corresponds well to locations of tourism activities and relevant infrastructures. The snow become more accessible to tourists by construction of cableways and buildings near peaks, and the number of tourists increase yearly. Tourism activities and relevant

Figure 7. Variability of snow coverage rate in different aspects in Meili and Yulong Snow Mountains. The words of N, NE, E, SE, S, SW, W and NW refer to the sectors between $-22.5 \sim 22.5^\circ$, $22.5 \sim 67.5^\circ$, $67.5 \sim 112.5^\circ$, $112.5 \sim 157.5^\circ$, $157.5 \sim 202.5^\circ$, $202.5 \sim 247.5^\circ$, $247.5 \sim 292.5^\circ$ and $292.5 \sim 337.5^\circ$, respectively, which was centred in each highest peak.

infrastructures probably had negative impacts on snow cover extent, as shown in Figure 7.

Conclusions

The aim of this study was to investigate spatial and temporal variability of snow cover extent in the Shangri-La County and its surrounding areas, and to explore the relationship between snow cover dynamics and both climate change and local tourism activities. This study indicates that snow cover extent had strong temporal variability, with an obvious decreasing trend during 1974–2012. There was 4188.45 km² of snow cover extent in 1974, and 901.55 km² of snow left in 2012, with a significant reduction of 78%. The decrease of snow cover generally occurred from low to high altitude, and was most pronounced at altitudes of 4000–5000 metres with a reduction of 2800 km². Snow cover decreased more significantly in the NW of the study area than in the SE. The primary reason for the decreased snow cover extent and increased altitude of the snow boundary was climate change, particularly the accelerated air temperature during the last 40 years (+0.22°C per decade in this area). In addition, tourism activities and relevant infrastructures in the snow mountains, causing direct disturbance of the snow, could have partially contributed to the decrease of snow cover extent. It implied that ongoing local and global climate change would lead to further decrease of snow cover extent, strongly influencing local ecological functions and resource management. Besides, reasonable arrangement and management of tourism activities are important for local snow mountains protection and regional sustainable development.

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