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Article

Temporal and Spatial Aspects of Snow Distribution in the Nam Co Basin on the Tibetan Plateau from MODIS Data

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Abstract: Large areas of the Tibetan plateau are only covered by a sparse network of ground snow sampling stations, while the snow cover is highly heterogeneously distributed due to wind, topography *etc*. Nevertheless, the snow accumulation and spatial patterns play an important role in the hydrological cycle. It releases moisture during the dry spring period before the onset of the monsoon season. Widely used MODIS snow cover products have been available globally since 2002. The understanding of the temporal and spatial distribution of snow cover in a given region calls for a comprehensive data representation method. In this paper a method to visualize both spatial and temporal aspects of snow cover distribution from MODIS 8-day composite data is presented. It is based on RGB display of the snow cover data which is grouped according to season. The RGB syntheses of snow cover distribution (RSD) were generated for the Nam Co Basin in the central part of the Tibetan Plateau during the years of 2002–2009. An alternating pattern of monsoon and autumn snow cover was identified in the western part of the basin which corresponds to the biennial character of the variations of the Indian monsoon. Monsoon snow cover was found in RSD images for the years 2002, 2004 and 2008 whereas in years 2003 and 2009 the autumn snow cover is dominant. The eastern part of the basin does not follow this general pattern since it is affected by the so called “lake effect”, which is a snow fall induced by the passing of dry and cold westerlies over the lake surface during the winter months. The years 2002, 2006 and 2007 were identified as years with a particularly strong lake effect from the RSD images. Areas with permanent snow cover and areas that were snow free were both found to be relatively stable. Comparison of the lake effect at Nam Co with nearby Siling Co, where the lake effect is smaller or absent, suggests that the presence of an effective barrier on the opposite side of the lake is a prerequisite for the occurrence of the strong lake effect.

Keywords: Tibetan Plateau; Nam Co Basin; MODIS; snow distribution; RGB synthesis

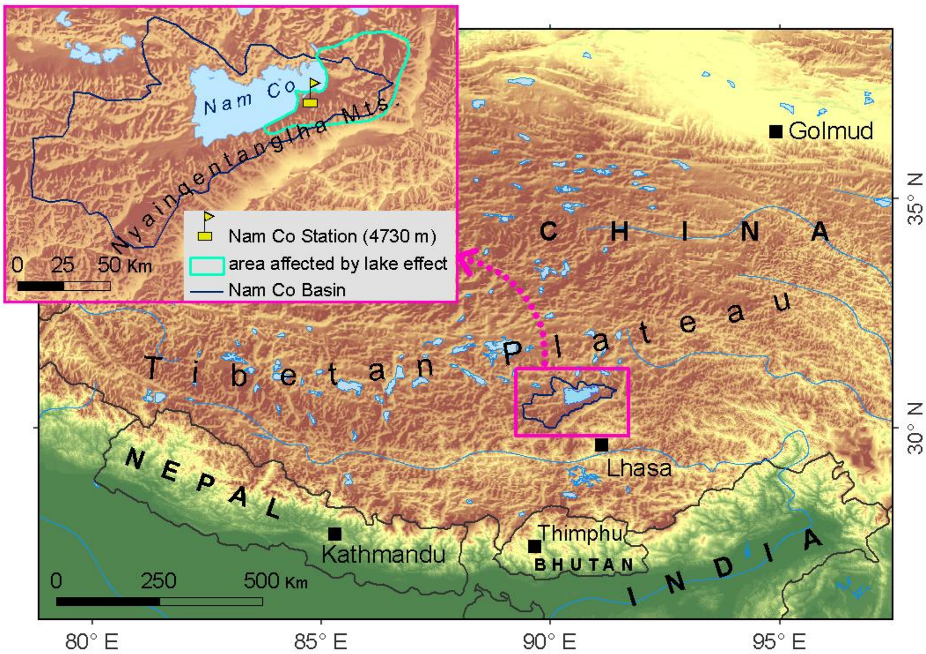
1. Introduction

The temporal and spatial distribution of the snow cover is an important indicator of the local climate. Snow distribution reflects variations of temperature and precipitation with high sensitivity and therefore in a longer perspective it can be an indicator of climate change. It is known that the snow cycle on the Tibetan Plateau affects Asian and global climates. For instance Li *et al.* [1] found a relationship between the winter snow cover over the Tibetan Plateau and the summer rainfall in China, especially in the region of the Yangtze River valley. Li *et al.* [2] argues that the Tibetan snow cover depth largely affects the Asian monsoon rainy season. Snow cover on the Tibetan Plateau is often linked to climate change, though much uncertainty remains regarding the magnitude and mechanisms since the monitoring of the snow cover is insufficient and is based on low resolution microwave instruments [3].

The Nam Co Basin was selected as study area for its outstanding characteristics of the snow cover distribution. It is situated in the central part of the Tibetan Plateau (30°N, 90°E), approximately 100 km NW from Lhasa (Figure 1). The basin is delimited from the south east by Nyainqentanglha Mountain Range which modifies movements of air masses and affects the distribution of precipitation. The basin is in a zone of marginal influence of the Indian monsoon. Snowfall is mainly concentrated in the eastern part of the basin. This effect was described as lake effect by [2]. It occurs when cold northwesterly winds pass over the relatively warmer lake water causing snowfall on the opposite side of the lake. The occurrence of the lake effect corresponds well to the period of the highest temperature difference between the air and the lake surface as reported by [4]. This choice of study area was also motivated by availability of hydro-meteorological data, which has been measured since 2005 at the Nam Co Station for Multisphere Observation and Research operated by the Institute of Tibetan Plateau Research (from hereon referred to as 'Nam Co station').

However, the point snow measurements have a limited validity for large areas. Even though an abundance of satellite based snow cover data is available or can be easily generated, it is not an easy task to get a comprehensive idea about the spatial and temporal distribution of the snow cover in a given region. Understanding the impact of various factors affecting the snow cover distribution, e.g., altitude, topography, prevailing winds or moisture loaded monsoons in a given area calls for a comprehensive data representation method.

Figure 1. Nam Co basin is located in the center of the Tibetan Plateau. Its altitude ranges from 4,718 m to 7,162 m. The background image is an elevation map based on the SRTM and GTOPO30 digital elevation models.



Methods of snow cover mapping from optical satellite imagery have been well established since the 1980s [5,6]. Attention is mostly paid to snow extent, estimation of spectral albedo, grain size, contaminants and liquid water content or water equivalent [7]. Since 2002, the snow-mapping community has benefited from the availability of MODIS snow-cover products [8,9]. MODIS (Moderate Resolution Imaging Spectro-radiometer) is a multispectral instrument onboard the Terra and Aqua satellites. MODIS data is acquired globally every one to two days by both Terra (in the morning) and Aqua satellites (in the afternoon). MODIS snow products feature global coverage and good distinction of snow and clouds at a reasonable resolution of 500 m [9].

Snow cover distribution over the Tibetan Plateau has been examined with optical instruments by [10] using MODIS/Terra data. They have reported a high accuracy (90%) of the data by comparison with Chinese *in situ* snow observations. They identified areas of the most persistent snow cover on the Tibetan Plateau which are located on the southern and western margins of the plateau and in the western part of the Yarlung Zangbo valley. Xu *et al.* [11] carried out sub-pixel classification of MODIS data for extraction of the fractional snow cover over the Tibetan Plateau for the year 2004. They reported a change of the overall snow cover for one year with a maximum in January and February. Shreve *et al.* [3] compared different optical snow indices for the estimation of the fractional snow cover in the western Tibetan Plateau calculated from MODIS data. They introduced new indices in order to improve the accuracy of actual snow estimates; however they don't account for temporal variability of snow cover.

The presented study is part of the Priority Program 1372 of DFG (German Research Foundation) (Tibetan Plateau: Formation–Climate–Ecosystems), which focuses on the formation of the Tibetan Plateau as well as its recent and future climate and ecosystem dynamics. This paper presents a method of visual representation of the time series from MODIS snow cover data that accounts for both spatial and temporal aspects. Usefulness of this method is tested by analysis of the influence of summer monsoon and of the lake effect on snow cover pattern in Nam Co Basin.

2. Study Area

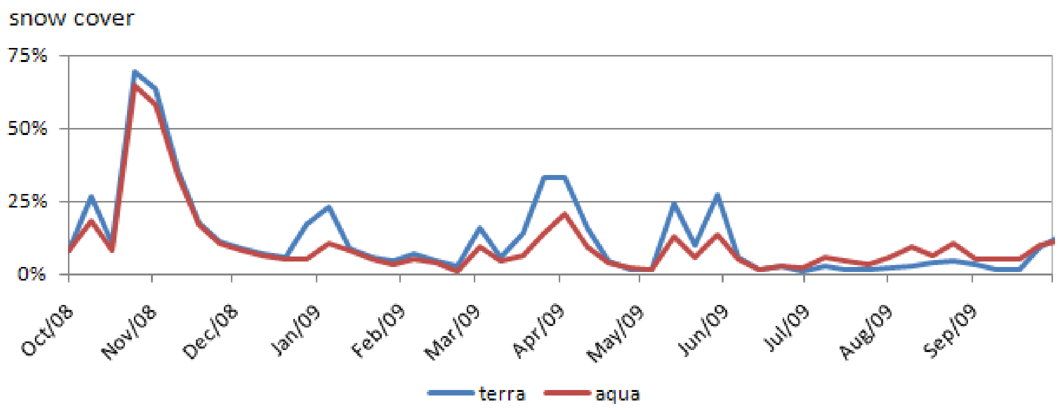
Nam Co is a large saline endorheic lake at an altitude of 4,725 m a.s.l. The basin includes the northern face of the glacier covered Nyainqentanglha Mountain Range that reaches 7,162 m. It is mainly covered by grasslands used as pastures for yaks and sheep [14]. With a mean annual precipitation of 414 mm (Nam Co Station) it belongs to the semiarid zone. Nam Co Basin is affected by the Indian monsoon in summer from June to September. In this period, the mean monthly temperatures rise above 0 ℃ [15]. During the cold period from October to May the weather is mainly driven by cold and dry westerlies [16]. The snow accumulation in the eastern part of the basin caused by the lake effect plays an important role in the hydrological cycle because it sustains water availability during the dry spring period before the onset of the monsoon season. This effect is known to the local nomadic population, who move together with their herds to the south eastern part of the basin in spring [17].

3. Methods: RGB Synthesis of Snow Distribution (RSD)

In order to understand the spatial and temporal variability of snow cover in the Nam Co Basin in the context of the Tibetan Plateau, we analyzed a time series of MODIS/Terra and MODIS/Aqua Snow Cover 8-day composite data. We used standard product MODIS Snow Cover 8-Day L3 Global 500 m Grid, Version 5 [8]. The data is based on a snow mapping algorithm that utilizes a Normalized Difference Snow Index (NDSI) and two additional criteria tests: The thresholds of Band 2 and Band 4. The NSDI together with the normalized difference vegetation index (NDVI) is used to map snow in dense forests. The 8-day composite data minimizes the influence of cloud cover. The data quality assessment was carried out by [12]. There is a slight difference in the snow detection algorithm used for Aqua and Terra. This is due to the malfunctioning of detectors of Band 6 on Aqua, which has been replaced by Band 7. However the bands are very similar and only small differences were found between Terra and Aqua snow products under good viewing conditions by Riggs and Hall [13].

To assess the differences of Terra and Aqua data for the studied region, curves of total snow cover area in the year 2009 for both Terra and Aqua satellites were extracted from MODIS 8-day snow composites (Figure 2). There is a difference between the curves especially noticeable in the spring period. These differences could possibly be explained by snow melt and cloud cover dynamics between Terra and Aqua flyovers. In particular, high solar radiation and low air pressure leads to fast snow melt and sublimation during the day. A small dissimilarity in snow algorithm used for Terra and Aqua products (as mentioned above) may also have contributed to the difference.

Figure 2. Comparison of snow cover percentage of the whole square subset area of Nam Co Basin from Terra (morning overpass) and Aqua (afternoon overpass) data for the year 2009.

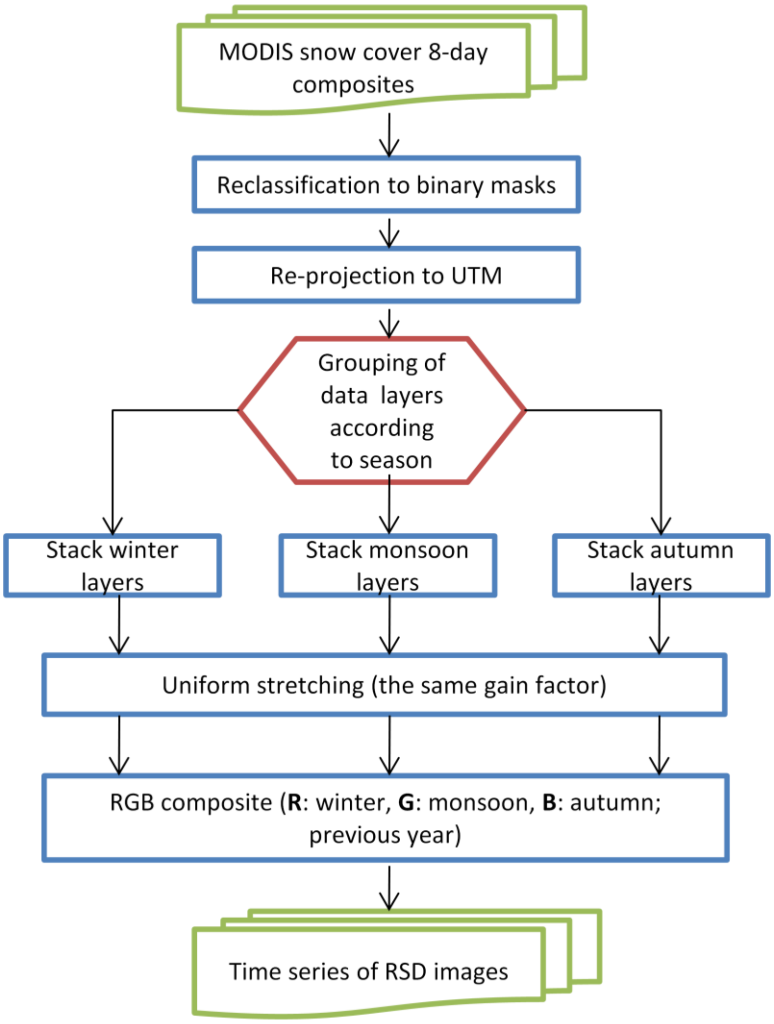


We developed a method for visualization of the annual cycle of spatial snow distribution by RGB synthesis. For the RGB synthesis of snow distribution (RSD), the 8-day MODIS snow data were divided into three groups representing three seasons (see below). Values representing the presence of snow in a particular pixel were summed up for every season. The resulting layers were stretched in a uniform way in order to fit the interval 0–255. The same gain values were used for all seasons and for all the years in order to preserve ratios between the three seasons and comparability of RSD images between the years. The obtained layers were visualized in the RGB display (Figure 3). No additional color contrast enhancements were applied on the resulting images.

The three seasons were set up in such a way that typical snow precipitation patterns were respected. We distinguished following seasons: autumn (October–December), winter (January–April) and monsoon season (May–September). During monsoon high precipitation and southerly winds prevail. monsoon season was thus defined as a time period with monthly mean temperatures above zero and high precipitations. The precipitations are mainly in the form of rain on the plateau and snow in the mountains. Meteorological records from the Nam Co Station were used for the period 2005–2009. The beginning of May and the end of September appears to be delimitation of the summer monsoon season in the Nam Co Basin. In the second part of the year temperatures drop below zero and the atmospheric circulation is driven by dry westerlies. The cold period from October to April was divided into autumn and winter seasons. For each year, the autumn season of the previous calendar year was used in order to keep adjacent autumn and winter season of the same cold period together. The division of the cold period into autumn and winter seasons allows one to distinguish during which parts of the cold period the occurrence of snow cover took place according to shades of blue, magenta and red.

The selected approach depicts snow cover distribution in such a way that the primary colors represent dominant snow cover in a single season. Secondary colors correspond to dominant snow cover that prolongs during two seasons. Magenta represents snow cover during both autumn and winter seasons. Cyan is used for the combination of monsoon and autumn seasons and yellow corresponds to dominant snow cover in both the winter and monsoon seasons. The color intensity also shows duration of the snow cover since it is dependent on the number of eight day periods of MODIS snow composites with detected snow cover (Figure 3). Legibility of these RSD images is aided by the fact that permanent snow is displayed in white and the areas of no snow cover are in black.

Figure 3. Flow chart of data processing of 8-day MODIS snow composites for a single year.

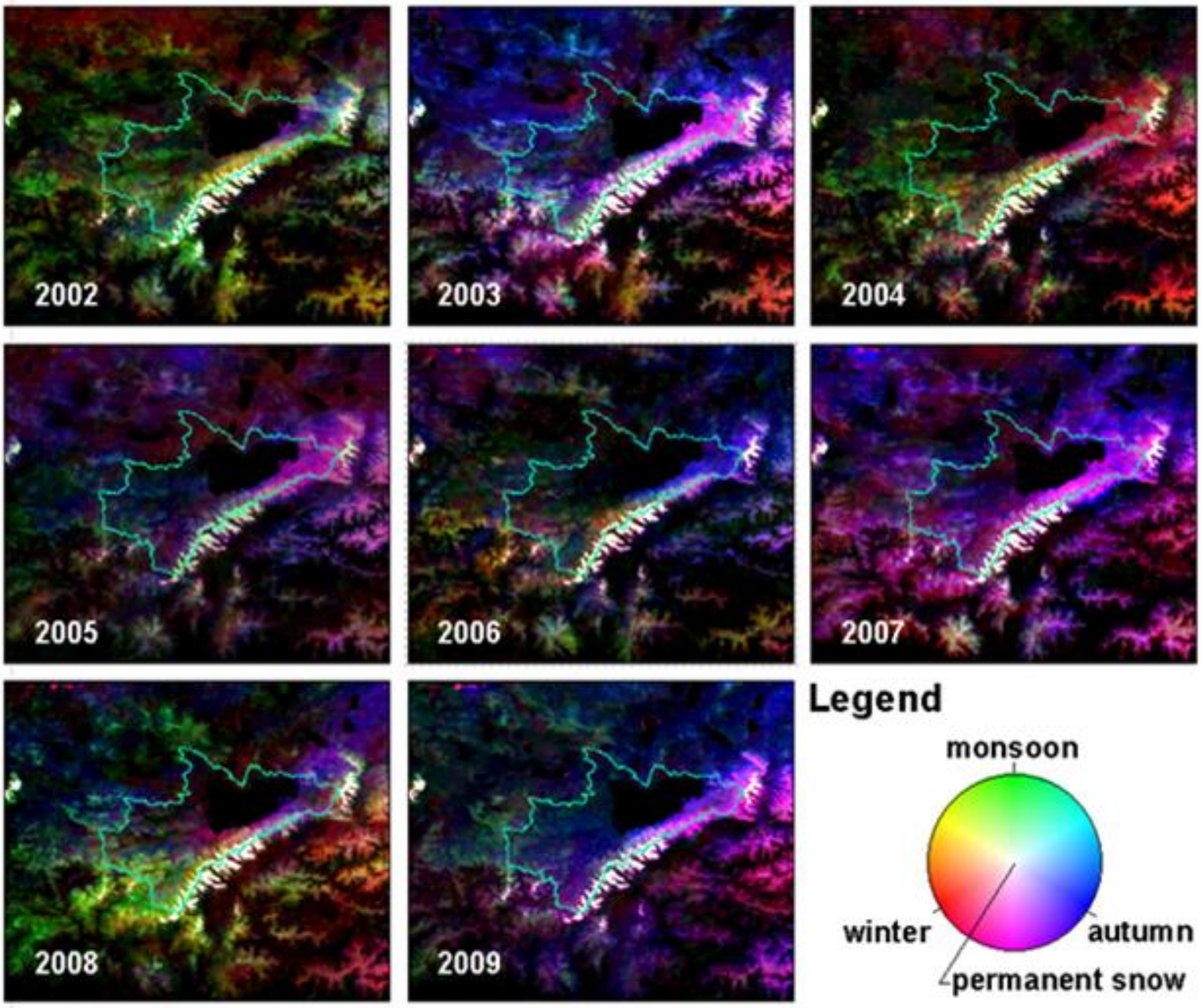


The RSD images provide a good overview of the spatial distribution of snow during particular years; however for inter-annual comparisons a quantification of the snow covered area for seasons is needed. In order to delineate the areas with dominant snow cover in particular seasons, an image segmentation was carried out. We applied the nearest neighbor method in RGB color space with training samples representing all eight classes. The training samples were defined as pure colors (255,0,0) for red, (0,255,0) green, (0,0,255) blue, (255,0,255) magenta, (255,255,0) yellow and (0,255,255) for cyan. This image segmentation provided us with homogeneous areas where snow covers in one or two combined seasons prevail. The resulting areas are presented in tabular form (Table 1). Stretching that was involved during formation of the RSD images was identical for all three color channels for every year; and therefore it cannot influence the result of the classification.

4. Results and Discussion

The RGB syntheses of snow distribution—RSD images were generated for both Terra and Aqua data. The MODIS/Terra and MODIS/Aqua snow data were available for periods 2002–2009 and 2003–2009 respectively. The RSD images for Terra for the years 2002–2009 show a high inter-annual variability in color distribution (Figure 4). Nevertheless some repetitive patterns exist. The most prominent feature is the snow cover in the eastern part of Nam Co Basin which is connected to the lake effect (for further details see below). The snow cover in the western part of the basin is highly variable. There is a pattern of monsoon snow cover in 2002, 2004, 2008, and to some degree also in 2006. This remarkable two year periodicity corresponds to the biennial character of the Indian monsoon that was described for instance by Mooley and Parthasarathy [18], Tian and Yasunari [19] and Gang and Li [20]. The years of dominant monsoon snow cover are alternated by years of dominant autumn snow cover in 2003, 2007 and 2009, while years 2005 and 2006 feature a rather mixed snow cover pattern. This biennial trend can also be seen clearly in Table 1 for the classes 'monsoon' and 'autumn'. Both permanent snow and snow free areas are relatively stable in the whole basin (Table 1). The area of permanent snow that covers on average 237 km^2, is limited to the upper reaches of the Nyainqentanglha Mountains. It has to be noted, that since the MODIS snow algorithm doesn't distinguish bare ice surfaces from snow, the class 'permanent snow' includes the area of both snow and glaciers.

Figure 4. Time series of RGB syntheses of snow cover distribution (RSD) from MODIS/Terra snow data for Nam Co Basin in the central part of the Tibetan Plateau for the years 2002–2009. Nam Co Basin is marked by a cyan water divide.



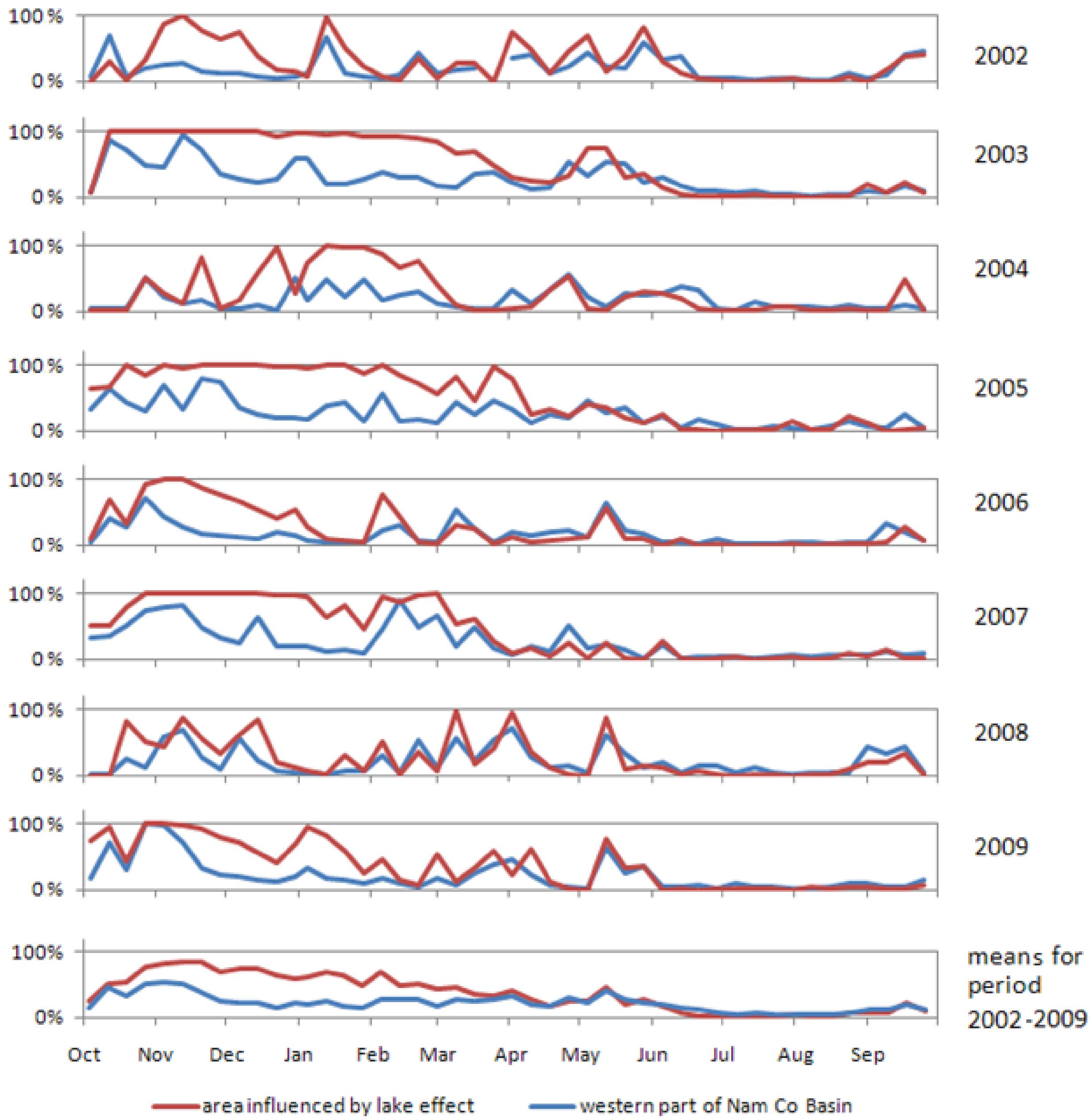
The segmentation of the RSD images allowed us to compare the extents of dominant snow cover in a particular season and to calculate the average extents for the whole period 2002–2009. The average area of dominant snow cover in the autumn, winter and the monsoon seasons, are 31%, 29% and 15% of the basin area, respectively. It should be mentioned that the snow cover during monsoon can be underestimated due to high cloud cover in this season. This can also affect to some extent the color representation of the RSD images. The snow covered areas of the combined seasons are marginal. Only the average area of dominant snow cover in combination of autumn and winter exceeds 1% (it reaches 3.6%) and it is mainly on account of the lake effect.

Table 1. Area of snow cover (km^2) in different seasons and their combinations in the Nam Co Basin during the period 2002–2009 from the 8-days composite MODIS/Terra snow data.

	2002	2003	2004	2005	2006	2007	2008	2009
autumn	742.5	5,452	248.5	4,477.5	3,044.5	4,553.5	1,672	6,908
winter	3,804.75	1,319	6,012.75	2,161.75	3,303.25	3,246.5	4,534.75	491.75
monsoon	3,999	775.25	2,019.25	966.25	1,851	118	2,308.75	854.25
autumn/winter	8	979	6.25	927.75	69.5	723.25	19.75	421.25
autumn/monsoon	14.5	34.75	3.25	20	3.25	2.5	2.75	0.5
winter/monsoon	64.75	33.75	77.75	32	22.5	12.75	50.25	13.25
permanent	232.5	303.5	197.75	257	219.5	240.75	227.75	218.75
no snow cover	44	12.75	344.5	67.75	396.5	12.75	94	2.25

The lake effect, which is represented by a magenta patch at the eastern part of the Nam Co Basin, is present in all RSD images from the Terra satellite (Figure 4). It is either bluish or reddish depending on prevailing snow cover in either autumn or winter season. The years 2002, 2006, 2008 and 2009 appear to have dominant snow cover in the autumn season, whereas the year 2004 has prevailing snow cover in the winter season. In the years 2003, 2005 and 2007 the dominant snow cover in this area affected by the lake effect occurred during both autumn and winter. The color intensity corresponds to the duration of the snow cover. The years 2003, 2004, 2005 and 2007 were characteristic with a particularly strong lake effect, as can be seen in the RSD Terra images (Figure 4). For the sake of validation of the RSD images, graphs of the percentage of snow covered area in Nam Co Basin were constructed from the original 8-day composite MODIS data for years 2002–2009 (Figure 5). Spatially averaged data for the whole period were added as a separate graph to the same figure. In order to distinguish the major processes affecting snow cover in the basin the region influenced by the lake effect and the western part of the basin were plotted separately in the graphs. The division of the basin into the two areas was delineated manually since the area affected by the lake effect forms a distinct patch in the RSD images and is relatively stable in terms of extent. Its part inside the basin amounts to 1,100 km^2 which is approximately half the size of the lake while the rest of the basin (the western part) amounts for 7,700 km^2. The onset of the snow falls and oscillations of the snow covered area during the cold period starting in October can be seen in the graphs. There is a good match between the snow distribution in time, shown by curves, and the color representation on the RSD images.

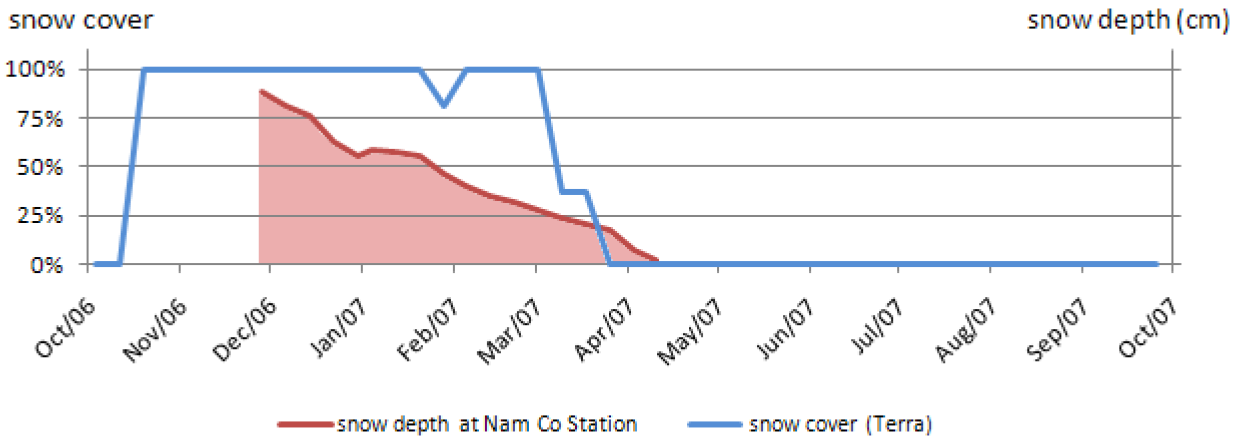
Figure 5. Percentage of snow covered area from October to September in years 2002–2009 from 8-day composites of MODIS Terra Snow data. The area affected by the lake effect and the rest of the basin (excluding the lake) are plotted separately. 100% corresponds to complete snow cover of the area.



In order to characterize the snow cover of the whole basin during a year, the original 8-day MODIS/Terra snow data were averaged for the period 2002–2009 (see the last graph in Figure 5). The maximum snow cover extent can be observed during November and December in the eastern part of the basin which is consistent with the observation at the Nam Co station (Figure 6). The snow cover reaches its minimum in July and August.

The described method was applied to MODIS Climate Modeling Grid (CMG) snow cover product. It has a global coverage with a resolution of 0.05 degrees. The RSD images were generated for the whole Tibetan Plateau in order to get an overview within the context of the study area. A comparison of the snow distribution around a lake of similar size and altitude, Siling Co, revealed that there is no extensive snow cover around its eastern shore. Siling Co is only some 300 km to the west of Nam Co and is influenced by westerlies during winter, but there are no high mountains forcing the air masses to rise. Here, the lake effect does not occur, or at least not in the same magnitude, as in the case of Nam Co (Figure 7). This suggests that the presence of an effective barrier on the opposite side of the lake is a prerequisite for the occurrence of the lake effect. Hence it would be more appropriate calling this feature the lake-orographic effect in the case of Nam Co because it better represents the cause of this snow accumulation.

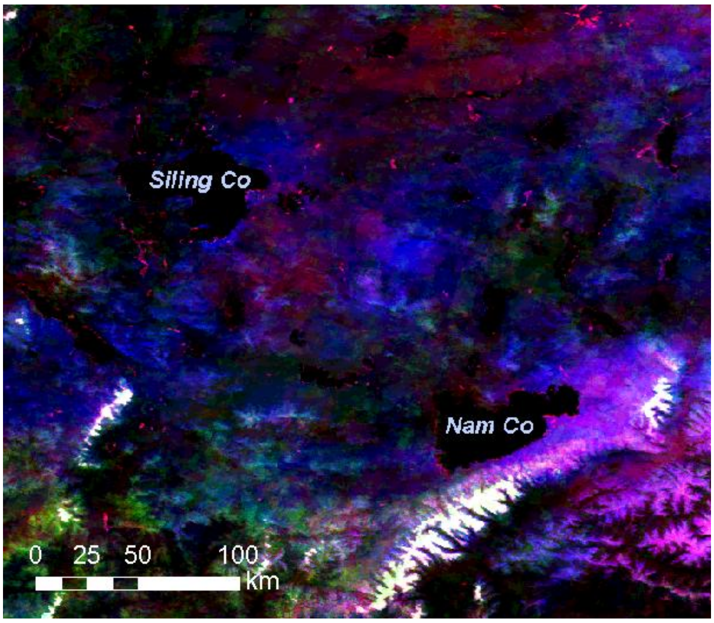
Figure 6. Comparison of snow cover percentage at the Nam Co Station from MODIS Terra (16 pixels around the station) with ground snow depth measurements for year 2007. The snow depth measurements started in November 2006 and they are only sparse in the following years. Averaged measurements over three plots inside and in the vicinity of Nam Co Station are plotted.



The color representation of the RSD images is sensitive to the delimitation of the three seasons. Therefore, much attention has to be paid to fit the seasons to the occurrences of the processes affecting snow fall in the study area. The seasons defined in this study differ in length. The question is whether the sums of 8-day composites mixed in the RGB displayed, should be weighted by the number of these composites allocated to particular seasons. Since we applied no weighting factor to particular seasons, the RSD images reflect ratios between snow cover duration in the seasons without respect to their length definition.

The division of the cold period from October to April into two separate seasons allowed us to identify the time of dominant snow cover in more detail. Shades of blue, magenta and red correspond to dominant snow cover in the time range from October to April. Although the magenta can mean both snow cover in transition between autumn and winter or lasting snow cover in autumn and winter. In this case the color intensity may indicate which of the alternatives is more likely. For more detailed analysis of dominant snow cover during the two seasons, the original MODIS snow data should be checked in the form of a graph of the percentage of snow cover during the year for a particular homogeneous area (as shown in Figure 5 for the area influenced by the lake effect).

Figure 7. RSD image from MODIS Terra (year 2004) covering both Siling Co (upper left corner) and Nam Co. SE part of Nam Co Basin features strong lake effect in comparison to Siling Co.



As was mentioned above (Figure 2), there is a difference between Terra and Aqua MODIS snow data. RSD images from Terra data were presented in this study since they contain morning and night snow fall in spring and summer, which is affected by melt and sublimation in Aqua data acquired in the afternoon.

5. Conclusions

A comprehensive method of representation of the spatial and seasonal snow cover distribution during a year has been developed. This method enables tracing of various seasonal factors that influence the snow cover in an effective and straightforward way. It has been shown through the example of the Nam Co Basin in Central Tibet that a time series of the RSD images is a suitable tool for analysis of snow cover patterns caused by both local geographical settings and major climate drivers. It allows identification of the seasons with dominant snow cover in areas that are not defined beforehand based on color shade and intensity of RSD images. In case of Nam Co, the time series of RSD images for the period from 2002 to 2009 enabled delineation of the area influenced by the lake effect. It helped to reveal the biennial character of the influence of the monsoon season in the western part of the basin. The time series also appeared to be a good source of information for distribution of permanent snow and areas with no snow cover.

The seasonal distribution of snow cover in Nam Co Basin is far from being spatially homogenous. The area of the basin can be roughly divided into three parts: The western part with biennial periodicity of the dominant monsoon induced snow cover; the lake effect influenced eastern part; and the mountain area covered by permanent snow. The snow measurements carried out at the Nam Co station, which is situated close to the southeastern shore, are therefore representative for this relatively sharply delimited part of the basin. The lake effect appears to vary in terms of onset, duration and spatial extent during the period of MODIS data availability. These variations represented as color patterns in the RSD images were verified with respect to the original MODIS/Terra snow cover data sets and to some extent to available ground measurements.

In summary, it is shown that the RSD images are useful for understanding the snow cover patterns in the study area. This method aims to qualitatively assess the snow cover distribution. Its independency of ground data makes it easy to use for areas with no or little ground snow measurements. Time series of RSD images provide a good overview of temporal and spatial snow cover distribution. It can be applied, for instance, in other important snow areas on the Tibetan Plateau, especially on its southern margin. Since the MODIS snow data is available in two resolution levels this method is suitable for a wide range of scales ranging from local to global. Generation of regional or global snow distribution datasets could be accomplished taking advantage of MODIS Climate Modeling Grid (CMG) snow cover product with a resolution of 0.05 degrees. Additional research on the relation of the lake effect to other processes, such as the lake icing cycle, is needed.

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