Change of Snow Cover and Its Impact on Alpine Vegetation in the Source Regions of Large Rivers on the Qinghai-Tibetan Plateau, China

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Change of snow cover and its impact on alpine vegetation in the source regions of large rivers on the Qinghai-Tibetan Plateau, China

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Abstract

Based on a Normalized Difference Vegetation Index (NDVI) and remote sensing data of snow cover, we analyzed the variation in NDVI in relation to trends in snow cover and vegetation of the source regions of large rivers on the Qinghai-Tibetan Plateau. We then calculated the relationship between snow cover duration, snow depth, and NDVI to reveal the effect of snow cover change on vegetation growth on a regional scale. The results show that both snow depth and duration tend to reduce gradually from northeast to southwest on the Qinghai-Tibetan Plateau. Furthermore, snow cover duration (snow depth > 0 cm) has high interannual fluctuation and generally shows an increasing trend ($P < 0.01$) from 1980 to 2004. The interannual fluctuations of the duration of days with snow depth ≥ 5 cm as well as the maximum and average snow depth are also quite high, but they generally show insignificant tendencies ($P > 0.05$) from 1980 to 2004. The snow cover characteristics (duration and depth) are insignificantly correlated to annual maximum NDVI. However, a significant positive correlation ($P < 0.05$) is observed between snow cover duration (snow depth > 0 cm) and the NDVI values of both April and July, and an obvious negative correlation ($P < 0.05$) is observed between snow depth and the NDVI value in October across all source regions from 1981 to 2004. In the study area, increasing snow depth and the prolongation of the duration of snow cover have adverse effects on vegetation growth the following year. The melting of snow brings increasing effects to the NDVI value in the spring.

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Introduction

The characteristics of the distribution and depth of snow cover are among the most active natural features on the surface of the earth (Qin et al, 2006; Ma et al., 2011). They are important input parameters in global energy balance, climatic, hydrological, and ecological models (Mao, 2010; Tang et al., 2013). Snow cover is very sensitive to climate change and especially to changes in temperature. Therefore, it is an important indicator of climate change (Immerzeel et al., 2009; Peng et al., 2010; Mu et al., 2010; You et al., 2011; Trujillo et al., 2012). Climate change on any spatiotemporal scale is accompanied by fluctuations in snow cover. Snow cover has a feedback effect on climate. For example, the fluctuations of the Eurasian snow cover influence atmospheric circulation in East Asia, monsoon activity in India, and early summer precipitation in China (Wu and Qian, 2003; Shaman and Tziperman, 2005; Qin et al., 2006). Additionally, snow cover is an important freshwater resource. It plays a prominent role in storing and preserving soil water, preventing spring drought, and promoting vegetation growth (Qin et al., 2006; Immerzeel et al., 2009; Peng et al., 2010). However, a large amount of snow cover not only buries pasture grass, but also has adverse effects on domestic animals that might freeze or starve to death, causing a snow-related disaster (Qin et al., 2006).

The Qinghai-Tibetan Plateau is one of the most important snow-covered areas in the world (You et al., 2011). It is also the source region of many large Asian rivers such as the Yangtze River, Yellow River, Nu (Salween) River, Lancang (Mekong) River, and Yarlung Zangbo (Brahmaputra) River (Immerzeel et al., 2009). In recent decades, the temperature and precipitation on the Qinghai-Tibetan Plateau have followed increasing trends, whereas the maximum potential evapotranspiration has exhibited a decreasing trend (Wu et al., 2005). Snow cover and its changing characteristics crucially affect the regional vegetation within the source areas of the large Asian rivers on the Qinghai-Tibetan Plateau. Changes in snow cover play a pivotal role in social and economic development as well as in the protection of the ecology and environment in large river basins (Qin et al., 2006). Previous research on the Qinghai-Tibetan Plateau has focused mainly on the influence of snow cover on the climate and hydrology in China or in large Asian river basins (Wu and Qian, 2003; Immerzeel et al., 2009), but little attention has been paid to the relationship between snow cover and vegetation in the source regions of the large Asian rivers.

The rapid developments of geographic information systems and remote sensing technology, and their wide application in monitoring snow cover, provide reliable regional-scale snow cover data and information on vegetation characteristics in areas that lack field survey data (Dye and Tucker, 2003; Qin et al., 2006). Satellite remote sensing has become the most ideal data source for the monitoring and research of snow cover. Research on snow cover using microwave remote sensing has also made significant progress in recent years (Qin et al., 2006; Singh et al., 2013; Wang et al., 2013). A Normalized Difference Vegetation Index (NDVI) is a vegetation index computed from the red and near-infrared bands of different remote sensors over long time sequences. It is widely used for monitoring vegetation growth and spatiotemporal patterns (Sellers, 1989; Nemani et al., 2003; Alcaraz-Segura et al., 2009). This research uses remote sensing data of snow cover and an NDVI both to analyze the variation and to investigate the trends in NDVI, snow cover, and vegetation of the source regions of large Asian rivers on the Qinghai-Tibetan Plateau. The relationship between snow cover characteristics (depth and duration) and NDVI is explored to analyze the effects of snow cover on the growth of regional vegetation, and to provide scientific evidence for vegetation management and the prevention and reduction of snow disasters.

Materials and Methods

STUDY AREA

The Qinghai-Tibetan Plateau (74–104°E, 25–40°N) is located west of the Hengduan Mountains, north of the Himalayas, and south of the Kunlun and Altun Mountains (Zheng, 1996). The average elevation of the Qinghai-Tibetan Plateau is above 4000 meters. It is the highest large area of terrain in the world, which has prompted names such as the "Third Pole" and the "Roof of the World" (Wu et al., 2005). It is also the source region and location of transformation of many important weather systems (Wu and Qian, 2003). The source regions of the Yellow River, Yangtze River, Mekong River, Salween River, and Yarlung Zangbo River are distributed in the southeast of the plateau. From northeast to southwest, their basins cover areas of about 200,000, 435,000, 84,000, 112,000, and 453,000 km^2, respectively (Zheng, 1996; Gao et al., 2009; Immerzeel et al., 2009). Their total area accounts for around half of the total area of the Qinghai-Tibetan Plateau (Fig. 1).

Because of the high elevation, the climate of the Qinghai-Tibetan Plateau is characterized by cold winters, cool summers, long sunshine duration, strong solar radiation, and large diurnal temperature differences. The mean temperature of the coldest months is –15 °C and of the hottest months is between 20 and 30 °C (Guo and Wang, 2011). Annual precipitation is distributed unevenly, with varying dry and wet conditions. In general, the rainy season extends from April to September with decreasing amounts of precipitation from the southeast to the northwest on the Qinghai-Tibetan Plateau (Wu et al., 2005; Yang et al., 2011). Restricted by orographic and atmospheric circulation features, the source regions of the large Asian rivers on the Qinghai-Tibetan Plateau form a gradation from warm and wet to cold and dry from southeast to northwest, respectively. There is a zonal vegetation change from forest to alpine meadow and alpine steppe to alpine desert (Zheng, 1996).

DATA

NDVI Data

We used the Global Inventory Modeling and Mapping Studies (GIMMS) 10-day maximum value composite NDVI data set with a spatial resolution of 8 km from July 1981 to December 2006 (http://glcf.umiacs.umd.edu/data/gimms/).

Snow Cover Data

Daily snow depth information was derived from passive microwave imagery (SMMR [Scanning Multichannel Microwave Radiometer] and SSM/I [Special Sensor Microwave Imager] data) with a spatial resolution of 25 km from 1979 to 2005 (http://westdc.westgis.ac.cn).

Other Data

Regional boundaries and river locations were overlaid on a digital elevation model to distinguish watershed boundaries for research on the characteristics of individual watersheds.

METHODS

First, for 1980–2004, we calculated the snow cover duration (days) for snow depths of 0, 5, and 10 cm as well as the maximum and average depths (cm) of snow cover during the natural snow cover season, that is, from 1 September of the initial year to 31 August of the following year. For example, the characteristics (duration and depth) for 1980 were derived from data obtained from 1 September 1979 to 31 August 1980. We also calculated the monthly maximum NDVI from April to October and annual maximum NDVI as indicators of vegetation growth for the growing season of 1981–2006 from the GIMMS NDVI data set.

Then, we analyzed the trend in vegetation growth (annual and monthly maximum NDVI) and the snow cover characteristics (depth and duration) for the entire region, in addition to the individual source regions. We used the equation: $y = a + bx$, where a and b are the regression coefficients, y is the monthly or annual snow cover characteristic (duration = days with different depth of snow cover; maximum and average snow depth; vegetation growth [NDVI]), and x is the time series. The trends are defined as significant at $P < 0.05$ and highly significant at $P < 0.01$.

Furthermore, we used correlation analysis to investigate the relationship between snow cover characteristics and vegetation growth (annual and monthly maximum NDVI), to reveal the effects of snow cover on vegetation growth in the source regions of the large Asian rivers from 1981 to 2004. Next, we calculated the Pearson's correlation coefficient of the spatially averaged snow cover and NDVI for each source region of the large Asian rivers from 1981 to 2004. If the correlation coefficient passed the significance test ($P < 0.01$ or $P < 0.05$), it was an "extremely significant" or "significant" linear correlation.

Results

CHANGES IN SNOW COVER DURATION AND SNOW DEPTH

During the natural snow cover seasons of 1980–2004, the snow cover duration and depths show a similar spatial distribution pattern on the Qinghai-Tibetan Plateau (Fig. 2). The average number of days that snow cover (i.e., snow cover duration) depth is greater than 0 cm is 158.95 days. There is huge interannual fluctuation (standard deviation [SD] = 31.54 days) and, generally, an increasing trend ($r = 0.507$, $P < 0.01$, $n = 25$) from 1980–2004 (Tables 1 and 2). However, there are obvious low values from 1986 to 1991. The average snow cover duration with snow depths above 5 cm is 65.1 days, and this shows a slight, but not significant rising trend ($r = 0.269$, $P > 0.05$, $n = 25$). The snow cover duration for depths above 10 cm is 13.21 days with a slightly decreasing trend ($r = -0.214$, $P > 0.05$, $n = 25$, Tables 1 and 2 and Fig. 3, part a). The regional averages of annual maximum and average snow depths are 8.51 and 4.89 cm, respectively (Table 1). Although the annual values of the maximum and average snow depths are similar, both have large interannual variations (SD of 1.95 and 0.97 cm, respectively) without significant trends from 1980 to 2004 (Table 2, Fig. 3, part b).

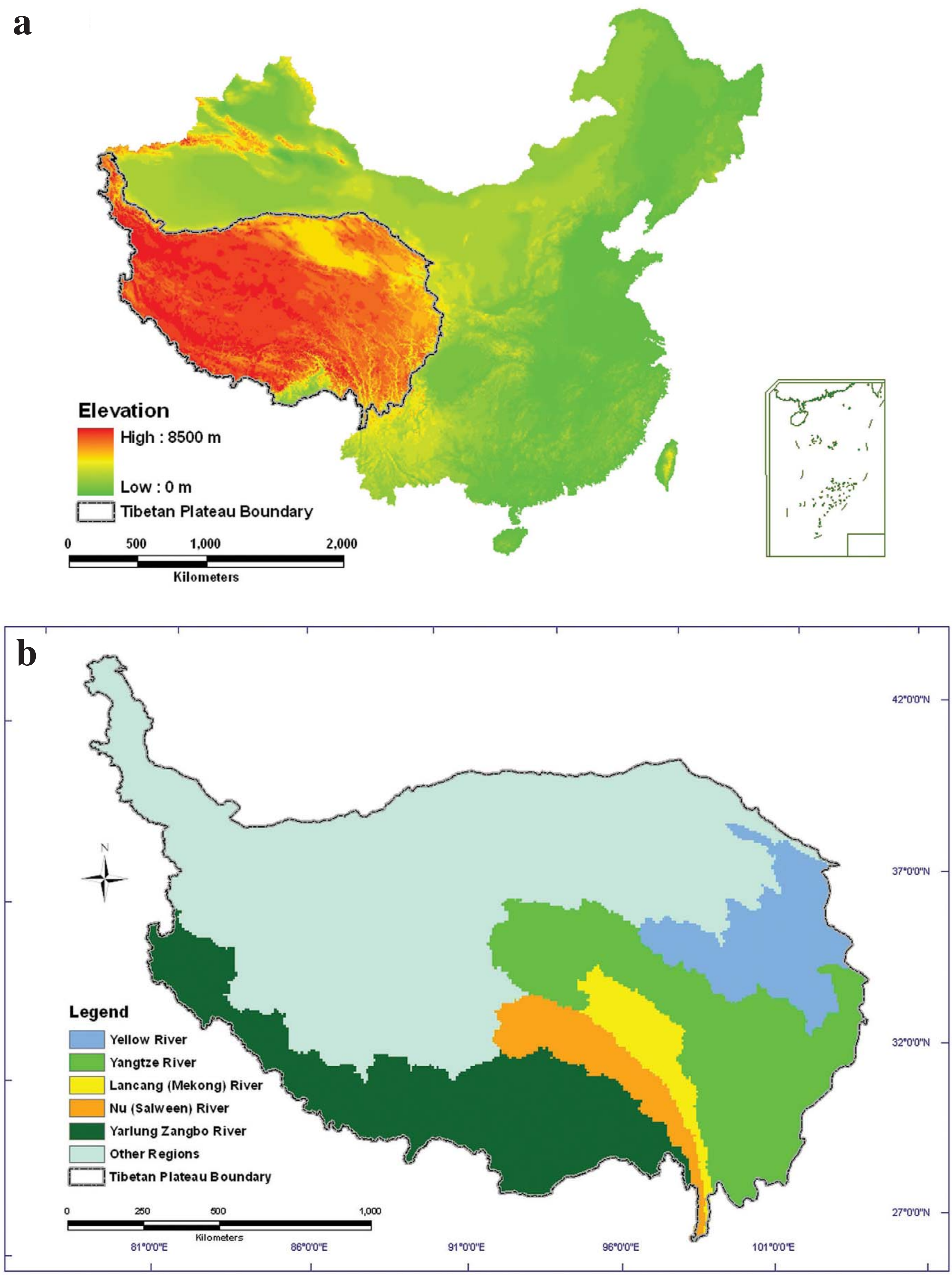


FIGURE 1. Distribution of the source regions of large Asian rivers on the Qinghai-Tibetan Plateau in China. (a) Location of the Qinghai-Tibetan Plateau in China; (b) location of the source regions of large Asian rivers on the Qinghai-Tibetan Plateau.

c

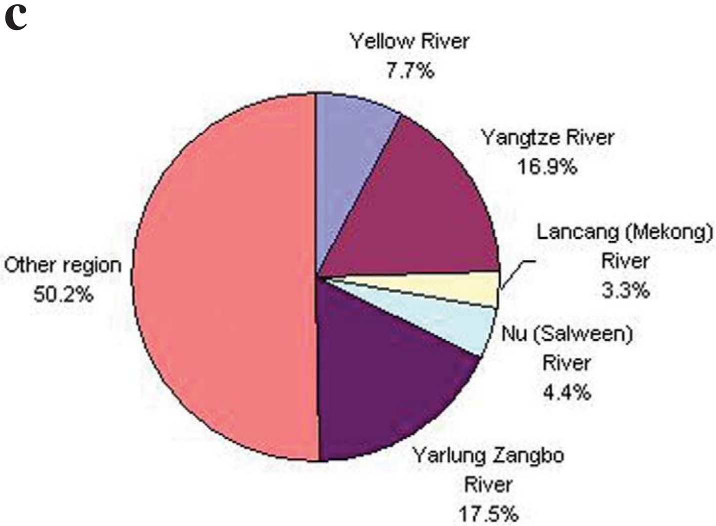


FIGURE 1 (continued). Distribution of the source regions of large Asian rivers on the Qinghai-Tibetan Plateau in China. (c) areal proportion of large Asian river basins in the Qinghai-Tibetan Plateau.

The source region of the Yarlung Zangbo River is covered with snow for the longest period. The number of days with snow depths above 0, 5, and 10 cm are 166.40, 112.41, and 28.09 days, respectively, from 1980 to 2004. The largest amounts in the annual maximum and average snow depth are 13.02 and 7.62 cm, respectively, in the source region of the Yarlung Zangbo River. Conversely, the Yangtze River source region is covered with snow for the shortest period and has the least snow depth (Table 1). The trends in snow cover characteristics are similar within each source region, whereas the snow cover duration (depth > 0 cm) within the source region of the Yarlung Zangbo River has a highly significant increasing trend (r = 0.827, P < 0.01, n =25) from 1980 to 2004 (Table 2).

NDVI AND ITS TRENDS IN THE SOURCE REGIONS OF LARGE ASIAN RIVERS ON THE QINGHAI-TIBETAN PLATEAU

From June to September, high values of NDVI are measured, with the maximum value observed in August (Table 3 and Fig. 4). The average value of annual maximum NDVI is above 0.44. The NDVI shows high interannual fluctuation and an insignificant decreasing trend (r = 0.063, P > 0.05, n = 26) from 1981 to 2006 (Tables 3 and 4, and Fig. 4). The Yellow River source region has the highest annual maximum NDVI value, followed by the Yangtze River, whereas the Yarlung Zangbo River source region has the lowest value, which is below 0.30 (Fig. 2). The NDVI values of the Yangtze River are higher than the Yellow River in April and October, whereas the maximum NDVI values of the Yellow River source region are the highest in the other months (Table 3). The annual maximum NDVI value decreases from the northeast to the southwest across the Qinghai-Tibetan Plateau.

From 1981 to 2006, the NDVI values of the entire source region show a significant rising trend in April and July (r = 0.430, P < 0.05, n = 25, and r = 0.453, P < 0.05, n = 26, respectively), whereas no trends are obvious in the other months. The NDVI values of the Yellow River source region show a significant increasing trend in June and July (r = 0.476, P < 0.05, n = 25, and r = 0.434, P < 0.05, n = 26, respectively), whereas no significant change was found in the Yangtze River source region during the same months. From 1981 to 2006, the NDVI values of the Mekong River and Salween River source regions show a significant increasing trend in July (r = 0.418, P < 0.05, n = 26, and r = 0.458, P < 0.05, n = 26, respectively), whereas the NDVI values of the Yarlung Zangbo River and the entire source region show a prominent rising trend (r = 0.531, P < 0.01, n = 25, and r = 0.397, P < 0.05, n = 26, respectively) in April and July (Table 4).

RELATIONSHIP BETWEEN SNOW COVER AND NDVI IN THE SOURCE REGIONS OF LARGE ASIAN RIVERS

The coefficients of the linear correlation between snow cover characteristics (duration and depth) and vegetation growth (NDVI) in the source regions of large Asian rivers from 1981 to 2004 are summarized in Table 5. It shows that snow cover duration and depth are insignificantly correlated to annual maximum NDVI. There is significant positive correlation between snow cover duration and the NDVI values of the entire source region in both April and July (r = 0.425, P < 0.05, n = 23, and r = 0.427, P < 0.05, n = 24, respectively) from 1981 to 2004. The snow cover duration for depths above 5 cm is positively correlated (r = 0.410, P < 0.05, n = 23) with the NDVI value in April (Table 5). The annual maximum snow depth of the entire region has an obvious negative correlation (r = –0.472, P < 0.05, n = 24) with the NDVI value in October from 1981 to 2004. Furthermore, the annual average snow depth has an obvious positive correlation (r = 0.417, P < 0.05, n = 23) with the NDVI value in April, and a significant negative correlation (r = –0.499, P < 0.05, n = 24) with the NDVI value in October from 1981 to 2004 (Table 5).

The snow cover characteristics do not have any obvious correlation with the NDVI value and the annual maximum NDVI value in the source region of the Yellow River, Mekong River, and Salween River in any month from 1981 to 2004. The characteristics of the Yangtze River source region are negatively correlated with the NDVI values in the early growing season from April to June. The negative correlation coefficients between the maximum and average snow depth and NDVI (r = –0.473, P < 0.05, n = 23, and r = –0.428, P < 0.05, n = 23, respectively) are most significant in May in the Yangtze River source region (Table 5). The snow cover

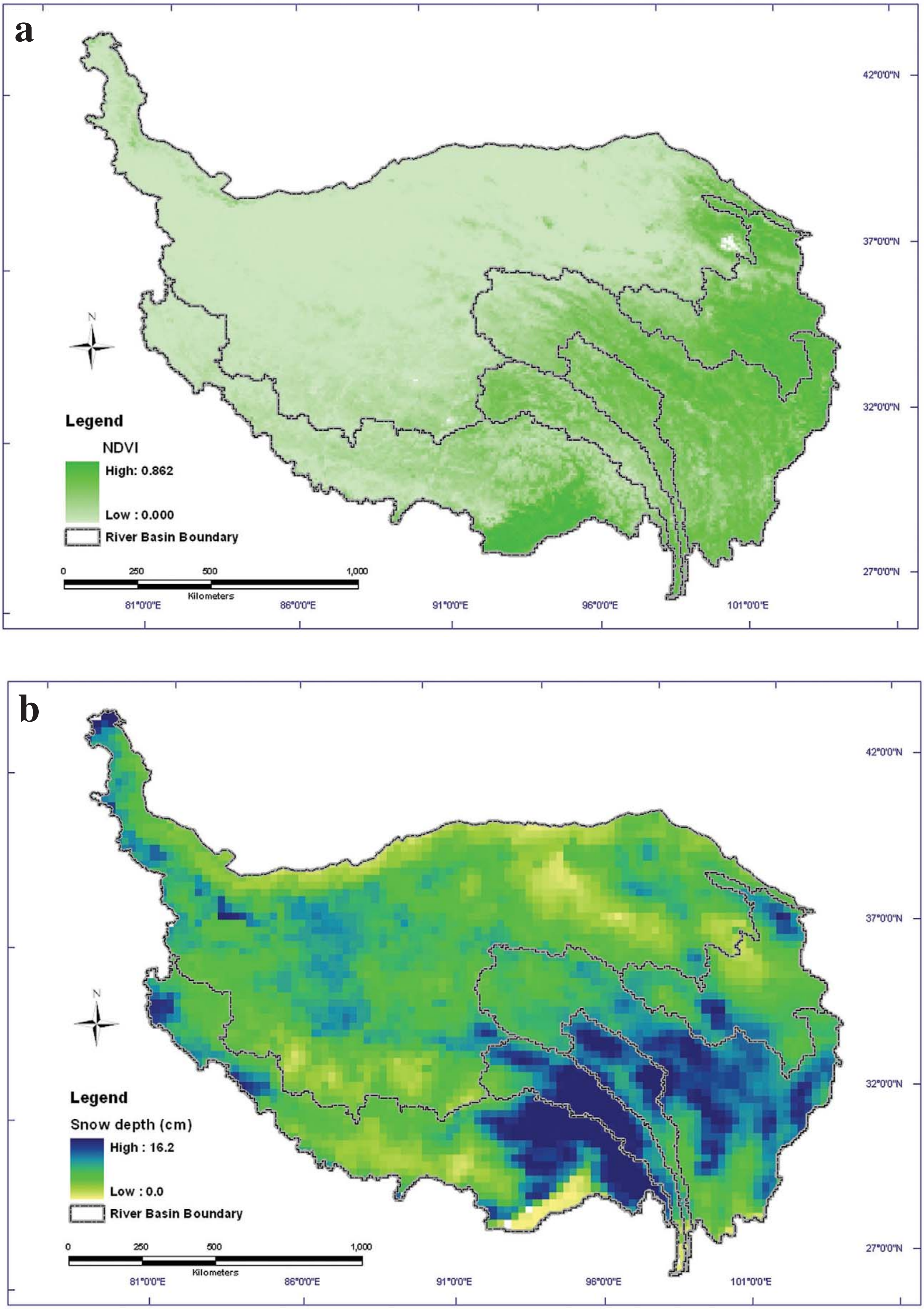
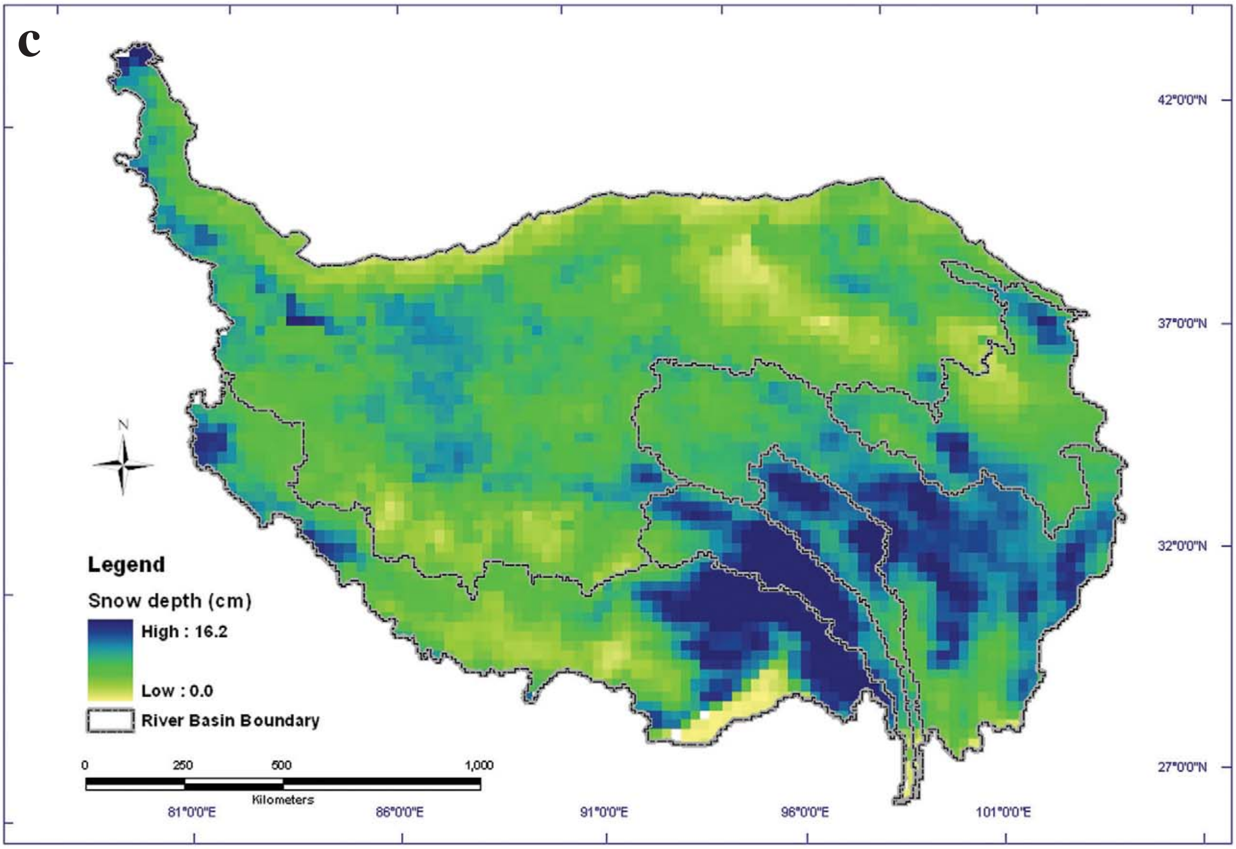


FIGURE 2. Spatial distributions of the average (a) annual maximum Normalized Difference Vegetation Index (NDVI) from 1981 to 2006; (b) snow cover duration (the cumulative number of days with snow depth >0 cm) from 1980 to 2004.



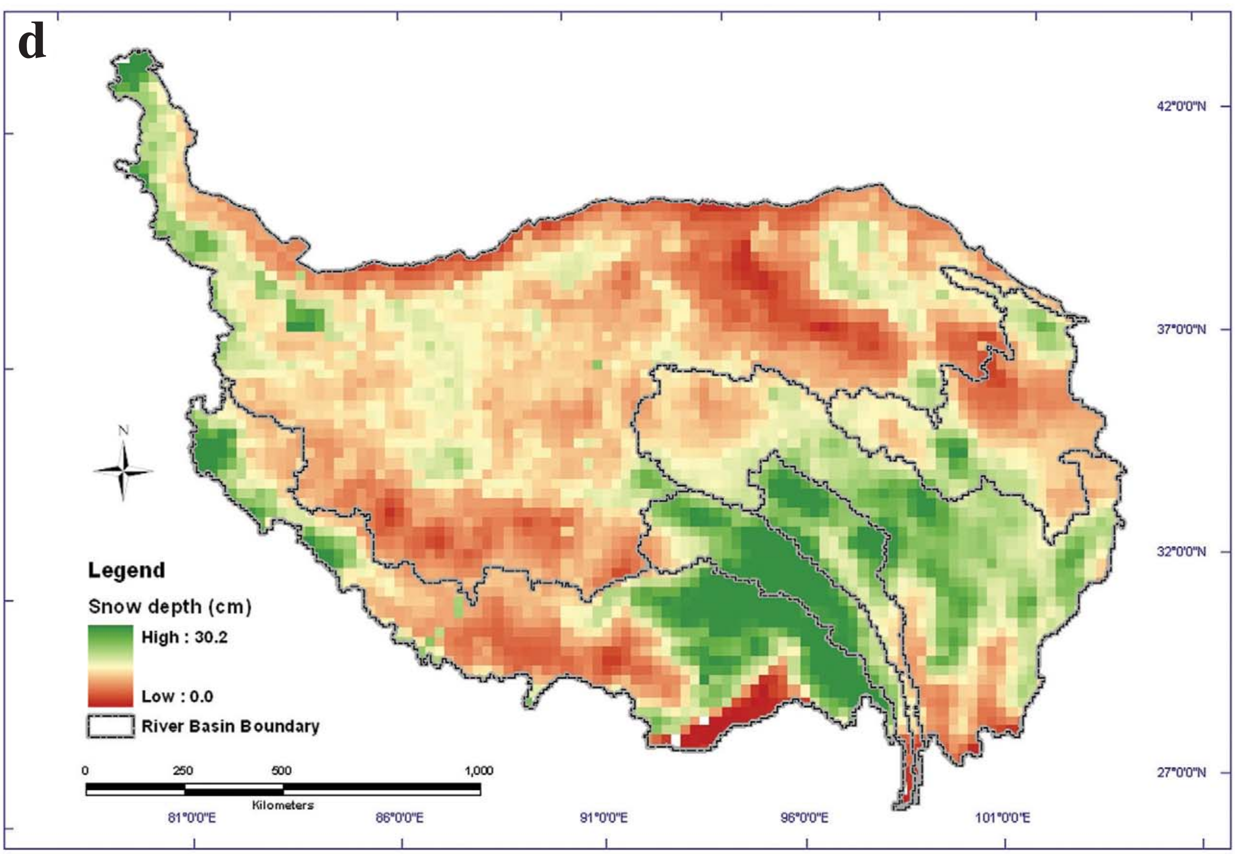


FIGURE 2 (continued). **Spatial distributions of the average (c) annual mean snow depth (cm) from 1980 to 2004; and (d) annual maximum snow depth (cm) from 1980 to 2004.**

TABLE 1

Statistical characteristics (mean and standard deviation) of snow cover duration and snow depth in the source regions of large Asian rivers on the Tibetan Plateau from 1980 to 2004.

Snow cover characteristics		Yellow River	Yangtze River	Mekong River	Salween River	Yarlung Zangbo River	Total source regions
The duration with snow depths above 0 cm (days)	Mean	136.54	107.83	115.08	154.99	166.40	158.95
	SD	25.27	24.99	28.87	31.10	24.71	31.54
The duration with snow depths above 5 cm (days)	Mean	67.20	43.26	62.37	99.63	112.41	65.10
	SD	22.83	20.60	27.03	38.59	34.69	20.16
The duration with snow depths above 10 cm (days)	Mean	13.65	6.73	12.00	21.51	28.09	13.21
	SD	6.64	5.48	7.84	10.19	14.28	6.87
Maximum snow depth (cm)	Mean	8.96	7.12	8.72	11.63	13.02	8.51
	SD	2.17	1.95	2.77	3.75	4.45	1.95
Mean snow depth(cm)	Mean	5.46	4.48	5.64	6.97	7.62	4.89
	SD	1.24	1.17	1.76	2.20	2.47	0.97

TABLE 2

Trend coefficients of snow cover duration and snow depth in the source regions of large Asian rivers on the Tibetan Plateau from 1980 to 2004.

Snow cover characteristics	Yellow River	Yangtze River	Mekong River	Salween River	Yarlung Zangbo River	Total source regions
The duration with snow depths above 0 cm (days)	0.344	0.143	0.097	0.314	0.827**	0.507**
The duration with snow depths above 5 cm (days)	0.212	0.233	0.162	0.211	0.322	0.269
The duration with snow depths above 10 cm (days)	–0.315	–0.189	–0.187	–0.155	–0.137	–0.214
Maximum snow depth (cm)	0.103	0.121	–0.016	0.043	0.263	0.156
Mean snow depth (cm)	0.198	0.233	0.071	0.034	0.303	0.239

Notes: $r_{0.05\,(2,\,24)} = 0.389$; $r_{0.01\,(2,\,24)} = 0.497$; * moderate significant level, ** high significant level.

characteristics of the Yarlung Zangbo River source region have an indistinctive positive correlation with NDVI values in April as well as from July to September, and a negative correlation in May and June. In June, the negative correlation coefficients for the snow cover duration (depth > 10 cm), maximum and average snow depths, and NDVI values pass the significance test (Table 5).

Discussion

CHANGES IN SNOW COVER AND NDVI IN THE SOURCE REGIONS OF THE LARGE ASIAN RIVERS

The snow cover data from SMMR and SSM/I have been widely used for climate analysis, hydrological simulation, and water resource management on large spatial and long temporal scales (Grippa et al., 2005; Qin et al., 2006), even though uncertainties about these data have been raised in recent years. These data need to be calibrated with field observation data or compared with MODIS (Moderate Resolution Imaging Spectroradiometer) snow cover data (Foster et al., 2009). The increase in global temperature means that snow cover in the northern hemisphere shows a generally decreasing trend, whereas on the regional scale, different changes are observed (IPCC, 2007; Singh et al., 2013). In China, changes of observed winter snow depths do not show distinctive patterns (Peng et al., 2010); however, the snow cover on the Qinghai-Tibetan Plateau shows a generally increasing trend (Qin et al., 2006; Ma et al., 2011). The results of our study show that the entire source region of the large Asian rivers on the Qinghai-Tibetan Plateau has experienced relatively long snow cover duration, high interannual fluctuations (snow depths > 0 cm), and a generally increasing trend from 1980 to 2004. Interestingly, the snow cover duration for snow depths above 5 cm shows slight decreasing tendency. Annual maximum and average snow depths also show relatively large interannual fluctuations, but without any obvious trends. From the snow cover characteristics of those different source regions, the values of snow depth and snow cover duration are seen to decrease significantly from northeast to southwest. The longest snow cover duration (with a significantly

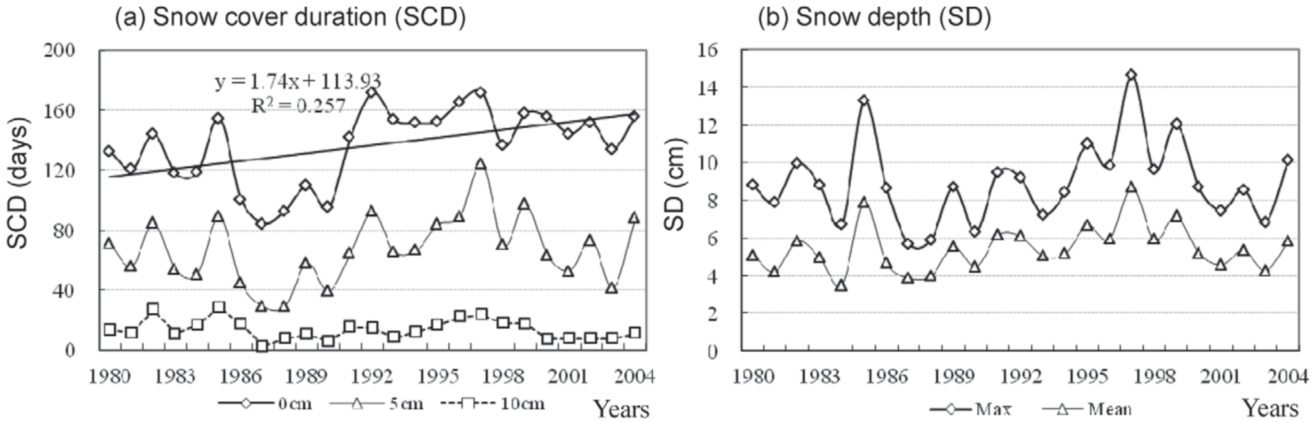


FIGURE 3. Changes in (a) snow cover duration and (b) snow depth in the source regions of large Asian rivers on the Qinghai-Tibetan Plateau from 1980 to 2004.

increasing trend) and greatest snow depth are found in the Yarlung Zangbo River source region, whereas the snow cover duration and snow depths of the Yangtze River source region are the shortest and lowest of all five source regions.

The NDVI is the most integrated indicator of ecosystem function and vegetation growth and has been widely used to describe global and regional patterns of vegetation cover and production (Nemani et al., 2003; Tucker et al., 2005; Grippa et al., 2005; Alcaraz-Segura et al., 2009). The GIMMS NDVI data set has been corrected to minimize the effects of volcano eruptions, solar angle, and sensor errors (Tucker et al., 2005; Seaquist et al., 2009) and can accurately reflect the seasonal and long-term states of vegetation growth on both global and regional scales. The NDVI values are relatively high from June through September, and reach their maximum values in August in the source regions of the large Asian rivers on the Qinghai-Tibetan Plateau. The interannual fluctuation of the regional average NDVI is also relatively high with an insignificant decreasing trend. The pattern of annual maximum NDVI decreases from northeast to southwest, while the interannual fluctuations are slightly different. From 1981–2006, the NDVI values of the entire source region show a significant increasing trend in April and July. However, the Yarlung Zangbo River source region does not have an obvious trend in any month. The NDVI values of the Yellow River source region show a prominent

TABLE 3

Statistical characteristics (mean and standard deviation) of monthly and annual maximum Normalized Difference Vegetation Index (NDVI) in the source regions of large Asian rivers on the Tibetan Plateau from 1981 to 2006.

NDVI		Yellow River	Yangtze River	Mekong River	Salween River	Yarlung Zangbo River	Total source regions
April	Mean	0.1841	0.2102	0.1658	0.1103	0.1079	0.1584
	SD	0.0160	0.0153	0.0149	0.0115	0.0109	0.0122
May	Mean	0.2811	0.2719	0.2315	0.1616	0.1387	0.2141
	SD	0.0331	0.0237	0.0219	0.0194	0.0163	0.0182
June	Mean	0.4461	0.3757	0.3583	0.2613	0.1781	0.3058
	SD	0.0444	0.0353	0.0391	0.0346	0.0282	0.0304
July	Mean	0.5633	0.4634	0.4590	0.3492	0.2159	0.3814
	SD	0.0346	0.0341	0.0327	0.0333	0.0310	0.0291
August	Mean	0.5751	0.4796	0.4782	0.3688	0.2379	0.3994
	SD	0.0183	0.0255	0.0238	0.0260	0.0272	0.0210
September	Mean	0.4860	0.4310	0.4247	0.3256	0.2323	0.3598
	SD	0.0420	0.0268	0.0334	0.0315	0.0271	0.0221
October	Mean	0.3342	0.3396	0.3118	0.2305	0.2097	0.2816
	SD	0.0257	0.0171	0.0218	0.0211	0.0121	0.0130
Annual maximum	Mean	0.6011	0.5172	0.5075	0.3873	0.2997	0.4415
	SD	0.0148	0.0143	0.0152	0.0165	0.0157	0.0111

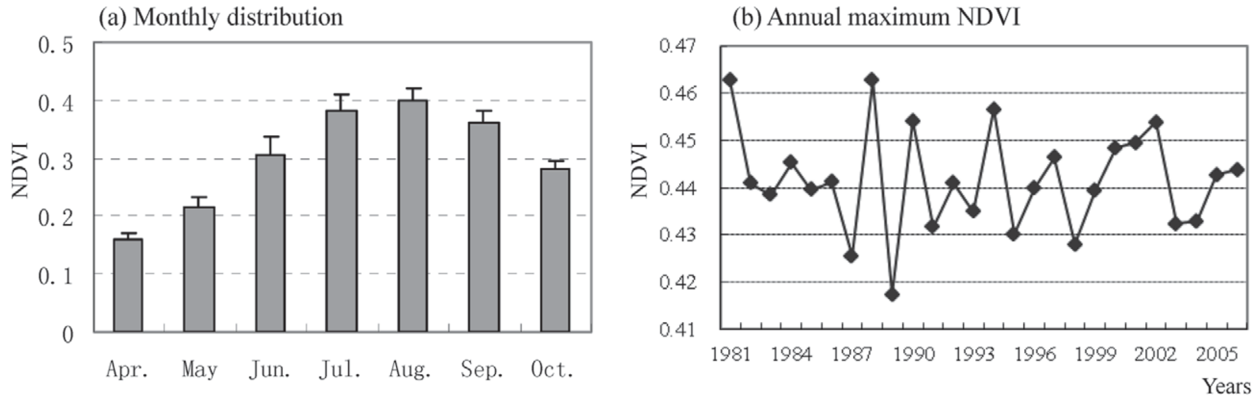


FIGURE 4. (a) Monthly distribution and (b) annual changes of maximum NDVI in the source regions of large Asian rivers on the Qinghai-Tibetan Plateau from 1981 to 2006.

increasing trend in June and July, whereas no significant trend has been found for the Yangtze River source region in July. From 1981–2006, the NDVI values of the Mekong River and Salween River source regions also show an increasing trend in July.

SNOW COVER IMPACTS ON VEGETATION GROWTH IN THE SOURCE REGIONS OF THE LARGE ASIAN RIVERS

In the seasonally snow-covered ecological system, the difference between snow cover duration and depth causes environmental heterogeneity (Walker et al., 2001). Snow cover conditions play a vitally decisive role in the plant growth of alpine ecosystems (Edmonds et al., 2006; Jorgen et al., 2006; Jonas et al., 2008; Trujillo et al., 2012; Wang et al., 2013). Generally, with the extension of snow cover duration, the spatial extent of plant-covered areas is reduced (Walker et al., 2001). Hence, the growing season of vegetation is simultaneously delayed and shortened, the vegetation area is reduced, and the vegetation index is decreased (Mu et al., 2010; Jonsson et al., 2010). This indicates that the increase in snow depth and snow cover duration has unfavorable effects on plant growth in the following year. From 1980 to 2004, snow cover duration (depth > 0 cm) shows an increasing trend, whereas the annual maximum NDVI value of this region does not show a significant trend in the source regions of the large Asian rivers on the Qinghai-Tibetan Plateau. The snow cover duration of the Yarlung Zangbo River source region is the longest and has the highest snow depths and lowest annual maximum NDVI values. Conversely, the snow cover duration of the Yangtze River source region is the shortest and has the lowest snow depths and relatively high NDVI values.

The insignificant correlation between snow cover characteristics and the annual maximum NDVI indicates that snow cover is just one of many influencing factors on vegetation growth on a regional scale (Wang et al., 2013). There are different relationships between the NDVI of different vegetation or different regions during the growing season and snow cover depth in winter (Tang et al., 2013). This might depend on the conditions of their growing environment, such as temperature and precipitation (Peng et al., 2010). For example, among all the source regions of the large river basins, the geographical position and weather conditions of the Yellow River source region are most suitable for the germination and growth of vegetation; hence, its annual maximum NDVI value is higher than the other source regions.

Snow cover in winter can add soil moisture and arrest soil heat exchange; thus, having crucial effects on soil heat and moisture preservation (Groffman et al., 2001; Fitzhugh et al., 2003). Snow cover depth and duration influence the exchange of

TABLE 4

Trend coefficients of monthly and annual maximum NDVI in the source regions of large Asian rivers on the Tibetan Plateau from 1981 to 2004.

NDVI	Yellow River	Yangtze River	Mekong River	Salween River	Yarlung Zangbo River	Total source regions
April	0.237	0.387	0.343	0.266	0.531**	0.430*
May	0.124	–0.115	–0.219	–0.247	0.162	–0.005
June	0.476*	0.231	0.255	0.104	–0.077	0.205
July	0.434*	0.355	0.418*	0.458*	0.397*	0.453*
August	0.131	–0.172	–0.170	0.044	0.002	–0.060
September	0.267	0.252	0.223	0.338	0.132	0.297
October	0.360	0.119	–0.003	–0.085	–0.022	0.154
Annual maximum	0.342	0.038	0.179	0.376	–0.177	0.063

Notes: $r_{0.05\,(2,\,25)} = 0.381$; $r_{0.01\,(2,\,25)} = 0.478$; $r_{0.05\,(2,\,24)} = 0.389$; $r_{0.01\,(2,\,24)} = 0.497$; * moderate significant level, ** high significant level.

TABLE 5

Correlation coefficients between snow cover and NDVI in the source regions of large Asian rivers on the Tibetan Plateau from 1981 to 2004.

Source regions	Snow cover characteristics	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Annual maximum
Yellow River	Duration with snow depths above 0 cm (days)	0.142	0.015	0.044	0.129	0.113	0.169	0.150	0.045
	Duration with snow depths above 5 cm (days)	0.181	–0.003	–0.176	–0.085	0.091	0.163	0.032	–0.174
	Duration with snow depths above 5 cm (days)	0.074	–0.032	–0.297	–0.107	–0.015	–0.057	–0.201	–0.299
	Maximum snow depth (cm)	0.170	0.011	–0.274	–0.075	–0.032	0.141	–0.081	–0.244
	Mean snow depth (cm)	0.239	0.089	–0.265	–0.085	–0.072	0.129	–0.060	–0.258
Yangtze River	The duration with snow depths above 0 cm (days)	–0.076	–0.264	–0.142	0.236	0.135	0.169	0.225	–0.030
	The duration with snow depths above 5 cm (days)	–0.238	–0.398	–0.148	0.013	0.174	0.238	0.196	–0.095
	The duration with snow depths above 5 cm (days)	–0.266	–0.305	–0.403	–0.213	0.357	0.224	0.012	–0.050
	Maximum snow depth (cm)	–0.238	–0.473*	–0.288	0.035	0.322	0.237	0.117	–0.001
	Mean snow depth (cm)	–0.183	–0.428*	–0.277	0.014	0.174	0.264	0.168	–0.035
Lancang (Mekong) River	The duration with snow depths above 0cm(days)	0.127	–0.054	–0.114	0.217	0.111	–0.112	–0.193	–0.114
	The duration with snow depths above 5cm(days)	0.245	0.037	–0.068	0.171	0.022	–0.063	–0.301	–0.230
	The duration with snow depths above 5cm(days)	0.027	0.230	–0.196	0.048	0.159	–0.149	–0.171	–0.234
	Maximum snow depth (cm)	0.183	0.164	–0.075	0.100	0.008	–0.002	–0.253	–0.174
	Mean snow depth(cm)	0.256	0.178	–0.021	0.133	–0.080	–0.022	–0.179	–0.195
Nu (Salween) River	The duration with snow depths above 0cm(days)	0.261	–0.244	–0.248	0.286	0.317	0.088	–0.005	0.135
	The duration with snow depths above 5cm(days)	0.366	0.003	–0.166	0.123	0.188	0.157	–0.229	0.013
	The duration with snow depths above 5cm(days)	0.164	0.070	–0.189	0.001	0.210	0.082	0.035	–0.003
	Maximum snow depth (cm)	0.129	0.164	–0.234	–0.010	0.138	0.033	–0.273	–0.039
	Mean snow depth(cm)	0.223	0.159	–0.223	0.004	0.100	0.110	–0.290	–0.045
Yarlung Zangbo River	The duration with snow depths above 0cm(days)	0.195	–0.156	–0.258	0.280	0.218	0.025	0.040	–0.021
	The duration with snow depths above 5cm(days)	0.270	–0.162	–0.371	0.160	0.283	0.112	–0.082	–0.040
	The duration with snow depths above 5cm(days)	0.184	–0.326	–0.489*	0.110	0.264	0.126	0.077	0.172
	Maximum snow depth (cm)	0.158	–0.127	–0.505*	0.190	0.245	0.072	–0.029	–0.060
	Mean snow depth(cm)	0.220	–0.098	–0.493*	0.211	0.215	0.108	–0.083	–0.019
Total source regions	The duration with snow depths above 0cm(days)	0.425*	0.053	0.119	0.427*	–0.093	0.138	0.118	0.030
	The duration with snow depths above 5cm(days)	0.410*	0.041	–0.229	0.271	0.210	0.192	–0.389	0.012
	The duration with snow depths above 5cm(days)	0.142	–0.014	–0.276	0.209	0.322	–0.142	–0.407	0.054
	Maximum snow depth (cm)	0.338	0.043	–0.173	0.317	0.227	0.015	–0.472*	0.030
	Mean snow depth(cm)	0.417*	0.110	–0.136	0.319	0.160	0.009	–0.499*	0.001

Notes: $r_{0.05\,(2,\,23)} = 0.398$; $r_{0.01\,(2,\,23)} = 0.507$; $r_{0.05\,(2,\,22)} = 0.406$; $r_{0.01\,(2,\,22)} = 0.517$; * moderate significant level, ** high significant level.

gas, moisture, and dissolved matter and affect the activity of the microbes in the soil, as well as the transformation of soil organic matter and nutrients. They also regulate soil respiration in winter, leading directly to changes of vegetative growth conditions in the area covered with snow (Schimel et al., 2004; Welker et al., 2005; Monson et al., 2006; Freppaz et al., 2008; Morgner et al., 2010). In July, there is significant positive correlation between snow cover duration (depth > 0 cm) and the NDVI values in the large Asian river source regions, which also promotes the effect of snow cover on plant growth during the growing season and its influence on soil and moisture. Except for the Yangtze River source region, the NDVI values of all source regions increase significantly in July from 1981 to 2005, which also shows that snow cover in winter can promote the growth of vegetation during the following growing season. In October, the snow cover duration (depth > 5 cm), and the annual maximum and average snow depth are negatively correlated with the NDVI value. The negative correlation between the annual maximum and average snow depth and the NDVI value reaches a significant level. This partially shows that early large snow depths (in October) have adverse effects on vegetation growth.

Even after the germination period of the vegetation, the melting of snow can lead to a continuous rise in the vegetation index (Schimel et al., 2004; Welker et al., 2005; Monson et al., 2006; Freppaz et al., 2008; Morgner et al., 2010). The linear correlation of snow cover characteristics and the NDVI value in April are all positive for the large Asian river source regions. This reveals the phenomenon of "deceptive vegetation growth" caused by snow melting, which implies rising NDVI values. Earlier increases in NDVI might be attributed to earlier vegetation germination or earlier snow melting (Dye and Tucker, 2003). In April, the NDVI value of the Yangtze River source region is relatively high, but its linear relation with snow cover characteristics shows a negative correlation. Due to the shallow snow depth and short duration of snow cover, snow melting starts earlier and the NDVI value increases earlier. This is why a higher NDVI value is observed in the early period of the growing season. It should be noted that occasional snowstorms in April could also have adverse effects on the vegetation growth in the large Asian river source regions.

A low snow depth in winter is mostly caused by a precipitation deficit, which involves insufficient soil moisture and soil heat isolation. This implies that the vegetation will not grow well during the following year. When the snow cover is thick and starts to melt in April, the phenomenon of high NDVI values is likely to be observed. The snow cover characteristics have a positive correlation with the NDVI values in the following April and in the later period of the growing season (July–September) in the Yarlung Zangbo River source region. This might be caused by deep snow cover in winter adding sufficient levels of moisture and nutrients to the soil and protecting the activity of the soil microorganisms, thus ensuring positive vegetation growth during the growing season of the following year. Conversely, it is observed that the duration of snow cover with snow depth over 10 cm and the annual maximum and average snow depth of the Yarlung Zangbo River source region have a significant negative correlation with NDVI values in May and June. Thus, snow cover duration and depth have great influence on the vegetation growth in the source regions of the large Asian rivers on the Qinghai-Tibetan Plateau. However, complex relationships between snow cover characteristics and vegetation growth are generated when changes in duration of snow cover and depth in different regions interact with environmental, social, and economic factors (Qin et al., 2006; Peng et al., 2010; Paudel and Andersen, 2012). Furthermore, watershed hydrologic processes need to be further observed and modeled to identify more thoroughly the interaction between snow cover and vegetation in the source regions of the large Asian rivers on the Qinghai-Tibetan Plateau.

Conclusions

From 1980 to 2004, the average number of days with snow cover and snow depth above 0 cm in the source regions of the large Asian rivers on the Qinghai-Tibetan Plateau is 158.95 days with significant interannual fluctuation (SD = 31.54 days) and a generally increasing trend ($P < 0.01$). The average duration of snow cover with a snow depth above 5 cm is 65.1 days, showing a slight, but not significant rising trend ($P > 0.05$). Meanwhile, the snow cover duration with a snow depth above 10 cm is 13.21 days with an unobvious decreasing trend ($P > 0.05$). The regional average of annual maximum and average snow depths are 8.51 and 4.89 cm, respectively. Both have large interannual variations without significant trends from 1980 to 2004. In the different source regions, the values of snow depth and duration of snow cover decrease significantly from northeast to southwest across the Qinghai-Tibetan Plateau.

The interannual fluctuation of the regional average NDVI is also relatively high, with an insignificant decreasing trend in the source regions of the large Asian rivers on the Qinghai-Tibetan Plateau from 1981 to 2006. The pattern of annual maximum NDVI decreases from southwest to northeast, whereas the interannual fluctuations are slightly different.

The snow cover characteristics (duration and depth) are insignificantly correlated with annual maximum NDVI in the source regions of the large Asian rivers on the Qinghai-Tibetan Plateau from 1981 to 2004. There is a significant positive correlation ($P < 0.05$) between the snow cover duration and the NDVI values in both April and July across all source regions from 1981 to 2004. The annual maximum snow depth of the entire region has an obvious negative correlation ($P < 0.05$) with NDVI value in October. The annual average snow depth has an obvious positive correlation with NDVI value in April, and a significant negative correlation with NDVI value in October. The Yarlung Zangbo River source region is covered by snow for the longest time and to the greatest depth, but has the smallest maximum NDVI value from 1981 to 2004. The Yangtze River source region is covered by snow for the shortest time with the least snow depth, but has the highest NDVI value. This indicates the adverse effect of increasing snow depth and prolongation of the duration of snow cover on vegetation growth the following year. The melting of snow brings increasing effects to the NDVI value in spring to the source regions of the large Asian rivers in the Qinghai-Tibetan Plateau.

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References Cited

Alcaraz-Segura, D., Cabello, J., Paruelo, J. M., and Delibes, M., 2009: Use of descriptors of ecosystem functioning for monitoring a national park network: a remote sensing approach. *Environmental Management*, 43: 38–48.

Dye, D. G., and Tucker, C. J., 2003: Seasonality and trends of snow-cover, vegetation index, and temperature in northern Eurasia. *Geophysical Research Letters*, 30: doi: http://dx.doi.org/10.1029/2002GL016384.

Edmonds, T., Lunt, I. D., Roshier, D. A., and Louis, J ., 2006 : Annual variation in the distribution of summer snowdrifts in the Kosciuszko alpine area, Australia, and its effect on the composition and structure of alpine vegetation. *Austral Ecology*, 31: 837–848.

Fitzhugh, R. D., Driscollb, C. T., Groffmanc, P. M., Tierneyd, G. L., Faheyd, T. J., and Hardye, J. P., 2003: Soil freezing and the acid-base chemistry of soil solutions in a northern hardwood forest. *Soil Science Society of American Journal*, 67: 1897–1908.

Foster, J. L., Hall, D. K., Kelly, R. E. J., and Chiu, L., 2009: Seasonal snow extent and snow mass in South America using SMMR and SSM/I passive microwave data (1979–2006). *Remote Sensing of Environment*, 113: 291–305.

Freppaz, M., Celi, L., Marchelli, M., and Zanini, E., 2008: Snow removal and its influence on temperature and N dynamics in alpine soils (Vallée d'Aoste, northwest Italy). *Journal of Plant Nutrition and Soil Science*, 171: 672–680.

Gao, Q. Z., Li, Y., Wan, Y. F., Qin, X. B., Jiangcun, W. Z., and Liu, Y. H., 2009: Dynamics of alpine grassland NPP and its response to climate change in northern Tibet. *Climatic Change*, 97(3/4): 515–528.

Grippa, M., Kergoat, L., Le Toan, T., Mognard, N. M., Delbart, N., L'Hermitte, J., and Vicente-Serrano, S. M., 2005: The impact of snow depth and snowmelt on the vegetation variability over central Siberia. *Geophysical Research Letters*, 32: L21412, doi: http://dx.doi.org/10.1029/2005-GL024286.

Groffman, P. M., Driscoll, C. T., and Fahey, T. J., 2001: Colder soils in a warmer world: a snow manipulation study in a northern hardwood forest ecosystem. *Biogeochemistry*, 56: 135–150.

Guo, D. L., and Wang, H. J., 2011: The significant climate warming in the northern Tibetan Plateau and its possible causes. *International Journal of Climatology*, 32: doi: http://dx.doi.org/10.1002/joc.2388.

Immerzeel, W. W., Droogers, P., de Jong, S. M., and Bierkens, M. F. P., 2009: Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. *Remote Sensing of Environment*, 113: 40–49.

IPCC, 2007: *Climate Change 2007: the Physical Science Basis*. Cambridge: Cambridge University Press.

Jonas, T., Rixen, C., Sturm, M., and Stoeckli, V., 2008: How alpine plant growth is linked to snow cover and climate variability. *Journal of Geophysical Research*, 113: G03013, doi: http://dx.doi.org/10.1029/2007-JG000680.

Jonsson, A. M., Eklundh, L., Hellstrom, M., Barring, L., and Jonsson, P., 2010: Annual changes in MODIS vegetation indices of Swedish coniferous forests in relation to snow dynamics and tree phenology. *Remote Sensing of Environment*, 114: 2719–2730.

Jorgen, H., Hansen, B. U., Tamstorf, M. P., and Pedersen, S. B., 2006: Snow-vegetation relations in a High Arctic ecosystem: inter-annual variability inferred from new monitoring and modeling concepts. *Remote Sensing of Environment*, 105: 237–247.

Ma, L. J., Qin, D. H., Bian, L. G., Xiao, C. D., and Luo, Y., 2011: Assessment of snow cover vulnerability over the Qinghai-Tibetan Plateau. *Advances in Climate Change Research*, 2: 93–100.

Mao, J. Y., 2010: Interannual variability of snow depth over the Tibetan Plateau and its associated atmospheric circulation anomalies. *Atmospheric and Oceanic Science Letters*, 3: 213–218.

Monson, R. K., Lipson D. L., Burns, S. P., Turnipseed, A. A., Delany, A. C., Williams, M. W., and Schmidt, S. K., 2006: Winter forest soil respiration controlled by climate and microbial community composition. *Nature*, 439: 711–714.

Morgner, E., Elberling, B., Strebel, D., and Cooper, E. J., 2010: The importance of winter in annual ecosystem respiration in the High Arctic: effects of snow depth in two vegetation types. *Polar Research*, 29: 58–74.

Mu, Z. X., Jiang, H. F., and Liu, F., 2010: Spatial and temporal variations of snow cover area and NDVI in the west of Tianshan Mountains. *Journal of Glaciology and Geocryology*, 32: 875–882.

Nemani, R. R., Keeling, C. D., and Hashimoto, H., 2003: Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science*, 300:1560–1563.

Paudel, K. P., and Andersen, P., 2012: Response of rangeland vegetation to snow cover dynamics in Nepal Trans Himalaya. *Climatic Change*, 117: doi http://dx.doi.org/10.1007/s10584-012-0562-x.

Peng, S .S., Piao, S. L., Ciais, P., Fang, J. Y., and Wang, X. H., 2010: Change in winter snow depth and its impacts on vegetation in China. *Global Change Biology*, 16: 3004–3013.

Qin, D. H., Liu, S. Y., and Li, P. J., 2006: Snow cover distribution, variability, and response to climate change in western China. *Journal of Climate*, 19: 1820–1833.

Schimel, J. P., Bilbrough, C., and Welker, J. A., 2004: Increased snow depth affects microbial activity and nitrogen mineralization in two arctic tundra communities. *Soil Biology and Biochemistry*, 36: 217–227.

Seaquist, J. W., Hickler, T., Eklundh, L., Ardo, J., and Heumann, B. W., 2009: Disentangling the effects of climate and people on Sahel vegetation dynamics. *Biogeosciences*, 6: 469–477.

Sellers, P. J., 1989: *Vegetation canopy spectral reflectance and biophysical processes*. *In* Asrar, G., (ed.), *Theory and Applications of Optical Remote Sensing*, New York: Wiley, 297–335.

Shabanov, N. V., Zhou, L., Knyazikhin, Y., Myneni, R. B., and Tucker, C. J., 2002: Analysis of interannual changes in northern vegetation activity observed in AVHRR data from 1981 to 1994. *IEEE Transactions on Geoscience and Remote Sensing*, 40: 115–130.

Shaman, J. E., and Tziperman, E., 2005: The effect of ENSO on Tibetan Plateau snow depth: a stationary wave teleconnection mechanism and implications for the South Asian monsoons. *Journal of Climate*, 18: 2067–2079.

Singh, S. K., Rathore, B. P., Bahuguna, I. M., and Ajai, 2013: Snow cover variability in the Himalayan–Tibetan region. *International Journal of Climatology*, 34: doi: http://dx.doi.org/10.1002/joc.3697.

Tang, Z., Wang, J., Li, H., and Yan, L., 2013: 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. *Journal of Applied Remote Sensing*, 7(1): 073582, doi: http://dx.doi.org/10.1117/1.JRS.7.073582.

Trujillo, E., Molotch, N. P., Goulden, M. L., Kelly, A. E., and Bales, R. C., 2012: Elevation-dependent influence of snow accumulation on forest greening. *Nature Geoscience*, 5: 705–709.

Tucker, C. J., Pinzon, J. E., Brown, M. E., Slayback, D. A., Pak, E. W., Mahoney, R., Vermote, E. F., and El Saleous, N., 2005: An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data. *International Journal of Remote Sensing*, 26: 4485–4498.

Walker, D. A., Billings, W. D., and De Molenaar, J. G., 2001: Snow-vegetation interactions in tundra environments. *In* Jones, H. G., Pomeroy, J. W., and Walker, D. A. (eds.), 2001: *Snow Ecology: an Interdisciplinary Examination of Snow-Covered Ecosystems*. Cambridge: Cambridge University Press, 266–324.

Wang, K., Zhang, L., Qiu, Y. B., Ji, L., Tian, F., Wang, C. Z., and Wang, Z. Y., 2013: Snow effects on alpine vegetation in the Qinghai-Tibetan Plateau. *International Journal of Digital Earth*: doi: http://dx.doi.org/10.1080/17538947.2013.848946.

Welker, J. M., Fahnestock, J. T., Sullivan, P. F., and Chimner, R. A., 2005: Leaf mineral nutrition of arctic plants in response to warming and deeper snow in northern Alaska. *Oikos*, 109: 167–177.

Wu, S. H., Yin, Y. H., Zheng, D., and Yang, Q. Y., 2005: Climate change on the Tibetan Plateau during the last three decades. *Acta Geographica Sinica*, 60: 3–11.

Wu, T. W., and Qian, Z. A., 2003: The relation between the Tibetan winter snow and the Asian summer monsoon and rainfall: an observational investigation. *Journal of Climate*, 16: 2038–2051.

Yang, K., Ye, B. S., Zhou, D. G., Wu, B. Y., Foken, T., Qin, J., and Zhou, Z. Y., 2011: Response of hydrological cycle to recent climate changes on the Tibetan Plateau. *Climatic Change*, 109: 517–534.

You, Q., Kang, S., Ren, G., Fraedrich, K., Pepin, N., Yan, Y., and Ma, L., 2011: Observed changes in snow depth and number of snow days in the eastern and central Tibetan Plateau. *Climate Research*, 46: 171–183.

Zheng, D., 1996: The system of physico-geographical regions of the Qinghai-Xizang (Tibet) Plateau. *Science in China*, 39(4): 410–417.

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