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Review on global change status and its impacts on the Tibetan Plateau environment

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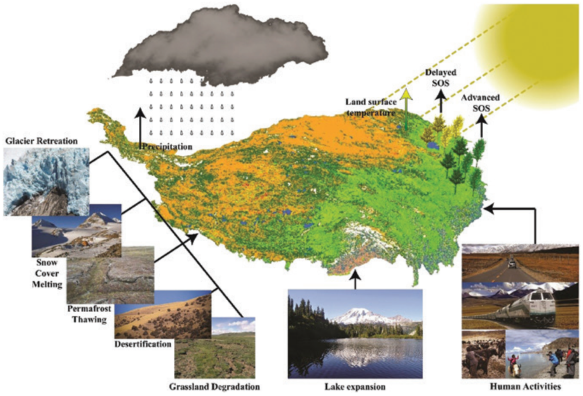
Abstract

The Tibetan Plateau (TP) holds fundamental ecological and environmental significances to China and Asia. The TP also lies in the core zone of the belt and road initiative. To protect the TP environment, a comprehensive screening on current ecological research status is entailed. The teased out research gap can also be utilized as guidelines for the recently launched major research programs, i.e. the second TP scientific expedition and silk and belt road research plan. The findings showed that the TP has experienced significant temperature increase at a rate of 0.2°C per decade since 1960s. The most robust warming trend was found in the northern plateau. Precipitation also exhibited an increasing trend but with high spatial heterogeneity. Changing climates have caused a series of environmental consequences, including lake area changes, glacier shrinkage, permafrost degradation and exacerbated desertification. The rising temperature is the main reason behind the glaciers shrinkage, snow melting, permafrost degradation and lake area changes on the TP and neighboring regions. The projected loss of glacial area on the plateau is estimated to be around 43% by 2070 and 75% by the end of the century. Vegetation was responsive to the changed environments, varied climates and intensified human activities by changing phenology and productivity. Future global change study should be more oriented toward integrating various research methods and tools, and synthesizing diverse subjects of water, vegetation, atmosphere and soil.



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INTRODUCTION

The Tibetan Plateau (TP), the biggest and highest elevation plateau in the world, covers an area of about 2.6 × 10^6 km^2 (Li *et al.* 2018b). It stretches from Pamir to Hindu Kush in the west, and Hengduan in the east. From north it is attached with Kunlun and Qilian mountains and to the south with Himalayas. The TP is named as 'Third Pole' or 'Roof of the world' because of its influential land surface process and strong interactions with atmosphere, cryosphere, hydrosphere and biosphere (Yao et al. 2012a). The plateau is the origin of many Asian rivers such as Brahmaputra, Ganges, Indus, Mekong, Yangtze and Yellow river and is also known as 'Asian water tower' (Xu *et al.* 2008b). It is estimated that the TP provides natural resources to >1.5 billion people in the form of fresh water, pasture and timber (Fig. 1).

Climatic conditions in this region have drastically changed since the middle of 20th century (Moors *et al.* 2011) and shifted the ecological conditions on the TP (Wang *et al.* 2007). Additionally, heightened anthropogenic activities have been observed on the TP (Agarwal 2009). The recent global change has impacted regional environment of the plateau to an unprecedented level, potentially threatening the livelihood of its inhabitants in the near future.

The plateau also exerts strong thermal influences on the regional and global climate system by isotropic, thermal and anthropogenic forcings (Duan and Wu 2005; Yanai *et al.* 1992; Yang *et al.* 2014). The TP not only influences the atmospheric circulation in the region but also affects the climate pattern of the globe (Fig. 2). Due to its strong effects on adjacent and remote regions (Xu *et al.* 2015; Yao *et al.* 2013; Zhao *et al.* 2015), understanding the dynamics of cryosphere, hydrosphere and vegetation dynamics on the TP is crucial (Cleland *et al.* 2007; Garonna *et al.* 2016; Morisette *et al.* 2009; Peñuelas *et al.* 2009).

The TP and the adjacent central Asia plateau lie in the center of the silk and belt road initiative, which is an international cooperation development plan initiated by China. To provide scientific basis for a sustainable silk and belt road plan, full understanding on the environmental conditions and future change is imperative. To meet these needs, Chinese national government launched the second scientific expedition, which aims to apply innovative investigation technique and tools to evaluate environmental changes on the TP in the past 40 years. Also Chinese Academy of Sciences initiated the level A strategic scientific research plan, which was designed to understand impacts of global change on the TP environment. In advocating these several unprecedented major scientific projects, it is entailed to comb through current research status on the TP and point out new research directions. The objective of this review was to summarize global change status and its impacts on environments of the plateau. The impacts include on glaciers, snow cover, hydrological processes, permafrost degradation and vegetation. Only with a thorough review, our research knowledge gap could be teased out and future research foci could be clarified.

OBSERVED CLIMATIC FACTORS ON THE TP

Surface air temperature

Temperature is the most commonly studied climatic factor on the TP due to its fundamental significances. To date, generally accepted viewpoint is about its overall mean and spatial pattern. The annual mean temperature observed on the TP is <0°C. Across the entire TP, temperature exhibits a high spatial heterogeneity, and it decreases from east to west (Sun *et al.* 2015). Over the last several decades, the TP is significantly affected by global warming and exhibited a uniform warming trend (Gao *et al.* 2015a). From the mid-20th century, temperature on the TP has increased by 1.8°C (Wang *et al.* 2008), with a warming rate 1.5 times the global average (Yao *et al.* 2012a; Zhang *et al.* 2013). For separate periods, temperature showed

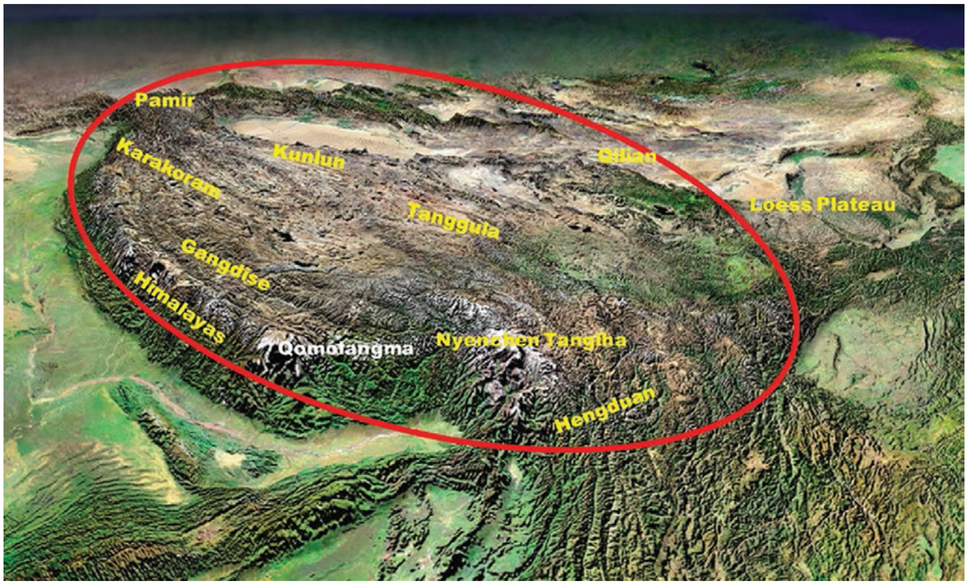

Figure 1: the geographical location of Tibetan Plateau, stretches from Pamir and Hindu Kush in the west to the Hengduan Mountains in the east from the Kunlun and Qilian mountains in the north to the Himalayas in the South. (Yao *et al.* 2012a).

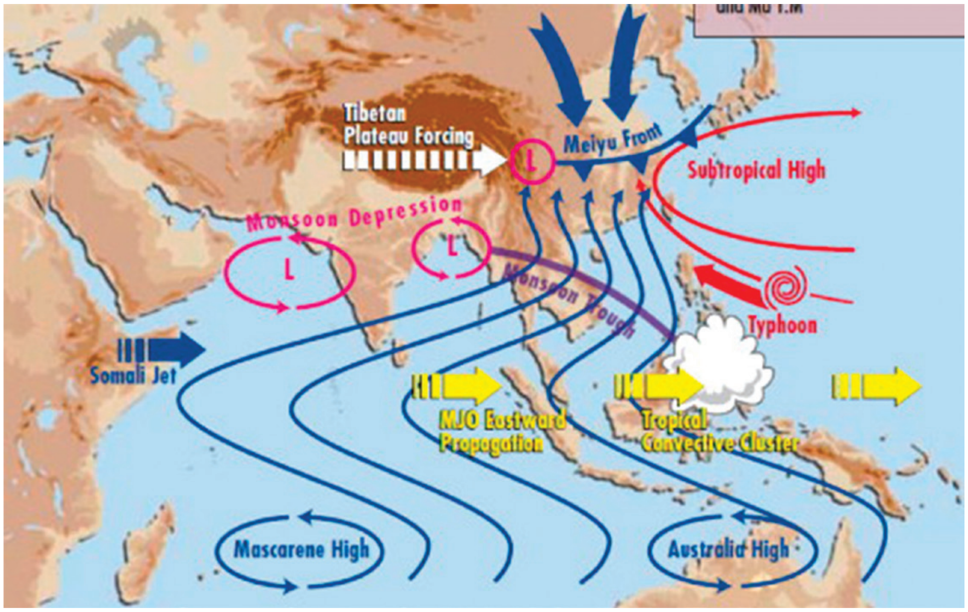

Figure 2: atmospheric circulation pattern influencing TP from summer monsoon. Water pattern is associated with the tropical and subtropical areas with the Tibetan Plateau force. *Note:* L represents low pressure cyclonic core (Yao *et al.* 2012a).

stability during 1970s, significantly increased during 1980s and drastically increased since 1990s (Zhang *et al.* 2014).

Observation data showed that mean annual air temperature increased at a rate of 0.25°C/decade during 1961–2014. The winter temperature increased twice the mean annual value (You *et al.* 2010, 2013), and winter and autumn showed faster warming trends than spring and summer (Kuang *et al.* 2016). Model based studies showed a shrink of −0.20°C/annum in diurnal-night temperature range during 1961–2013 due to a higher warming rate at night (You *et al.* 2016a) and this trend is predicted to continue in the near future (Zhu *et al.* 2013). Warming on the TP started earlier than other regions of China and Polar regions of the world (Liu and Chen 2000). Extended to a long temporal dimension, results from the ice core records revealed that climate varied more widely in the TP than Greenland and other cold regions of the world (Thompson *et al.* 1997).

Numerous studies have been conducted on the TP about the temperature changes in the past decades (Table 1). Each study reported discrepant temperature increasing values, and the conclusion about the faster temperature increasing rate on the TP than the Northern Hemisphere is also preliminary. Whether the warming hiatus exists is also still illusive. The main reason is because that each study relies on distinct datasets and targeted different periods. In the future study, a comprehensive field observation and remote sensing data integration is imperative. By this integration, the data scarcity in the remote west TP can be surmounted to a certain degree.

Variable precipitation

Precipitation is the key source of water on this planet and it holds paramount importance for life existence on the Earth. It also plays a profound role in the energy balance, hydrological cycle and terrestrial ecosystem sustainability by affecting the biological, hydrological and ecological processes (Wan *et al.* 2017). Different from temperature, the trend of precipitation has not been as apparent. Due to the scarcity and low accuracies of remote sensed precipitation data, research findings about precipitation are composed of considerable controversies.

The conclusion about its spatial pattern is unanimous. The meteorological station and remote sensing data both showed that annual mean precipitation exhibits a spatial pattern of decreasing from southeast to northwest (You *et al.* 2015). The precipitation also varied strongly with season. The summer precipitation (June–September) consists of 60–90% while the winter precipitation (December–February) accounts for <10% of the annual total (Xu *et al.* 2008a). The southern edges of Himalayas and the other widespread valleys receive large amount of convective precipitation (Fig. 3).

Temporally, the TP precipitation does not show a uniform increasing or decreasing trend (Gao *et al.* 2015a; Tong *et al.* 2014b; You *et al.* 2015). The precipitation increasing rate calculated over a 55-year period for the entire plateau is 3.8 mm/decade (Wan *et al.* 2017). The variable precipitation trend is significantly characterized by the regional physiognomies. The studies based on meteorological stations observation and simulations showed that the TP received yearly increasing precipitation in the northeast, central and southwest regions (Gao et al. 2015a, 2015b; Li and Xue 2010; Wang *et al.* 2014), while southeastern plateau has shown a decreased annual precipitation trend (Kuang and Jiao 2016).

Indian monsoon, Asian monsoon, and block effects from complex mountain chain on the TP all exert influences on

Table 1: warming trend on the Tibetan Plateau since the mid of 20th century

Number	Time period	Number of stations	Warming trend (°C per decade)	Reference
1	1955–1996	197	0.16	Liu and Chen (2000)
2	1957–2000	161	0.16	Frauenfeld *et al.* 2005)
3	1971–2000	77	0.20	Wu *et al.* (2007)
4	1961–2000	43	0.24	Rangwala *et al.* (2009)
5	1961–2003	71	0.25	Duan and Wu (2006)
6	1961–2003	64	0.28	Duan *et al.* (2006)
7	1966–2003	75	0.28	Zhang (2007)
8	1961–2004	71	0.25	You *et al.* (2010)
9	1961–2005	71	0.27	You *et al.* (2016b)
10	1970–2005	75	0.31	Liu *et al.* (2011)
11	1961–2007	72	0.28	Guo and Wang (2012)
12	1961–2007	90	0.36	Wang *et al.* (2008)
13	1960–2008	63	0.25	Song *et al.* (2014b)
14	1970–2009	75	0.34	Xie and Zhu (2013)
15	1984–2009	97	0.67	Zhang *et al.* (2013)
16	1981–2010	80	0.50	Yin *et al.* (2013)
17	1957–2012	49 to 95	0.36	Zhang *et al.* (2014)
18	1970–2012	26	0.36	Xie *et al.* (2015)
19	1971–2015	88	0.30	Liu *et al.* (2017)

Modified from (Kuang *et al.* 2016).

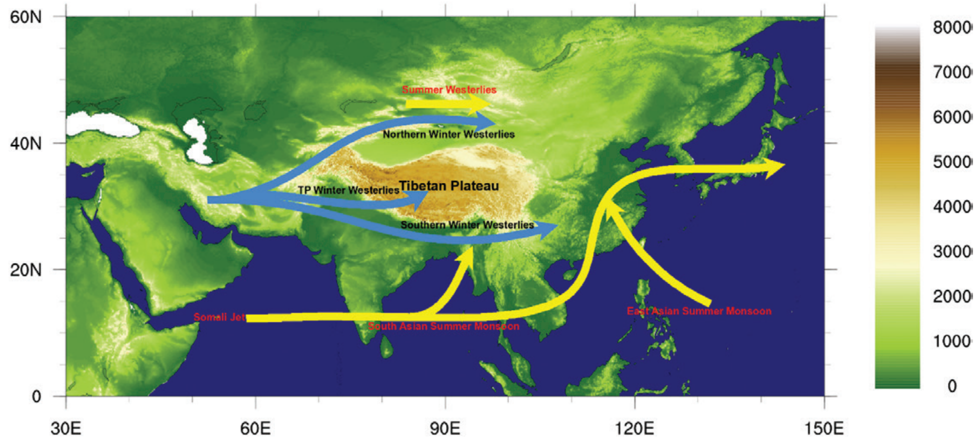

Figure 3: atmospheric circulation system influencing TP from different geographical locations. Yellow arrows indicating summer monsoon while blue winter monsoon (Yang *et al.* 2014).

precipitation pattern on the TP, thereby a heterogeneous spatial pattern. The TP is influenced primarily by East and South Asian monsoon, as well as westerlies to a modest extent. As a result, the TP gets wetting episodes during monsoon seasons (Yang *et al.* 2008). Land surface processes also feedback to climates. Heavy precipitation in the form of snowfall can slow down summer monsoon on TP (Liu *et al.* 2004). Warming trend on the plateau has increased the atmospheric water holding capacity and results in high precipitation in some parts of the plateau (Trenberth 2011). But precipitation is also affected by many other factors, e.g. increasing CO_2, North Atlantic Oscillation and El Nino (Dai 2013). As a whole, warming did not cause pronounced precipitation increment on the TP since 1980s (Fang *et al.* 2015).

Due to the remoteness and inaccessible terrain of the TP, meteorological stations are insufficient and sparsely distributed. Currently, most of the meteorological stations are located in central and eastern TP (semi-arid and humid region) while only few are in the western part (arid region). The development in the satellite remote sensing technology has provided an unprecedented opportunity to monitor precipitation in this environmentally harsh region. To date, remotely sensed data have been widely used to monitor precipitation pattern on the TP, which greatly increased the data accuracies (Bai *et al.* 2008; Fujinami and Yasunari 2001; Ma *et al.* 2016; Tong *et al.* 2014a; Wang *et al.* 2014). The spatial pattern of precipitation on the TP is quite complicated and the magnitude from each causing factor is difficult to quantify. To increase the accuracies of monitoring and prediction, there are several pending issues awaiting to be resolved: (i) generating new precipitation data series by integrating multiple sources of data, including remote sensing data and field observation data; (ii) tracking water vapor movement pathway from the southeastern TP; (iii) separating the contribution of local evapotranspiration and water vapor influx from outside the TP to precipitation formation on the TP; and (iv) setting up site monitoring equipment to increase the density of field measurements.

STRENGTHENED HUMAN ACTIVITIES

Due to the roughness and harsh environments of the plateau, it is speculated that human settled on the TP ~20 000 years ago, when the presence of worked stones, handprints and footprints were discovered >4200 m.a.s.l. in the southern parts of the TP (Aldenderfer 2011). Agropastoral was thought to be the main source of living over the high elevated regions (Chen *et al.* 2015). After thousands of years, the plateau population reached ~12 million nowadays. This population increasing rate is higher than that of the entire China (Zhang *et al.* 2005). The number of tourists has also exponentially increased from 3530 to 6 851 400 during 1980–2010 in Xizang province. In Qinghai province, the tourists increased from 3 209 592 to 20 056 000 during 2000–14 (Chung *et al.* 2018). Livestock in Xizang grew from 955 000–2 349 000 during 1951–2010 (Yu *et al.* 2012).

All human activities are spatially heterogeneous on the TP. For example, the livestock grazing occurs across the TP but high grazing pressure is exerted on regions down valleys and around human settlements. Such a spatial heterogeneity of human activities set the stage for spatially varied responses of ecosystems (Li *et al.* 2019). However, it is difficult to separate out effects of human activities on ecosystems and this knowledge is crucial for ecosystem management (Feng *et al.* 2017; Wang *et al.* 2016b).

In the future studies, the following pathways entail immediate attentions. First, livestock grazing pressure needs to be spatially explicit mapped. The current livestock amount is recorded for each county and each county in the TP is too large to make effective analysis of livestock effects on ecosystems. Second, fences locations are needed to be mapped. Grazing exclusion by fence is commonly applied on the TP. We can hypothesize that vegetation dynamics in fenced regions are mostly driven by climates, while ecosystems outside are regulated by both human activities and climates. But only with spatially explicit distribution of grazing fences, can we separate the relative effects of climate changes and human activities.

IMPACTS OF CLIMATIC CHANGE ON THE CRYOSPHERIC COMPONENTS OF THE TP

Glaciers

The TP has third largest concentration of glaciers after Polar Regions in the world, containing 84% glacial of China (Liu and Chen 2000). The TP is the 'water tower' of Asia and the glaciers provide the majority of water sources. Mountain glacier status is also an indicator of climate changes. The monitoring results from a variety of sources revealed that the total number of glaciers on the TP is >36 973, covering an area of ~49 873 km^2 and with a total volume of ~5600 km^3 (Yao *et al.* 2007).

Extensive glacier melting has occurred on the TP since the middle of last century and it accelerated since late 1980s. The glacier retreat exhibited a strong spatial heterogeneity on the TP. The retreat rate is comparatively low in the interior plateau, medium at the lower elevated margins and maximum at high elevated edges (Yao *et al.* 2007). Spatially, the rate of glacial retreat wanes from southeastern TP to central TP, although the negative trend appears on both sides. The greatest retreat was found in the Himalayas mountain region, followed by continental interior and the least in the eastern Pamir (Yao *et al.* 2012b). Such systematic variations are due to increasing temperature and less precipitation on the Himalayas and high precipitation on the eastern Pamir along with varied atmospheric circulation processes (Yao *et al.* 2012b). It is projected that the TP would lose 43% of its total glacial by 2070 and 75% by the end of this century, respectively (Maclean 2009). Accelerated glacier retreat results in increased frequent flooding (Lee *et al.* 2013; Wang *et al.* 2013a; Yao *et al.* 2012a).

Rising temperature plays a crucial role in causing the glacial shrinkage on the TP and surrounding regions (Scherler *et al.* 2011; Zhang *et al.* 2017a). Temperature increases in a greater magnitude along rising altitude and the increasing rate reaches the highest between 4800 and 6200 m a.s.l. (Qin *et al.* 2009), which marks as the ablation zone for most glaciers on the plateau. Precipitation decreased in Himalayas region, while eastern Pamir received more precipitation. Besides increasing temperature and precipitation anomalies, black carbon is also a necessary element in causing glacier melting by modifying surface albedo and energy balance (Menon *et al.* 2010).

Glacier retreat has caused various hydrological process changes, such as increased river runoff and lake volumes, along with higher probability of natural disasters, such as ice avalanches or flooding (Faillettaz *et al.* 2015; Haeberli *et al.* 2017; Yao *et al.* 2004). To protect and retard its retreat, it is imperative to monitor the spatial-temporal patterns of glaciers and dig into the causing factors. To reach these goals, the following points are pressing in the future glacier researches: (i) introducing new techniques to monitor glacier area, depth and volume changes. Previous monitoring has been focused on area change. Recently, developed techniques make glacier depth and volume measurement possible; (ii) gathering historical photo and documents and extend the past coverage of glacier records; (iii) establishing fixed and long-term environmental change stations to monitor environmental changes related to glaciers; (iv) monitoring closely environmental change outside China, industry development in Southern Asia has transported massive pollution, such as black carbon to the TP and accelerate the glacier melting.

Snow cover

Snow is an essential and delicate part of cryosphere. It plays a dominant role in maintaining the hydrological cycles and also controls the seasonal distribution of water supplies in arid and semi-arid areas of the plateau (Ma *et al.* 2011). Snow is related to a wide range of land features, such as glacier area changes, glacial lakes outburst and lake area variations (Zhang *et al.* 2012). The TP contains third largest snow-covered area after Polar Regions in the world. Snow cover on the TP is strongly sensitive to climate change and also provides feedback to climates, implicating its robust and strong interactions with atmosphere, hydrosphere and biosphere. Thus, it is crucial to timely monitor responses of snow cover to climate variations on the plateau (Tang *et al.* 2013b).

Previous researches concluded that snow cover change has occurred on the TP in the past several decades, but plenty of variations remain. Snow cover is regulated by temperature and precipitation on the entire TP or at an individual river basin. Some studies revealed slightly positive trend in snow covered area prior to 1997 utilizing ground and satellite data (Li and Yanai 1996; Qin *et al.* 2006), while the trend turned during 1997–2012 (Ma *et al.* 2011; Pu *et al.* 2007; Shen *et al.* 2015; Su *et al.* 2016). Spatially, high snow cover was found on the southern and western edges of the plateau, which receives moist air transported by East Asian monsoon (Li *et al.* 2018b).

Snow affects surface processes through changing surface energy balance (Qu and Hall 2014). Albedo acts as a pivotal interaction media between surface and local climates.

Based on the Coupled Model Intercomparison Project versions 3 (CMIP3) and 5 (CMIP5) (Guo *et al.* 2018), an increasing absorption of solar radiations due to decreased snow albedo amplified snow cover effects at high elevated regions of the TP (Wang *et al.* 2015). The snow–albedo relationship is highly influenced by several factors, such as snow grain size, solar zenith angle, liquid water content, snow impurities, layer structure in the snowpack, snow depth and so on. Out of these factors, snow grain size is found the key factor regulating snow–albedo relationship (Aoki *et al.* 2011; Flanner *et al.* 2007).

The recent advancement in satellite technology boosts snow cover monitoring for the remotely inaccessible and physically hostile regions (Rittger *et al.* 2013; Tang *et al.* 2013a; Yang *et al.* 2015). Different remote sensing products have been used to monitor snow cover changes over the entire TP. Comparatively, MODIS products have shown higher accuracies than the Interactive Multisensor Snow and Ice Mapping System (IMS) products, with an overall accuracy higher than 91% in accordance with field station data (Yang *et al.* 2015). Due to lack of ground observation data, results of various remote sensing data contain much spatiotemporal uncertainty. It is strongly recommended to use land surface models coupled with remote sensing observations in monitoring snow cover change on the plateau. Only integration of multiple data sources could we increase monitoring accuracies, and facilitate our predicting future snow cover conditions under different climate scenarios.

Permafrost

The TP is underlain by ~1.4 million km^2 of permafrost, ~75% of the total in China. The permafrost existence requires an average annual temperature between −0.5°C and −0.3°C and they are highly susceptible to global and regional climate change (Yang *et al.* 2010). The thickness of the TP permafrost varies spatially from 1 m to 130 m, depending on geography, biophysical components and climatic factors (Cheng 1997).

As a result of rising temperature globally, extensive permafrost degradation on the plateau has been reported during the past decades. In total, the TP has lost almost 10% of its permafrost during the last decade (Qiu 2008). The hydrological model simulated 8.8% of permafrost reduction within elevation range of 3500–3900 m during 1971–2013 (Gao *et al.* 2017). The fastest permafrost degradation occurred as being deepened by 0.032 m per decade. On average, the seasonally frozen soil layer showed a submerging trend of 0.032 m per decade, and the active layer thickness increased by 0.043 m per decade (Gao *et al.* 2017).

Numerous studies based on observational data has confirmed the warming trend over the plateau (mostly in the central, eastern and northwestern), and the trend is predicted to continue into the 21st century (Li and Cheng 1999). The fast temperature increment would further exacerbate TP permafrost degradation. Due to the relatively high population density on the TP, effects of human activities on permafrost is more intensive on the TP than in the Arctic and subarctic soils (Yang *et al.* 2010). It has been observed that the southern limit of permafrost has shifted by 16 km northward while northern limit moved by 2 km southward under the combined effects of human activities and climate changes (Cheng *et al.* 1993).

The permafrost degradation caused an ensemble of environmental consequences such as land subsidence, soil erosion, and grassland degradation (Qin *et al.* 2006). The permafrost degradation also influences the interactions between land surface and atmosphere and disrupts the energy–water balance on the terrestrial land (Walvoord and Striegl 2007). Understanding permafrost variations and its consequences on regional hydrological processes is integral for sustainable management of water resources and ecosystem management in this cold region. Previous related studies still contains plenty of uncertainties, which open grounds for improving our understanding on its current spatial and temporal characteristics, also its future variations and their effects on regional environments (Gao *et al.* 2017). In the future studies, permafrost thawing and its effects on soil carbon storage need further studies. Organic carbon is mainly preserved in soil on the TP. Whether permafrost thawing causes carbon emission or sink is still illusive. The second pressing matter about permafrost research is to couple ecosystem process model with permafrost dynamics model. Only with their tight coupling, can we improve the prediction of ecosystem status as caused by permafrost changes. Third, novelty soil penetration technology should be introduced into permafrost depth and dynamics monitoring, especially for the edge zone where permafrost is distributed.

Lake dynamics and its response to climate change

The inland lake surface areas and water volume on the TP are strong indicators of hydrological cycles and regional climate changes. Interactions of hydrological processes and climates influence the water budget of these lakes seasonally and annually. The TP contains >1500 lakes, and the lake areas on the TP accounts for 49% of the total in China (Ma *et al.* 2010). The TP lakes are the primary water sources of the region and several other major outflowing rivers. Periodic monitoring of these resources is essential (Lei *et al.* 2014).

The water balance of the TP lakes is highly responsive to climate change, in particular to temperature, precipitation, evaporation, and duration of solar radiation (Yao *et al.* 2010). Due to the warming and wetting on the TP in the last 50 years, one-third of the TP lakes have expanded and vast area of dryland has submerged under lakes (Dong *et al.* 2018). Different factors determine the interannual and seasonal lake area dynamics. For example lakes are affected primarily by East Asian monsoon and subtropic westerlies in summer, while by dry and cold westerlies during winter (Yao *et al.* 2012a).

Precipitation has not been an unusual factor in increasing lake water level in the north and east regions. The reason lies in that evaporation rate is three times higher than precipitation in these regions. So expanded lakes size is also subject to glacier melting and permafrost degradation (Zhang *et al.* 2017b). Due to less precipitation and high evaporation in northern Changtang Plateau, numerous lakes have shrunk or completely disappeared because of their total dependency on seasonal snowpack and snowmelt. The alpine lakes on the high altitudes are mostly sustained by melting glaciers/snowpack and meltwater, which render them vulnerable to climate change (Lin *et al.* 2018). Furthermore, the spatial and temporal responses of the TP lakes are varied due to their nonhomogeneous climatic conditions and locations within distinct biomes (Song *et al.* 2014a). Lake area growth in the TP Interior (TPI) during late 1990s was found to be completely associated with the changing climate (Lei *et al.* 2014).

The lake expansion or shrinkage have caused various ecological and hydrological consequences, such as glacial lake outburst flow and flooding across the TP. The glaciers melting and accelerated snow thawing caused by increasing temperature has modified lake environment, which in turn alters hydrology and biochemical settings of the river discharges and runoff (Lin *et al.* 2018).

The complex topography of the TP makes it difficult to conduct in situ observations on lake variations. The reason behind decreasing water levels in the lakes of southern TP, even with increased rates of glacier melting in Himalayas, still remains unclear (Kehrwald *et al.* 2008). Therefore, space borne satellite remote sensing and optical photogrammetry are entailed to monitor lakes variations on a regular basis. Though many quantitative studies have been conducted on monitoring lake phenology, surface area change, and water balances, information associating them with climate change is still lacking (Sadia *et al.* 2018). Timely monitoring and predicting the lake phenology on the entire TP is crucial for safe and sustainable development of regional economy, also for policy makers in sustaining the environment safety of this remote area (Yang *et al.* 2018).

CLIMATE EFFECTS ON VEGETATION

Response of vegetation phenology to climate change

The TP is mainly covered by vegetation of alpine grasslands and meadows (Bingrong *et al.* 2006; Pu *et al.* 2007), which are very sensitive to climate dynamics and an ideal bioindicator of climate change (Ding *et al.* 2013). Plant phenology is one important and convenient parameter indicating plant species responses to interannual climate change (Rosenzweig *et al.* 2007). It can be inferred from agricultural practices, animal husbandry, forestry, industries, tourism and so on (Beaubien and Freeland 2000; Gilbert *et al.* 2006; Rauste *et al.* 2007). Moreover, it has been observed by various studies, particularly on the TP that plant phenology can influence pasturage, on which livestock depends (Ding *et al.* 2007; Xue *et al.* 2005; Fig. 4).

The delayed green-up date has been monitored during 2000–11 in the southwestern TP, caused by rising preseasonal temperature and reduced preseasonal precipitation (Shen *et al.* 2014). This study revealed the significant precipitation effects on the alpine spring vegetation phenology. Other studies reported that enhanced preseasonal precipitation on the TP may delay starting of season (SOS) of alpine grassland and tundra due to its cooling effect (Piao *et al.* 2006; Shen *et al.* 2014). Findings from each study varied due to their distinct targeted periods or data sources employed (Table 2). At a community level, various plant species of a community demonstrate different phenological responses toward climatic variations, resulting in modified species composition (CaraDonna *et al.* 2014; Cleland *et al.* 2007). Other ecological processes, including trophic incongruity and pollinator–host disagreement, can further be influenced (Kerby and Post 2013).

Precipitation as rainfall or snow fall plays a great role in sustainable vegetation growth (Dorji *et al.* 2013). Temperature and precipitation profoundly interact with snow cover and exert effects on alpine vegetation phenology (Qin *et al.* 2006; Rammig *et al.* 2010; Wang *et al.* 2016a). Especially at high elevated regions, snow cover dynamics is deeply associated with the shifting of spring phenology (Wang *et al.* 2017). Besides spring temperature and precipitation, the chilling winter, photoperiod and degrading permafrost also effects the life cycle of green vegetation on the TP (Wang *et al.* 2017).

For a short-time period, vegetation phenological changes would affect the geomorphology, as well as biophysical processes and land surface parameters, such as albedo, evapotranspiration, energy budget and eventually regional climates (Babel *et al.* 2014; Jeong *et al.* 2009). Large scale changes in vegetation growing season could also bring drastic variations in biogeochemistry of soil environment through variations in carbon fluxes and trophic levels' energy flow (Peñuelas and Filella 2009). Peculiar to the TP, it is not yet known how altered spring vegetation phenology affects surface heat intensity, then further feedback to climates. Remarkable warming on the TP is likely to inhibit the growth of alpine grassland and probably increases the atmospheric aridity. It is reported that vapor pressure deficit is projected to increase by 10–38% on the plateau in the future and this would further increase the atmospheric drought pressure on the Tibetan alpine grasslands and cause anisohydricity in Tibetan grasslands (Gao *et al.* 2015a).

Remote sensing data have been increasingly applied in addressing vegetation phenology dynamics on the TP. But findings generated by differed data present a certain inconsistence. To understand the response mechanism of the TP vegetation phenology, future studies should increasingly collect field observations, including specific phenology monitoring network and other useful information related to phenology (e.g. carbon fluxes network). Second, remote sensing monitoring results are better to be integrated with other heat requirement models to predict phenology dynamics. Third, precipitation frequency and timing, and accumulated temperature need to be integrated to address their combined effects on vegetation phenology.

Climatic effects on vegetation productivity

Ecosystem productivity holds great value to ecosystem carbon cycle. Increasing temperature and precipitation extensively affects ecosystem productivity on the plateau. Increasing temperature influences physiological activities like photosynthesis

Table 2: spatiotemporal vegetation phenological changes on Tibetan Plateau

SR	Period	Data type	SOS	EOS	LOS	Region	Reference
1	1999–2009	SPOT–VGT	Earlier 6 days/decade	Delayed by 2 days/decade	Lengthened by 8 days/decade	TP	Jin *et al.* (2013)
2	1989–2008	GIMMS	Advanced 4.6–9.9 days	Delayed 7.3–10.5 days		TP	Jin *et al.* (2013)
3	1982–2011	GIMMS		Delayed 0.7day/decade		TP	Cong *et al.* (2016)
4	1983–2012	GIMMS	52.21%	34.30%	—	TP	Wang *et al.* (2017)
5	2000–16	MODIS	Advanced 1.4 days/decade			Northeastern TP	Li *et al.* (2017)
6	1982–2014	NOAA/AVHRR	Advanced	Delayed	Increased	TP	Cheng *et al.* (2018)
7	1960–2013	Temperature and MODIS	Advanced by 1.42 days/decade using temp data	6.04 days/decade using MODIS			Yu *et al.* (2018)
8	1960–2014				Averaged 103 days	TP	He *et al.* (2018)
9	1982–2013	AVHRR	Advanced 2–3 days/decade	Delayed 1–2 days/decade	Lengthened by 1–2 days/decade	TP	Zhang *et al.* (2018a)

Abbreviations: SOS = start of growing season, EOS = end of growing season, LOS = length of growing season.

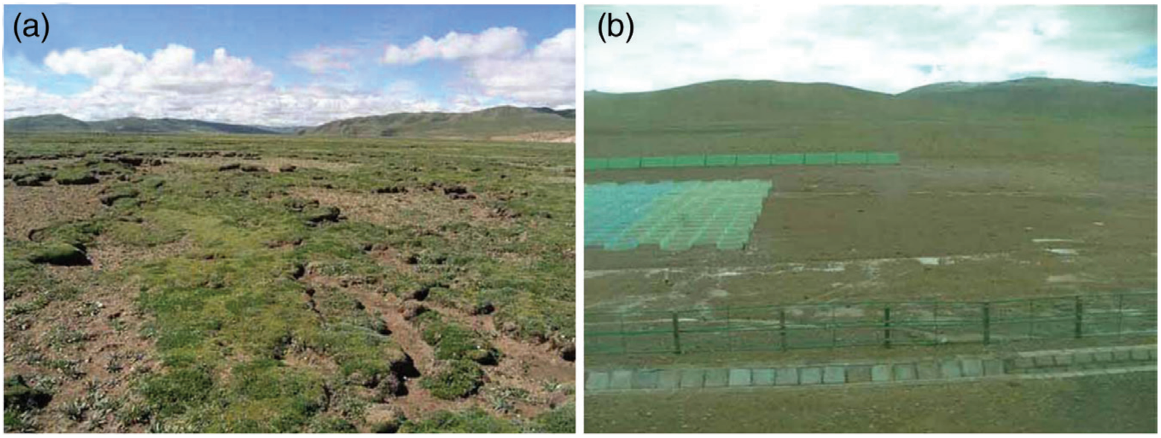

Figure 4: forms of rangeland degradation in representative geographic regions on the TP. (**a**) Alpine meadow degradation in South Qinghai; (**b**) Alpine steppe degradation near a major highway in Northern Tibet (Li *et al.* 2013).

Figure 5: grassland degradation in the Qaidam Basin (Li *et al.* 2013).

and respiration (Ganjurjav *et al.* 2015; Hu *et al.* 2016; Wu *et al.* 2011), so does precipitation (Angert *et al.* 2005). They eventually accelerate plant growth, and the magnitude varies with respective ecosystem types (Craine *et al.* 2012; Davi *et al.* 2006; Oberbauer *et al.* 2007; Sage and Kubien 2007; Zhang *et al.* 2018b). Generally, increased temperature causes higher NPP for the alpine ecosystem, but the effects differ with plant species (Li *et al.* 2018c; Rustad *et al.* 2001). Carbon fluxes in the active growing seasons are also greatly influenced by water stress for the alpine ecosystem (Zhang *et al.* 2018b).

Due to its value in providing basic surviving materials for humans, NPP can also be considered as a significant socioeconomic well-being indicator. Based on economic losses attributed to reduced alpine grassland growth, the direct loss caused by decreased NPP on the Plateau was estimated to be $2.44 billion in 2008 (Wen *et al.* 2013). Aggravated grassland degradation on the TP significantly shrink its ecosystem service capacity (Li *et al.* 2018a; Fig.5).The grassland degradation can be caused by overgrazing, climate change, wind and rain erosion and rodents (Chen *et al.* 2014; Marston *et al.* 2014; Shang and Long 2007). The future studies about ecosystem productivity on the TP need to overcome the following restrictions. First, model parameter needs to be optimized using field collected data to increase model accuracies. Second, studies on belowground vegetation parts need to be strengthened. The belowground part accounts for a significant proportion of the alpine ecosystem, but its productivity and annual flux has still plenty of uncertainties.

FUTURE RESEARCH DIRECTIONS

Under the ongoing climate change, changed vegetation status would bring about profound impacts on the related surface processes such as, surface albedo, soil moisture and energy cycles, thereby providing feedback to climates (Notaro and Liu 2008). Due to its high altitude and large body size, influences of the TP on climates can be further amplified. Considering its environmental and ecological significances and our knowledge gap, the following pursuit avenues for ecological and environmental research were teased out:

1. Integration of multiple research methods: remote sensing and field observation entail to be assembled seamlessly and observation needs to be structured from field to low sky and then to high sky satellite remote sensing.
2. Field observation network: considering sparsely distributed long-term field observation sites, more efforts are required for constructing long-term field observation network along environmental gradient.
3. Model parameter optimization: the TP possesses many unique environmental and ecological features, which underlines that parameter values on other systems are not applicable. Then locally optimizing model parameters are necessary before being utilized.
4. Strengthening interdisciplinary study: the TP is a typical region where cryospheric system, biospheric system,

hydrospheric system and ecosystem interact. Investigation on one sole system is hard to explain the core processes and mechanisms. Only interdisciplinary cooperation can advance our comprehensive understanding on interactions among each system.

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