Using remote sensing technology to estimate phenology change in the hinterland on Tibet Plateau

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Abstract. Recent studies have detected the amplitude of spring plant phenology in whole Tibet Plateau and growing season by remote sensing technology. However, few studies have examined that how the plant phenology has changed in the past decade. At the regional scale, we investigated the phenological variations in five regions (Dingri, Gaize, Pula, Yangtze River and Yellow River source areas) in the hinterland of the Tibetan Plateau from 2001 to 2010 using remote sensing technology. To analyze differentiation of vegetation phenology, we characterize the green up variation along a gradient from outer edge to inland horizontal zonation on the Tibetan Plateau using remote sensing technology. To examine phenological inter-annual variation, we found that a significant lengthening of vegetation growing season has been occurring in most study regions, marked by an earlier beginning. Taking 31°N as the boundary, the beginning of the growing season (BGS) for alpine vegetation in Dingri area in the southern Tibetan Plateau delayed of 11.6 days from 2001 to 2010, however it shows an obvious advance trend in northern area of the Tibetan Plateau. Interestingly, the advance days of BGS is increasing from 5.1 days/decade to 13.1 days/decade in northern Tibet Plateau during the last decade. The inter-annual variation of the end of the growing season for alpine vegetation was not obvious, and most of the study regions had natural inter-annual fluctuations. Analysis of the meteorological records in the study areas shows that spring temperature rising appears to be a critical factor contributing to the earlier green up and prolonged growing season in the northern TP; nevertheless, spring precipitation plays a more important role than spring temperature in Dingri region in the southern Tibetan Plateau.

Introduction

Phenology changes has been a hot topic in global ecology, environment and climate change research in recent [1,2,3]. Phenological changes are sensitive and easily observable indicators of biospheric changes in response to climate warming. Climate warming is expected to alter seasonal biological phenomena such as plant growth and flowering, which primarily depend on effective accumulated temperature. Many studies have suggested that global warming impacted the terrestrial ecosystems, on the other hand, the ecosystem showed corresponding responses via phonological changes across the Northern Hemisphere [4,5]. These phenological changes are likely to have a wide range of impacts on ecological processes, agriculture, forestry, human health, and the global economy. Changes in timing of important events such as flowering or fruiting could result in failure to produce offspring or to have adequately dispersed [1]. Phenological changes not only reflect regional climate signals, but could be enhanced or dampened by different temperature sensitivities across climate and vegetation types [6]. A remote sensing analysis of growing season changes at high northern latitudes showed a delaying trend in the onset of spring greening from 1993 to 2004, just following an advancing trend from 1982 to 1991 [7].

The Tibetan Plateau has an average elevation greater than 4000 m a.s.l., and where vegetation has unique vegetation communities and less influenced by human activities. The Tibetan Plateau has experienced extraordinary warming (0.16˚C/decade) during the past half of century [8,9], in particular in spring and winter [10,11]. The climate of Tibetan Plateau is characterized by a long winter and a relatively short growing season, so phenology of plant in this area should be sensitive to climate change. Long-term interactions between vegetation and the environment should lead to spatial and temporal phonological changes. Some studies have focused on the whole Tibetan Plateau, but there are different characteristics for different parts in the hinterland of Tibetan Plateau in phenology. However, field phenological measurement is tedious and expensive, and full coverage of all regions can never be obtained. Estimating regional variation in vegetation phenology from time-series remote sensing data is urgent. Remote sensing technology has been widely used in regional and global vegetation phenology research because of the strong coincidence between the satellite-derived metrics and ground-observed phenological characteristics [12]. Normalized Difference Vegetation Index (NDVI) is generally recognized as an effective indicator of terrestrial vegetation activity [13,14]. Accordingly, MODIS NDVI dataset are used to investigate spatial-temporal vegetation spring phenology date variations on the hinterland of the Tibetan Plateau. We focused on 1) the spatio-temporal vegetation spring phenology date variations on the study area, and 2) the main forces of the spring greening up date changes.

Study regions and Methods

Study regions. Our study regions are in the hinterland of the Tibetan Plateau, including Gaize，Pulan，Dingri，Yangtze River and Yellow River source regions (Fig. 1a). According to the regional climate characteristics [15] the Yangtze River and Yellow River source regions belong to Plateau sub-frigid zone; Gaize basin belongs to Plateau sub-frigid zone and semi-arid zone. Pulan basin is in the plateau sub-temperate and sub-arid zone, and Dingri locates at plateau temperate and sub-arid zone. Mountain shrubland, alpine grassland and alpine meadow are primary vegetation species distributed widely with similar proportion in these regions excluding Gaize region characterized with shrubland and alpine grassland (Fig. 1b).

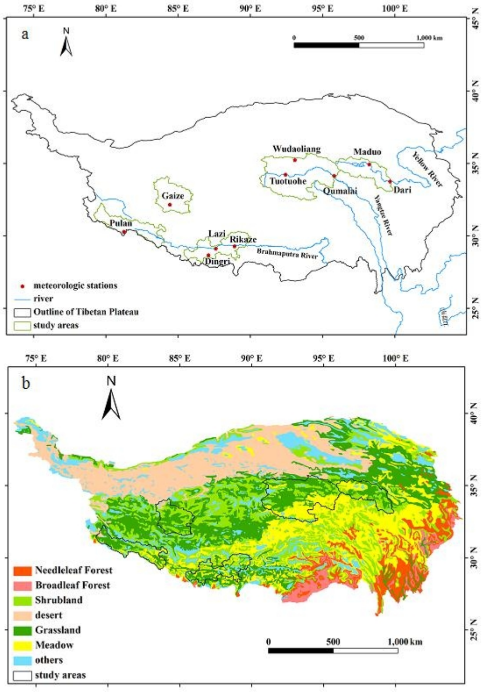

Fig. 1 a, Geographical setting and distribution of study areas (Gaize, Pulan, Dingri, Yangtze River and Yellow River source regions) on the Tibetan Plateau; b, vegetation coverage from 1:4,000,000 China Vegetation data sets published in 1996 by Institute of Botany of Chinese Academy of Sciences

Data and Methods. We analyzed changes in the beginning (BGS), end (EGS), and length (LGS) of the growing season for alpine vegetation in five regions from 2001 to 2010 based on a NDVI dataset. The NDVI dataset is derived from imagery obtained from the Moderate Resolution Imaging Spectro-radiometer (MODIS) with a spatial and temporal resolution of 250 m and 16 day, respectively. MODIS NDVI is generated from the level 2 daily surface reflectance products which are corrected for molecular scattering, ozone absorption, and aerosols [16].

In general, we defined NDVI threshold less than 0.1 as non-vegetation zones [17]. Firstly, zone NDVI was calculated from vegetation pixels after excluding the non-vegetation pixels. There are not enough adequate in-situ observation data available, so we transformed NDVI to an index, $NDVI_{ratio}$, according to a method developed by White [18] as following:

$$NDVI_{ratio} = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \qquad (1)$$

Where $NDVI_{ratio}$ is the output ratio ranging from 0 to 1, NDVI is the daily NDVI, $NDVI_{max}$ and $NDVI_{min}$ is the maximum and minimum annual NDVI, respectively. The $NDVI_{ratio}$ is designed to consistently detect onset and end across land covers for special community [18]. Finally, according to results of White [18] we selected an $NDVI_{ratio}$ threshold of 0.2 as BGS date, and take the point of $NDVI_{ratio}$ below 0.6 as the EGS. This threshold is suitable for the Tibetan Plateau by comparing ground observation data from 22 grassland-monitoring stations in Qinghai Province in the study of Yu [3]. The thresholds are based on field check and are appropriate in Tibetan Plateau, which have been testified effectively. The BGS and EGS were estimated for each pixel of the five study areas for each year using these thresholds. The LGS was obtained by the date of EGS minus that of BGS. We averaged these dates over all image pixels for five regions represent the regional BGS, EGS and LGS.

Monthly temperatures and precipitations for the entire observation period were used. The meteorological data was from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do). There are less Meteorological stations in the hinterland of the Tibetan Plateau. By extraction using watershed boundaries, we select all the meteorological stations distributed in the study regions (Fig.1a). We used these meteorological stations data to represent corresponding regional climate. The linear regressions were used to detect the change rate of the BGS, EGS, LGS, temperature and precipitation. The trends of them were tested by t-test at level of 95%. The partial least square regression was used to detect response of the changes in BGS, EGS and LGS to temperature and precipitation. The PLS analysis provides an indication of which independent variables are useful for explaining the variation in the dependent variable, and of the direction in which that influence is exerted (model coefficients of the centered and scaled data).

Results

Trends of phenological change. The latest BGS was occurred in early June in Dingri and Gaize regions, whereas the earliest started in early May in the Pulan region. The BGS varied across the five study regions and the BGS in Pulan region was 15 days later than that in Gaize region (Table 1). The BGS was in late May for the source regions of Yangtze River and Yellow River. This result showed that the BGS was postponed from outer edge of the plateau to more inland locations.

Table 1 Average timing of vegetation phenology in five regions on the Tibetan Plateau during 2001-2010

	Yangtze River source	Yellow River source	Dingri region	Gaize region	Pulan region
a. mean BGS of 10 years	146	147.8	152.5	156.5	138.4
b. mean EGS of 10 years	256.7	258.9	261.7	253.4	259.5
c. mean LGS of 10 years	108.9	112.4	105.2	97.9	121.1
d. correlation coefficient between BGS and LGS	-0.835	-0.876	-0.537	-0.814	-0.8

The EGS was almost similar for five study regions with the average timing of EGS in the mid-June (Table 1). The LGS therefore were different for the five regions. The trend of advance BGS for the source region of Yangtze River was most statistically significant ($R^2 = 0.44$) among all study areas. However, the BGS over the Dingri region was delayed obviously, especially after 2006. In addition，the vegetation BGS had statistically advanced by 13.1 days over Yangtze River source region, and it had advanced respectively by 7.3, 8.4, and 5.1 days for Yellow River source region, Gaize region and Pulan region. Inter-annual variation of EGS was not obvious, and most of the region had natural inter-annual fluctuations. If we take 31°N as a boundary line, advance trends of BGS for the study areas were occurred on the northern Tibetan Plateau, however, delayed trend was occurred in Dingri area (11.6 days) on the southern Tibetan Plateau. This line is matched to the geographical phenomena boundary (32°~33°N) between the northern and southern Tibetan Plateau with different variations in the warm season air temperatures on the decadal time scale, and most atmospheric, geological and geophysical phenomena over the Tibet Plateau [19].

LGS is influenced by green up and senescence dates, but was chiefly affected by advanced green up date that lengthens the growing season in our study regions. The longest LGS was occurred in Pulan region with about 121.1 days, and the shortest LGS was occurred in Gaize region with about 97.9 days. The LGS was significantly negatively correlated with BGS ($p < 0.1$ for Dingri region) for the other study regions ($p < 0.01$), but no statistically significant correlation with EGS. This indicated the variations of LGS were mainly depended on changes on BGS in our study area. The LGS for the regions was lengthened in last decade except for Dingri region.

Relationships of climate factors and phenology change

The annual mean temperature during 2001-2010 for Pulan region is 4.24˚C in the plateau sub-temperate and semi-arid zone, and the annual mean temperature for Dingri region is 3.82 ˚C. The lowest annual mean temperature of our study areas occurs in Yangtze River source region (-2.77˚C). The annual precipitations during 2001-2010 for our study areas are different from each other. The maximum precipitation occurred in Yellow River source region with 456.1 mm, and the minimum occurred in Pulan region with 151mm.

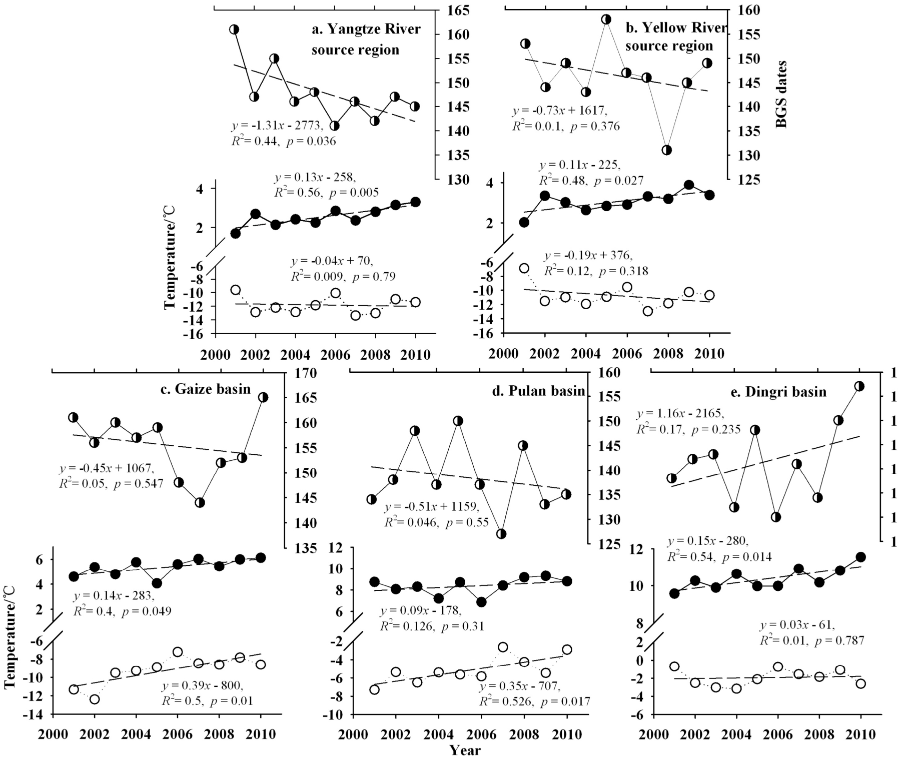

Fig. 2 The beginning of vegetation growing season (BGS) averaged for alpine vegetation of the hinterland regions on the Tibetan Plateau. BGS was calculated by the methods proposed by White et al. (1997). Temperature in winter and spring are the average data of several weather stations in corresponding region. The circle with semi-filled right indicates average timing of the beginning of the growing season (BGS), the black circle indicates temperature in the spring, and the empty circle shows temperature in the winter.

Temperature has been considered a main factor influencing leaf onset in boreal and alpine regions [20]. We found that in some regions despite the continued winter warming and the fluctuating spring temperature (the mean temperature of March, April, and May) during the period from 2001 to 2010, BGS showed no continuous delaying trend (Fig.2). Mean spring temperature and mean winter temperature (the mean temperature of December, January, and February) calculated from weather stations and BGS were shown in Figure 2, indicated that spring phenology was not consistently related to winter warming in most of areas on study areas. In some regions, the relationships between the winter temperature and BGS were positive such as Yangtze River and Yellow River source regions (Fig.2a, b). In other regions, the relationships between the winter temperature and BGS were negative such as Gaize and Pulan regions (Fig.2c,d). Contrastingly, BGS was significantly related to spring temperature in most of our study areas. This view coincides with that of Shen [2]. Temperature in January, April and May in these areas is important for phenology change. This is likely to imply that temperature in January can also contribute to BGS in addition to spring temperature. Plant growth has often been correlated with warmer temperatures in the 1-3 months prior to the growing season [21,22,23].

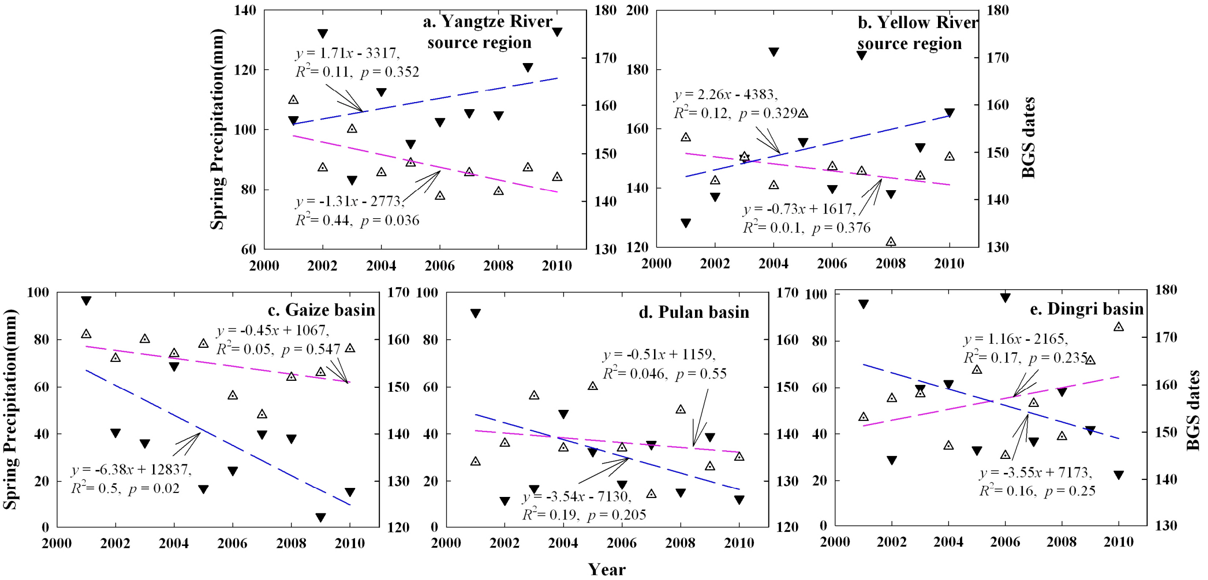

Fig. 3 The beginning dates of the growing season (BGS) and spring precipitation (the mean of April, May, and June) of the five study areas, respectively. The pink dash lines indicate average timing of the BGS, and the blue dash lines show average timing of spring precipitation of corresponding weather stations.

Table 2 shows three groups for the five regions on the Tibetan Plateau considering changes of temperature and precipitation in spring. The first group includes the source regions of Yangtze River and Yellow River, and the BGS in this group advanced about ten days in past decade, with increasing spring temperature and increasing spring precipitation. The second group included Pulan and Gaize regions, where BGS advanced a few days with increasing spring temperature and decreasing spring precipitation. Finally, Dingri region, a basin in the southern TP, in which BGS delayed nearly eleven days, with increasing spring temperature and decreasing spring precipitation in recent ten years. The annual mean temperature during 2001-2010 for Dingri region is higher relatively, so slightly warming might not be enough to change the spring phenology. Therefore, climate warming may not be the only dominant factor controlling the spring phenology change trend in this region.

Figure 3 shows the average timing of spring precipitation trend of this decade calculated from corresponding weather stations. As can be seen, the trend of spring precipitation increases in the source regions of Yangtze River and Yellow River in the northern Tibetan Plateau (Fig. 3a, b), conversely, it decreases for Gaize, Pulan and Dingri basins (Fig. 3c, d, e). There is a notable negative relationship between the BGS and spring precipitation for Dingri region ($r = -0.73$).

Discussion

Long-term surface data and remote sensing measurements indicated that plant phenology has been advanced by 2–3 days in spring per decade in the past 30–80 years on a global scale [24]. The change magnitude of plant phenology for the BGS over 4/5 of study areas advanced more largely about 3-10 days per decade for the last decade than that of plant phenology over the global average. It means that the plant phenology change in the last decade is more strenuous than the past 3-8 decades, and the alpine vegetation is more sensitive to warming climate. Recent studies have also reported similar results in the northern high latitudes [25,26]. However, Yu [3] reported that the BGS of the alpine steppe and meadow on the Tibetan Plateau was delayed since the mid-1990s to 2006. These differences might be from the different timescales and spatial scales. In this study, the BGS in Dingri region during 2001-2010 is delayed, which is different from other four study areas. We take 31°as boundary between the northern and southern Tibetan plateau to analyse. Actually, on Tibetan Plateau, it has been found that differences exist for many phenomena between the northern and southern Tibetan plateau. Such as different summer moisture origins in the south of the Himalayan mountains, the moisture provided by the Indian monsoon is recycled over the Indian peninsula; in the north of the Tanggula mountains, the moisture is not provided by the monsoon anymore but by continental water recycling [27]. Most atmospheric, geographical, geological and geophysical phenomena over the Tibetan Plateau match the boundary between the northern and southern Tibetan Plateau [28].

We found that the spring phenology was correlated with spring temperature in our study areas. Northern hemisphere phenology patterns in the estimated start and end of the growing season were strongly correlated with temperature patterns [29]. Available data and current knowledge of plant phenology, including numerous experimental studies indicate that the observed changes are mostly due to the increased temperatures [30]. The vegetation of both the northern latitudes and the highlands of the Tibetan Plateau are characterized by strong temperature dependence, and their environments have experienced abnormally strong temperature increases in recent years [31]. Yang [32] have reported a strong correlation between accumulated growing degree days and NDVI (r = 0.81), and suggested that the total energy accumulation could strongly influence the plant growth. However, Yu [3] reported that the BGS of the alpine steppe and meadow on the Tibetan Plateau was delayed since the mid-1990s under winter and spring warming. They suggested that this delay appeared to be related to later fulfillment of chilling requirements and continued warming may strengthen this effect or even reverse the advancing trend in spring phenology. According to their suggestions the delaying trend should continue if winter warming continues and spring warming does not accelerate. However, two of our study regions showed an advanced trend when winter temperature increasing (Fig. 3). This indicated that the winter temperature is not the only controlling factor for BGS changes in our study area during 2001-2010.

The BGS changes in Dingri region are different from the other regions (Table 2), and the difference may be originated from water availability. Variability in the phenology of seasonally dry climate regions is strongly correlated with precipitation. Reduced precipitation could not fulfill the water need of vegetation, as a result the spring phenology postponed. Both precipitation and temperature directly influence water balance, causing changes in soil moisture regime which, in turn, influence plant growth [33]. In Dingri region, the combination of the advancing effect of spring temperature and the delaying effect of reduced spring precipitation could result in a delayed BGS from 2001 to 2010. The Pearson correlation between precipitation and BGS (r = -0.73) is greater than that of between temperature and BGS (r = 0.12) in Dingri region, which indicated that the phenology-advancing effect of spring warming was relatively low compared with the delaying effect of reduced spring precipitation. Our results suggest that the vegetation phenology change faster in semi-arid zone (Dingri region) than that in humid-temperate zone. Precipitation might play different roles in different regions. The annual spring temperature of Dingri had an insignificant increasing trend; however the trend of precipitation in this region was decreasing. Although there are similar change trends of spring temperature and precipitation for Dingri and Pulan regions, the trend of BGS in Pulan region differ with that of Dingri region. It meant that the effect of precipitation to BGS in Pulan region is not as important as in Dingri. Duan [34] have revealed that precipitation variation is much different between the northern and southern Tibetan Plateau，both in decade and secular time scales，which is due to the monsoon prevailing in the southern Tibetan Plateau and the westerly prevailing in the northern Tibetan Plateau. So this may explain the different phenology change response to precipitation of Dingri and other study areas. However, we cannot eliminate other causal factors, which is important in regulating spring phenology not investigated in our study. A full analysis requires a more knowledge about the interactions between temperature, precipitation and other factors, which is closely related to within-season NDVI.

Table 2 Classification of vegetation phenology change in five regions on the Tibetan Plateau with trends of spring temperature and spring precipitation during 2001-2010 (↗ represent increase trend, and ↘ represent decrease trend)

Classification	Region name	Temperature (°C)	Precipitation （mm）	Trend （days）	Spring temperature trend	Spring precipitation trend
I	Yellow River source region	-1.27	456.4	advance 13.1	↗	↗
I	Yangtze River source region	-2.77	377	advance 7.1	↗	↗
II	Gaize region	1.17	206.9	advance 8.4	↗	↘
II	Pulan region	4.24	151.3	advance 5.1	↗	↘
III	Dingri region	3.82	298.3	delay 11.6	↗	↘

Conclusion

This study demonstrates that the spring phenology in five areas in the hinterland of the Tibetan Plateau is spatially divergent and 31°N is the boundary for BGS change trends of different regions in the past decade. The BGS for alpine vegetation in Dingri area in the southern Tibetan Plateau delayed by 11.6 days from 2001 to 2010; however it shows an obvious advance trend in northern areas of the Tibetan Plateau. Interestingly, in addition to spring temperature, there is also an obvious negative relationship between January temperature and BGS dates calculated from MODIS NDVI dataset in the hinterland of Tibetan Plateau. Spring precipitation plays a more important role in semi-arid grasslands, which can be used to interpret the spring phenology delayed in Dingri region.

Using remote sensing data to estimate regional variation in vegetation phenology is important in global climate change study. Satellite detection of phenological events is a subjective process. The terms onset and end are popular in the satellite phenology field precisely because they avoid a connection to field measurements of specific phonological stages such as budburst or flowering. The agreement and realism of these results provides confidence regarding the quality of results from MODIS. We therefore conclude that the global data sets described in this study provide substantial information for understanding and modeling the effects of climate variability on ecosystem processes including energy, water, and carbon fluxes at regional to global scales. Actually MODIS estimates of phenological transition dates are geographically and ecologically realistic. Our analyses also provide the basis for understanding the interactions among temperature, precipitation and predicting changes in productivity that accompany changes in temperature and spring precipitation in the central Tibetan Plateau. Further studies will be needed to examine temporal relations of temperature and precipitation as they influence energy balance, and in turn determine actual evapotranspiration.

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