Green-up dates in the Tibetan Plateau have continuously advanced from 1982 to 2011

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As the Earth's third pole, the Tibetan Plateau has experienced a pronounced warming in the past decades. Recent studies reported that the start of the vegetation growing season (SOS) in the Plateau showed an advancing trend from 1982 to the late 1990s and a delay from the late 1990s to 2006. However, the findings regarding the SOS delay in the later period have been questioned, and the reasons causing the delay remain unknown. Here we explored the alpine vegetation SOS in the Plateau from 1982 to 2011 by integrating three long-term time-series datasets of Normalized Difference Vegetation Index (NDVI): Global Inventory Modeling and Mapping Studies (GIMMS, 1982–2006), SPOT VEGETATION (SPOT-VGT, 1998–2011), and Moderate Resolution Imaging Spectroradiometer (MODIS, 2000–2011). We found GIMMS NDVI in 2001–2006 differed substantially from SPOT-VGT and MODIS NDVIs and may have severe data quality issues in most parts of the western Plateau. By merging GIMMS-based SOSs from 1982 to 2000 with SPOT-VGT–based SOSs from 2001 to 2011 we found the alpine vegetation SOS in the Plateau experienced a continuous advancing trend at a rate of ∼1.04 $d \cdot y^{-1}$ from 1982 to 2011, which was consistent with observed warming in springs and winters. The satellite-derived SOSs were proven to be reliable with observed phenology data at 18 sites from 2003 to 2011; however, comparison of their trends was inconclusive due to the limited temporal coverage of the observed data. Longer-term observed data are still needed to validate the phenology trend in the future.

Vegetation plays an important role in the interaction between the biosphere and the atmosphere (1). Phenology is a sensitive and critical feature of vegetation, and it could reflect the effects of climate variability and change on vegetation growth (2, 3). Thus, monitoring the vegetation phenology changes at regional and global scales could help quantify the effects of climate change on terrestrial ecosystems. Time-series data from satellite remote sensing have been widely used for studying vegetation phenology at the landscape, regional, and global scales (3–6), such as the multidecadal time series of Normalized Difference Vegetation Index (NDVI) from the Advanced Very High Resolution Radiometer (AVHRR) (4). AVHRR NDVI-based studies have shown that the start of the vegetation growing season (SOS) has advanced in most parts of the Northern Hemisphere from 1982 to the end of the 1990s due to global warming (3–5, 7–9). Since the end of the 1990s, however, this advancement trend in SOS has weakened and even reversed in some areas (3, 10–16). For example, the AVHRR NDVI-based SOS advancement in temperate vegetation of the Northern Hemisphere weakened from 5.2 $d \cdot y^{-1}$ in the early period (1982–1999) to 0.2 $d \cdot y^{-1}$ in the later period (2000–2008) (3).

As the Earth's third pole, the Tibetan Plateau is mostly covered by typical alpine meadow and steppe, which are highly sensitive to climate change (10, 11, 15, 17). Although long-term observed phenological data are scarce in the plateau due to the harsh physical environment, remote sensing data, including decadal time-series NDVI data from AVHRR, SPOT VEGETATION (SPOT-VGT), and Moderate Resolution Imaging Spectroradiometer (MODIS), are available. Several recent studies using AVHRR NDVI time-series data have reported that the alpine steppe and meadow also underwent an SOS advancement from 1982 to the end of the 1990s, but an SOS delay was found from the end of the 1990s to 2006 (10, 11, 15, 17). Several explanations for this trend of reversal were proposed but remain controversial (10, 11, 15, 17–21). One study based on MODIS NDVI data showed that the alpine vegetation SOS advanced in 60% of this region in the Northern Tibetan Plateau from 2001 to 2010 (22). Another study based on SPOT-VGT NDVI data found an SOS delay from 1998 to 2003 and an advancement from 2003 to 2009 (20). Overall, the studies concerning the alpine vegetation SOS trend in the Tibetan Plateau turned out varying results when using different remote sensing data, yet the reasons remain unclear.

The goal of this study was to investigate the SOS trends of alpine vegetation in the Tibetan Plateau from 1982 to 2011 by comparing and combining three time-series NDVI datasets: Global Inventory Modeling and Mapping Studies (GIMMS, 1982–2006), SPOT-VGT (1998–2011), and MODIS (2000–2011) NDVIs. Specifically, we began by comparing NDVI data over the overlapping period when all of the three NDVI datasets are available to evaluate the NDVI data quality. We then integrated the three NDVI datasets to explore the trend of SOS in the Tibetan Plateau from 1982 to 2011 and further characterize their relationship with air temperature based on the meteorological dataset.

Results

Alpine Vegetation SOS Change. The SOS of alpine vegetation was retrieved from the GIMMS, SPOT-VGT, and MODIS NDVI datasets for the entire Tibetan Plateau (*Materials and Methods*). Variations in the vegetation SOS based on the three NDVI datasets were significantly different (Fig. 1*A*). The GIMMS-based SOS showed two distinctly different trends between 1982–1998 and 1998–2006. There was a significant advancement in the former period at a rate of 1.017 $d \cdot y^{-1}$ (coefficient of determination $R^2 = 0.49$, P value of a standard t test statistic $P = 0.002$, sample size $n = 17$) and an evident delay in the following period at a rate of 2.333 $d \cdot y^{-1}$ ($R^2 = 0.64$, $P = 0.009$, $n = 9$). These findings are consistent with the previous studies that used the GIMMS dataset (10, 11, 17). However, both the SPOT-VGT and MODIS NDVI datasets showed significant SOS advancements during 2000–2011 on the order of 1.357 $d \cdot y^{-1}$ ($R^2 = 0.49$, $P = 0.011$, $n = 12$) and 0.780 $d \cdot y^{-1}$ ($R^2 = 0.34$, $P = 0.045$, $n = 12$), respectively. These are fundamentally different from the findings based on the GIMMS NDVI from 2001 to 2006, especially in the alpine steppe and alpine meadow regions (Fig. 1 *B* and *C*). The divergence of the alpine vegetation SOS from these three NDVI datasets mainly occurred in the period 2001–2006.

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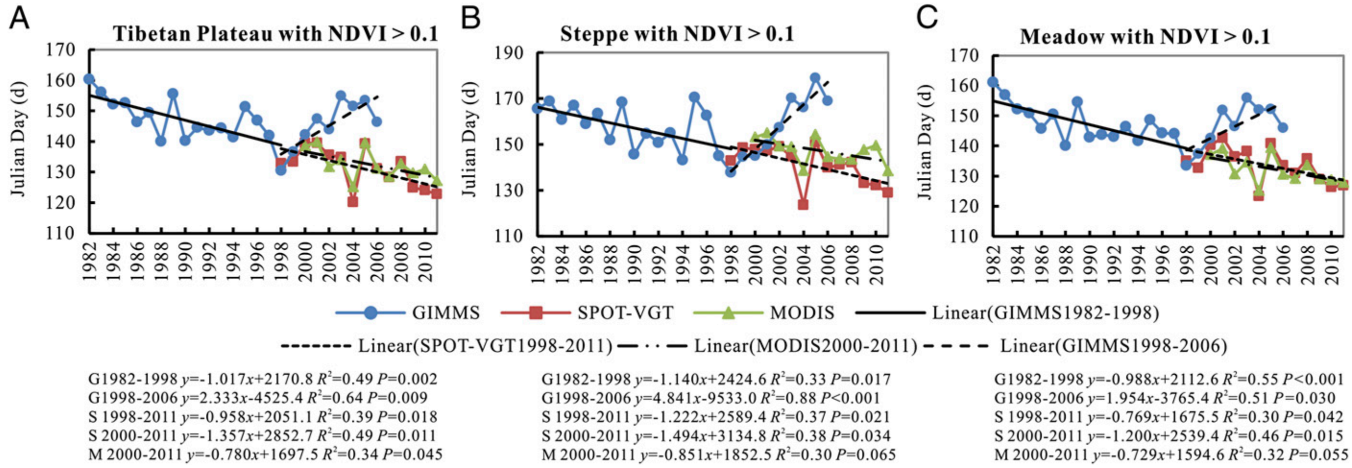

Fig. 1. Interannual variations in vegetation SOS from 1982 to 2011 based on the GIMMS (1982–2006), SPOT-VGT (1998–2011), and MODIS (2000–2011) NDVI datasets in the whole Tibetan Plateau region (*A*), alpine steppe region (*B*), and alpine meadow region (*C*). Note: alpine steppe and alpine meadow are the primary vegetation types in the plateau. The formulas show the linear fitting functions of the green-up dates and year. G, S, and M before the formulas are the abbreviations for the GIMMS, SPOT-VGT, and MODIS datasets, respectively.

Investigating the Discrepancy of Vegetation SOS from the Three Datasets. We conducted spatial comparison analyses among the three NDVI datasets at different temporal scales, including the plant growing season (April–October), individual climatic seasons (spring, summer, and autumn), and individual months (April–October). First, we analyzed interannual variations in NDVI from the three datasets by comparing the NDVI when averaged over the plant growing season as well as individual climatic seasons. The interannual variations in averaged NDVI within a plant growing season (GSNDVI) differed among the three datasets (Fig. 2*A*). The SPOT-VGT and MODIS GSNDVIs showed similar increasing trends in their available periods (1998–2011 and 2000–2011, respectively). The GIMMS GSNDVI increased from 1982 to 2002, but it dropped substantially in 2003, before showing a slight increase again from 2003 to 2006. Although the GIMMS GSNDVI was consistent with the SPOT-VGT GSNDVI during 1998–2002, the discrepancy between the GIMMS GSNDVI and the other two NDVI datasets was evident during 2003–2006, particularly in the spring and summer (Fig. 2 *B* and *C*).

Next, we compared the spatial patterns of the GSNDVI and monthly NDVI trends between the GIMMS and SPOT-VGT datasets from 1998 to 2006. The GIMMS GSNDVI exhibited a decreasing trend in most parts of the Tibetan Plateau, whereas the SPOT-VGT GSNDVI showed an increasing trend (Fig. 3). Specifically, the GIMMS GSNDVI decreased in 59.3% of the study area, and the decreasing trend was significant in 18.5% of the study area with a significance level of $P < 0.05$, mainly in the Tibet Autonomous Region. Meanwhile, the GIMMS GSNDVI showed a significant increasing trend in only 5.6% of the study area ($P < 0.05$), concentrated in the Qinghai Province (Fig. 3 *A* and *C*). In comparison, the SPOT-VGT GSNDVI exhibited a quite different pattern. The GSNDVI increased in 88.9% of the

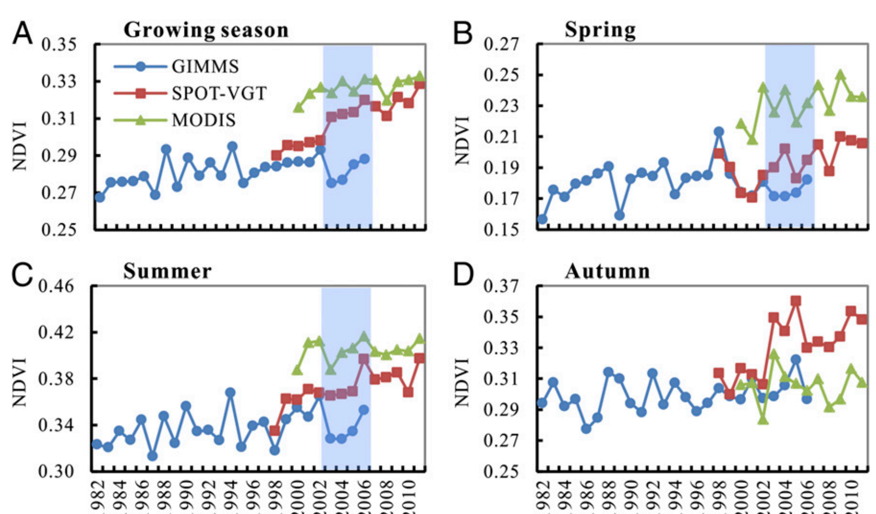

Fig. 2. Interannual variations in NDVI over the entire Tibetan Plateau during the growing season (*A*), spring (*B*), summer (*C*), and autumn (*D*) based on the GIMMS (1982–2006), SPOT-VGT (1998–2011), and MODIS (2000–2011) datasets. During the growing season, the slopes of the increasing trend based on the GIMMS, SPOT-VGT, and MODIS NDVI datasets are 4.64×10^{-4} y^{-1} ($R^2 = 0.21$, $P = 0.021$, $n = 25$), 26.56×10^{-4} y^{-1} ($R^2 = 0.87$, $P < 0.001$, $n = 14$), and 9.14×10^{-4} y^{-1} ($R^2 = 0.40$, $P = 0.028$, $n = 12$), respectively. The correlation coefficients between the SPOT-VGT and MODIS NDVI in growing season, spring, summer, and autumn during their overlapping period (2000–2011) are 0.7440 ($P = 0.005$), 0.8469 ($P < 0.001$), 0.6300 ($P = 0.028$), and 0.5968 ($P = 0.041$), respectively. The gray pillars show the time range with abnormal GIMMS data.

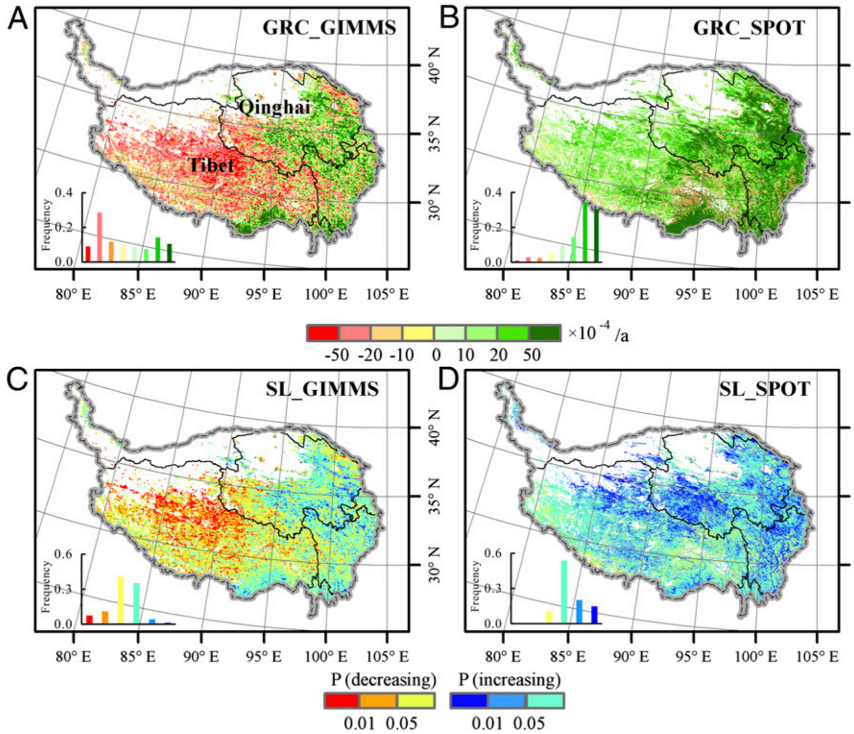

Fig. 3. Spatial distributions of the greenness rate of change (GRC) (*A* and *B*) and significance levels (SL) (*C* and *D*) of the NDVI change in the Tibetan Plateau during the growing season from 1998 to 2006 based on the GIMMS and SPOT-VGT datasets. *P*(decreasing) and *P*(increasing) are the *P* values of the decrease and increase in the growing season NDVI, respectively, which are divided into three levels: $P < 0.01$, $0.01 < P < 0.05$, and $P > 0.05$. The insets show the frequency distributions of corresponding trends (*A* and *B*) and different significance levels (*C* and *D*).

study area, with 35.0% of the pixels undergoing statistically significant changes ($P < 0.05$), and decreased in the remaining areas (only 0.62% with a significance level of $P < 0.05$) (Fig. 3 *B* and *D*). The spatial patterns of the monthly NDVI trend in the GIMMS data differed from those in the SPOT-VGT data from 1998 to 2006, particularly in April, May, June, and October (Fig. S1 and Table S1). Among the seven months from April to October, the difference in NDVI between the GIMMS and SPOT-VGT NDVI datasets was largest in May. The GIMMS NDVI in May decreased significantly ($P < 0.05$) in 30.1% of the study area, especially in the Tibet Autonomous Region and the southwestern part of Qinghai Province (Fig. S1*I*), whereas the SPOT-VGT NDVI significantly decreased only in 1.9% of the study area (Fig. S1*P*).

To further examine the potential GIMMS data abnormality, we extracted two regions of interest (ROIs) from the areas with significant GIMMS NDVI decrease in May ($P < 0.05$) during 1998–2006 and with increasing trends in SPOT-VGT (1998–2011) and MODIS NDVI data (2000–2011) (Fig. S1*I*). We explored the different variation curves fitted for the three NDVIs at different temporal scales (i.e., plant growing season, individual climatic seasons, and individual months from April to October) (Figs. S2 and S3). We found that the GIMMS growing season and spring NDVIs in the selected ROIs decreased abnormally from 2002 to 2006, showing completely different trends from the SPOT-VGT and MODIS NDVI datasets (Fig. S2). This was especially prevalent in April, May, and June (Fig. S3), as evidenced by turning points in the GIMMS NDVI around 2001 according to the piecewise regression model (*Materials and Methods*). In addition, the interannual variation curves of 200 randomly selected pixels, covering 12.6% of the region, showed a significant decrease ($P < 0.05$) in the GIMMS NDVI in May during 1998–2006, which revealed that it deviated from the normal trajectory for 2001–2006 (Fig. S4).

In summary, the comparisons among the GIMMS, SPOT-VGT, and MODIS NDVI datasets at multiple temporal and spatial scales suggest that the GIMMS NDVI dataset may have low-quality NDVI data in most parts of the western Tibetan Plateau during 2001–2006, especially in the spring season, when the GIMMS NDVI values are significantly lower than those of the SPOT-VGT and MODIS NDVI data. Increased aerosol concentrations (19) or the renewal of different AVHRR sensors [National Oceanic and Atmospheric Administration (NOAA)-14, NOAA-16, NOAA-17, and NOAA-18] (23) may have contributed to the GIMMS data quality from 2001 to 2006.

Actual SOS Change in the Past 30 y and Its Reasons. The SOS from the GIMMS NDVI dataset was similar to that from the SPOT-VGT NDVI dataset in the period of 1998–2000, and the SOSs from the SPOT-VGT and MODIS NDVI datasets were consistent during their overlapping period (2000–2011) (Fig. 1). Therefore, we merged the SOS based on the GIMMS NDVI dataset from 1982 to 2000 and the SPOT-VGT NDVI dataset from 2001 to 2011 to track the 30-y alpine SOS variation and the trend in the Tibetan Plateau (Fig. 4). The merged data results showed that the SOS of the alpine vegetation in the Tibetan Plateau exhibited an advancing trend during 1982–2011, from the 152th Julian Day in the 1980s to the 142th Julian Day in the 1990s, then to the 131th Julian Day in the 2000s, at an overall rate of 1.04 $d \cdot y^{-1}$ ($R^2 = 0.76$, $P < 0.001$, $n = 30$) (Fig. 4). This advancement agrees with the findings in SOS studies in the Tibetan Plateau that use SPOT-VGT and MODIS datasets after 1998 (20, 22, 24). Furthermore, the mean, mean maximal, and mean minimal temperatures in prior winters (November–March) and springs (April–May) showed similar significant increasing trends in the plateau during 1982–2011 (Fig. 4), as calculated from all available meteorological stations. The correlation analysis between these temperature indicators and SOS showed that warmer springs and winters are likely the

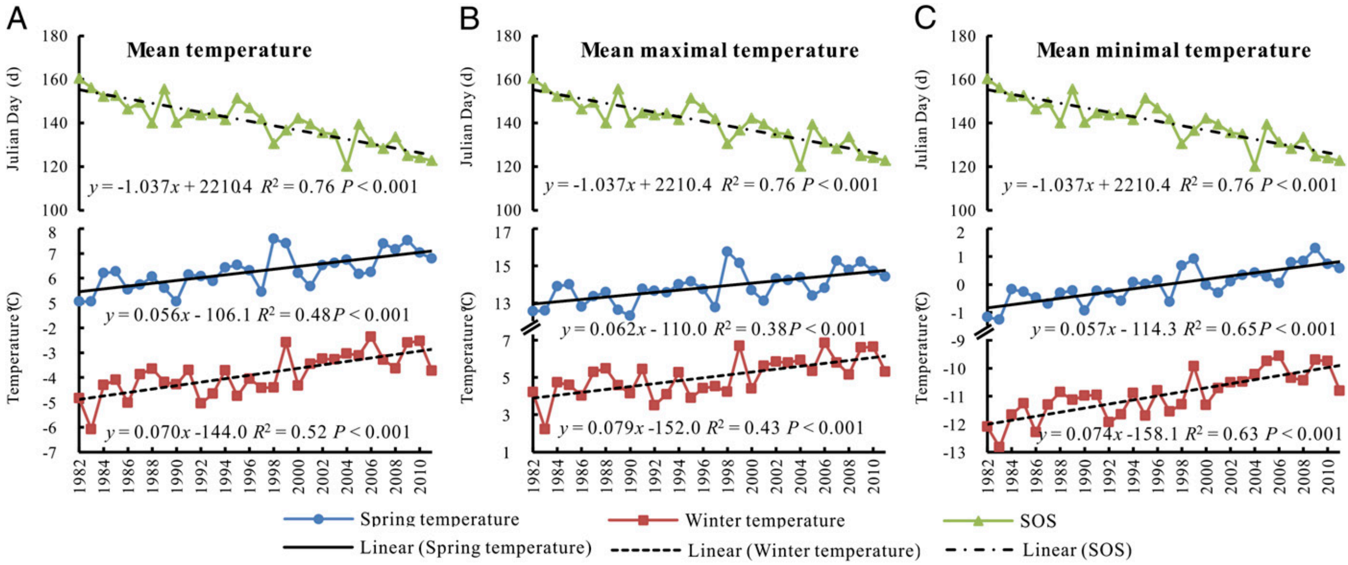

Fig. 4. Interannual variations in mean temperature (*A*), mean maximal temperature (*B*), and mean minimal temperature (*C*) in winters (from November of the prior year to March of the following year) and springs (April and May) and vegetation SOS integrating GIMMS-based SOS (1982–2000) and SPOT-VGT–based SOS (2001–2011) from 1982 to 2011 in the Tibetan Plateau. The correlation coefficients between the SOS and the mean temperature in springs and winters, the mean maximal temperature in springs and winters, and the mean minimal temperature in springs and winters are −0.7052 and −0.7029, −0.6718 and −0.6704, and −0.7591 and −0.7313, respectively. All correlation coefficients are significant at the 0.001 level.

main forces driving the SOS advancement in the Tibetan Plateau throughout the last 30 y.

Discussion

The low data-quality issue of the GIMMS NDVI dataset over a large portion of the western Tibetan Plateau during 2001–2006, as detected in this study, substantially affected spring phenology estimates and confounded our understanding of phenology in response to climate change in this region. Based on identified areas with and without the GIMMS data bias, we sampled three sites with different GIMMS data quality to explore the effects of the data quality on phenology retrieved in 2006. The sampled site in Anduo was covered by alpine steppe with low-quality GIMMS NDVI data, whereas the sampled sites in Qumalai and Dangxiong were covered by alpine meadow and alpine steppe, respectively, with normal-quality GIMMS NDVI data. As shown in Fig. 5, the vegetation SOS at the Anduo site was around the 145th Julian Day based on both SPOT-VGT and MODIS data, but the SOS based on the GIMMS data were the 181th Julian Day, which was significantly later than the results from the SPOT-VGT and MODIS NDVI datasets. However, at the Qumalai and Dangxiong sites with normal-quality GIMMS data, vegetation SOS began around the 136th and 143th Julian Days, respectively, with a high consistency among the SOSs based on the GIMMS, SPOT-VGT, and MODIS datasets. The green-up date in the Tibetan Plateau usually occurs between the end of April and the end of June, earlier in the east and later in the west (10). The data quality issues of GIMMS NDVI in the Tibetan Plateau mainly occur in April, May, and June (especially in May), which overlaps the period of vegetation green-up and would thus affect the vegetation phenology retrieved. Although the deviation of the GIMMS NDVI is relatively low due to the absolute low NDVI values in the alpine grassland, it could cause a relatively large error in retrieving the vegetation SOS (19).

Previous studies using the GIMMS NDVI dataset have shown a prominent reversal of the vegetation SOS trend in the Tibetan Plateau by the end of the 1990s, with a significant advanced trend from 1982 to the end of the 1990s and a delayed trend from the end of the 1990s to 2006 (10, 11, 15, 17). The reasons for the mechanism of the spring phenology delay in the Tibetan Plateau in the later period were diverse (10, 11, 15, 17). These reasons included opposite temperature trends in the two periods (10),

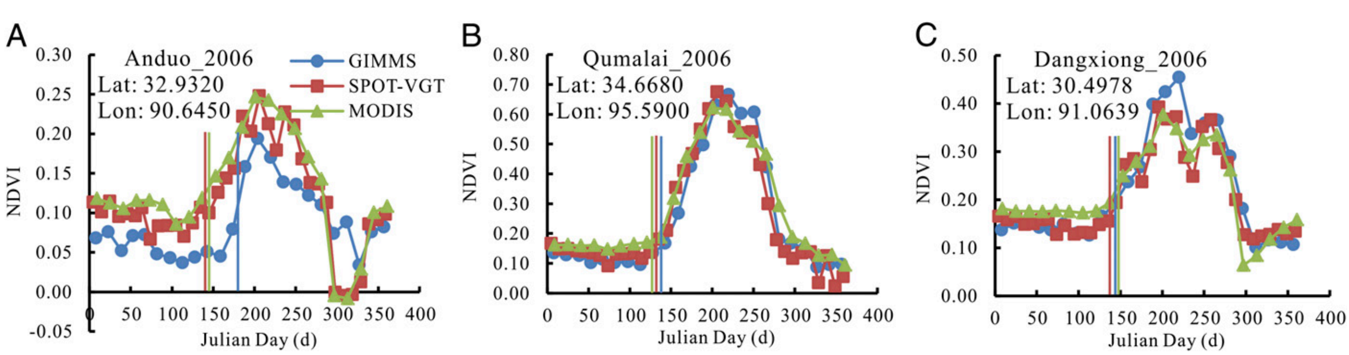

Fig. 5. Vegetation growth curves in the three sampled sites in 2006 (*A*, Anduo; *B*, Qumalai; and *C*, Dangxiong) based on the GIMMS, SPOT-VGT, and MODIS NDVIs. The blue, red, and green straight lines show the retrieved vegetation SOS dates based on GIMMS, SPOT-VGT, and MODIS NDVIs, respectively. The NDVIs were averaged over a round area with a 5-km radius centered on each site. These dates are calculated by the SOS retrieval method (*Materials and Methods*).

failure to fulfill vegetation chilling in previous winter (e.g., dormancy) (11), factors other than climate change (such as decreased grassland coverage and thawing–freezing processes) (18), or possible GIMMS data quality problems due to increasing aerosol concentrations (19). Based on our results, we argue that the GIMMS NDVI data-quality problem in spring during 2001–2006 in most parts of the western Tibetan Plateau explains why previous studies reported a delay of spring phenology in the Tibetan Plateau from the end of the 1990s to 2006. Note that the GIMMS NDVI data have also been used to study phenology and greenness change of vegetation from 1982 to 2008 in the mid and higher latitudes of the Northern Hemisphere (3, 5, 14, 15). A previous study also shows that the key phenology parameters (e.g., SOS) from the AVHRR and MODIS data were significantly different in the 2000–2008 period over the northern high latitudes (23). Our results suggest that the quality of NDVI data needs to be carefully evaluated when they are used to retrieve vegetation phenology information and vegetation greenness at a large scale (25), and the integration of AVHRR, SPOT-VGT, and MODIS NDVI datasets would better address issues of uncertainty related to remote sensing applications in vegetation phenology studies.

The remotely sensed continuous and significant advancing of alpine vegetation SOS in the Tibetan Plateau during the past 30 y in this study may have significant implications for land–atmosphere dynamics and interactions. The advancement in vegetation SOS may extend the length of the plant growing season, which is closely related to gross and net primary production. A prolonged growing season (due to earlier SOS) can potentially enhance the carbon sink capacity of terrestrial ecosystems, which has been shown in terrestrial ecosystems in the northern mid and higher latitudes during 1980–2002 (26). An earlier start of the growing season will change forage production for livestock (e.g., yak), which could affect the local economy significantly.

Materials and Methods

We analyzed the spring vegetation phenology trends in the Tibetan Plateau from 1982 to 2011 by using three remote sensing datasets, GIMMS (1982–2006), SPOT-VGT (1998–2011), and MODIS (2000–2011) NDVI data, before exploring the relationships between spring phenology and climate change based on the meteorological dataset.

NDVI Dataset from GIMMS. The GIMMS NDVI, the longest time-series NDVI dataset, from 1981 (July) to 2006, was provided by the Global Land Cover Facility from the University of Maryland (27). The data were obtained from the AVHRR instrument onboard the NOAA satellite series 7, 9, 11, 14, 16, and 17. The GIMMS NDVI products, with a spatial resolution of 8 km, were compiled by merging segments (data strips) during a half-month period using the maximum value composites (MVC) method (28). These data had been corrected for calibration, view geometry, and volcanic aerosols and were verified using a stable desert control point.

NDVI Dataset from SPOT-VGT. The SPOT-VGT NDVI product from 1998 (April) to 2011, with a 1-km spatial resolution, was compiled by merging 10-d segments (data strips) using the MVC method. The data had been preprocessed by the VEGETATION Processing Centre at the Flemish Institute for Technological Research in Belgium (29). A series of processes, including atmospheric correction, radiometric correction, and geometric correction, were performed to ensure data quality.

NDVI Dataset from MODIS. The MODIS data (MOD13A2), with a 1-km spatial resolution and 16-d intervals, were generated from atmospherically corrected bidirectional surface reflectances that had been masked for water, clouds, heavy aerosols, and cloud shadows. The accuracy had been assessed over a widely distributed set of locations and time periods via several ground-truth and validation efforts (30).

Preprocessing of NDVI Data. The GSNDVI was calculated by the average monthly NDVI from April to October (10), and the seasonal NDVIs for spring, summer, and autumn were calculated as the average NDVIs of April–May, June–August, and September–October, respectively. To minimize the impacts of soil in sparsely vegetated regions on vegetation, we chose areas with a multiyear average GSNDVI greater than 0.1 in the Tibetan Plateau as the targeted study region based on GIMMS (1982–2006), SPOT-VGT (1998–2011), and MODIS (2000–2011) data (5, 10). There were small differences in the spatial domains among the regions with an NDVI greater than 0.1, as determined from the GIMMS, SPOT-VGT, and MODIS data. The main vegetation types in the study area are alpine steppe and meadow (Fig. S5) according to the vegetation atlas of China (31).

Climate Data. The monthly mean temperature data of 85 available meteorological stations (Fig. S5) located in the Tibetan Plateau with an NDVI >0.1 from 1981 to 2011 were used in this study. These data were obtained from the China Meteorological Data Sharing Service System of the China Meteorological Administration. The seasonal winter and spring temperatures for the vegetated regions in the plateau were calculated as the average monthly temperature from November of the prior year to March of the following year, and from April–May, respectively.

SOS Retrieval Method. The date of the vegetation SOS was retrieved using NDVI green-up thresholds determined from the rate of seasonal changes in the mean multiyear NDVI and the annual seasonal curves in NDVI from January to September generated by order polynomial fit (7, 10). Taking the GIMMS NDVI as an example, we first calculated the multiyear average NDVI time-series curve from 1982 to 2006 for each pixel and the $NDVI_{ratio}$ using the following formula: $NDVI_{ratio}(t) = [NDVI(t+1) - NDVI(t)]/[NDVI(t)]$, where t is time (temporal resolution of 15 d). We then used the corresponding NDVI(t) with the maximum $NDVI_{ratio}$ as the NDVI threshold for the SOS date. Next, we obtained the annual NDVI time-series curves for each pixel, removed evident noise, and performed a least-square regression analysis on the relationship between the biweekly NDVI time-series data from January to September and the corresponding Julian Day for the whole study area (formula: $NDVI = a + a_1x + a_2x^2 + a_3x^3 \ldots + a_nx^n$, $n = 6$, where x is the Julian Day corresponding to the middle day of the NDVI compositing period) before obtaining the daily NDVI data through the sixth-order polynomial fit (7, 10). Finally, we identified the SOS date of each year by integrating the NDVI threshold and the fitted NDVI curve, resulting in the day when the fitted NDVI curve first reached the NDVI threshold. The remote sensing retrieved SOSs were validated by using the observed phenological data from 18 agrometeorological stations in the Tibetan Plateau during 2003–2011 (Fig. S6 and *SI Materials and Methods*). The validation showed that for almost all sites, there is a high consistency between the observed and retrieved results, which indicated our retrieved SOSs have a reasonably high accuracy considering the temporal resolution of the remote sensing datasets in the Tibetan Plateau, and the assumption that the NDVI value corresponds to the middle day of the NDVI compositing period is reasonable. We calculated the SOS trends from the NDVI datasets and in situ observation datasets during 2003–2011, but the comparison of the SOS trends between these two datasets was inconclusive, largely owing to the limited number of sites and only 9-y observations. Large interannual variations in climate and vegetation in the Tibetan Plateau suggest that there is a need to find longer-term in situ observation data to evaluate and validate the conclusion (on the 30-y trend) in the future.

NDVI Trend Analysis. The spatial distributions of the GSNDVI change trends in the Tibetan Plateau from 1998 to 2006 based on the GIMMS and SPOT-VGT datasets were characterized by the greenness rate of change (GRC), which was calculated as the slope of the linear least squares regression line fit to the interannual variation of the NDVI value (32) (Fig. 3 *A* and *B*). The statistical significance of GSNDVI and the monthly NDVI change across the Tibetan Plateau was mapped and assessed based on the two-tailed significance tests (Fig. 3 *C* and *D* and Fig. S1). GRC was calculated with the following formula:

$$GRC = \frac{n \times \sum_{i=1}^{n}(i \times NDVI_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} NDVI_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2}, \quad [1]$$

where i is the order of year from 1 to n, and n is the number of years; $NDVI_i$ is the GSNDVI of year i; and GRC is the NDVI change rate. If GRC > 0, the NDVI increases; otherwise, the NDVI decreases.

Piecewise Regression Analysis. To identify the abnormal trends of the GIMMS-based monthly NDVI in ROIs, we applied the piecewise regression model to quantitatively identify the turning points from 1982 to 2006. The model was applied as follows (13, 15, 33):

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$$y = \begin{cases} \beta_0 + \beta_1 x + \varepsilon, & x \le \alpha \\ \beta_0 + \beta_1 x + \beta_2 (x - \alpha) + \varepsilon, & x > \alpha \end{cases}, \quad [2]$$

where x is the year; y is the NDVI; α is the estimated breakpoint of the vegetation change trend, which was determined by the least square error method; β_1 and $\beta_1 + \beta_2$ represent the change rates before and after the breakpoint, respectively; and ε is the residual error. A t test was used to test the significance in the single and piecewise regressions, and a P value < 0.05 was considered significant.

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