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Variations in satellite-derived phenology in China's temperate vegetation

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Abstract

The relationship between vegetation phenology and climate is a crucial topic in global change research because it indicates dynamic responses of terrestrial ecosystems to climate changes. In this study, we investigate the possible impact of recent climate changes on growing season duration in the temperate vegetation of China, using the advanced very high resolution radiometer (AVHRR)/normalized difference vegetation index (NDVI) biweekly time-series data collected from January 1982 to December 1999 and concurrent mean temperature and precipitation data. The results show that over the study period, the growing season duration has lengthened by 1.16 days yr^{-1} in temperate region of China. The green-up of vegetation has advanced in spring by 0.79 days yr^{-1} and the dormancy delayed in autumn by 0.37 days yr^{-1}. The dates of onset for phenological events are most significantly related with the mean temperature during the preceding 2–3 months. A warming in the early spring (March to early May) by 1 °C could cause an earlier onset of green-up of 7.5 days, whereas the same increase of mean temperature during autumn (mid-August through early October) could lead to a delay of 3.8 days in vegetation dormancy. Variations in precipitation also influenced the duration of growing season, but such influence differed among vegetation types and phenological phases.

Keywords: China, climate change, green up, growing season, NDVI (normalized difference vegetation index), precipitation, temperate zone, temperature, vegetation phenology

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Introduction

Phenology refers to seasonal biological life stages driven by environmental factors, and is considered to be a sensitive and precise indicator of climate change (Zhu, 1973; Lieth, 1974; Schwartz, 1998; Menzel & Fabian, 1999; Beaubien & Freeland, 2000). Changes in phenological events have the potential to broadly impact terrestrial ecosystems and human societies, for example, by altering global carbon, water, and nitrogen cycles, interspecific interactions, crop production (risk of frost damage), the duration of pollination season and distribution of diseases (Schwartz, 1998; White *et al*., 1999; Menzel, 2000). Therefore, phenology has emerged recently as an important focus for ecological research (Schwartz, 1999; Menzel *et al*., 2001).

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Most previous phenological studies employ field-based surveys of interannual variations of phenological events and responses to changing climate at the species level. However, such approaches are limited by the number of *in situ* observation sites, and thus, are nearly impossible to obtain information on biomes-scale responses to changing climate. Satellite remote sensing provides powerful techniques that can monitor and characterize phenological trends at large scales (White *et al*., 1997, 2005). With a broad spatial coverage and high temporal resolution, the normalized difference vegetation index (NDVI) time-series data set derived from the national oceanic and atmospheric administration (NOAA)/advanced very high resolution radiometer (AVHRR) is available since the 1980s. This data set has been widely used to quantify ecological responses to changing climates at regional, continental and global scales over the past decades (e.g. Reed *et al*., 1994; Markon *et al*., 1995; Moulin *et al*., 1997; Myneni *et al.*, 1997; Huemmrich *et al.*, 1999; Tucker *et al.*, 2001; Zhou *et al.*, 2001, 2003; Lee *et al.*, 2002; Yu *et al.*, 2003; Stöckli & Vidale, 2004; White *et al.*, 2005).

Evidence from observed atmospheric CO_2 concentration (Keeling *et al.*, 1996), *in situ* phenological networks (Menzel & Fabian, 1999; Ahas *et al.*, 2000; Menzel, 2000; Schwartz & Reiter, 2000; Chmielewski & Rotzer, 2001; Penuelas & Filella, 2001), remote sensing data (Myneni *et al.*, 1997; Tucker *et al.*, 2001; Zhou *et al.*, 2001) and phenological modeling (Lucht *et al.*, 2002) all have revealed that spring has advanced and growing season duration has significantly lengthened over the past two decades at the middle and high latitudes in the northern hemisphere. However, the magnitude of this advance varied with species, location, and investigation period (Walther *et al.*, 2002).

Several factors can profoundly influence plant phenological status, such as disease, competition, soil factors and weather conditions (Menzel, 2000). Among these factors, climate change, particularly the global warming induced by increasing atmospheric greenhouse gases, has been suggested to be the major cause of the advance and extension of the growing season (Schwartz, 1998; Menzel & Fabian, 1999; Penuelas & Filella, 2001; Tucker *et al.*, 2001; Zhou *et al.*, 2001, 2003). Hence, investigation on the relationship between phenology and climate may help understand the mechanisms of the vegetation responses to climate changes, and thereby, allow more precise predictions of the effects of future climatic variability on phenology and improve global carbon cycle modeling.

In this study, we used NOAA/AVHRR NDVI data set and climate records to examine the recent trends in plant phenology in the temperate zone of China from 1982 to 1999. The NDVI data set was at a spatial resolution of $8 \times 8\,\text{km}^2$ and 15-day interval. This study aims to: (1) quantify changes in plant phenology of China's temperate vegetation over the past two decades, and (2) investigate the relationships between the onset dates of phenology and climatic factors, in order to better understand the underlying process, and eventually improve carbon cycle models for these biomes.

Data and methods

Study area

We chose the temperate zone (north of about 30°N in latitude, Fig. 1) of China as our study area, because in these areas the seasonality is evident and the satellite measured NDVI trends are least contaminated by solar zenith angle effects at middle and high latitudes (Slayback *et al.*, 2003). Humid tropical and subtropical areas were excluded from our analysis because of the lack of

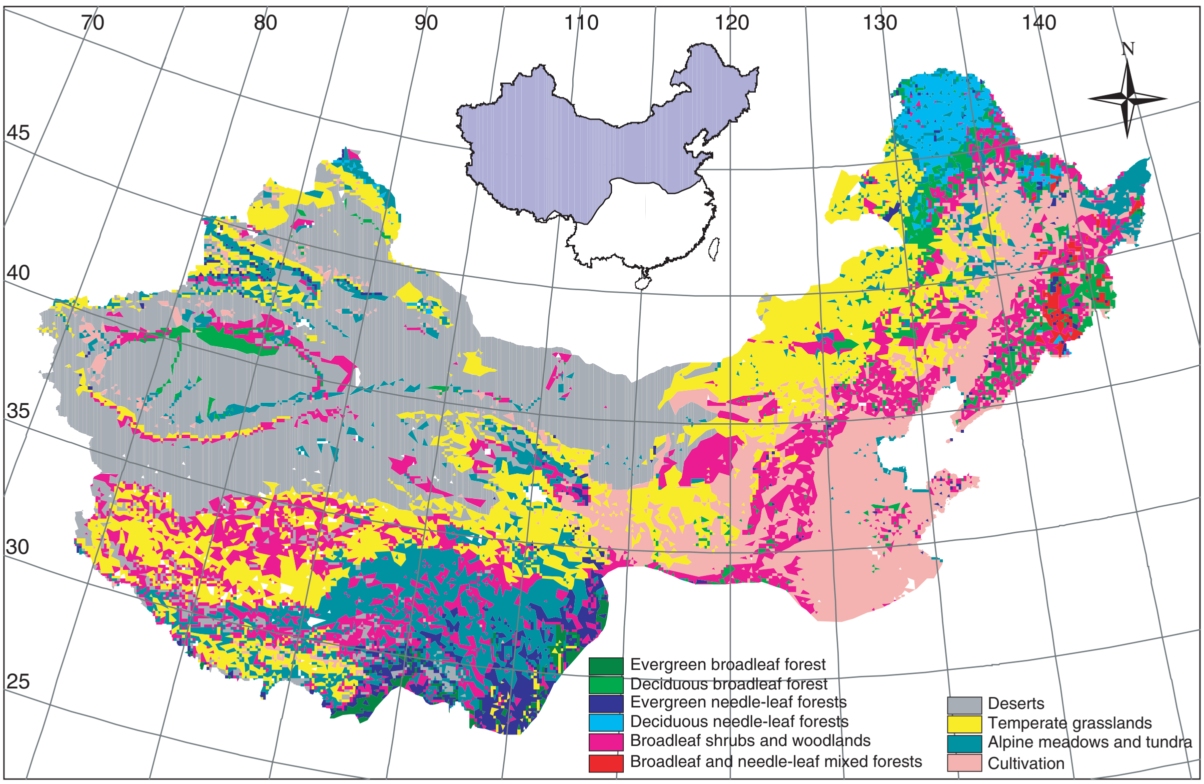

Fig. 1 Distribution of vegetation in temperate zone of China (adapted from Institute of Geography, Chinese Academy of Sciences, 1996).

seasonality, presence of evergreen vegetation cover and aberrant NDVI seasonal fluctuations related to nonvegetation weather impact. The boundaries of the study area follow the physiographical regions of China (Northwest Normal College, 1984).

Data

The evidence of long-term change in phenology using satellite data are limited by the availability of high-quality, calibrated NDVI data sets (White *et al*., 1997; Schwartz, 1999). NDVI data at a spatial resolution of $8 \times 8\,km^2$ and 15-day interval were acquired from the global inventory monitoring and modeling studies (GIMMS) group derived from the NOAA/AVHRR series satellites (NOAA 7, 9, 11, and 14) for the period January 1982 to December 1999 (Tucker *et al*., 2001; Zhou *et al*., 2001). The GIMMS NDVI data have been corrected to remove some nonvegetation effects caused by sensor degradation, clouds and stratospheric aerosol loadings from volcanic eruptions (Kaufmann *et al*., 2000; Myneni *et al*., 2001; Tucker *et al*., 2001; Zhou *et al*., 2001). Quality issues of the GIMMS NDVI database have been discussed by Slayback *et al*. (2003), who concluded that the data set is applicable for identifying long-term trends in vegetation activity. Further, in order to reduce the impact of bare soils and sparsely vegetated grids on the NDVI trends, grid cells with annual mean NDVI smaller than 0.1 during the 18 years were excluded for analysis, as done in Zhou *et al*. (2001, 2003).

Biweekly mean temperature and precipitation data at $0.1^\circ \times 0.1^\circ$ resolution were compiled from the 1982–1999 temperature/precipitation database of China. These gridded data sets were generated from 680 weather stations throughout the country (Fang *et al*., 2001; Piao *et al*., 2003, 2004).

Vegetation type data were obtained from a digitized 1 : 4 000 000 vegetation map of China (Institute of Geography, Chinese Academy of Sciences, 1996). China's vegetation was grouped into the following 10 types: evergreen broadleaf forest, deciduous broadleaf forest, broadleaf and needle-leaf mixed forest, evergreen needle-leaf forest, deciduous needle-leaf forest, broadleaf shrub, temperate grassland, alpine meadow and tundra, desert and cultivation (Fig. 1). As mentioned above, evergreen broadleaf forest type, which is located in tropical and subtropical areas, was not included in our study.

Methods

Generally, there are two approaches for determining the dates of growing season onset (onset dates of vegetation green-up) from the seasonal variation in NDVI. The first one uses a NDVI threshold to identify the beginning of photosynthetic activity in the spring (Lloyd, 1990; Fischer, 1994; Markon *et al*., 1995; White *et al*., 1997; Duchemin *et al*., 1999; Zhou *et al*., 2001; Suzuki *et al*., 2003). The second one identifies the period of greatest increase in NDVI as the beginning of growing season (Reed *et al*., 1994; Kaduk & Heimann, 1996; Moulin *et al*., 1997; Lee *et al*., 2002; Yu *et al*., 2003; Zhang *et al*., 2003). In this study, using the second approach, we first inferred fastest changes (rates) of NDVI corresponding to the vegetation green-up and dormancy (or the beginning and end of the growing season, or the onset and offset dates of the growing season) from the seasonal cycle of NDVI during 1982–1999. Then the onset dates of vegetation green-up and dormancy were determined based on the inferred rates and the NDVI seasonal cycles. The specific steps are illustrated in Fig. 2.

Determining the 18-year averaged seasonal NDVI curves. We calculated the 18-year averaged seasonal NDVI curves (patterns) for the whole study area and each vegetation type at 15-day intervals from the entire data set during 1982–1999.

Determining the rates of changes in the average seasonal NDVI curves. We first calculated the NDVI ratio, $NDVI_{ratio}$, from the series of consecutive 15-day periods. The $NDVI_{ratio}$ was calculated from the 18-year averaged NDVI seasonal curves for the whole study area and for each biome using

$$NDVI_{ratio}(t) = [NDVI(t+1) - NDVI(t)]/[NDVI(t)], \quad (1)$$

where t is time (temporal resolution of 15 days). We then used the timing of greatest NDVI change, namely the maximum and minimum values of $NDVI_{ratio}$, to determine the average onset dates of vegetation green-up and dormancy.

Determining the NDVI thresholds associated with the onset dates of vegetation green-up and dormancy. We first detected the time t with the maximum $NDVI_{ratio}$, and then used the corresponding NDVI(t) as the NDVI threshold for the onset date of green-up. Likewise, we detected the time t with the minimum $NDVI_{ratio}$, and then used the corresponding NDVI($t+1$) at time ($t+1$) as the NDVI threshold for the onset date of vegetation dormancy.

Fitting a smooth NDVI seasonal curve as a function of time. In general, for a pixel, with increasing Julian day, its NDVI value gradually increases first and then decreases after reaching its maximum. Therefore, we performed a least-square regression analysis of the relationship between the biweekly NDVI time-series data from January to September and from July to December and

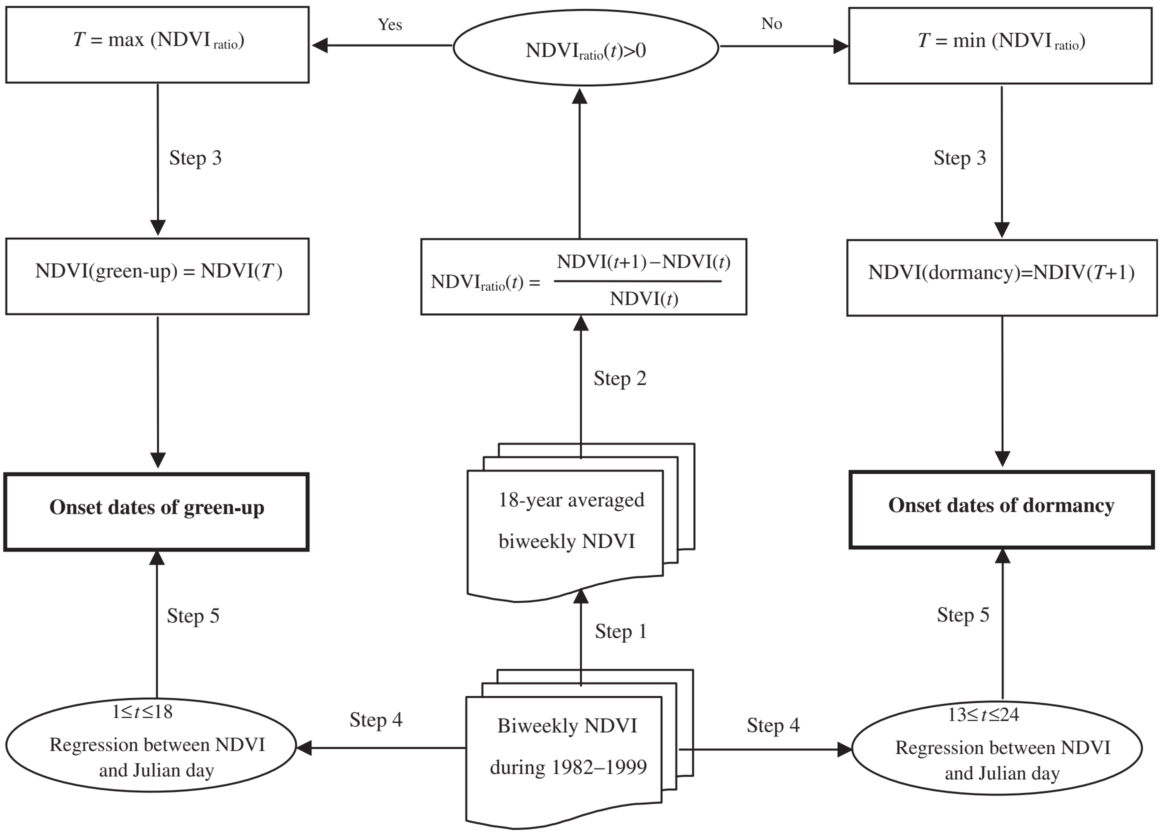

Fig. 2 Flowchart of procedures used to determine the onset dates of phenological event from normalized difference vegetation index (NDVI) time series. In this figure, t is biweekly period; NDVI(t) is the NDVI in period t; $NDVI_{ratio}(t)$ is the ratio of NDVI change between the period t and the period $t+1$; NDVI(green-up) is the NDVI threshold of the onset of green-up; and NDVI(dormancy) is the NDVI threshold of the onset of vegetation dormancy.

the corresponding Julian day for the whole study area and vegetation types for each year (Eqn (2)), to represent the seasonal changes in NDVI as a function of Julian day. Generally, this seasonal NDVI curve can be fit by an inverted parabola equation

$$\mathrm{NDVI} = a + a_1x^1 + a_2x^2 + +a_3x^3 + \cdots + a_nx^n, \qquad (2)$$

where x is the Julian days. Because of the impact of some nonvegetation effects of cloud, atmosphere, solar zenith angle, and other factors, some NDVI values are lower than their two adjacent ones. Evidently, using Eqn (2) can help smooth these abnormal values. A sixth-degree polynomial function ($n = 6$) was applicable to the regression in most cases.

Identifying the onset dates of vegetation green-up and dormancy. We determined the onset dates of vegetation green-up and dormancy for the whole study area and each vegetation type for each year, using the polynomial equations obtained in step 4 and the NDVI thresholds calculated in step 3. These onset dates were then used to analyze their trends over year.

Results

Characterization of vegetation phenology

Figure 3 shows the seasonal variations in the 18-year averaged NDVI and temperature at the interval of 15 days for the entire study area. The NDVI peaks in early August and the maximum increase in the NDVI ratio (25% or 1.7% per day) occurs in May, from 0.2 in early May to 0.25 in late May, whereas the maximum decrease in the NDVI ratio (−24% or −1.6% per day) occurs from late September to early October. Therefore, we identified early May as the mean onset period of vegetation green-up and early October as the mean onset period of vegetation dormancy for the entire study area (national level). The NDVI thresholds corresponding to these periods are 0.20 and 0.22, respectively, and the temperature thresholds corresponding to these NDVI values are 11.3 °C and 8.2 °C at the national level.

Table 1 lists the onset dates of vegetation green-up and dormancy, and their corresponding thresholds of

Table 1 Average parameters of the onset of vegetation green-up and dormancy by vegetation type from 1982 to 1999

Vegetation type	Onset date		NDVI threshold		Temperature threshold (°C)	
	Green-up	Vegetation dormancy	Green-up	Vegetation dormancy	Green-up	Vegetation dormancy
Deciduous broadleaf forests	Early May	Early October	0.275	0.287	12.2	8.2
Broadleaf and needle-leaf mixed forests	Early May	Early October	0.346	0.327	10.9	7.7
Deciduous needle-leaf forests	Early May	Early October	0.277	0.251	7.8	2.2
Broadleaf shrubs	Early May	Early October	0.203	0.241	10.4	7.8
Deserts	Early May	Early October	0.110	0.127	12.3	8.4
Temperate grasslands	Early May	Early October	0.162	0.203	9.7	6.5
Alpine meadows and tundra	Early May	Early October	0.181	0.253	8.7	6.3
Cultivation	Late April	Early October	0.226	0.246	12.8	12.4

NDVI, normalized difference vegetation index.

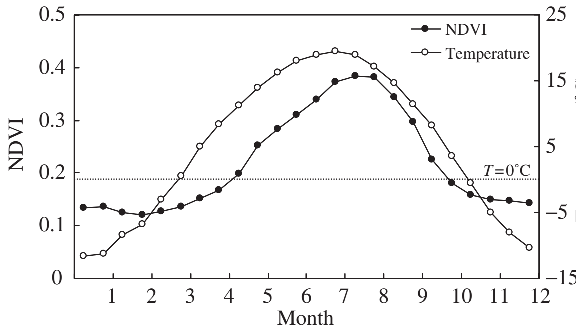

Fig. 3 Seasonal curves in the 18-year averaged biweekly normalized difference vegetation index and temperature for the entire study area.

NDVI and temperature for each vegetation type. Cultivation shows the earliest onset of green-up in late April, whereas all other vegetation types exhibit their maximum $NDVI_{ratio}$ in early May. In contrast, the mean onset dates of dormancy do not differ among vegetation types; all occur in early October.

However, the NDVI thresholds for the onset dates of either green-up or dormancy differ considerably among vegetation types (Table 1). The highest NDVI thresholds for the onset dates of green-up (0.346) and dormancy (0.327) occur in broadleaf and needle-leaf mixed forest, whereas the lowest thresholds (0.110 and 0.127, respectively) are founded in deserts. Similarly, the temperature thresholds of onset dates are dependent strongly on vegetation types. Deciduous needle-leaf forest require the lowest temperature thresholds, 7.8 °C and 2.2 °C, respectively, and cultivation demands the highest temperature, 12.8 °C and 12.4 °C, respectively.

Trends in the onset dates of vegetation green-up and dormancy at the national and biome levels

The mean onset date of green-up over temperate China has significantly advanced over the past 18 years ($R^2 = 0.45$, $P = 0.003$), with an annual advance of 0.79 days yr^{-1} (Fig. 4a). The earliest green-up occured in 1998, probably related to El Nino consequence in that year (i.e. the relatively higher spring temperature compared with the preceding years and abundant rainfall in most parts of China in 1998) (Piao *et al*., 2004).

The mean onset date of vegetation dormancy was delayed by 5 days over the 18 years ($R^2 = 0.36$, $P = 0.008$), from Julian day 279 in the early 1980s (average of 1982–1984) to Julian day 284 in the late 1990s (average of 1997–1999), with an annual delay of 0.37 days (Fig. 4b).

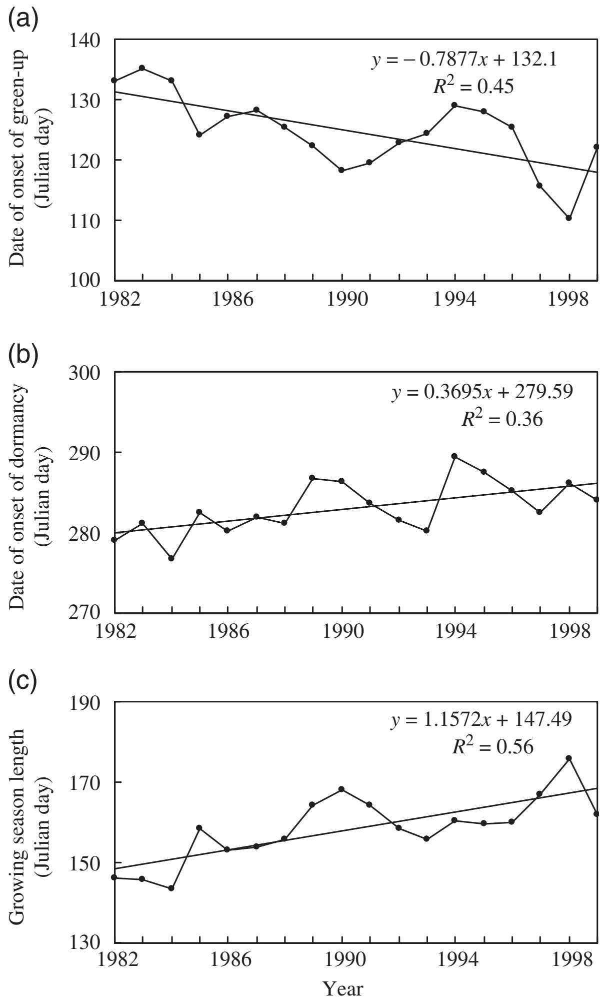

Fig. 4 Interannual variations in the onset dates of (a) green-up, (b) vegetation dormancy, and (c) growing season duration for the entire study area from 1982 to 1999.

Overall, the length of the growing season has increased by 1.16 days yr^{-1} from 1982 to 1999 ($R^2 = 0.56$, $P < 0.001$) (Fig. 4c).

Figure 5 illustrates the trends of the onset dates of vegetation green-up and dormancy by vegetation type. All vegetation types exhibit advanced green-up and delayed dormancy. Both the largest advance of green-up onset (1.54 days yr^{-1}) and the longest delay of dormancy (1.01 days yr^{-1}) occur in cultivation and desert vegetation. Both the smallest advance (0.11 days yr^{-1}) and delay (0.21 days yr^{-1}) occur in needle- and broad-leaved mixed forests. The growing season duration shows the similar trends: the greatest lengthening (2.28 days yr^{-1}) occurs in desert vegetation, followed by cultivation (1.88 days yr^{-1}), whereas the smallest lengthening (0.33 days yr^{-1}) is in broadleaf and needle-leaf mixed forest.

Green-up trends in relation to climate

In order to further explore possible causes of the lengthened growing season, correlation coefficients between the onset dates of vegetation green-up and dormancy and temperature and precipitation were calculated. Several studies have suggested a time lag between vegetation growth and climate variability (Braswell *et al*., 1997; Potter & Brooks, 1998; Piao *et al*., 2003; Zhou *et al*., 2003). Hence, when analyzing the relationships between the onset dates of green-up and the climatic variables, we calculated the average temperature and cumulative precipitation before the onset date of green-up and since preceding date of dormancy. We then computed the correlation coefficients between these average climate variables and the onset dates of green-up. Like Yu *et al*. (2003), we used the term 'preseason' to refer to the period before the mean onset dates (close to the term of nongrowing season) to analyze the relationships between the onset date and preseason climatic variables. According to such a definition, the length of preseason expands to 14 15-day (half month) periods, from early May (mean onset date of green-up) to the preceding October (date of dormancy).

Figure 6 shows the correlation coefficients between the onset dates of green-up and preseason climatic variables for the 1982–1999. The onset date of green-up was significantly and negatively correlated with temperature for all the 14 preseason periods, indicating that increasing preseason temperature could advance the onset date of vegetation green-up (Fig. 6a). The highest correlation is as found in the preceding 2–3 months (Fig. 6a), suggesting that the mean temperature at that time could have the greatest influence in triggering the green-up of the temperate zone of China.

The preseason precipitation also significantly influenced the onset date of green-up (Fig. 6b). The statistically significant correlation ($R^2 > 0.22$, $P < 0.05$) between the onset date of green-up and cumulative preseason precipitation occur in 5 months before the vegetation onset, suggesting the importance of winter precipitation in determining the beginning of vegetation growth in the coming year.

The different ecosystems denoted various responses to preseason climates. Figure 7 illustrates the correlation coefficients between onset dates of green-up and preseason temperature and precipitation by vegetation type. The two points can be summarized in the following:

(1) The onset date of green-up for all vegetation types is significantly and negatively correlated with mean preseason temperature for almost all the preseason periods, suggesting that warmer winters probably benefit an earlier the following spring green-up. The

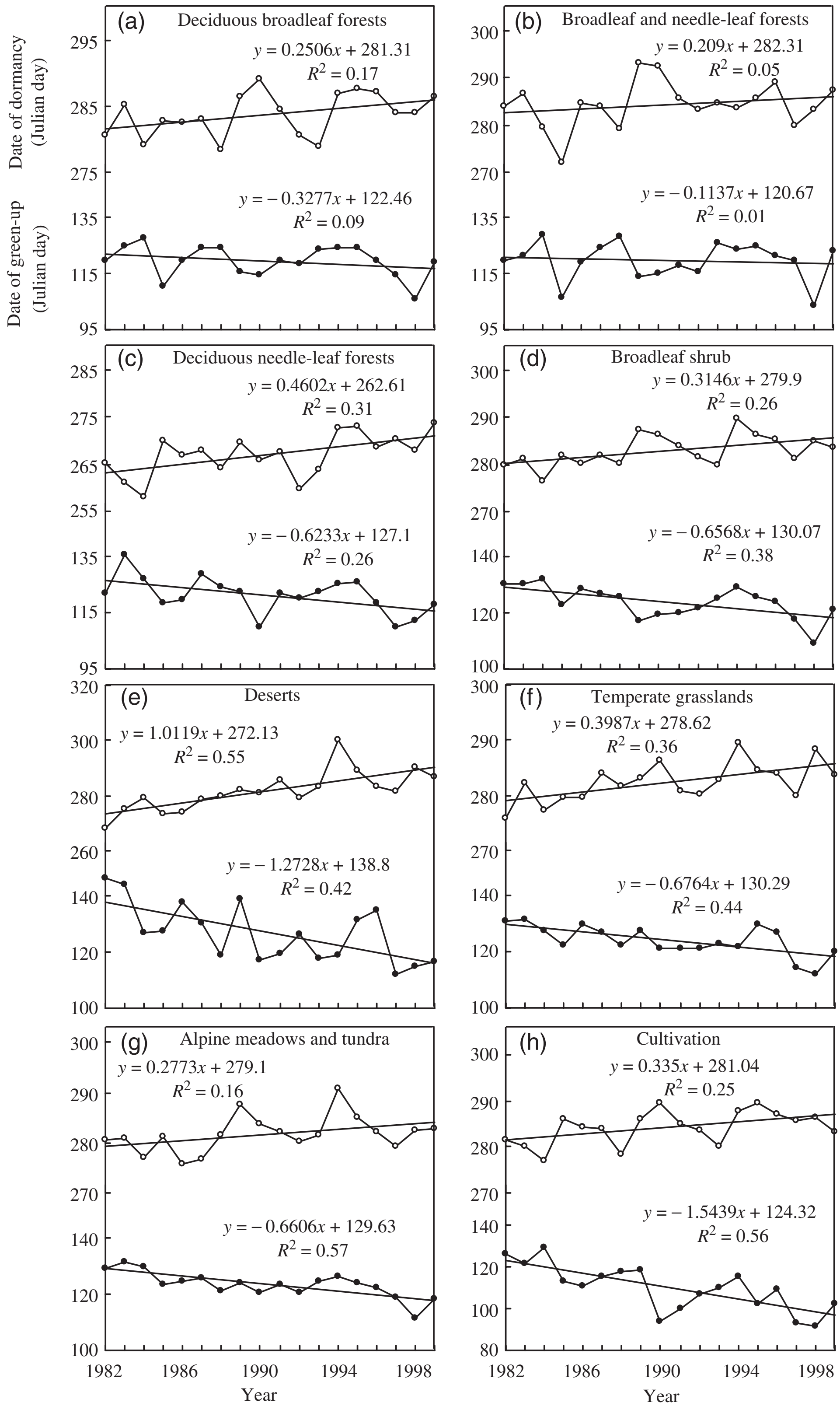

Fig. 5 Interannual variations in the onset dates of green-up (solid circles) and vegetation dormancy (open circles) for different vegetation types from 1982 to 1999 in China: (a) deciduous broadleaf forests, (b) broadleaf and needle-leaf mixed forests, (c) deciduous needle-leaf forests, (d) broadleaf shrub, (e) desert, (f) temperate grassland, (g) alpine meadows and tundra, and (h) cultivation.

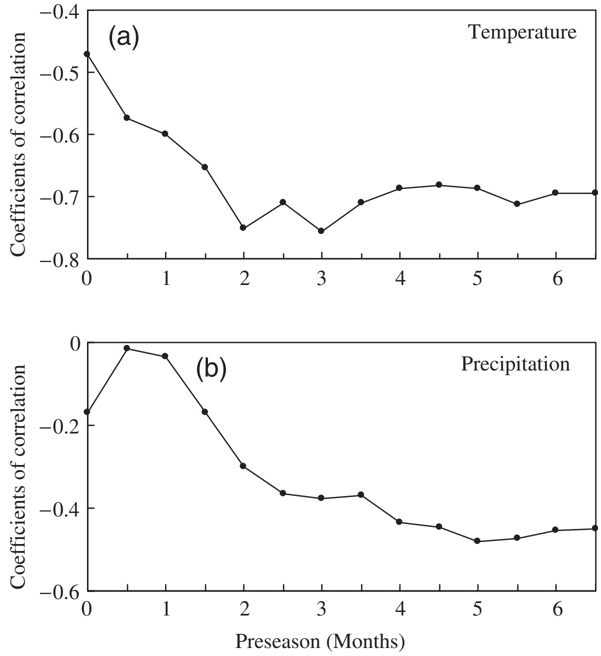

Fig. 6 Correlation coefficients between the onset date of green-up and (a) mean preseason temperature and (b) precipitation over the study area for different preseason periods. The *x*-coordinate (*i*) denotes the period from *i* months before early May through early early May. For example, the number 2 denotes the period from early March to early May.

absolute value of the correlation coefficient decreases with increasing preseason length back to the preceding year for all the three forest biomes (Fig. 7a–c), implying that the cumulative temperature during the two months (March and April) just before the onset of green-up significantly contributes to the forest growth. In contrast, the correlation coefficient increases with increased preseason duration back to the preceding year for cultivation (Fig. 7h), suggesting that increasing winter temperatures could be beneficial for crop growth.

(2) The onset date of green-up is not significantly coupled with preseason cumulated precipitation for forest and shrub biomes (Fig. 7a–d). Increased precipitation likely advanced the plant onset dates (negatively correlated) for desert, temperate grassland, and cultivation (Fig. 7e, f and h), but postponed the start of green up (positively correlated) for alpine meadows and tundra biome (Fig. 7g).

Dormancy trends in relation to climate

To investigate the relationship between the onset dates of vegetation dormancy and climate during the preceding periods, we calculated the averaged temperature and cumulated precipitation during the growing season (from early May to early October) by increasing each half-month from the onset date of vegetation dormancy, and obtained temperature and precipitation values for 10 periods. We then computed the correlation coefficients of these 'predormancy' climatic conditions with the onset date of vegetation dormancy for the 1982–1999.

The results show that the onset dates of vegetation dormancy are significantly and positively correlated with the predormancy mean temperature for almost all the averaging periods over the whole temperate China (Fig. 8a). This suggests that increased temperature during the preceding growing season has postponed the dormancy of vegetation at regional scale. However, the onset dates of vegetation dormancy are not correlated with the cumulative precipitation during all of the averaging periods ($P > 0.05$), with the exception of a significantly positive correlation for early October (Fig. 8b).

At the biome level, the relationship between the onset dates of vegetation dormancy and mean temperature for different earlier averaging periods shows a similar pattern to that for while temperate zone. Warmer preceding temperatures led to a delay of the dormancy (positive correlation) for all vegetation types (Fig. 9). However, three categories are observed for the relationship between the onset date and the preceding cumulative precipitation by vegetation type: (1) no significant correlation for deciduous broadleaved forest, broadleaf and needle-leaf mixed forest, shrub, alpine meadows and tundra, and cultivation (Fig. 9a, b, d, g, and h); (2) significant positive correlation for desert and temperate grassland (Fig. 9e and f); and (3) significant negative correlation for deciduous needle forest (Fig. 9c).

Discussion

NDVI and temperature thresholds

A 'sudden change' in NDVI can be related to the onset or cessation of 'significant photosynthetic activity' (Reed *et al*., 1994; Kaduk & Heimann, 1996; Moulin *et al*., 1997; Lee *et al*., 2002). The mean NDVI in the temperate zone of China shows a greatest increase and decrease in early May and early October, respectively. The corresponding mean NDVI values are 0.20 and 0.22 for the onset dates of vegetation green-up and dormancy, which is in agreement with those (0.2) for the phenological events of northern Asia used by Suzuki *et al*. (2003), but lower than those (0.3) for Eurasia by Zhou *et al*. (2001). Furthermore, various biomes require the use of different NDVI thresholds (Reed *et al*., 1994). The NDVI threshold of broadleaf and

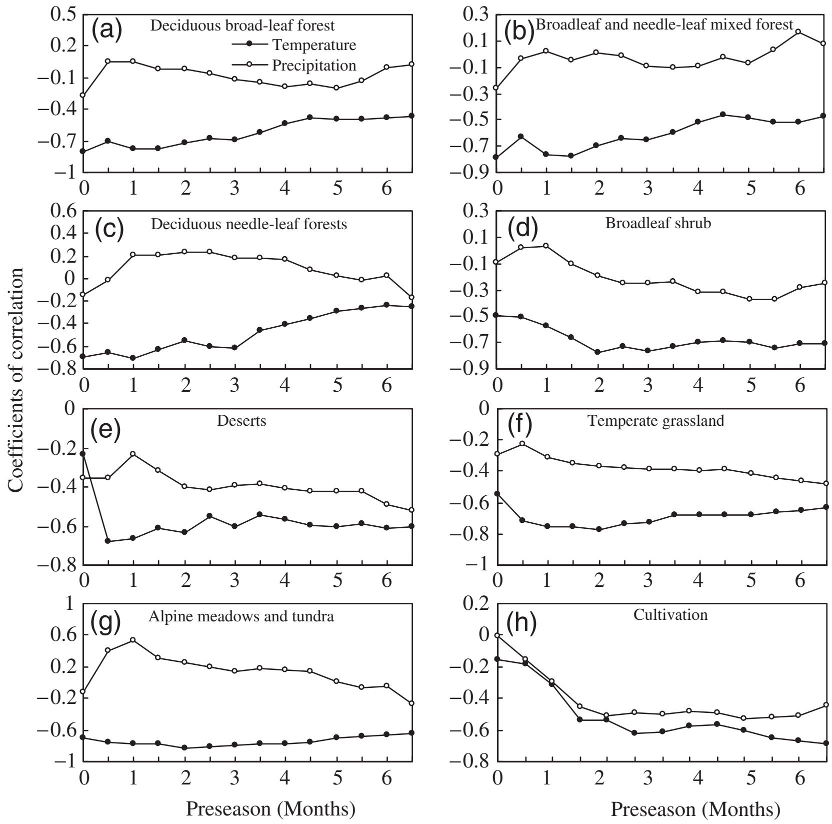

Fig. 7 Correlation coefficients between the onset date of green up and mean preseason temperature (solid circles) and precipitation (open circles) in different preseason periods by vegetation type: (a) deciduous broadleaf forests, (b) broadleaf and needle-leaf mixed forests, (c) deciduous needle-leaf forests, (d) broadleaf shrub, (e) desert, (f) temperate grassland, (g) alpine meadows and tundra, and (h) cultivation. The *x*-coordinate (*i*) denotes the period from *i* months before early May through early May, except cultivation whose x-coordinate (*i*) denotes the period from *i* months before late April to late April.

needle-leaf mixed forests (0.35 and 0.33), for example, is three times higher than that of deserts (0.11 and 0.13).

It is important to note that the phenological events in this study are determined only by satellite data. Although considerable efforts have been paid to their corrections, some bias because of satellite drift/changeover, incomplete corrections for calibration loss and atmospheric effects (clouds, aerosols, etc.) may still remain in the GIMMS NDVI data. Tucker *et al*. (2001) reported that the average slope of change in the GIMMS NDVI values for the Taklimakan desert and Arabian desert is within 0.001 over the 18 years, which was assumed to be the remaining noise caused by the abovementioned nonvegetation factors over the study periods (Tateishi & Ebata, 2004). This value was less than our minimum NDVI threshold value of 2%, suggesting that our NDVI threshold for phenological events was sufficiently larger than the effect of these noises.

The corresponding temperature thresholds of vegetation green-up and dormancy may provide useful information for their global application in meteorological phenology models and carbon cycle models. In our study area, these values are 11.3 °C and 8.2 °C, respectively, close to the threshold of growing season of cultivation in China (10 °C) (Feng & Tao, 1990), but relatively higher than that of the beginning and end of growing season (5 °C) determined by Prentice *et al*. (1992). Additionally, different vegetation types may require different temperature thresholds to trigger green-up. Vegetation in cold environments requires lower threshold temperature than that in warm conditions (Table 1), which may be explained as a result of vegetation adaptations to temperature (White *et al*., 1997; Jobbagy *et al*., 2002).

Trends in phenology

This study estimated that the mean onset date of green-up of the temperate zone of China has advanced on average by 0.8 days yr^{-1} from 1982 to 1999. There is evidence from a wide range of taxa and across a wide range of geographic locations that spring events have

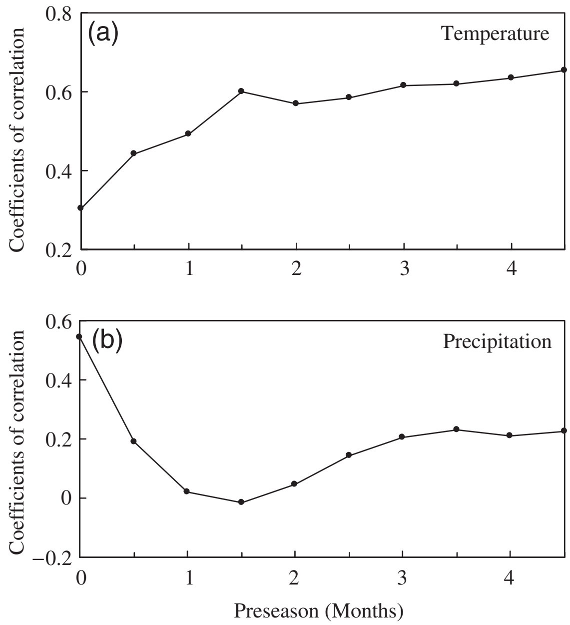

Fig. 8 Correlation coefficients between the onset date of vegetation dormancy and (a) preseason mean temperature and (b) precipitation over our study area for different preseason periods. The *x*-coordinate (*i*) denotes the period from *i* months before early October to early October.

been occurring increasingly earlier in recent decades (Myneni *et al.*, 1997; Menzel & Fabian, 1999; White *et al.*, 1999; Menzel, 2000; Schwartz *et al.*, 2000; Chmielewski & Rotzer, 2001; Tucker *et al.*, 2001; Zhou *et al.*, 2001; Penuelas *et al.*, 2002; Stöckli & Vidale, 2004). However, the magnitudes of the phenological trends differ dramatically among different authors, because of their attention to different species, phenological events, locations, and temporal and spatial scales (Walther *et al.*, 2002). For instance, Chmielewski & Rotzer, (2001) found that average leaf unfolding of four tree species in Europe advanced by 8 days from 1989 to 1998, whereas Zhou *et al.* (2001) used NOAA/AVHRR NDVI data to estimate an advance of 0.3 and 0.4 days yr^{-1} of the growing seasons for Eurasia and North America, respectively, during the 1981–1999 period.

Some evidence also indicates a later onset of autumnal phenological events, but these shifts are less pronounced and show a more heterogeneous pattern (Chmielewski & Rotzer, 2001; Walther *et al.*, 2002). Our results show that the onset date of vegetation dormancy has significantly delayed over the past two decades, but the magnitude was about half of that of the advance in green-up.

The length of growing season duration profoundly impacts the interannual variability of plant growth, and thereby, also strongly affects the net carbon dioxide uptake (Keeling *et al.*, 1996; Randerson *et al.*, 1999). The growing season of the temperate zone of China has experienced a distinct lengthening trend over the past two decades, with an annual extension of 1.16 days, greater than those of Eurasia and North America (1 and 0.7 day yr^{-1}, respectively) (Zhou *et al.*, 2001). This striking extension of the growing season may have enhanced vegetation growth. For example, White *et al.* (1999) found that a 1-day extension in growing season length could increase the mean forest (net primary production (NPP)) by 0.5%, with the greater increase in the colder environments. Fang *et al.* (2003) suggested that the lengthening of growing season derived from an increase in temperature made a large contribution to the annual NPP increase in China during the recent years.

Phenology and climate change

Several studies have suggested that the significant extension of growing season was coupled with the unprecedented rate of global warming in the past two decades (e.g. IPCC, 2001). China has also experienced significant climate changes (Zhai *et al.*, 1999; Chinese Climate Change National Research Group, 2000; Huang *et al.*, 2005) in the past decades. More than 97% of China exhibited an increase in spring temperature (49.3% with a significant increase), whereas about 95% of the area showed a positive trend in autumn temperature (23.9% with a significant increase) during the period of 1982–1999. Over the study area, the mean temperature from March to early May and from late August to early October increased at an annual rate of 0.078 °C ($R^2 = 0.45$, $P = 0.002$) and 0.038 °C ($R^2 = 0.16$, $P = 0.100$), respectively. For the precipitation in the study area, all seasons did not show significant trend ($P > 0.10$).

The relationship between phenology and temperature is a crucial topic in global change research because it indicates dynamic responses of terrestrial ecosystems to climate changes. Based on the observations of the first flowering date (FFD) of 385 British plant species from 1954 to 2000, Fitter *et al.* (2002) found that FFD was most sensitive to the mean temperature of the previous month and an increase of 1 °C for the mean temperature of the previous month had led to an advance in FFD of 4 days. Chmielewski & Rotzer (2001) have identified a significant negative relationship between the onset of spring and mean temperature of early spring (February–April) and found that a warming of 1 °C caused an advance in the beginning of growing season by 7 days. Our results indicated that the onset dates of phenological events correlated most significantly with the mean temperature during the previous 2–3 months, which is consistent with previous studies (Ahas *et al.*, 2000). The regression analysis between the onset dates of

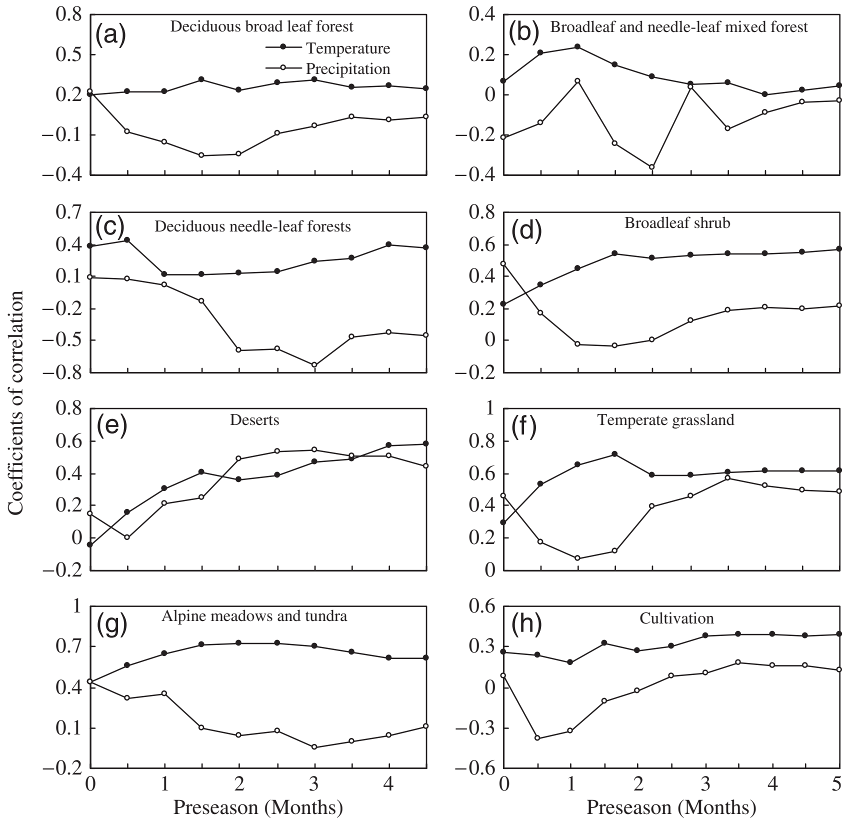

Fig. 9 Correlation coefficients between the onset date of vegetation dormancy and preseason mean temperature (solid circles) and precipitation (open circles) for different preseason periods by vegetation type: (a) deciduous broadleaf forests, (b) broadleaf and needle-leaf mixed forests, (c) deciduous needle-leaf forests, (d) broadleaf shrubs, (e) deserts, (f) temperate grassland, (g) alpine meadows and tundra, and (h) cultivation. The *x*-coordinate (*i*) denotes the period from *i* months before early October to early October.

phenological events and temperature indicated that over the entire study area, a warming in spring (from March to early May) by 1 °C will result in an advance in green-up of 7.5 days, whereas an increase in mean temperature from late August through early October by 1 °C will induce a delay in vegetation dormancy of 3.8 days.

On the other hand, little research has been performed for the relationship between precipitation and phenology (Kramer *et al*., 2001). Our results showed a meaningful impact of precipitation on the onset dates of phenological events at the national level although such impact differed among vegetation types. The onset date of green-up for the alpine meadows and tundra, for example, postponed with a increase in precipitation of the preceding months, whereas that of deserts and temperate grasslands showed advanced trends. The onset date of green-up for forests was not significantly correlated with the precipitation of the preceding months. These different patterns may be associated with their growth environments (Moulin *et al*., 1997; Kramer *et al*., 2001). Forests are always located in areas with relatively abundant rainfall, whereas deserts and temperate grasslands are distributed in arid and semi-arid areas, where winter snow may provide soil moisture through the spring drought (Yu *et al*., 2003). On the other hand, alpine meadows and tundra mainly appears under conditions of abundant precipitation and low temperature, in which temperature is the limiting factor for its vegetation growth (Piao *et al*., 2004). Furthermore, increased precipitation is accompanied by an increase in clouds and thus, a reduction in incoming solar radiation and temperature. Similar pattern can be also observed for the relationships of precipitation vs. onset date of vegetation dormancy. For example, the significantly positive correlation occurred in the arid and semiarid vegetation (desert and temperate grassland), whereas significantly negative correlation in the deciduous needle-leaf forest in northeastern China where climate is considerably cold.

Phenological events for cultivation, most severely affected by anthropogenic activities, are controlled not only by climate change (Atkinson & Porter, 1996), but also by crop type, planting, irrigation, fertilization, use of pesticides, and harvest (White *et al*., 1997; Zhang *et al*., 2004). Climate data indicate that temperature in crop area has significantly increased at an annual mean rate of 0.06 °C yr^{-1} since the 1980s. Moreover, use of chemical fertilization was dramatically increased during the study period in China (ECCAY, 2004), which was also a cause of the earlier green up for the cultivation (Chau *et al*., 2005). However, we could not determine the relative contribution of these factors, because of the interaction of these mechanisms. How to separate the impact of human activities and climatic changes on phenological events of cultivation remains a great challenge for further studies.

Conclusions

Based on NOAA/AVHRR NDVI biweekly time-series data and concurrent climate information, we estimated that the growing season duration of China's temperate vegetation has significantly lengthened, primarily through an earlier green-up and a later dormancy during the period of 1982–1999. This strongly supports the lengthening of growing season duration owing to the global warming at the northern high latitudes in recent decades. In addition, the relationship between the onset dates of vegetation activity and precipitation shown in this paper illustrates that growing season duration is also sensitive to variations in precipitation, but denotes various responses for different vegetation types. This finding not only underlines the importance of precipitation for vegetation phenology, but also suggests that the effects of precipitation on vegetation phenology should be included in future phenological models.

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