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## Recent spring phenology shifts in western Central Europe based on multiscale observations

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### ABSTRACT

**Aim** Although numerous studies have reported advanced Northern Hemisphere spring phenology since the 1980s, recent studies based on remote sensing have reported a reversal or deceleration of this trend. This study aimed (1) to fully understand recent spring phenology shifts using both *in situ* observations and satellite-based normalized difference vegetation index (NDVI) datasets, and (2) to test whether the NDVI methods capture the trends observed *in situ*.

**Location** Western Central Europe.

**Methods** Temporal spring phenology trends (leaf unfolding dates) were examined using 1,001,678 *in situ* observations of 31 plant species at 3984 stations, as well as NDVI-based start-of-season dates, obtained using five different methods, across the pixels that included the phenology stations.

**Results** *In situ* and NDVI observations both indicated that spring phenology significantly advanced during the period 1982–2011 at an average rate of  $-0.45$  days  $\text{yr}^{-1}$ . This trend was not uniform across the period and significantly weakened over the period 2000–2011. Furthermore, opposite trends were found between *in situ* and NDVI observations over the period 2000–2011. Averaged over all species, the *in situ* observations indicated a slower but still advancing trend for leaf unfolding, whereas the NDVI series showed a delayed spring phenology.

**Main conclusions** The recent trend reversal in the advancement of spring phenology in western Central Europe is likely to be related to the response of early spring species to the cooling trend in late winter. In contrast, late spring species continued to exhibit advanced leaf unfolding, which is consistent with the warming trend during spring months. Because remote sensing does not distinguish between species, the signal of growing-season onset may only reflect the phenological dynamics of these earliest species in the pixel, even though most species still exhibit advancing trends.

### Keywords

*in situ* observations, NDVI, spring phenology, start of season, temporal trend, western Central Europe.

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### INTRODUCTION

Spring phenology determines the onset of the growing season, and its timing is highly sensitive to climate, especially to temperature (Menzel *et al.*, 2006; Piao *et al.*, 2006; Schwartz *et al.*, 2006; Hänninen & Kramer, 2007; Jeong *et al.*, 2011; Fu *et al.*, 2013). Changes in spring phenology alter the length of the

growing season and thereby affect ecosystem productivity and regional and global carbon balances, plant–animal interactions and other essential ecosystem processes (Piao *et al.*, 2007, 2008; White *et al.*, 2009; Polgar & Primack, 2011; Richardson *et al.*, 2012; Fu *et al.*, 2014a). Thus, understanding how spring phenology has changed in response to ongoing climate change would be helpful to understand current ecology and to forecast

future ecosystem dynamics (Cleland *et al.*, 2007; Piao *et al.*, 2007; Jeong *et al.*, 2011; Polgar & Primack, 2011; Richardson *et al.*, 2012).

Two completely different approaches, each with its merits and shortcomings, are widely used to investigate spring phenology changes. The first approach involves traditional *in situ* observation of spring phenological events, such as leaf unfolding. Such observations provide us with long and rich phenological records (Menzel *et al.*, 2006; Cleland *et al.*, 2007), but are often limited to particular species. Their spatial coverage is also relatively poor (Cleland *et al.*, 2007), which prevents them from detecting synoptic patterns (White *et al.*, 2009). The second approach involves the use of the satellite-based normalized difference vegetation index (NDVI). This technique offers large spatial coverage, even on a regional or global scale (White *et al.*, 2005; Cong *et al.*, 2013), but cannot be used for monitoring individual plants or species, and only relatively short time-series of data are usually available (White *et al.*, 2005; Polgar & Primack, 2011). In addition, results vary considerably depending on which algorithm is used to extract the date of onset of greenness (or start of season, SOS) from annual NDVI series (Hird & McDermid, 2009; White *et al.*, 2009; Cong *et al.*, 2012). For example, differences of more than 30 days were found when different methods were applied to extract the SOS dates in temperate China (Cong *et al.*, 2012). Both the *in situ* and the remote-sensing approach have been successfully applied to capture spring dynamics (Cleland *et al.*, 2007; Polgar & Primack, 2011; Richardson *et al.*, 2013), but the correlation between the two methods is typically weak (Chen & Pan, 2002; Badeck *et al.*, 2004; Cleland *et al.*, 2007; Schwartz & Hanes, 2010; Polgar & Primack, 2011) and therefore a multiscale approach for observing spring phenology changes is preferred, combining both *in situ* observations and NDVI-based data.

Numerous studies have reported a consistent advancement of spring phenological events worldwide (2–10 days per decade), including *in situ* observed leaf unfolding and NDVI-based SOS dates (Myneni *et al.*, 1997; Parmesan & Yohe, 2003; Menzel *et al.*, 2006; Piao *et al.*, 2006; Jeong *et al.*, 2011; Richardson *et al.*, 2013) (see Table S1 in Supporting Information for a summary). Some discrepancies exist among these studies. First, large differences in the reported temporal phenology trends occur, which are likely to be due to the different study periods and areas (Dose & Menzel, 2004; White *et al.*, 2009; Piao *et al.*, 2011; Polgar & Primack, 2011). Second, most of these studies explored changes in spring phenology from the 1950s to the 2000s, and few have investigated the phenology shift after 2000 (Yu *et al.*, 2010; Jeong *et al.*, 2011; Piao *et al.*, 2011; Zeng *et al.*, 2011; Zhang *et al.*, 2013). Third, debate is ongoing on the amplitude of the advancement of spring phenology since the 1980s. Some studies suggest that the advancement of spring phenology accelerated from the early 1980s to the end of the 1990s but slowed thereafter (Yu *et al.*, 2010; Jeong *et al.*, 2011; Shen, 2011; Wang *et al.*, 2011), which may relate to the reduced warming trend after the year 2000 (Cane, 2010). On the contrary, other studies have reported a continuous advance since the 1980s (Zeng *et al.*, 2011; Zhang *et al.*, 2013). Because all these findings are based on

the trends in NDVI series, long-term *in situ* observations provide a valuable tool for reaching a consensus about the changes in spring phenology over the last decade. To the best of our knowledge, however, few studies have investigated recent spring phenology changes using *in situ* observations. These studies meta-analytically merged different species, as well as different locations for each species, to explore recent regional spring phenology changes (Fitter & Fitter, 2002; Parmesan & Yohe, 2003; Menzel *et al.*, 2006). To date, no study has investigated the last decade's spring phenology changes using *in situ* observations.

Here, we examined the temporal trends of spring phenology in western Central Europe using both *in situ* observations and satellite-based NDVI data. First, we studied the spring phenology dynamics (leaf unfolding and first flowering) over the past three decades (1982–2011), available through the Pan European Phenological Database. The entire period was split into two to investigate phenology trends before and after the year 2000. The SOS dates were then derived from satellite-based NDVI data, using five different methods. The mean SOS trends were analysed across pixels that also included observations in the phenology network. To explain the phenological changes, gridded climate data were used. This study aimed to analyse (1) how spring phenology changed in western Central Europe over the past three decades, and (2) whether the NDVI methods could capture the trends observed *in situ*.

## MATERIALS AND METHODS

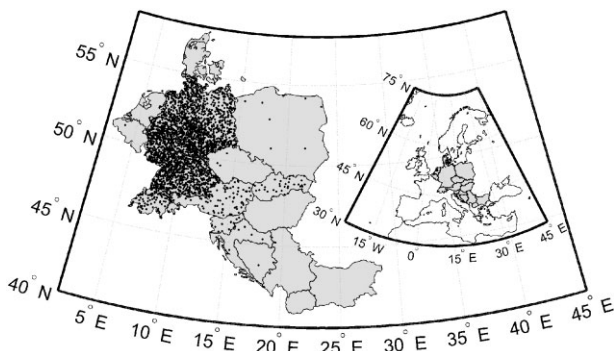
### *In situ* observation dataset

An abundant dataset of *in situ* phenology observations was obtained from the Pan European Phenology network (available at: <http://www.pep725.eu/>), which provides an open European phenological database comprising multiple plant phenological records. For this study, we selected the records of leaf unfolding and first flowering date of 31 plant species for the period 1982–2011. Data were excluded from the analysis when the plants flushed or flowered later than the end of June. (Details of the selected species are shown in Table S2.) The leaf unfolding and first flowering dates were defined according to the BBCH code (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie; Meier *et al.*, 2007). In total, 31 plant species, 3984 phenology stations and 1,001,678 phenological records were used. The distribution of the selected phenology stations is shown in Figure 1.

### Temperature data

The monthly average air temperatures at each phenology station were taken from a gridded climate dataset with a spatial resolution of  $0.5^\circ \times 0.5^\circ$  (CRU, <http://www.cru.uea.ac.uk/data>). An adjustment of the air temperature for differences in elevation was conducted, based on the equation

$$T_{\text{sta}} = T_{\text{grid}} - \gamma \times \Delta H \quad (1)$$



**Figure 1** Distribution of the European phenology stations used in this study, with an inset map of Europe.

where  $T_{\text{sta}}$  is surface air temperature at the specific phenology station,  $T_{\text{grid}}$  is the gridded surface air temperature for the pixel including the phenology station,  $\Delta H$  is the difference in elevation between the phenology station and the mean elevation of the pixel, and  $\gamma$  is the average adiabatic temperature lapse rate, fixed at  $6.4^{\circ}\text{C km}^{-1}$ .

The average annual temperatures, as well as the monthly temperatures, were calculated for all phenology stations. The relevant periods for leaf unfolding and flowering are typically one to three months prior to the phenological events (Menzel *et al.*, 2006; Fu *et al.*, 2012a), differing among species and locations. Because it is impossible to select one common period that suits all species and locations, we selected the monthly temperatures from November of the previous year to May of the following year as the mean temperatures for this analysis. The temporal temperature trends ( $^{\circ}\text{C yr}^{-1}$ , both annual and monthly temperatures) were analysed using linear regression for the three separate study periods (1982–2011, 1982–1999 and 2000–2011), and the slopes, standard errors and statistical significances of the regression were calculated.

### NDVI-based observations

The SOS dates were estimated with the 8-km, 15-day composites 1982–2011 NDVI data series from the Advanced Very High Resolution Radiometer (AVHRR), which were processed by the NASA Global Inventory Modeling and Mapping studies (GIMMS) (Tucker *et al.*, 2005). NDVI is directly related to the photosynthetic capacity and energy absorption of plant canopies (Asrar *et al.*, 1984), and has been widely used as an indicator of vegetation canopy functions (Myneni *et al.*, 1997; Zhou *et al.*, 2001; Tucker *et al.*, 2005; Park *et al.*, 2006; Wang *et al.*, 2011). The NDVI is calculated from the reflectance of red (R, 580–680 nm) and near-infrared (NIR, 725–1100 nm) bands of the sensor-AVHRR:

$$\text{NDVI} = \frac{\text{NIR} - \text{R}}{\text{NIR} + \text{R}} \quad (2)$$

In this study, the third-generation GIMMS-NDVI3g data were used to estimate the SOS dates. Once the biweekly NDVI series

were derived from the satellite, they were converted into daily time-series that are suitable for phenological studies (White *et al.*, 2009; Cong *et al.*, 2012). After that, critical thresholds for spring SOS dates were determined from the reconstructed satellite-signal time-series with different methods (White *et al.*, 2002, 2009; Piao *et al.*, 2006). The methods differ in the rules for interpolating the time-series, and for determining the critical thresholds for specific phenological events. Because the methods are known to yield different SOS dates, the results of our comparison between *in situ* observations and NDVI might largely depend on the selected method. In this study, we therefore used five methods to infer the SOS dates from NDVI time series: Gaussian midpoint (Gauss), spline midpoint (spline), HANTS maximum (HANTS), polyfit maximum (polyfit) and timesat SG (TS) (see Cong *et al.*, 2012, for details).

### Data analysis

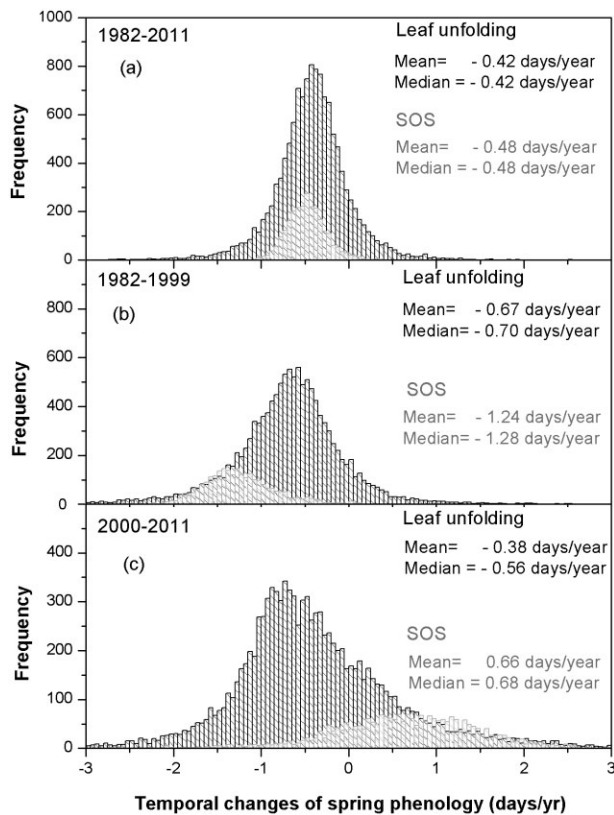
For each phenology station, linear regression analyses of the dates of leaf unfolding and first flowering against year were performed for each species in the three study periods: 1982–2011 (minimum of 15 annual records required per site); 1982–1999 (minimum of 10 annual records required per site); and 2000–2011 (minimum of 10 annual records required per site). For each pixel that included a phenology station, linear regression analyses of the temporal changes of SOS dates were also performed for these three study periods. Histograms were made to show the frequency distribution of the regression coefficients for leaf unfolding (SOS) across all species (and pixels). The mean temporal trend across all species and stations (all pixels, across all five methods) was defined as the average *in situ* (remote-sensing) spring phenology trend. The species-specific *in situ* average temporal changes (e.g. mean values of the regression coefficients) were compared using one-way ANOVA.

For both *in situ* leaf unfolding and remote-sensing-based SOS dates, the difference in mean temporal trend between the periods 1982–1999 and 2000–2011 was tested by an independent *t*-test. The independent *t*-test was also used to test the difference in the mean temporal changes between *in situ* and remote-sensing-based SOS dates for each of the three study periods. The regional differences in the mean temporal changes of spring phenology during the period 1982–2011 above and below  $50^{\circ}\text{N}$ , for both *in situ* leaf unfolding and remote-sensing-based SOS dates, was also studied using an independent *t*-test. Consistent with previous findings (Menzel *et al.*, 2001), no significant difference was found between these two regions for either *in situ* leaf unfolding or remote-sensing-based SOS dates (Fig. S1). All statistical analyses were conducted using *s* 16.0 (SPSS, Chicago, IL, USA).

## RESULTS

### *In situ* spring phenology changes

The *in situ* observations show that the timing of spring leaf unfolding has significantly advanced over the past three decades



**Figure 2** Histogram of the number of observed temporal trends for in-situ based leaf unfolding (black histograms) and remote-sensing-based start-of-season (SOS) dates (grey histograms) in western Central Europe for three periods: (a) 1982–2011; (b) 1982–1999; and (c) 2000–2011. The mean and median values of the temporal trends are provided. All temporal trends were obtained as linear regression coefficients (days  $\text{yr}^{-1}$ ).

(1982–2011; Fig. 2a). The advancing trends were observed in more than 80% of the observation stations, and half of these trends were statistically significant ( $P < 0.05$ ). The average *in situ*-observed spring phenology has advanced by 12.6 days between 1982–2011, at a mean rate of  $-0.42 \text{ days yr}^{-1}$  (negative values indicating advancing trends). A similar pattern was also found in dates of first flowering (Fig. S2): since 1982, the timing of first flowering has advanced by 15.6 days. The average date of leaf unfolding (day of year,  $\text{DOY} = 113 \pm 10$ ) was markedly later than the average date of first flowering ( $\text{DOY} = 108 \pm 27$ ), but these two phenological events cannot be directly compared because of the different species and sites used in each group.

The advancing trend of leaf unfolding was not uniform over the entire period (1982–2011), however. Compared to the faster and significantly advancing trend over 1982–1999 ( $-0.67 \text{ days yr}^{-1}$ ), the advancement was significantly ( $P < 0.05$ ) slower over the period 2000–2011 ( $-0.38 \text{ days yr}^{-1}$ ) (Fig. 2b,c). This decelerating trend was also observed for dates of first flowering, and was even more pronounced (Fig. S2b,c). The trend distribution of leaf unfolding dates in the period 2000–2011 is slightly negatively skewed (Fig. 2c), and the median value was  $-0.56$

days  $\text{yr}^{-1}$ . This indicates that more advancing than delayed trends were observed. Nevertheless, for 2000–2011, significant advancing trends were only observed at a small portion 20% of the observation stations.

Because the second study period (2000–2011) was short, single years with rather extreme data may have had a large effect on the regression results and the derived temporal trends. To test for such possible leverage effects, we repeatedly calculated the mean temporal changes of leaf unfolding and remote-sensing-based SOS dates for the period 2000–2011, each time omitting one year. The test results suggested no leverage effect on the temporal changes of spring phenology; i.e. all *in situ* observed temporal changes were negative (advancing trends), but the remote-sensing-based temporal changes were positive (Fig. S3), and these two temporal changes were significantly different.

Significant differences of spring leaf unfolding trends among species were found over the whole study period ( $\text{d.f.} = 18$ ,  $F = 25.0$ ,  $P < 0.001$ ). The species-specific spring leaf unfolding trends are shown in Figure 3, with species ranked by date of leaf unfolding from early to late. Similar patterns were also found in dates of first flowering ( $\text{d.f.} = 31$ ,  $F = 134.7$ ,  $P < 0.001$ , Fig. S4). Compared to the uniformly advancing trends across all species over 1982–1999 (Fig. 3, top panel), different temporal patterns were found between the species with early and late unfolding and flowering between 2000 and 2011 (Figs 3 & S4, bottom panel). Positive temporal changes, i.e. delayed trends, were found mainly in plants with earlier leaf unfolding or flowering. In contrast, the timing of leaf unfolding and first flowering was still found to be advancing in species with late unfolding and flowering.

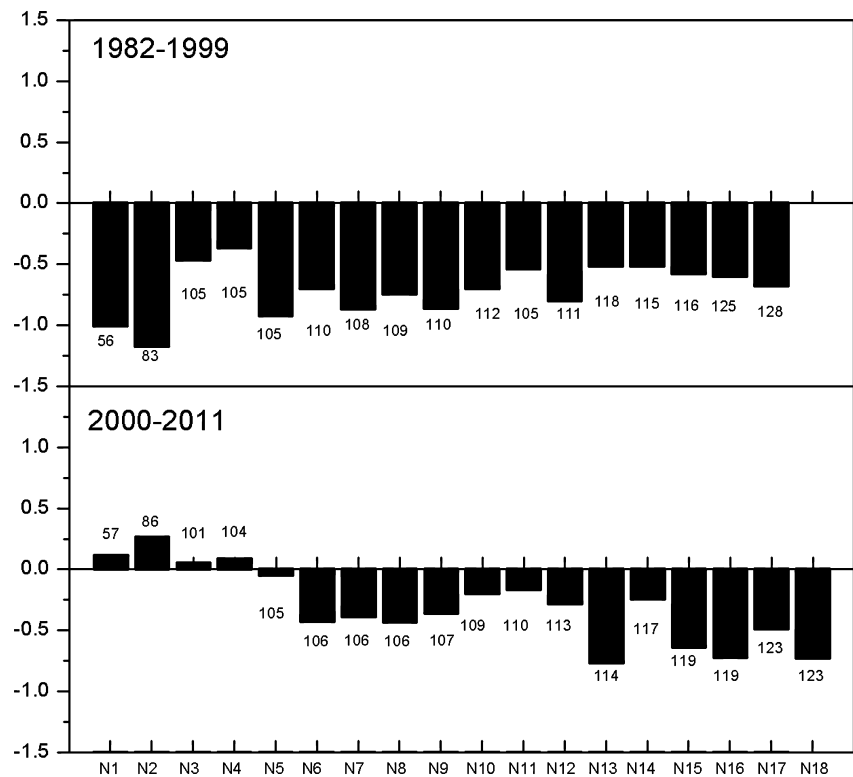
### NDVI-based SOS changes

The average SOS dates retrieved from the five methods all showed significantly advancing trends ( $P < 0.05$ ) during the period 1982–2011 (Fig. 2a, grey histogram). The variation of the temporal changes among these methods is, however, large (Fig. S5). The HANTS, polyfit and spline methods found advancing trends (around  $-0.50 \text{ days yr}^{-1}$ ) comparable to the *in situ* spring phenology changes, whereas the TS and the Gauss methods yielded more pronounced advancing changes ( $-0.59$  and  $-0.69 \text{ days yr}^{-1}$ , respectively). Large variation was also found in the SOS dates among these NDVI methods, such as a difference of 33 days for the mean SOS date between the earliest method (TS:  $\text{DOY} = 63$ ) and the latest method (polyfit:  $\text{DOY} = 96$ ). In general, NDVI-based SOS dates (mean  $\text{DOY} = 80$  across five SOS dates) are all consistently earlier than the *in situ* observed dates of leaf unfolding ( $\text{DOY} = 113$ ) and first flowering ( $\text{DOY} = 107$ ).

Consistent with the *in situ* observed spring phenology trends, the SOS dates of all NDVI methods showed two significantly different trends between the periods 1982–1999 and 2000–2011 (Fig. 2b,c). There was a significant advancement in the former period at a mean rate of  $-1.2 \text{ days yr}^{-1}$  ( $P < 0.05$ ), which is in concordance with but two times larger than the *in situ*-observed leaf flushing advancement ( $-0.67 \text{ days yr}^{-1}$ ). A reversed trend



**Figure 3** The species-specific trends of spring leaf unfolding during the two periods (1982–1999 and 2000–2011, time series). The numbers above or below the column are the average dates of species-specific phenological events for the study period. The number N1 to N18 indicates the id of these study species. N1: *Prunus amygdalus*; N2: *Sambucus nigra*; N3: *Prunus spinosa*; N4: *Prunus avium*; N5: *Syringa vulgaris*; N6: *Aesculus hippocastanum*; N7: *Alnus glutinosa*; N8: *Betula pendula*; N9: *Sorbus aucuparia*; N10: *Corylus avellana*; N11: *Prunus domestica*; N12: *Pyrus communis*; N13: *Fagus sylvatica*; N14: *Tilia cordata*; N15: *Acer pseudoplatanus*; N16: *Quercus robur*; N17: *Fraxinus excelsior*; N18: *Robinia pseudoacacia*. The details of these species are explained in Table S2 in the supplementary material.



was found in the following period at a rate of  $0.7 \text{ days yr}^{-1}$ , which differs significantly from *in situ* observations.

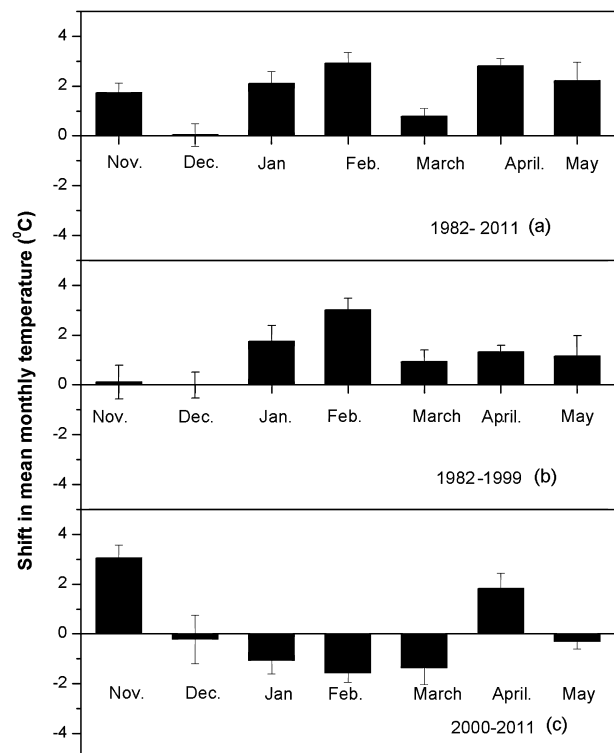
### Temperature changes

The mean annual temperatures across all selected phenology stations showed statistically significantly increasing trends during the study period 1982–2011 ( $0.034^\circ\text{C yr}^{-1}$ ,  $P = 0.01$ ). The warming trend was, however, no longer significant after 2000 ( $P = 0.60$ ). Compared to the mean annual temperature, monthly temperatures are more relevant or determinant of the timing of phenological events. Figure 4 shows that the monthly temperature shifts during winter and spring were significantly different in the two study periods. Between 1982 and 1999, the winter temperature (November and December) increased only slightly (average  $0.05^\circ\text{C}$ , Fig. 4), but the late-winter to spring temperatures (January to May) were considerably increased (average  $1.63^\circ\text{C}$ ). In contrast, during the period 2000–2011, winter temperature was considerably increased, but late winter to early spring temperatures decreased, with an average change of  $-0.50^\circ\text{C}$ . These warmer winters and colder early springs could have contributed to the decreased spring phenology trends over the last decade.

## DISCUSSION

### Multi-scale observation of spring phenology shifts in Europe

In this study, we used *in situ* phenological observations and NDVI-based SOS data to analyse spring phenology changes in



**Figure 4** Changes in average monthly temperatures in western Central Europe, with standard error, for three time periods: 1982–2011; 1982–1999; and 2000–2011.

western Central Europe from 1982 to 2011. Both approaches suggest that spring phenology has significantly advanced over this period at an average rate of  $-0.45$  days  $\text{yr}^{-1}$ . This significant advancing trend is consistent with results from other studies (see Table S1). The advancing trend was not, however, uniform across the entire study period. Previous studies have also reported that the decadal change of spring phenology is not a continuous event (Schaber & Badeck, 2005). Consistent with this finding, we found that the timing of the spring phenology indicators (leaf unfolding, first flowering and SOS dates) all significantly advanced over 1982–1999, but this trend significantly changed in the following period, 2000–2011. Remarkably, in our study, the time series based on NDVI and those based on *in situ* observations differed in the way the phenology time-series shifted after the year 2000. The NDVI-based dataset suggested that the advancing trend was reversed after 2000, which is consistent with other recent studies based on AVHRR-NDVI (Jeong *et al.*, 2011; Piao *et al.*, 2011). The *in situ* observations, on the other hand, showed that the advancing trend was only weakened in the 2000s, and was still present for many species. This discrepancy between *in situ* observed and NDVI-based spring phenology changes over the period 2000–2011 may result from the differences in the basic characteristics of the two methods, which are discussed in detail below.

The slowing down of the spring phenology advancing trend in the period 2000–2011 may be attributed to the trend in the temperatures of the relevant months. Previous studies have reported that marked differences in spring phenology trends could be explained by different trends in monthly temperatures (Scheffinger *et al.*, 2002; Schaber & Badeck, 2005). There is ample evidence to suggest that the timing of spring phenology is a function of temperature (Hänninen & Kramer, 2007; Fu *et al.*, 2012b), especially the timing of spring leaf unfolding and flowering at middle and higher latitudes (Hänninen & Kramer, 2007). In most plants of the temperate zone, buds need cold winter temperatures (chilling) to break dormancy, as well as warm spring temperatures (forcing) to promote cell division (Lapointe, 2001; Hänninen & Kramer, 2007). In our study, the significant winter and spring warming over the entire period is very likely to have elicited the advance of spring phenology. In contrast, the weakened phenological trends over the period 2000–2011 may have resulted from the combined effects of warmer late winter (November and December) and colder early springs (January and March) over the same period. The warmer winters may have reduced chilling accumulation, which would subsequently retard spring phenology, because more forcing temperatures would be required to initiate leaf phenology (Fu *et al.*, 2013, 2014b). The reduced temperatures in February and March may explain why spring phenology is retarded in earlier plants (Schuster *et al.*, 2013). In contrast, April has continued to warm in the past decade, and this late-spring warming may have accelerated the phenology of the later-unfolding and later-flowering plants. The complex winter–spring temperature interactions can thus explain both advancing and delayed dates of spring phenological events over the period 2000–2011.

## NDVI-based SOS versus *in situ* spring phenology

NDVI-based SOS dates have been widely used to study regional and global phenology (Myneni *et al.*, 1997; White *et al.*, 2002; Park *et al.*, 2006; Yu *et al.*, 2010). Recent comparison studies have found that the spring SOS dates estimated from different NDVI methods differ significantly and that no single method could perfectly reproduce the ground-based observation of spring phenology dates across different vegetation types and regions (White *et al.*, 2005; Cong *et al.*, 2012). Consistent with these studies, we also found large variations in the estimated SOS dates between the five selected methods. For example, a difference of more than one month was found between the latest (polyfit) and the earliest (TS) SOS dates. These differences may result from the different filtering modes used in these methods (White *et al.*, 2002; Cong *et al.*, 2013).

Consistent with the temporal trend observed *in situ*, all five NDVI methods showed advancing trends during the entire study period. The correspondence of the spring phenology trends between *in situ* and NDVI observations was, however, weak (Chen & Pan, 2002; Badeck *et al.*, 2004; Cleland *et al.*, 2007; Schwartz & Hanes, 2010; Polgar & Primack, 2011). We found that the SOS dates estimated from all five NDVI methods (mean 21 March) were roughly one month earlier than the *in situ*-observed unfolding dates (mean 23 April). This discrepancy may be due to the qualitative differences in the characteristics of the two methods (Badeck *et al.*, 2004). The NDVI-based SOS dates reflect the average date of the start of ecosystem growth within satellite pixels, which is a mixture of different species and even different land uses. This heterogeneity in vegetation cover within pixels has been shown to contribute to mismatches between satellite and ground observations (Doktor *et al.*, 2009). The SOS dates based on remote sensing may therefore reflect only the phenology of the earliest species within the pixel, such as the understory plants, which often green up earlier and are not necessarily the selected species in phenological gardens. Such species-specific differences in phenological time-series have indeed been reported previously (Scheffinger *et al.*, 2002; Schaber & Badeck, 2005). In this study, the selected phenology stations were concentrated in western Central Europe, which is dominated by agricultural land. For example, 52% and 37% of total land area was covered by agricultural land in Germany and Switzerland, respectively, in 2009 (data available at: <http://forest.jrc.ec.europa.eu/>). Most of the *in situ*-observed plant species are common European forest or garden tree species that unfold their leaves much later than grasses or evergreen crops, including winter cereals. The large degree of forest fragmentation, as well as the large contribution of agricultural area in this study, may therefore prevent the low spatial resolution (8 km) of the NDVI dataset from reflecting the forest phenology dynamics well. Instead, it probably mirrors the phenology of some early folding/flowering plants and the canopy expansion of crops in Europe.

Besides the large difference in the timing of spring phenology between the NDVI-based SOS dates and the *in situ* observations, both methods agreed on a spring phenology trend during the

period 2000–2011 that was different from the trend over the period 1982–1999. The NDVI-based SOS data suggested a delaying trend, opposite to the (slowed) advancing trend in the *in situ* observations. The reversed trend in the NDVI time-series has been discussed, using different NDVI methods and different remote sensors, i.e. AVHRR versus MODIS and SPOT (Zeng *et al.*, 2011; Zhang *et al.*, 2013). The discrepancy between the *in situ* observations and the NDVI data set has, however, seldom been reported. We provide two explanations. First, as discussed above, the NDVI-based SOS date may mainly reflect the spring phenology of some early plant species in the study regions. If so, the NDVI-based phenology trends should match the trend observed *in situ* for early-unfolding or early-flowering species over the period 2000–2011. This was confirmed by the species-specific trend analysis. In agreement with the NDVI data, we found a delayed trend across most species that unfold or flower in early spring. Furthermore, the timings of unfolding and flowering of these early spring species are close to the average SOS date (21 March) estimated by the NDVI time-series. A second explanation for the discrepancy between NDVI-based and *in situ*-observed trends could be the quality of the AVHRR dataset. Recent studies have suggested that the altered quality of the AVHRR NDVI data may have at least partly induced the reversed trend (Shen, 2011; Zeng *et al.*, 2011; Zhang *et al.*, 2013). Evaluating the quality of NDVI data is beyond the scope of this study, however, an integration of different satellite NDVI datasets and *in situ* observations would be expected to better address the uncertainty related to the application of different remote sensors in phenological studies (Badeck *et al.*, 2004).

The results of this study have important implications for the evaluation of recent annual vegetation growth and carbon budgets. Despite the contrasting trends between NDVI-based SOS and *in situ*-observed dates in the last decade, an advancing trend over the entire period and a weakening of this trend over the last decade is clearly derived by both approaches. These phenological changes can have significant implications for land–atmosphere dynamics and interactions (Piao *et al.*, 2007; Richardson *et al.*, 2013). Changes in the timing of spring phenology are likely to extend the length of the growing season for plants, which is closely related to annual gross and net primary production (Piao *et al.*, 2007). Thus, an extending growing season in response to the advancing spring phenology could potentially enhance the carbon sink capacity of terrestrial ecosystems (Schaefer *et al.*, 2005; Piao *et al.*, 2007).

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## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site.

**Figure S1** Histogram of the number of temporal trends below versus above 50° N.

**Figure S2** Histogram of the temporal trends of first flowering dates over the three study periods.

**Figure S3** Histogram of observed temporal trends for the whole study period 2000–2011, or for the period omitting one year.

**Figure S4** Species-specific trends of spring first flowering during the periods 1982–1999 and 2000–2011.

**Figure S5** Histogram of the remote-sensing-based temporal trends for five methods and for the three study periods.

**Table S1** Spring phenology trends (days yr<sup>-1</sup>) from previous studies, as seen in the *in situ* phenological records (P) and normalized difference vegetation index (NDVI) from different satellite sensors (AVHRR, SPOT and MODIS).

**Table S2** Details of the studied species and phenophases. LU, leaf unfolding; mean dates are the average dates of the phenophases during the period 1982–2011. ID indicates the species identifiers used in Fig. 3 (N) and in Fig. S4 (F).

## BIOSKETCH

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