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ORIGINAL ARTICLE

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Plant phenology in Germany over the 20th century

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Abstract Analysis of observational phenological data has indicated that the length of the vegetation period (VP), here defined as the time between leaf onset and leaf colouring (LC), has increased in the last decades in the northern latitudes mainly due to an advancement of bud burst. Analysing the patterns of spring phenology over the last century (1880–1999) in Southern Germany showed that the strong advancement of spring phases, especially in the decade before 1999, is not a singular event in the course of the 20th century. Similar trends were also observed in earlier decades. Distinct periods of varying trend direction for important spring phases could be distinguished. Marked differences in trend direction between early and late spring phases were detected, which can be explained by different trends in March and April mean temperatures. The advancement of spring phenology in recent decades is part of the multi-decadal fluctuations over the 20th century that vary with the species and the relevant seasonal temperatures. However, for all Natural Regions in Germany, spring phases were advanced by about 5–20 days on average between 1951 and 1999, LC was delayed between 1951 and 1984, but advanced after 1984 for all considered tree species and the length of the VP increased between 1951 and 1999 for all considered tree species by an average of 10 days throughout Germany.

Keywords Phenological trends · Combined time series · Standard periods · Natural Regions

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Introduction

There is an increasing body of empirical evidence proving that growing season length or vegetation period (VP), here defined as the time between leaf onset and leaf colouring (LC), has increased in the northern latitudes in the last decades (Keeling et al. 1996; Myneni et al. 1997; Menzel and Fabian 1999; Peñuelas et al. 2002; Menzel 2003). These trends could coherently be related to a global warming signal (Root et al. 2003; Parmesan and Yohe 2003). The VP has a strong impact on carbon sequestration of deciduous ecosystems (Kramer and Mohren 1996; Goulden et al. 1996; Chen et al. 1999; White et al. 1999). Moreover, it has been stressed that phenology becomes increasingly relevant also for other sectors as agriculture, socio-economy and public health within the context of global change (Peñuelas and Filella 2001).

In general, all of the above mentioned studies recorded an advancement of spring phases and a delay of autumn phases during the last decades. However, as Menzel (2000) pointed out, the reverse pattern can be observed at the local scale also. This phenomenon can partly be attributed to the fact that linear trend analysis of phenological time series is often biased because of incompleteness of the data and several sources of errors and uncertainty (Schaber and Badeck 2002). Trends of single time series with varying start and end dates are critical to compare (Menzel et al. 2001; Fig. 3). Some authors solved this problem by averaging phenological time series (Sparks et al. 2000; Chmielewski and Rötzer 2001; Menzel 2003). Schaber and Badeck (2002) showed that using yearly averages results in biased trends when station data are unequally distributed in time and space.

The method that overcomes drawbacks of analysing both single time series and average time series is analysing combined time series (Häkkinen et al. 1995; Linkosalo et al. 1996). Combining several fragmentary phenological time series for a certain region not only reduces the noise in the resulting time series, but also allows for application of proper outlier detection methods and normalization of the combined time series to a common observation period (Schaber and Badeck 2002).

It has been emphasized that the key to a better understanding of the change in phenology and its causes and future aspect is the availability of long time series of phenological observations (Peñuelas and Filella 2001). Here, we present for the first time an analysis of the wealth of phenological data that not only cover a time frame of 120 years but, at the same time, different regions.

Detected phenological trends also depend on the start and end year of individual time series, if periods with advancement and delays in the onset of phenophases follow one another or if the pace of change is varying. Thus, when phenological time series are compared, they should cover the same observational period and it is desirable to analyse phenological trends for time periods with characteristic climatic forcing trends (e.g., cooling, warming or constant temperatures). As the data used here to derive the century-long time series have varying start years (they all had 1999 as end year), we try to define standard periods in which the time series are comparable among species and regions.

The key-questions analysed in the following are:

– How do phenological trends develop in the course of the 20th century and what determines them? What do we learn when we extend the time frame from the usual 50 years (1951–2000) to 120 years (1880–1999)?
– What are the differences in phenological trends between phases/plants and regions?

Data and methods

Data

In the following, phenological data refer to reports on the Julian day of the onset of a specific phenological phase mentioned below. The phenological data used in this study come from three main sources. The major source is the German Weather Service (GWS) that provided digital data from its actual network for the period 1951 through 1999. From this network, we use 3,694 stations that are distributed all over Germany.

Moreover, we use the historical phenological database of the GWS. This digital database comprises data from various sources and covers the years 1880 until 1941 (Schaber 2002). From this database, 354 stations are selected that are situated in Germany and have at least four observations of the below-mentioned phases being analysed.

To supplement the data for the time before 1951 and to fill the gap between 1941 and 1951, we digitalized phenological data that are available only in printed form. These data were collected by the volunteer network of the precursor of the GWS, the Deutscher Reichswetterdienst (Schnelle and Witterstein 1952; Schnelle and Witterstein 1964). These observations cover the years 1922 through 1944. Additionally, we digitalized the phenological data that were published between 1945 and 1950 in the meteorological yearbooks of the GWS and are not stored in any digital database of the GWS (Schnelle and Volkert 1957). For the time from 1922 through 1950, data from 1,516 phenological stations were digitalized. For a map of the spatial distribution of the phenological stations from all three sources; see Schaber (2002).

The most abundant data was recorded in southern Germany. To compare the regions where continuous time series for the whole period from 1880 until 1999 for several phase are available, we have to restrict our analysis to the Natural Regions No. 3 (Fore alpine uplands), No. 11 (Franken) and No. 23 (River Rhine–Main lowlands) with the following species and phases:

– Early spring: Blossoming (B) of Snowdrop (*Galanthus nivalis* L.) and for the analysis for the whole of Germany also B Hazel (*Corylus avellana* L.) is included.
– Spring: BB of European white birch (*Betula pendula* Roth.), common horse chestnut (*Aesculus hippocastanum* L.), European beech (*Fagus sylvatica* L.) and English oak (*Quercus robur* L.).
– Early summer: B of *A. hippocastanum*, common lilac (*Syringa vulgaris* L.), European black elder (*Sambucus nigra* L.) and for the analysis for the whole of Germany also may shoot (M) of Scots pine (*Pinus sylvestris* L.) is included.
– Autumn: LC of *B. pendula*, *A. hippocastanum*, *F. sylvatica* and *Q. robur*.
– Length of VP of *B. pendula*, *A. hippocastanum*, *F. sylvatica* and *Q. robur*.

Climate data for the years 1901–2000 are also obtained from the GWS. We use daily mean temperatures of 20, 21 and 11 climate stations for the three selected Natural Regions, No. 3, 11 and 23, respectively. For the temperature series for whole Germany (Fig. 6), we used 403 stations.

Combined time series

There are some phenological stations that report observations in all three phenological data sets. Even though it is evident that the observers at these stations changed during the century, possibly introducing a systematic bias, such time series have to be treated as continuous observations of the same observer because an observer change is not reported in the data. These century-spanning time series play a key role in connecting the different phenological data sets because they produce overlapping time series, a prerequisite to obtain long-combined time series. We estimate the combined time series by the procedure recommended in Schaber and Badeck (2002). This procedure is based on a two-way linear model that simultaneously accounts for station and year effects. Outliers are removed according to the 30-day rule after a robust fit of the model.

A critical question is over what geographical extent phenological time series should be combined. Because, here we are interested in regional differences of trends, the so-called Natural Regions (NRs) of Germany were used. These NRs are defined by the homogeneity of certain aspects of the landscape like vegetation, soil, climate and phenology (Meynen et al. 1962; for maps see Schaber 2002).

Trends and linear regression

The time series are tested for normal distribution with the Shapiro–Wilk-test. Some combined time series are not normally distributed according to the Shapiro–Wilk-test ($P < 0.05$). For the LC phases, this is certainly due to a marked shift in the observations in the middle of the 20th century (results not shown). Applying the non-parametric Mann–Kendall trend test does not change the significance levels of the trends in most cases. Thus, we report significance levels of the *t* test for all trends.

Standard periods

We define standard periods by detecting potential trend turning points using the sequential Mann–Kendall test (Kendall and Gibbons 1990; Sneyers 1990; Gerstengarbe and Werner 1999; Böhm et al. 2001). Subsequently, the trends of the phenological phases are analysed and compared within those standard periods over the last century in the three selected NRs. Apart from that, we focus on the trends and their change in time in all NRs in Germany for the period from 1951 through 1999.

Gap filling

Even though the gaps in individual time series (years without observation) are filled by the process of combination, there still remained some combined time series with gaps. These gaps reside all before the year 1951 and mostly around 1945. These gaps are filled by corresponding values of combined time series from adjacent NRs corrected for their average deviation from the time series to be completed. Especially for the LC phases, gaps around 1945 are sometimes large (maximal 11 years) and cannot be filled with data from adjacent NRs. To be able to follow the course of the length of the VP over the century, those LC time series remain in the analysis. Only those time series are considered for which less than 10% of the data are generated by gap filling. For a summary of the resulting times series, their observational time span and their completeness before gap filling; see Table 1.

Results

Combined time series

The further we go back in time, the lower the number of phenological stations for which observations are reported. This has consequences for the quality of the estimated combined time series per phase and NR.

The large theoretical body coming with the theory of linear models also provides tools that measure the reliability of the obtained time series, e.g., confidence intervals for the estimated parameters. To obtain an overall picture of the reliability of the estimated combined time series, we pool the ranges of the 95% confidence intervals (RCIs) over all phases per year for spring (and early summer) phases and autumn phases, respectively. Figure 1a, b show the median, the 5% and 95% quantiles of the RCIs for spring and autumn phases (Fig. 1), respectively. There is a clear distinction between the reliability of spring phases (B and BB) and autumn phases (LC) that is due to the lower amount of available data for autumn phases. The median of the RCIs of spring phases varies between 20 and 5 days generally decreasing until 1951 from when it remains constant at around 5 days. The RCIs for the autumn phases are almost twice as large at the beginning of the considered time period as the spring phases (20–40 days). Between 1922 and 1950, the RCIs decreased from about 20 days to around 8 days, where they remained until 1999. Moreover, many LC phases showed a marked shift between 1920 and 1945 that can possibly be due to a change in the instructions for observers (results not shown). Thus, the combined time series for LC and therefore also the derived time series of the length of the VP for the three natural regions are unreliable for the period between 1880 and 1922. LC and VP are therefore only considered between 1951 and 1999 in the following. A compilation of diagrams of all derived and analysed combined time series of the three NRs can be found in Schaber (2002).

Overall trends

Trends as reported in recent literature (advancement of spring phases, delay of autumn phases) can be detected by visual inspection for the last decades but over the course of the whole century, the trends of the last decades appear as parts of larger fluctuations, e.g., for BB of *A. hippocastanum* in NR No. 23 (Fig. 2) the trends observed in the last decades can also be found earlier in the 20th century. Varying trend behaviour can also be analysed with trend matrices (Scheifinger et al. 2002). In Fig. 3 we display the trend matrix of BB of *A. hippocastanum* in NR No. 23 from Fig. 2. The trend pattern for this particular phase shows consistent negative trends only for the last decade (1990–1999) and positive trends in the mid-1980s almost irrespective of the start

Table 1 Phenological phases blossoming (*B*), bud burst (*BB*), leaf colouring (*LC*) for the three selected Natural Regions (NRs) No. 3, No. 11 and No. 23, their coverage during the observational time span and number of values within this time span (*N*). Completeness before gap filling and number of filled data gaps (%). For the LC phases, the number of remaining gaps (years without observations) is given in brackets

Natural region	Phase	Coverage	N	Completeness (%)	No. filled gaps
NR No. 3	B *G. nivalis*	1895–1999	105	95.2	5
	BB *A. hippocastanum*	1890–1999	110	100	0
	BB *B. pendula*	1890–1999	110	93.6	7
	BB *F. sylvatica*	1890–1999	110	98.2	2
	BB *Q. robur*	1890–1999	110	91.8	9
	B *A. hippocastanum*	1890–1999	110	100	0
	B *Syringa vulgaris*	1890–1999	110	100	0
	B *Sambucus nigra*	1890–1999	110	100	0
	LC *A. hippocastanum*	1890–1999	110	100	0
	LC *B. pendula*	1890–1924 1935–1999	99	100	0 (10)
	LC *Q. robur*	1890–1941 1945–1999	107	94.4	6 (3)
NR No. 11	B *G. nivalis*	1935–1999	65	100	0
	BB *A. hippocastanum*	1883–1999	117	99.1	1
	BB *B. pendula*	1883–1999	117	91.5	10
	BB *Q. robur*	1883–1999	117	90.6	11
	B *A. hippocastanum*	1883–1999	117	98.3	2
	B *S. vulgaris*	1883–1999	117	100	0
	B *S. nigra*	1880–1999	120	97.5	3
	LC *A. hippocastanum*	1883–1999	117	94.9	6
	LC *B. pendula*	1883–1928 1936–1999	110	94.5	6 (7)
	LC *F. sylvatica*	1883–1941 1945–1999	114	90.4	11 (3)
	LC *Q. robur*	1893–1999	108	99.1	1
NR No. 23	B *G. nivalis*	1983–1999	108	99.1	1
	BB *A. hippocastanum*	1882–199	118	99.2	1
	BB *B. pendula*	1880–1999	120	99.2	1
	BB *F. sylvatica*	1880–1999	120	96.7	4
	BB *Q. robur*	1882–1999	118	96.6	4
	B *A. hippocastanum*	1880–1999	120	99.2	1
	B *S. vulgaris*	1880–1999	120	99.2	1
	B *S. nigra*	1880–1999	120	99.2	1
	LC *A. hippocastanum*	1880–1999	120	97.5	3
	LC *B. pendula*	1880–1999	120	95.8	5
	LC *F. sylvatica*	1880–1941 1945–1999	117	96.6	4 (3)
	LC *Q. robur*	1882–1941 1945–1999	115	98.3	2 (3)

year. Trend calculation starting before 1925 and in the end of 1940s yields almost exclusively positive trends except for the decade 1990–1999.

Trends for spring and early summer phases, BB and blossoming (B), are calculated for the whole period that was available and for the three selected NRs. LC and VP are only considered starting 1951 because of the unreliability in earlier decades (Table 2). Out of 23 resulting spring time series ten are significantly negative ($P < 0.05$), and all of those, except one (*G. nivalis* NR 11), cover more than 100 years, indicating that BB and B have advanced up to 16 days throughout the 20th century. However, the trends are not consistent among the NRs. Not only do significance levels change, but so do the signs of the trends. Trends of B of *G. nivalis* are negative for the NRs 3 and 11 but positive for NR 23. Trends of BB of *A. hippocastanum* are positive for NR 11 and negative for the NRs 3 and 23. Trends of BB of *F. sylvatica* are positive but not significant. In general, LC phases are delayed (positive trend) after 1951. For LC of *A. hippocastanum* we find an advancement (negative trend) for two NRs, however, it is not significant. Consequently, together with the general advancement of spring phases, the VP also has increased after 1951. This phenomenon can also be seen on average for all NRs in Germany (Table 3).

Standard periods

To determine start and end points for trend analysis common to all considered phases, i.e. standard periods, we cannot apply the sequential version of the Mann–Kendall test to the phenological time series themselves. This would give us different standard periods for each phase. Nevertheless, we are interested in defining standard periods that are linked to phenology and possibly give us an indication of varying trend behaviour.

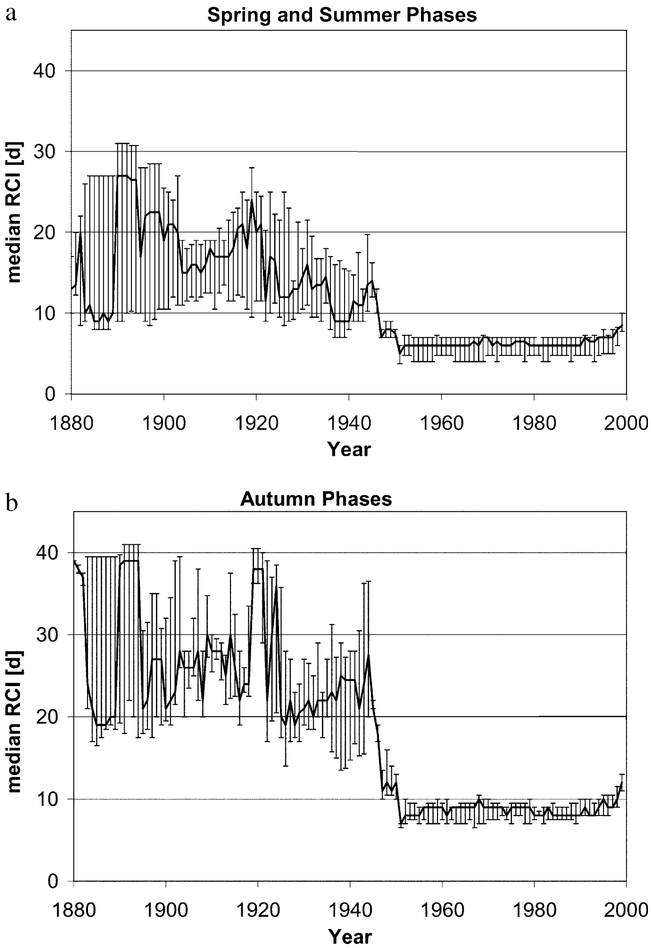

Fig. 1 **a** Median of the ranges of the 95% confidence intervals (*RCIs*) for the combined time series of Table 1 with 5% and 95% quantiles as *error bars*. Spring and early summer phases (blossoming and bud burst). **b** Median of the RCIs for the combined time series of Table 1 with 5% and 95% quantiles as *error bars*. Autumn phases (leaf colouring)

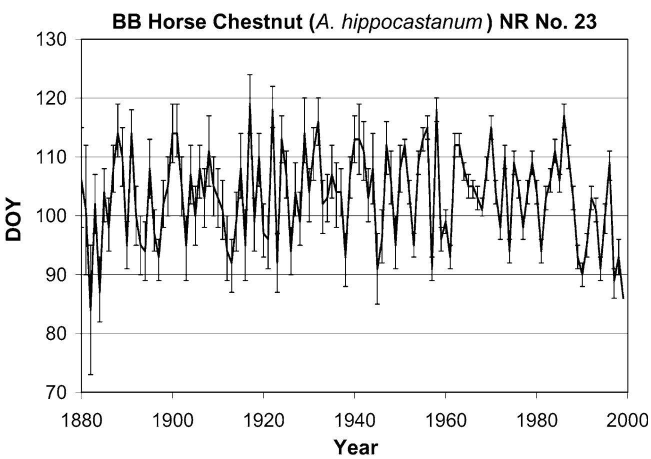

Fig. 2 Combined time series for bud burst (*BB*) of Horse Chestnut (*Aesculus hippocastanum* L.) for the NR No. 23. *Error bars* show the estimated 95% confidence intervals. Values in Julian day of year (*DOY*)

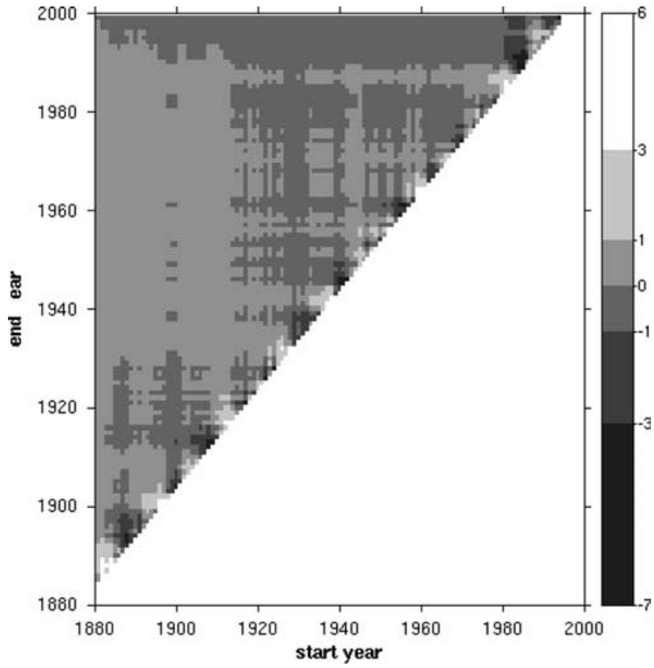

Fig. 3 Trend matrix of bud bust of *A. hippocastanum* in NR No. 23 (see Fig. 2). Trends are colour-coded in days (see legend) according to the start and end year of the trend calculation

Therefore, we would rather apply the Mann–Kendall test to a signal that integrates as much phenological information as possible. Former analysis and modelling studies demonstrate that temperature is the main factor influencing spring phenology (Kramer 1994; Chuine 2000; Menzel 2003). Direct effects of other climatological factors like, e.g., atmospheric CO_2 concentration are unlikely (Badeck et al. 2004). According to the temporal and spatial distribution and aggregation of our data, we figured that the average of mean March and April temperatures in the considered NRs serves as an appropriate signal, because March and April temperatures largely determine regional spring phenology in Germany (Menzel 2000; Schaber 2002) except for the early spring phase B of *G. nivalis* where mean February temperature has the largest influence (Schaber 2002). The sequential Mann–Kendall test only gives approximate trend turning points (Sneyers 1990) and is not reliable at the beginning of the time series due to the small amount of available data in the first sub-series. Thus, we defined the standard periods by extreme values in the temperature series that are closest to the detected approximate potential trend turning points and we neglected trend turning points at the beginning and the end of the time series (Fig. 4).

We distinguish three potential trend turning points, i.e. 1931, 1948 and 1984, that are defined by the intersections of the so-called progressive and retrograde series of the sequential Mann–Kendall test (Sneyers 1990; Schaber 2002). They are not or only weakly significant (Sneyers 1990). Nevertheless, the three intersections mimic trend behaviour of the mean March–April

Table 2 Trends (days) of all analysed phases (Table 1) for three NRs

Phase	Trends NR 3	Trends NR 11	Trends NR 23
Whole period (1880–1999)			
B *G. nivalis*	**−10**	**−16**	**3**
BB *A. hippocastanum*	**−6**	3	**−1**
BB *B. pendula*	**−9**	−4	**−3**
BB *F. sylvatica*	0	NA	3
BB *Q. robu*	**−11**	−1	−1
B *A. hippocastanum*	−3	−7	−5
B *S. vulgaris*	−3	−3	−3
B *S. nigra*	**−11**	**−10**	**−5**
1951–1999			
LC *A. hippocastanum*	−3	−1	2
LC *B. pendula*	0	**12**	0
LC *F. sylvatica*	3	NA	**5**
LC *Q. robu*r	5	**7**	**6**
VP *A. hippocastanum*	6	**10**	**12**
VP *B.pendula*	6	**20**	**9**
VP *F. sylvatica*	5	NA	**9**
VP *Q. robu*r	8	**10**	**11**

For bud burst (*BB*) and blossoming (*B*) phases the whole observational period is covered (for coverage of the observational period see Table 1). For leaf colouring (*LC*) and length of vegetation period (*VP*) the time frame 1951–1999 is considered
Significance of the trends are indicated by bold face ($P < 0.05$)
NA not available

temperatures in the three NRs over the century. Therefore, they are taken as clues to define normal periods in which phenology can be properly analysed and compared. Thus, we consider four standard periods in the following: (1) until 1931, (2) 1931–1948, (3) 1948–1984 and (4) 1984–1999. Trends for spring and summer phases are calculated for these four periods for each of the three NRs considered. Here, we display only the results for NR No. 3 (Fig. 5). The results for the other NRs are similar (Schaber 2002).

Trends in the three NRs have significantly changed in the course of the last century (Fig. 5). Trends for advanced spring and early summer phases as determined for the last 15 years have already been found in the first half of the last century in the 17 years between 1931 and 1948. When we focus on trend developments of the last three periods, we can see that the early spring phases B of *G. nivalis*, BB of *A. hippocastanum* and *B. pendula* always show consistently negative trends that change only in magnitude and significance.

The late spring and early summer phases BB of *F. sylvatica*, *Q. robur* and B of *A. hippocastanum*, *Syringa vulgaris* and *Sambucus nigra* change from significant negative trends to significant positive trends back to significant negative trends.

The example of *A. hippocastanum* in NR No. 23 given in the trend matrix in Fig. 3 also exhibits negative trends in the decade before 1999 and positive trends between 1948 and 1984.

Germany 1951–1999

We find similar standard periods as in Fig. 3 when mean temperatures averaged over March and April for Germany are analysed. Even though the picture of varying temperature trends for Germany is not as clear as for the three NRs analysed above, a trend turning point can be determined in the mid-1980s (Schaber 2002). As the earliest common starting point of phenological time series for all NRs in Germany is 1951, we calculate trends for the spring, summer and autumn phases mentioned above for the two periods 1951–1984 and 1984–1999. Trend maps for all analysed phases for the NRs in Germany (Table 1) are compiled in Schaber (2002).

In Table 3, the mean trends over all NRs that completely cover the respective periods 1951–1984 and 1984–1999, as well as mean trends over all NRs for the whole period 1951–1999 are displayed. On average, our previous finding for the three selected NRs as well as for the trend maps are confirmed for all NRs in Germany.

Table 3 Average trends over all NRs for which combined time series cover the periods 1951–1984, 1984–1999 and 1951–1999

Phase	Avg ± σ	N	Trends '51-'84 Total (days)	Trends '84-'99 Total (days)	Trends '51-'99 Total (days)
B *C. avellana*	59 ± 25.7	4,934	**−7**	**−31**	**−20**
B *G. nivalis*	60 ± 17.9	69,527	**−5**	**−21**	**−12**
BB *B. pendula*	112 ± 11.6	64,527	−1	**−11**	**−9**
BB *A. hippocastanum*	113 ± 12.4	75,672	**−1**	**−12**	**−9**
BB *F. sylvatica*	120 ± 9.9	60,901	**2**	**−9**	**−5**
BB *Q. robur*	127 ± 11.1	62,609	**3**	**−10**	**−6**
B *A. hippocastanum*	131 ± 11.0	63,843	**6**	**−9**	**−2**
M *P. sylvestris*	133 ± 12.	44,764	**5**	**−13**	**−4**
B *Syringa vulgaris*	133 ± 11.1	66,529	**7**	**−12**	**−4**
B *Sambucus nigra*	157 ± 12.1	62,975	**1**	**−14**	**−9**
LC *A. hippocastanum*	277 ± 12.5	71,354	1	**−4**	−1
LC *B. pendula*	278 ± 14.0	60,626	**3**	0	2
LC *F. sylvatica*	282 ± 13.5	59,663	**4**	−1	**3**
LC *Q. robur*	287 ± 12.9	62,956	**6**	−1	**5**
VP *Q. robur*	161 ± 16.1	55,157	**3**	**9**	**11**
VP *F. sylvatica*	162 ± 15.8	54,674	**1**	**7**	**8**
VP *A. hippocastanum*	164 ± 16.5	67,612	**3**	**8**	**9**
VP *B. pendula*	166 ± 17.7	56,912	**4**	**11**	**11**

Avg ± σ: overall mean date of the phase in Julian day of year ± standard deviation
N total number of observations used for the analysis. *Total* total mean trend in the respective period rounded to days. *Bold numbers* the mean trend over all used NRs is significantly different from zero at the 5% level ($P < 0.05$)

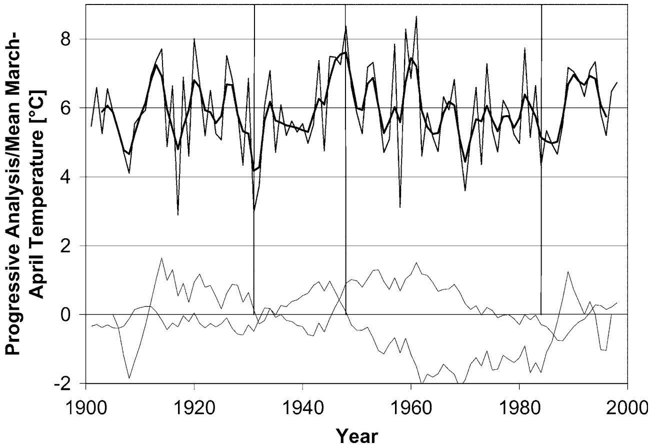

Fig. 4 *Upper line* mean March and April temperature averaged over the three selected NRs No. 3, 11 and 23. *Bold line* time series smoothed with a 5-year Gaussian filter. *Vertical lines* defined standard periods as extreme values closest to approximate potential trend turning points. *Lower two lines* progressive and retrograde series from the sequential Mann–Kendall test. The intersections of the progressive and retrograde series of the sequential Mann–Kendall test mark approximate trend turning points (Sneyers 1990)

There is a sharp increase in the magnitude of negative trends from the period before 1984 to the period after 1984 for the early spring phases (mean DOY of the phase <115). The trends for very early spring phases, B of *C. avellana* and *G. nivalis*, change substantially from about a week advancement between 1951 and 1984 to a month advancement in the last 15 years. The trends of BB of the early leafing tree species *B. pendula* and *A. hippocastanum* increase from a small, partly non-significant, advancement of BB before the mid-1980s to an advancement of 1.5 weeks in the last 15 years. Consequently, trends over the whole period from 1951 through 1999 are also negative and range from a 20 days advancement for *C. avellana* to 9 days for BB of *B. pendula* and *A. hippocastanum*. BB of *F. sylvatica* and *Q. robur* as well as the B and M phases of early summer switch from small but significant positive trends between 1951 and 1984 to significant negative trends of 9–14 days in the period 1984 through 1999. However, trends over the whole period remain negative because the negative trends of the last 15 years outbalance the positive trends before the mid-1980s. They vary between −2 and −9 days for spring and early summer phases.

The development of autumn phases reveals a less clear picture. Whereas, before the mid-1980s autumn phases are mostly significantly delayed, they advance after 1984 but less pronounced except for *A. hippocastanum* that shows a significant advancement. For this reason *A. hippocastanum* is the only species with a net advancement of LC between 1951 and 1999 whereas all other tree species experience a net delay.

In terms of length of VP of the four considered tree species, the behaviour of the spring phases dominates due to its larger magnitude. Thus, we can see a lengthening of the VP of about 10 days for the whole time span of 1951 to 1999.

Thus, on average, the trend patterns all over Germany mirror the general behaviour documented for the three NRs above. Trend patterns among the NRs are also consistent all over Germany. For all phases,

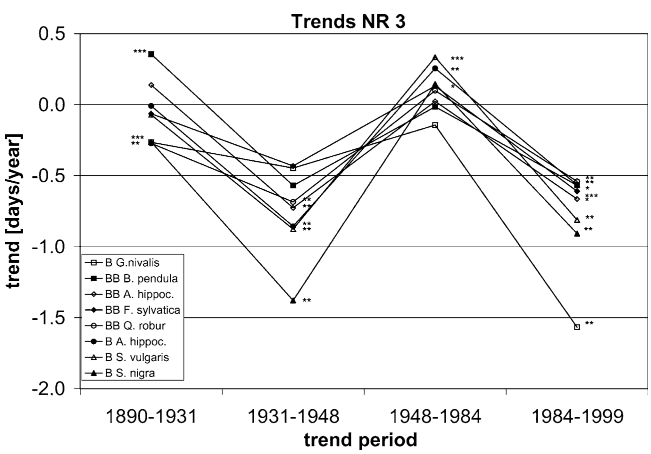

Fig. 5 Trends in NR No. 3 of spring and summer phases for the four periods detected by the sequential Mann–Kendall test. *B* Blossoming, *BB* bud burst. *Stars* indicate significance of trends: $^{*}P<0.1$; $^{**}P<0.05$; $^{***}P<0.01$

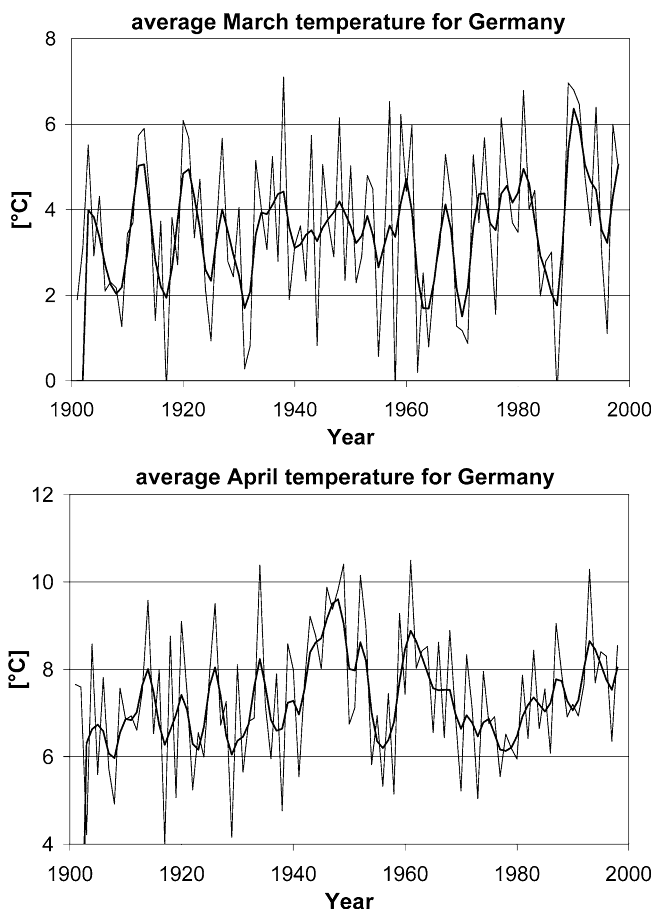

Fig. 6 Mean March and April temperatures Germany. *Bold curves* smoothed with a 5-year Gaussian filter

however, there exist a small number of exceptional NRs that do not fit into the general picture, especially before 1984 (results not shown). For the early spring phases B of *G. nivalis* and the late summer phase B of *S. vulgaris*, e.g., there are four out of 46 and one out of 52 NRs, respectively, that show trends of different sign than the average trend. For the more intermediate phases, there are more NRs that show trends opposing to the mean. A preliminary spatial analysis of the deviating NRs reveals no clear regional pattern of NRs that do not follow the mean trend.

Discussion

Centennial trends

When analysing phenological trends for the last five decades, we can generally confirm the findings of other authors (Sparks et al. 2000; Menzel et al. 2001; Scheifinger et al. 2002; Menzel 2003) indicating an advancement of spring phases. Extending the observational time frame, we obtain time series for eight spring and early summer phases, i.e. leaf BB and B, in three NRs in Germany, some of which extend up to 120 years from 1880 through 1999. Most time series show negative trends over the 120 years with an advancement of spring phases between 6 and 11 days. No firm conclusions could be drawn from long time series of autumn phases due to high variance in the data. Two options for improvement of the database need to be checked: (1) Can additional data be supplied for autumn phases in the early 20th century? (2) Information on the exact procedures of observation beyond the information provided with the databases should be searched and analysed for potential changes in the phase definitions.

Opposite trends among NRs for the spring phases indicated possible trend reversals in the course of the 20th century and the need to define standard periods in which phenological time series become better comparable among species and regions.

Varying trends in the 20th century

To derive a criterion for the definition of standard periods that is common for the observed species and consistent across Germany, we analyse trends in the temperatures most relevant for spring phases, i.e. mean March and April temperatures. The very early spring phases, like BB of *G. nivalis*, are not triggered by March and April temperatures. Nonetheless, they were useful in detecting varying trends even for those phases. Four periods of different general trend behaviour can be distinguished. The first period ranged from 1901 to 1931 with slightly decreasing temperatures, followed by a period of increasing temperatures until 1948. After that, temperatures decreased again until 1984, followed by a marked warming until 1999. Trends in phenological spring phases varied among the four periods: near constancy until 1931 is followed by an advancement until 1948, succeeded by a delay until 1984, that is again followed by a strong advancement until 1999. Thus, extending our view backwards from the usual start year 1951 to 1880 not only allowed for the definition of meaningful standard periods of sufficient length but also relativates the strong trends we observed in the last decades. This was obviously not an extraordinary event in the 20th century. Similar trends were observed between 1931 and 1948.

Menzel et al. (2001), also analysing data from the GWS, found both significant positive and negative trends when analysing 20 and 30 years time series within a time frame of 46 years (1951–1996). The analysis of combined time series within the two periods of contrasting trends (1951–1984 and 1984–1999) leads to a much more consistent picture of trends in phenological phases. We show that the trends in all NRs for BB and B of the analysed species are negative in the period 1984 through 1999. Other studies confirm that during the 1980s, there is a marked shift in trend behaviour of phenological phases. Crick and Sparks (1999) relate shifts in egg-laying trends of birds in the mid-1980s to changed temperature patterns and Scheifinger et al. (2002) recognized a discontinuity in plant phenological trends in the late 1980s where positive trends switch to negative trends.

We claim that the use of combined time series is the appropriate way to analyse trends in phenological data on large observational data sets. This approach removes several limitations implicated in the analysis of single station series. At first, a high number of single station series of equal observational time span and coverage cannot be retrieved from networks as the GWS-network. Therefore, the time span covered by the individual series varies relative to the other series. This leads to substantial changes in the predicted trends. Second, Menzel et al. (2001) also analysed mean phases for several subintervals. In their analyses mean BB of *F. sylvatica* and *Q. robur* did not change between the periods 1974–1996 and 1951–1973. This is probably the case because the period 1951–1973 sampled across a period with predominantly late bud break at the start through two decades where bud break tended to occur progressively earlier. Sampling over 1974–1996 will combine a period of downward trends with a period of upward trends.

Interestingly, the analysis of 20th-century phenology in Germany has led us to recognize trends in temperatures at sub-seasonal time scales that still have to be explained. Schönwiese and Rapp (1997) analysed trends of monthly temperatures for Europe. However, they considered the periods 1891–1990 and 1961–1990. Within these periods, both March as well as April temperatures exhibited no significant trends for Germany. The determination of potential trend turning points, however, and the subsequent definition of standard periods where phenology shows a qualitatively different behaviour reveals substantial differences in the development of March and April temperatures that are crucial for differential spring plant development. Thus, this study provides a good example of how analysing climate impacts can give hints on interesting developments of the climate system itself.

Differences between early and late spring phases

There are obviously marked differences in March and April temperatures in Germany over the last century. In March, temperatures increased on average as well as its standard deviation over the last 50 years, whereas April temperatures cooled between the end of the 1940s and the beginning of the 1980s, followed by a marked warming (Fig. 6). This structurally different behaviour is mimicked by the phenological phases that are dominated by these monthly temperatures (Fig. 5). Interestingly, April temperatures at the end of the 1940s were higher than in the 1990s. This corresponds well with the finding that B for *S. vulgaris* was earlier at the end of the 1940s than in the last 10 years (Schaber 2002). Similar to Menzel et al. (2001), we do not find obvious regional patterns of trends. However, this should be further analysed when more historical time series become available.

Change in the length of the VP

The changes in BB date for the four deciduous tree species, *F. sylvatica, B. pendula, A. hippocastanum*, and *Q. robur* in the period 1951–1999 are higher than the changes in LC dates. For all species, BB was significantly advanced by 5–9 days. LC of beech and oak was delayed by 3 and 5 days, respectively, while horse chestnut and birch showed no significant change. These results are in accordance to the findings of Menzel (2003). In consequence, this leads to a prolongation of the VP by 8–11 days over the five decades after 1951, corresponding to a 4.9 through 6.8% increase of average length of the VP. The rate of change in spring is higher leading to a higher gain of potentially absorbed radiation and increasing the whole season carbon dioxide potential assimilation.

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