

Annette Menzel

Trends in phenological phases in Europe between 1951 and 1996

Received: 21 October 1999 / Accepted: 2 March 2000

Abstract Increases in air temperature due to the anthropogenic greenhouse effect can be detected easily in the phenological data of Europe within the last four decades because spring phenological events are particularly sensitive to temperature. Our new analysis of observational data from the International Phenological Gardens in Europe for the 1959–1996 period revealed that spring events, such as leaf unfolding, have advanced on average by 6.3 days (-0.21 day/year), whereas autumn events, such as leaf colouring, have been delayed on average by 4.5 days ($+0.15$ day/year). Thus, the average annual growing season has lengthened on average by 10.8 days since the early 1960s. For autumn events, differences between mean trends of species could not be detected, but for spring events there were differences between species, with the higher trends for leaf unfolding and flowering of shrubs indicating that changes in events occurring in the early spring are more distinct. These observed trends in plant phenological events in the International Phenological Gardens and results of other phenological studies in Europe, summarised in this study, are consistent with AVHRR satellite measurements of the normalized difference vegetation index from 1981 to 1991 and with an analysis of long-term measurements of the annual cycle of CO_2 concentration in Hawaii and Alaska, also indicating a global lengthening of the growing season.

Key words Growing season · Phenology · Climate · Change · Time series · Europe · Germany

Introduction

Phenology, the traditional science of seasonal plant and animal activity (Lieth 1974), has experienced a renewal in the context of climate change, because it plays an important role in many biological processes such as seasonality of vegetation, risk of frost damage and the carbon balance of ecosystems, thus making the vegetation an important feedback factor in the climate system. Phenological phases of plants, such as leaf unfolding and leaf colouring of trees, as well as animal events, such as the arrival of migrant birds, are mainly driven by environmental factors. Among these factors influencing plant phenology are biological ones such as pests, diseases, competition, soil factors, genetics and age. But the most important factors are the weather conditions during the actual vegetation period, the past vegetation period and the dormancy period as well as the photoperiod (Schnelle 1955; Defila 1991). Thus, changes from year to year may be a sensitive and easily observable indicator of changes in the biosphere. It is well documented that spring events, such as leaf unfolding or needle flush, are particularly sensitive to temperature (Sarvas 1972, 1974; Lechowicz 1995). Therefore, analysing trends of spring phenological phases for the past few decades provides information about changes in the temperature during winter and spring with high spatial resolution.

Phenological monitoring has a long tradition in many European countries and therefore many long-term data sets exist. Several isolated local studies in Europe have already revealed shifts of different phenological phases caused by changes in climatic conditions in recent decades. The results of some of these studies using phenological data for global change monitoring are summarised in Table 1.

Phenological studies, for example, have revealed an earlier onset of spring events, such as plant flowering in Hungary or Estonia or the arrival of migrant birds in Estonia and in the United Kingdom. An extended growing season in Europe was recently described by Menzel and Fabian (1999). Their analysis of observational data from

Prepared in conjunction with a symposium “The phenological response to climate change” held during the XVI International Botanical Congress, St. Louis, Missouri, 4 August 1999

A. Menzel (✉)
Chair of Bioclimatology and Pollution Research,
Faculty of Forest Sciences, Technische Universität München,
Am Hochanger 13, D-85354 Freising, Germany
e-mail: menzel@met.forst.tu-muenchen.de
Tel.: +49-8161-714743, Fax: +49-8161-714753

Table 1 Changes in the phenological phases in Europe (review). (IPG International Phenological Gardens)

Parameter	Period	Linear trend	Reference
Spring data			
Plant Phenology			
Trees in Europe (IPG)	1959–1993	–0.20 day/year	Menzel and Fabian 1999
Trees in North and Central Europe (IPG)	1959–1993	–0.31 day/year	Menzel and Fabian 1999
Trees in Germany (IPG)	1959–1993	–0.31 day/year	Menzel and Fabian 1999
May shoot of Norway spruce in Germany	1951–1996	–0.10 day/year	Menzel 1998
Flowering of locust tree in Hungary	1851–1994	From –3 to –8 days (total)	Walkovszky 1998
Plant flowering in Estonia	1952–1996	From –0.14 to –0.29 day/year	Ahas 1999
Animal phenology			
Spawning of fish in Estonia, arrival of migrant birds	1952–1996	From –0.11 to –0.34 day/year	Ahas 1999
Arrival of migrant birds in the United Kingdom	1966–1996	Trend towards earliness	Sparks 1999
Egg-laying of birds in the United Kingdom	1971–1995	31% of species sign. earlier	Crick et al. 1997
	1939–1995	53% of the birds earlier through the 1980s and 1990s	Crick and Sparks 1999
Butterfly species/Europe	Past century	Poleward shift in geographical ranges	Parmesan et al. 1999
Others			
CO ₂ record (Mauna Loa)	1970–1994	–0.28 day/year	Keeling et al. 1996
CO ₂ record (Pt. Barrow)	1975–1994	–0.20 day/year	Keeling et al. 1996
AVHRR NDVI data 45°–70° latitude north	1982/3–1989/90	–8±3 days (total) –1.0 day/year	Myneni et al. 1997
Thermal seasons in Germany	1949–1985	up to –0.38 day/year (max)	Rapp and Schönwiese 1994
Autumn data			
Trees in Europe (IPG)	1959–1993	+0.16 day/year	Menzel and Fabian 1999
AVHRR NDVI data 45°–70° latitude north	1982/3–1989/90	+4±2 days (total) +0.5 day/year	Myneni et al. 1997
Thermal seasons in Germany	1949–1985	up to +0.32 day/year (max)	Rapp and Schönwiese 1994
Vegetation period			
Trees in Europe (IPG)	1959–1993	+0.36 day/year	Menzel and Fabian 1999
Birch in Germany	1951–1996	+0.17 day/year	Menzel 1998
European beech in Germany	1951–1996	+0.11 day/year	Menzel 1998

the International Phenological Gardens (IPG) for the 1959–1993 period revealed that spring events, such as leaf unfolding, have advanced by 6 days (–0.20 day/year), whereas autumn events, such as leaf colouring, have been delayed by 4.8 days (+0.16 day/year). Thus, the average annual growing season has lengthened by 10.8 days since the early 1960s. Furthermore, indirect approaches have indicated a lengthening of the growing season in Europe, such as the analysis of northern hemispheric CO₂ data (Keeling et al. 1996) and analysis of normalized difference vegetation index (NDVI) time series, calculated from NOAA/AVHRR data (Myneni et al. 1997).

The aim of this study is to reanalyse the observed lengthening of the growing season in Europe (Menzel and Fabian 1999) using an extended data set (1959–1996) from the IPG. At the same time, the results of this analysis of trends will be compared with data for different regions in Europe and for different species or groups of species. Information about the shifts in the phenological phases during the past four decades can be used for integrating phenological ground observations and satellite data and helps us to understand the impacts of phenological changes on ecology, agriculture, forestry and human health.

Materials and methods

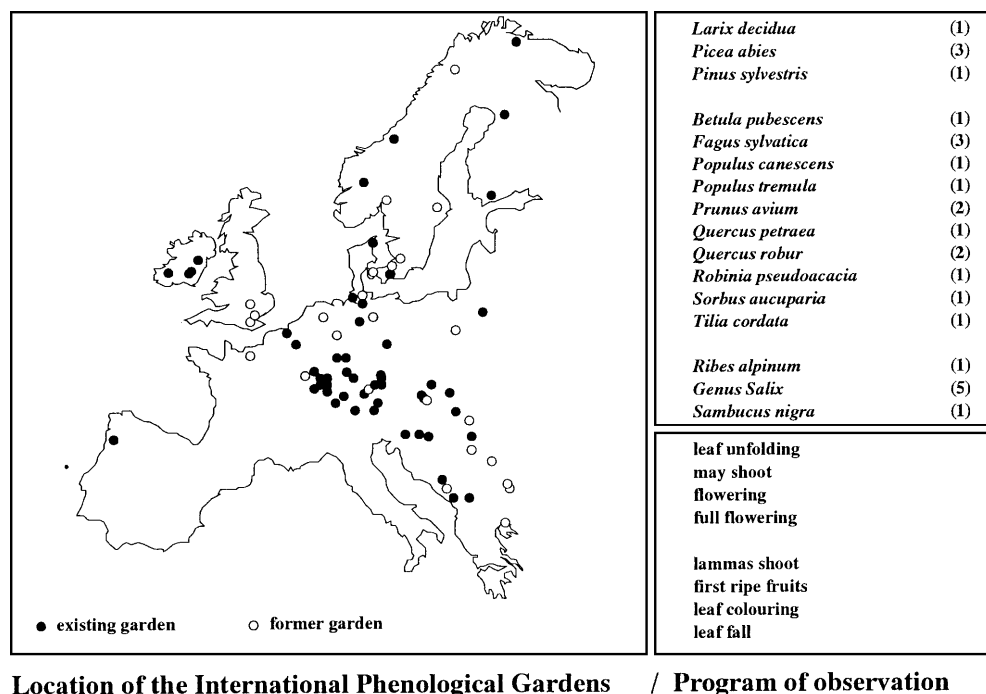
Phenological database: International Phenological Gardens

For the study of shifts in phenological phases in Europe we have analysed observational data for the 1959–1996 period from the IPG, a Europe-wide network covering a large latitudinal and longitudinal range that has genetically identical clones of trees and shrubs. Figure 1 shows the locations of the IPG in several European countries and lists the clones and phenophases observed. Only one garden started observations in 1959, many others were installed during the 1960s and the beginning of the 1970s. Moreover, there are sometimes gaps in the phenological records resulting from different kinds of damage to the plants, such as lack of competition, salt damage and wind, fungus and mouse attack, snow, frost, drought and storm (Menzel 1999).

Methods

For our study on phenological trends we examined springtime phases such as leaf unfolding, needle flush and flowering, and autumn phases such as leaf colouring and leaf fall of trees and shrubs. First, an intensive quality check of the data was made including plotting of all phenological records. All observations were examined intensively and probable errors were corrected, if possible, or those data were eliminated (fewer than 1%); (see Menzel 1997). No data were added because filling-in the gaps would multiply the trends of complete records. Secondly, in order to look for

Fig. 1 Network of the International Phenological Gardens (IPG). Sites of the different gardens, planted species and number of clones (in parentheses) in the standard programme as well as phenological phases observed



trends that might reflect global warming, we calculated linear trends for observational series of at least 20 years and determined their significance according to the *F*-test, the trend/noise ratio and the Mann-Kendall trend test. Significance levels of the *F*-test and the two other tests were similar, so only the *F*-test results are shown here.

Results

Trends in Europe (International Phenological Gardens)

The trends of all 751 springtime observation series longer than 20 years (leaf unfolding, May shoot, flowering, full flowering) are given in Fig. 2a, the trends of all 281 autumn series (leaf colouring and leaf fall) in Fig. 2b.

Only 27% of the trends of the spring records are significant (14% at the 0.01 level, 13% at the 0.05 level; 73% were not significant) owing to high interannual variability and the short length of the time series. Moreover, not all trends of the spring events are in the same direction. In total, 73% of them have a negative sign (22% significant, 51% not significant records) and only 27% have a positive sign (5% significant and 22% not significant records).

The regional pattern of the trends of the spring events can be derived from Fig. 2a. In north and central Europe, such as Scandinavia, Denmark, Ireland, Belgium, Germany, Switzerland and Austria (International Phenological Gardens 1–50), there are mostly negative trends, indicating an earlier onset of leaf unfolding, needle flush and flowering in these regions during the past three decades. Some of the Balkan stations, in contrast, show mostly positive trends, indicating a later onset of spring, but this is probably due to different regional patterns of

changes in mean winter temperature resulting in altered chilling conditions during dormancy.

For the autumn phases (leaf colouring and leaf fall) the results of the trend analysis, summarised in Fig. 2b, are not so homogeneous: 41% of the records have a positive (9% significant and 32% not significant) and 59% a negative sign (20% significant and 39% not significant), indicating that there are tendencies towards both an earlier and a later onset of autumn. Similar to the results of the spring events, only 29% of all records have significant trends (16% of the records are significant at the 0.01 level and 13% significant at the 0.05 level). In contrast to the spring events, no clear regional pattern of the autumn trends in Europe can be recognised in Fig. 2b.

The mean linear trend for the springtime phenophases is -0.21 day/year (751 time series), indicating an advance of springtime in the last three decades, and $+0.15$ day/year for the autumn phases (281 time series), which means a later onset of autumn. Thus, the trend for the length of the growing season is $+0.36$ day/year, indicating a lengthening of the growing season in the past decades. These figures are nearly equivalent to the figures for the 1959–1993 period (Menzel and Fabian 1999). For this latter period the mean advance for spring events was -0.20 day/year (616 time series), a mean delay of $+0.16$ day/year (178 time series) for autumn events, resulting in a lengthening of the growing season by $+0.36$ day/year.

Figure 2a shows that there are only small differences between the observed trends for springtime phases of different species or groups of species (ignoring clones). The mean (day/year) linear trends range from -0.02 for *Pinus sylvestris*, -0.13 for *Betula pubescens*, -0.13 for *Picea abies*, -0.16 for *Fagus sylvatica*, -0.22 for other

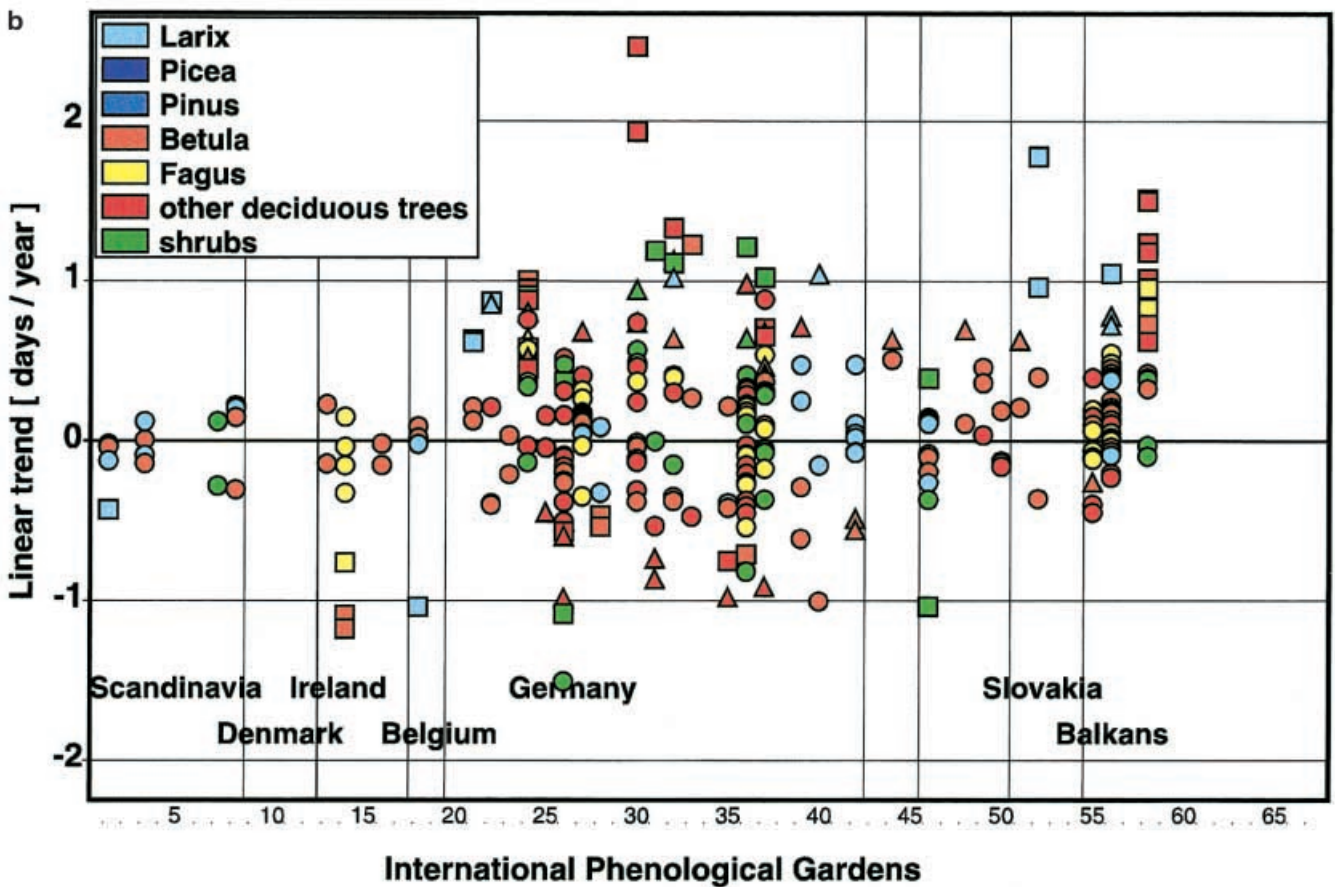
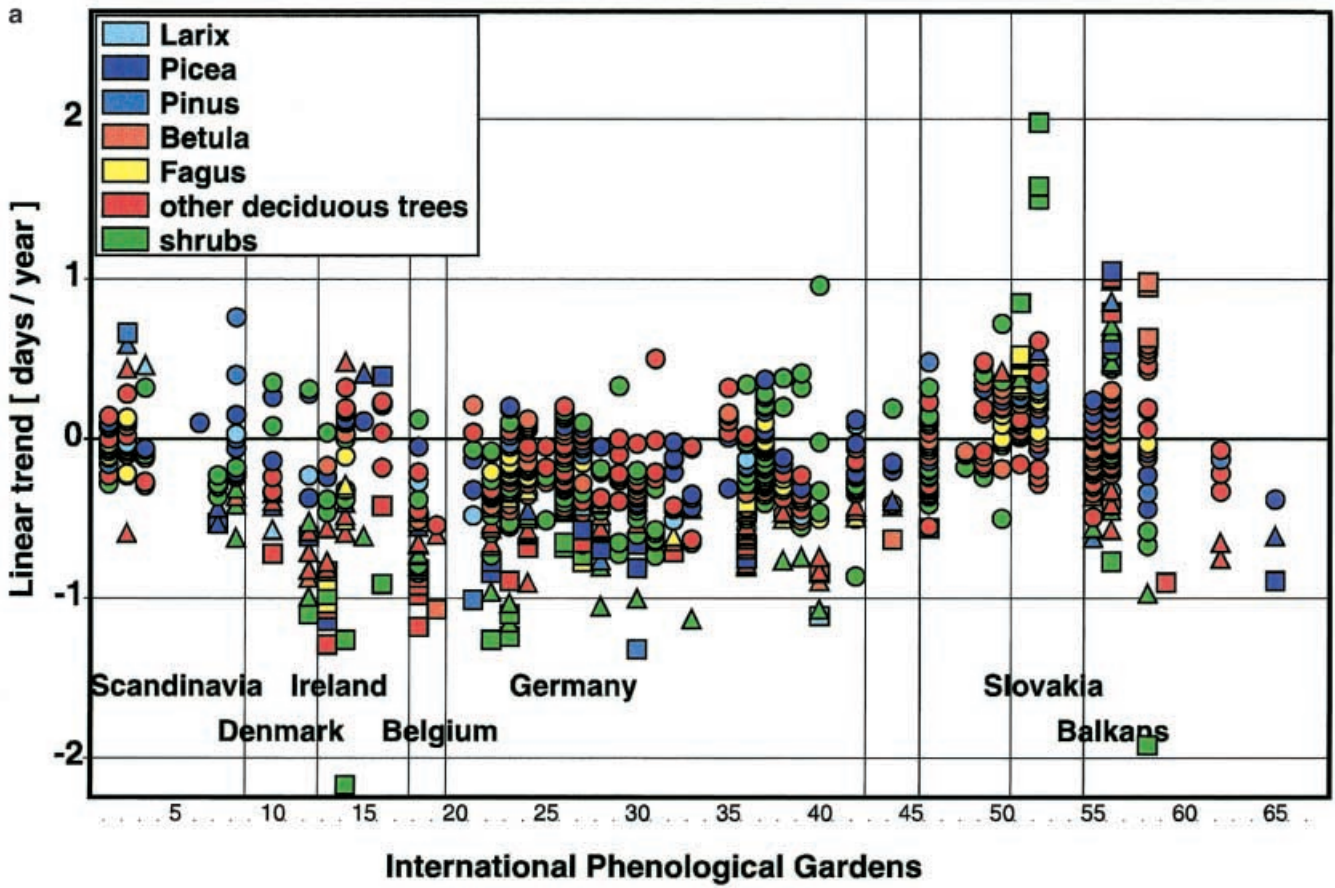
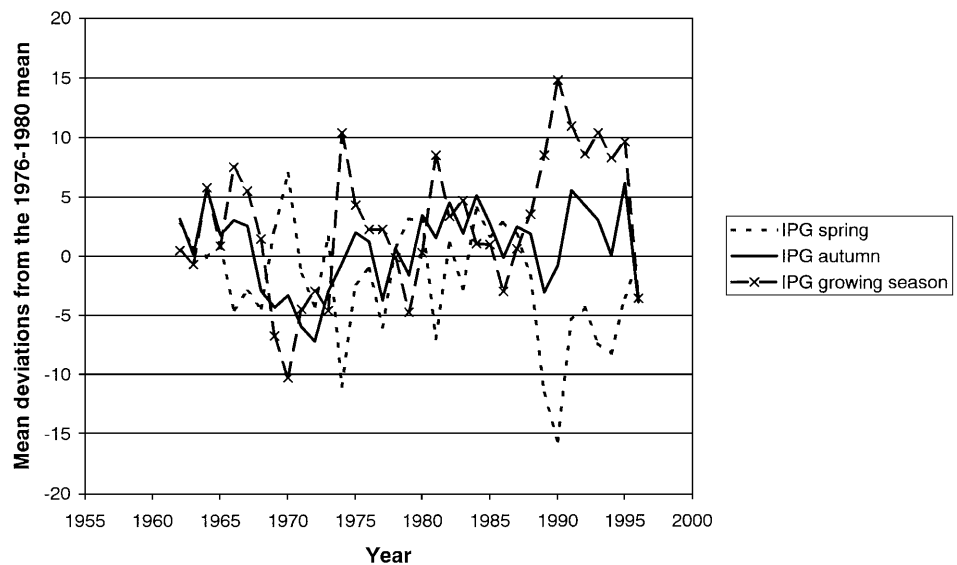


Fig. 3 Annual departures from the 1976–1980 mean of spring phases and autumn phases, and the resulting annual departure from the mean of the length of the growing season in the IPG of Europe (1962–1996)



deciduous trees (average for *Populus canescens*, *Populus tremula*, *Prunus avium*, *Quercus petraea*, *Quercus robur*, *Robinia pseudoacacia*, *Sorbus aucuparia*, *Tilia cordata*), -0.27 for *Larix decidua* and -0.28 for shrubs (*Ribes alpinum*, diff. *Salix* species and *Sambucus nigra*). However, a multiple comparison of mean values (procedure GLM (General Linear Model) of SAS (Statistical Analysis System) including the Sidak and Scheffe test) revealed that there are significant differences between the mean trends of the groups of species mentioned above. There are also significant differences between the mean trends of all species (clones) in the phenological network, but only the spring trends of *R. alpinum* differ significantly from those of other species at the 0.05 level.

The same effect can be observed for the autumn phases (Fig. 2b) in the IPG. There are small differences for the observed mean linear trends of the different clones ($+0.00$ day/year for *B. pubescens*, $+0.15$ for shrubs, $+0.18$ for *F. sylvatica* and for other deciduous trees and $+0.26$ for *L. decidua*). When a multiple comparison is calculated between all clones, the differences are significant; between the groups of species (*B. pubescens*, *F. sylvatica*, other deciduous trees, shrubs) the differences in mean trends are not significant and the Sidak and Scheffe tests did not reveal any comparisons significant at the 0.05 level between mean linear trends for these groups or single clones.

Thus, in springtime, or during the first half of the year, the mean trends of different phenological events, occurring from the end of winter to early summer, differ significantly and suggest that changes of events occurring in the early spring, such as flowering of *R. alpinum*,

are more distinct, whereas in autumn no differences between species can be detected.

Taking longer time series, for example only those spanning at least 27 years, the mean linear trends of these series become smaller than those for the shorter series: -0.11 day/year for the onset of spring and $+0.10$ day/year for the onset of autumn, yielding a trend for the length of the growing season of $+0.21$ day/year. This result reflects the mean temperature conditions in the past three decades, with most of the temperature increase occurring in the late 1980s and 1990s. Thus, trend analysis for shorter periods of time, mostly ending in 1996, strengthen the apparent phenological trend.

To summarise these results and to give an overview of the phenological observations of the last four decades, we calculated yearly anomalies for a composite spring and autumn time series as well as for the length of the growing season (Fig. 3). First, for each time series we calculated the yearly departures (anomalies) from its 1976–1980 average. Then we constructed average values for each year for spring and autumn and finally calculated the anomalies for the length of the growing season as the difference between spring and autumn anomalies. For the period 1959–1961 only a few observations were recorded in Europe, so the results are not reliable. In the years 1974, 1981, 1989, 1990, 1993 and 1994 the mean onset of spring in Europe was more than 1 week earlier than in the 1976–1980 period. In contrast, spring 1970 was relatively late. The anomalies of the onset of autumn are smaller than those of spring. The resulting growing season was very long in the years 1974, 1981 and 1989–1995.

Calculating the linear regressions of these curves (1962–1996) we obtain trends of -0.16 day/year for the spring events, $+0.07$ day/year for the autumn events and $+0.23$ day/year for the length of the growing season. These figures are more conservative than the average trends of all time series of 20 years or more, presented in Fig. 2, but they also confirm that there is a lengthening

◀ **Fig. 2** Linear trends of phenological phases. Data are for long observational series (20 years or more) during the 1959–1996 period. Species or species groups are represented by different colours. The symbol denotes the significance of the trend: $\square$ $P < 0.01$, $\triangle$ $P < 0.05$ and $\circ$ $P > 0.05$. **a** Spring phases (leaf unfolding, May shoot, flowering); **b** autumn phases (leaf colouring, leaf fall)

of the growing season, showing that most of the effect occurred in the late 1980s and early 1990s.

Discussion

Our analysis of the data on times of leafing, flowering, leaf colouring and leaf fall for the 1959–1996 period, observed in the IPG, mostly revealed trends to earlier springtime phenological events, although countries differ in the proportion of species and events showing trends. However, three quarters of the records show clear tendencies to an earlier onset of spring events, almost one-third of these records being significant. Autumn has tended to be delayed in the past three decades, but this effect is not as clear as changes in the spring events. Considering a period of 30 years, we found that spring events have advanced on average by 6.3 days whereas autumn events have been delayed by 4.5 days. This means that the mean annual growing season has lengthened by +0.36 day/year or by 10.8 days since the early 1960s. Our Europe-wide results are clearly supported by other studies of plants and animals in Hungary, the United Kingdom, Estonia and Germany (Estrella 1999). Moreover, the observed trends in plant phenological events are consistent with AVHRR satellite measurements of the NDVI from 1981 to 1991, which show that the beginning of the growing season has advanced by 8 days and it ends 4 days later (Myneni et al. 1997). Analysis of long-term measurements of the annual cycle of CO₂ concentration in Hawaii and Alaska also indicates a global lengthening of the growing season (Keeling et al. 1996).

Our analysis of the data of the IPG shows that most of the effect of a lengthening of the growing season is due to an earlier start, the effect of a later end of the growing season being rather less, and that this spring advance is more pronounced in north and central Europe than in the south-eastern part of Europe. There are differences among the spring trends of different species observed, the higher trends being found for leaf unfolding of *Larix* and especially for the flowering of shrubs, indicating that changes of events occurring in the early spring are more distinct.

Acknowledgements Phenological data sets of the network of the IPG were kindly offered by the German Weather Service and the Humboldt University Berlin. This work was supported by the Bavarian State Ministry of Agriculture and Forestry.

References

- Ahas R (1999) Long-term phyto-, ornitho- and ichthyophenological time-series analyses in Estonia. *Int J Biometeorol* 42: 119–123
- Crick HQP, Sparks TH (1999) Climate change related to egg-laying trends. *Nature* 399:423–424
- Crick HQP, Dudley C, Glue DE, Thomson DL (1997) UK birds are laying eggs earlier. *Nature* 388:526
- Defila C (1991) Pflanzenphänologie der Schweiz. Inaugural-Dissertation an der Universität Zürich
- Estrella N (1999) Trends der forstlichen Vegetationsperiode von 1951–1996 in Deutschland. Diploma thesis at the Chair of Bioclimatology and Pollution Research, Technical University Munich
- Keeling CD, Chin FJS, Whorf TP (1996) Increased activity of northern vegetation inferred from atmospheric CO₂ measurements. *Nature* 382:146–149
- Lechowicz MJ (1995) Seasonality of flowering and fruiting in temperate forest trees. *Can J Bot* 73:175–182
- Lieth H (1974) Phenology and seasonality modeling. Springer, Berlin Heidelberg New York
- Menzel A (1997) Phänologie von Waldbäumen unter sich ändernden Klimabedingungen – Auswertung der Beobachtungen in den Internationalen Phänologischen Gärten und Möglichkeiten der Modellierung von Phänodaten. *Forstliche Forschungsberichte* 164, München
- Menzel A (1998) Zeitliche Trends ausgesuchter phänologischer Phasen in Deutschland aus dem Zeitraum 1951–1996. Unveröff. Bericht an den Deutschen Wetterdienst
- Menzel A (1999) How are the observations made in the IPGs? Results of the '94 Questionnaire to the IPGs. *Arbor Phaeol* 42:43–44
- Menzel A, Fabian P (1999) Growing season extended in Europe. *Nature* 397:659
- Myneni RB, Keeling CD, Tucker CJ, Asrar G, Nemani RR (1997) Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* 386:698–702
- Parmesan C, Ryrholm N, Stefanescu C, Hill JK, Thomas CD, Descimon H, Huntley B, Kaila L, Kullberg J, Tammaru T, Tennent WJ, Thomas JA, Warren M (1999) Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature* 399:579–583
- Rapp J, Schönwiese C-D (1994) "Thermische Jahreszeiten" als anschauliche Charakteristik klimatischer Trends. *Meteorol Z* 3:91–94
- Sarvas R (1972) Investigations on the annual cycle of development of forest trees. I. Active period. *Commun Inst For Fenn* 76. 3:1–110
- Sarvas R (1974) Investigations on the annual cycle of development of forest trees. II. Autumn dormancy and winter dormancy. *Commun Inst For Fenn* 84. 1:1–101
- Schnelle F (1955) Pflanzen-Phänologie. Geest & Portig, Leipzig
- Sparks TH (1999) Phenology and the changing pattern of bird migration in Britain. *Int J Biometeorol* 42:134–138
- Walkovszky A (1998) Changes in phenology of the locust tree (*Robinia pseudoacacia* L.) in Hungary. *Int J Biometeorol* 41:155–160