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Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961-2000

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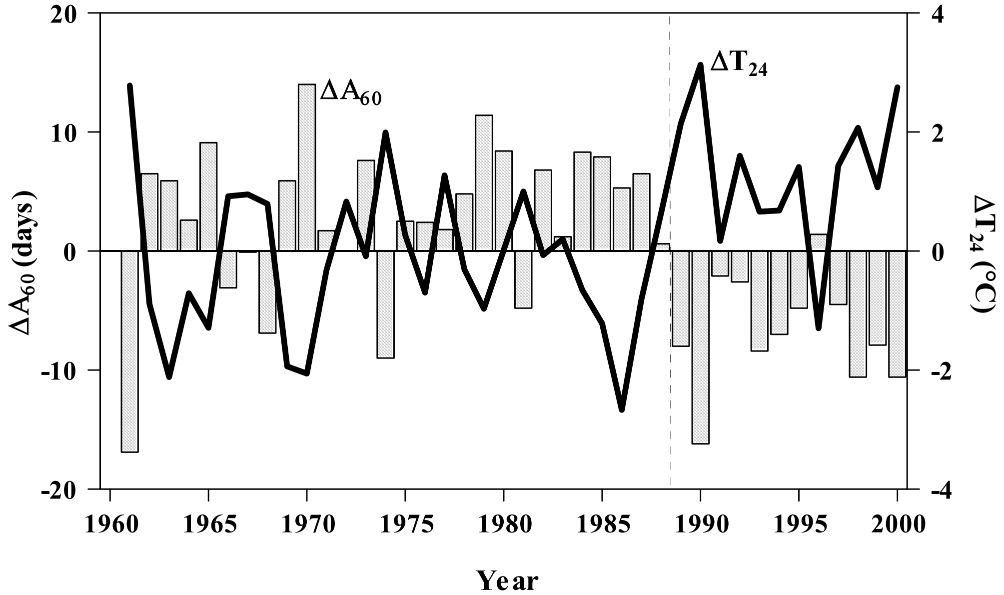

Fig.: Anomalies in the beginning of apple tree blossom (A_{60}) and in the average air temperature from February to April (ΔT_{24}) in Germany, 1961-2000.

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Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961-2000

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Abstract

In mid- and high latitudes the plant development is mainly driven by air temperature. The higher the temperature after the release of dormancy the earlier the pheno-phases, usually appear in spring. Distinct changes in air temperature since the end of the 1980s led to clear responses in plant phenology in many parts of the world.
In Germany phenological phases of the natural vegetation as well as of fruit trees and field crops have advanced clearly in the last decade of the 20th century. The strongest shift in plant development occurred in the very early spring phases. The late spring phases and summer phases reacted also to the increased temperatures, but they usually show lower trends.
While an extended growing season could have some positive effects for agriculture and horticulture, the shift of individual phenophases of crops and fruit trees is to be evaluated differently. For example, the advanced blossom of fruit trees can increase the risk of late-frost damages. For field crops a shortening of developmental periods can also affect yield forming processes.
Until now the changes in plant development are still moderate, so that no strong impacts on crop yields were observed. But further climate changes will probably increase the effect on plants, so that in the future stronger impacts on crop yields are likely.

Keywords: *Phenology · Germany· Fruit trees · Field crops· Climate changes*

1. Introduction

The distinct increase in air temperature in many parts of the northern hemisphere since the end of the 1980s and the demand for indicators of climate change impacts caused a growing interest in phenological data. From this time onwards, phenological data were more and more accepted by climate researchers.
Since then many papers report on trends in the timing of spring events in mid- and high latitudes (Braslavska and Kamensky 1999, Schwarz and Reiter 2000, Defila and Clot 2001, Müller 2002) and on relationships between air temperature changes and variations in the timing of phenological stages (Bradley et al. 1999, Beaubien and Freeland 2000, Sparks 2000, Schmerbach 2000, Chmielewski and Rötzer 2002). The most papers focus on changes in the natural vegetation, but only a few studies deal with trends of agricultural and horticultural varieties (Schelling 2000). However, changes in the timing of phenophases of fruit trees or field crops could be of great economical importance, because they could have direct impacts on yield formation processes and so on the final crop yield.

In mid- and high latitudes, with a vegetation-rest in winter (dormancy) and an active growing period in summer, plant phenology is mainly driven by temperature. After the release of dormancy the development of plants strongly depends on air temperature. With increasing temperature the biochemical reactions are accelerated up to a threshold where enzyme systems are destroyed and cells die.
An indirect effect of increasing air temperatures is thus the prolongation of the growing season (Menzel and Fabian 1999, Chmielewski and Rötzer 2001, Schaber 2002) and the modification of the phenological phases of individual plants, i.e. the sequence of the development stages. The extension of the growing season will have mostly positive effects on crop farming in the mid- and high-latitudes, since a longer growing season will improve the scope for cultivars selection, catch cropping and crop rotation. Shorter developmental periods for field crops could have rather negative effects on the formation of the individual yield components, as for cereals: the crop density, the kernel number per ear, and the kernel weight.

2. Data

2.1 Phenological data

For this study, mainly the phenological observations of fruit trees (apple, sweet cherry) and field crops (winter rye) from the German Weather Service (DWD) between 1961 and 2000 were used. The phenological network of the DWD consists of about 1,500 observers, who do the observations on a voluntary basis (Bruns 2001).
For apple and sweet cherry, flowering dates of early maturing varieties were selected. The beginning of flowering was defined when in at some places of the plant the first flowers have opened completely (BAPH, 1991). Winter rye is one of crops for which phenological observations in Germany has been done in detail.
To define the average beginning of growing season in Germany, data from the International Phenological Gardens (IPG) in Europe were used. In this study the beginning of growing season (B_G) was defined in the same way as it was done before for Europe (Rötzer and Chmielewski 2001). For that study the onset of spring was represented as the average date of leaf unfolding of white birch, wild cherry, mountain ash, and alpine current. The selection of plants will not affect the results which were achieved, because the investigations will show that all phenological phases in spring are well correlated to each other. This time only phenological data from the 22 German IPG-stations in the period 1961-2000 were considered to calculate this average leaf unfolding index.

2.2 Climatic data

In order to describe the relationships between temperature and plant development, station data of air temperature from the *World Weather Records* (WWR) were used to calculate the average air temperature for Germany. Altogether 16 stations were considered which rages in elevations between 4 m (Rostock, NE-Germany) and 462 m (Munich) and which are well distributed across Germany. Since air temperature is constant for relatively large areas, 16 stations should be sufficient to calculate an average monthly temperatures for Germany. For example the seasonal air temperature at Frankfurt a.M. is a representative of up to a radius of 500 km around this station (Schönwiese et al. 1998).

3. Results
3.1 Air temperature changes in Germany

For the standard period 1961 - 1990, the average annual air temperature in Germany is 8.6 °C. In the period 1961 - 2000 the temperature increased continuously (Fig. 1). The linear trend in the data is + 0.36 °C / decade ($p<0.01$). This means, for the whole period (40 years) the observed warming is 1.4 °C. The most interesting feature in this time series is the relatively strong change in air temperature since the end of the 1980s, which corresponds well to similar trends in many parts of the world (Houghton et al., 2001). Since then nearly all years were to warm. The only exception in Germany was in 1996, because of a relatively strong winter in 1995/96.

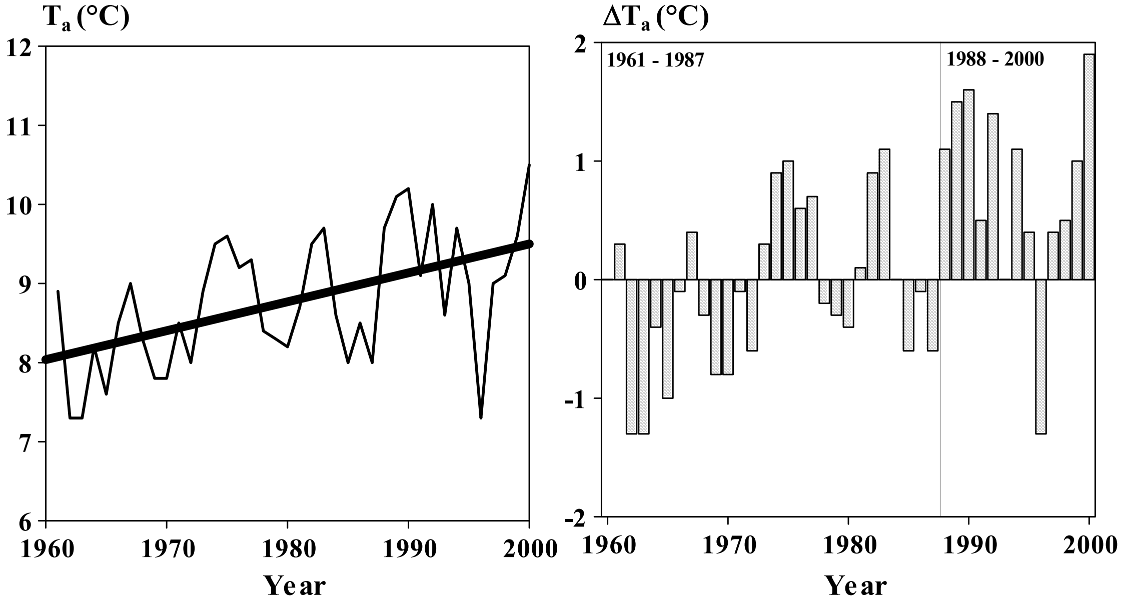

Fig. 1: Av. annual air temperature (T_a) for Germany, 1961-2000, left: annual mean, right: anomalies to the 1961-1990 standard period.

Many phenological phases as the leafing of trees and the flowering of fruit trees are observed in Germany in April and May. April is the time of the year when the onset of spring usually starts. The variability of weather from year to year leads to certain fluctuations in the annual timing of phenophases. Previous investigations showed that for the timing of spring phases the average air temperature from February to April (T_{24}) is a good climatic indicator (Chmielewski and Rötzer 2001).

Table 1: Statistical parameters (x: mean, s: standard deviation) and trends (°C/decade) of av. monthly and annual air temperature in Germany, 1961-2000 (Average of 16 stations from the WWR), p: error probability

Month	01	02	03	04	05	06	07	08	09	10	11	12
x	0.4	1.2	4.3	8.0	12.6	15.6	17.4	17.0	13.6	9.2	4.4	1.5
s	2.7	2.6	2.0	1.2	1.4	1.1	1.7	1.4	1.4	1.3	1.5	2.1
Trend	+0.59	+0.37	+0.58	+0.28	+0.53	+0.09	+0.48	+0.64	+0.13	+0.10	-0.01	+0.60
p	-	-	0.05	0.10	0.01	-	0.05	0.01	-	-	-	0.05
Year	x =8.8 °C, s=0.8 °C, Trend = +0.36 °C/decade (p<0.01)											

The average increase of air temperature in these months (+0.41 K/decade, $p<0.05$) is slightly stronger than that, calculated for the annual average (Tab. 1). The strongest trend was found for March (+0.58 °C/decade).
The anomalies of T_{24} from the standard period 1961-1990 show the same abrupt change since 1988 as shown before for the annual average. Again, nearly all years since 1988 were to warm in this period (Fig. 2).

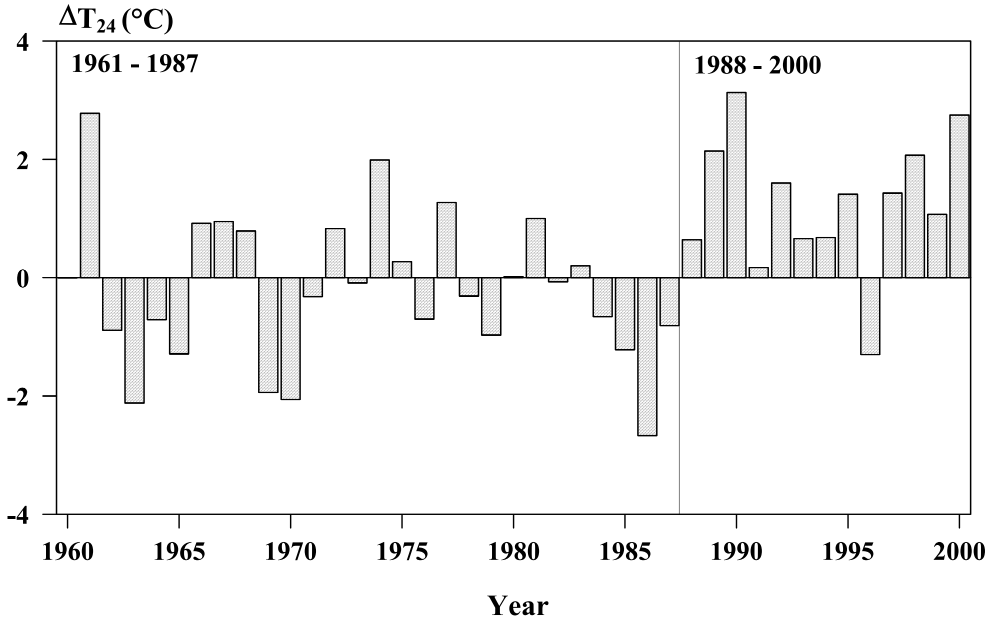

Fig. 2: Av. air temperature from February to April for Germany, 1961-2000, anomalies (ΔT_{24}) to the 1961-1990 standard period.

3.2 Changes in the timing of phenological events

In this section trends in the beginning of growing season (B_G), in the beginning of blossoming (stage BBCH 60) of apple (A_{60}) and cherry (C_{60}) trees as well as in the beginning of stem elongation (BBCH 31) for winter rye (R_{31}) were investigated. All these phenophases are observed between the end of April and the beginning of May (Tab. 2). The standard deviation of these phases is about of the same order and the trends for all phases are significant, ranging between 2 and 3 days per decade. This means that the plants react very similar to the environmental conditions in the early spring.

Table 2: Statistical parameters for the timing of different phenophases in Germany, 1961-2000. P: phenophase (B_G: beginning of growing season, R_{31}: beginning of stem elongation for winter rye, C_{60}: beginning of cherry tree blossom, A_{60}: beginning of apple tree blossom), n: number of stations are used, x: average date, s: standard deviation. Trends are significant with $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.10$

P	**n**	**x**	**s**	**Trend in P** (days/decade)
B_G	22	20.04.	7.3	-2.3^{**}
R_{31}	637	26.04.	6.0	-2.9^{***}
C_{60}	1068	27.04.	7.6	-2.0^{**}
A_{60}	908	05.05.	7.5	-2.2^{**}

The correlation coefficients (r) between the individual phases are all significant (p<0.01) and ranges between 0.88 ($r(B_G,R_{31})$) and 0.96 ($r(A_{60},C_{60})$). A good correlation also exists between the beginning of growing season and the tree blossom of apple (r=0.92) and sweet cherry (r=0.95) in Germany.
Toward the end of the investigated period clear changes in the timing of all phenological events are discernible which explains the negative trends in Table 2 (Fig. 3). These changes seem to correspond to the observed changes in air temperature since the end of the 1980s.

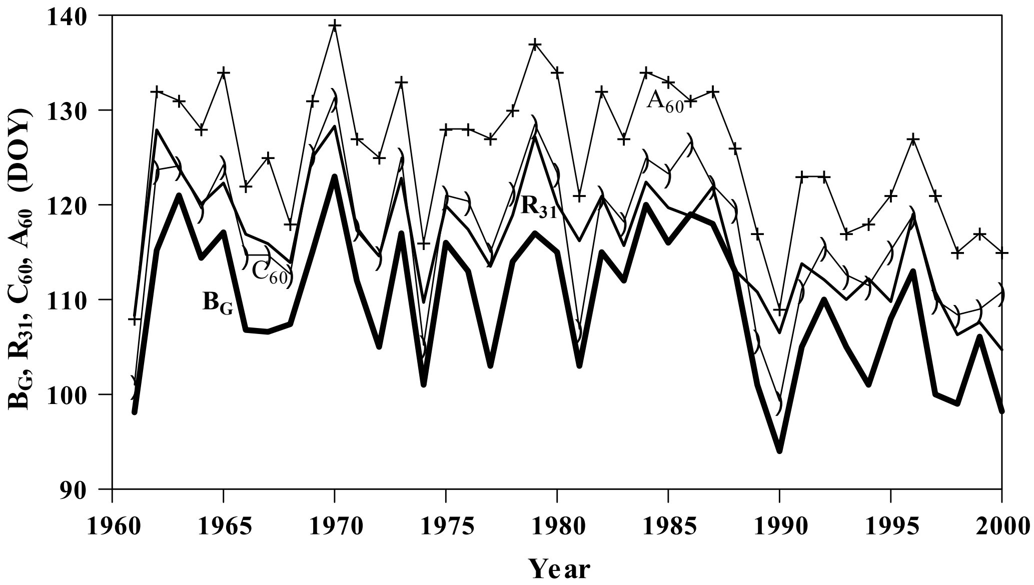

Fig. 3: Av. dates of the beginning of growing season (B_G), beginning of stem elongation for winter rye (R_{31}), beginning of cherry tree blossom (C_{60}), and beginning of apple tree blossom (A_{60}) in Germany, 1961-2000. DOY: Day of the year

3.3 Relationships between trends in air temperature and phenophases

As expected, all phenophases are well correlated to the average air temperature from February to April (Tab. 3). The significant correlation coefficients range between -0.85 and -0.89, indicating that higher temperatures after the winter rest of plants accelerate the developmental processes and finally lead to an advanced timing of spring events. The regression coefficients show that an increase in average air temperature between February and April of 1 °C lead to an advanced beginning of growing season and blossoming of fruit trees by about 5 days. Only the beginning of shooting of winter rye shows a smaller temperature response of only – 3.8 days per 1°C.

Table 3: Correlation coefficients (r) between the av. air temperature from February to April (T_{24}) and the timing of phenophases (P) in Germany, 1961-2000. Sensitivity of phenophases to the air temperature changes (ΔT_{24}), significance level: $^{***}p<0.01$

P	$r(P,T_{24})$	Temperature response ($\Delta P/\Delta T_{24}$)
B_G	-0.89^{***}	-4.7 days/°C***
R_{31}	-0.86^{***}	-3.8 days/°C***
C_{60}	-0.88^{***}	-4.7 days/°C***
A_{60}	-0.85^{***}	-4.6 days/°C***

Another interesting feature in the advanced timing of spring events is shown in Figure 4. The changes in plant phenology occurred abruptly since the end of the 1980s, right in the time when the temperatures increased in a similar way (see Fig. 2). The abrupt changes in the timing of phenophases were observed for all species in Table 3. Just as the natural vegetation, fruit trees and field crops show the same behaviour that is shown in Figure 4.

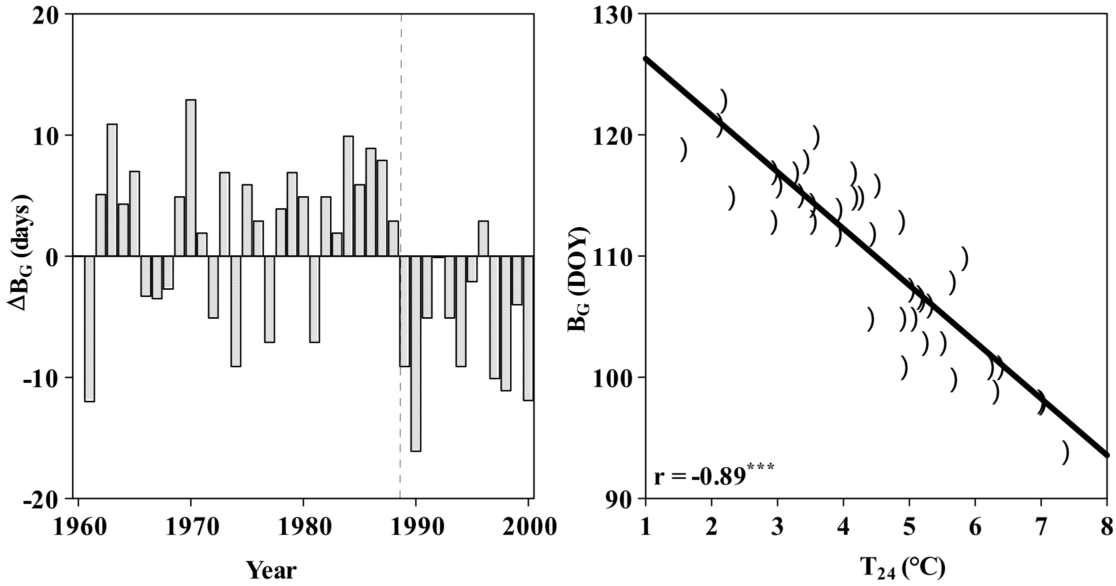

Fig. 4: Left: anomalies in the beginning of growing season (B_G) for Germany (data from the German IPG stations) and right: correlation between B_G and the av. air temperature from February to April (T_{24}), 1961-2000. The correlation coefficient of r=-0.89 is significant with p<0.01.

As an impressive example the response of the beginning of apple tree blossom to the annual deviations in air temperature is presented in Fig. 5.

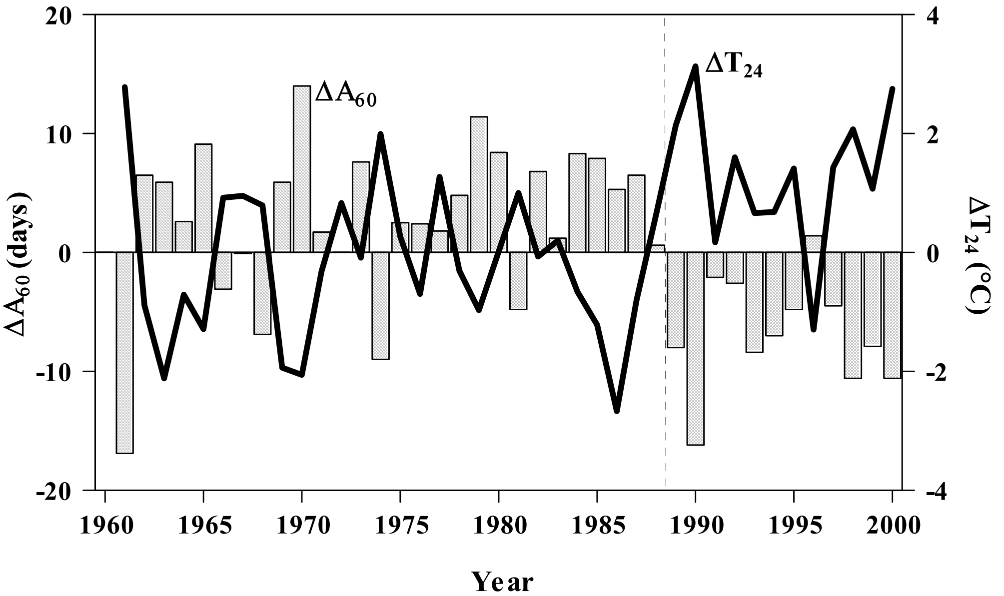

Fig. 5: Anomalies in the beginning of apple tree blossom (A_{60}) and in the average air temperature from February to April (ΔT_{24}) in Germany, 1961-2000. The regression equation between the time series is $A_{60} = 145.9 - 4.56\ T_{24}$

Years with temperatures above normal in late winter and early spring are clearly related to negative anomalies in the date of blossom. Interesting are the years 1961 and 1990 which are characterised by very early dates in the beginning of apple tree blossom. Both years show comparable deviations in air temperature of about +3 °C.

In order to investigate, whether the changes in apple tree phenology in the 1990s were observed in any time before since reliable records of air temperature are available, we used the regression equation between air temperature (T_{24}) and the blossoming date (A_{60}) to estimate the beginning of apple tree blossom for Germany since 1761 (Fig. 6). Long-term observations of this event are unfortunately not available for Germany. The result shows that the recent changes in the timing of cherry tree blossom seem to be the strongest in the last 240 years. In no decade before as in the 1990s such early dates were observed (av. blossom of apple trees in the 1990s: day 121, s=5.4; 1761-1989: day 129, s=6.5). Thus, the timing of this event has advanced more than one week.

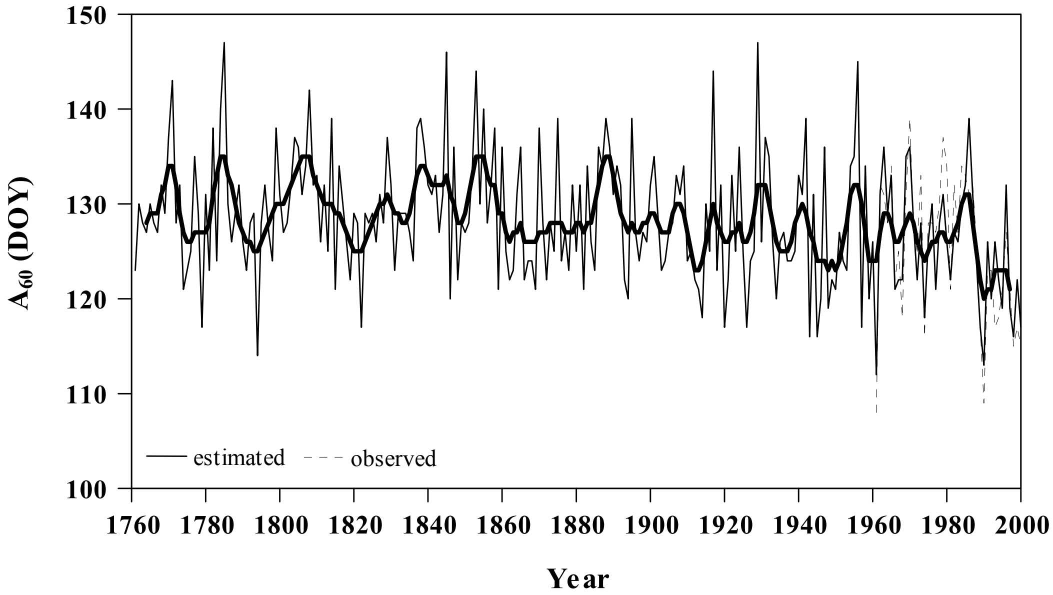

Fig. 6: Estimated (solid line, 1761-2000) and observed (dashed line, 1961-2000) dates of the beginning of apple tree blossom in Germany. The bold line represents an 11year running mean (Gausian filter), which shows the long-term variations in this time series. The time series of air temperature was taken from Rapp (2000).

At the end of this section once again we will focus on the phenology of winter rye. For this crop very detailed phenological observations during the growing time are available. All phenophases from seeding to harvest show negative trends (Tab. 4). The strongest trend occurs for the beginning of stem elongation after the tillering period in the end of April. Until full flowering the negative linear trends decrease slightly and also the significance level reduces. This indicates that mainly the early phases highly depend on the course of air temperature. With increasing temperatures in May and June the mean temperatures are closer to the optimum for the plant development, so that the plants do not react so sensitive to the variability of air temperature in this time of the year as in the early spring.

Table 4: Statistical parameters of winter rye phenology in Germany, 1961-2000 (x: mean, s: standard deviation, min, max: extremes) and trends (trends are significant with ***p<0.01, **p<0.05, *p<0.10). BBCH-Code: R_{00}: seeding, R_{09}: emergence, R_{31}: beginning of stem elongation, R_{51}: beginning of heading, R_{65}: full flowering, R_{89}: beginning of harvest (fully ripe)

Phase (BBCH-code)	x (DOY)	Date	s (days)	Min (DOY)	Max (DOY)	Trend (days/10a)
R_{00}	275.1	02.10.	2.72	269	282	-1.4***
R_{09}	288.2	15.10.	3.29	281	298	-1.6***
R_{31}	116.4	26.04.	6.20	105	128	-2.9***
R_{51}	140.9	21.05.	5.00	129	151	-2.0***
R_{65}	157.7	07.06.	4.77	146	167	-1.4**
R_{89}	219.1	07.08.	6.67	209	232	-1.5*
Duration of Phases						
R_{00} – R_{09}	13.1		0.88	12	16	-0.3**
R_{31} – R_{51}	24.5		2.44	21	31	+1.0***
R_{51} – R_{65}	16.8		2.69	11	24	+0.6
R_{65} – R_{89}	61.4		5.03	52	78	-0.1

Because of shifts of individual phenological phases, the developmental periods of winter rye are slightly shortened, as the period from seeding to emergency (BBCH 00-09), or extended as the shooting period (BBCH 31-51). Such changes in the duration of phenological periods directly influence the yield formation of winter rye (Römer 1988, Petr 1991, Chmielewski and Köhn 2000). In spring an early beginning of shooting (BBCH 31) ends the tillering period earlier. A high number of tillers before shooting is always a good prerequisite for a sufficient crop density at harvest. But until now the relatively moderate changes in phenology did not have any negative effects on the final crop density, because during the mild winters in the last decade, tillering was continued also in winter, so that the number of tillers was not limited. A longer period from shooting to heading is also advantages for the very complex yield forming processes in this phase.

4. Conclusions

The investigations showed that not only the natural vegetation responds to the distinct climate changes in the 1990s, but also fruit trees and even annual crops like winter rye. For other field crops like sugar beet and maize very similar phenological trends were found (Müller 2002). All plants showed an advanced timing of phenophases, mainly in spring. The mean air temperature from February to April is a good index which explains the annual variability of phenological phases in this time of the year.

An earlier blossom of fruit trees holds the danger of damages by late frosts. Frosts before the beginning of blossom may cause masked injuries in flower buds, but the damages are not so strong as they would be in the period of blossom. Frost during the flowering period can harm the blossoms, so that total crop failures can occur. The year 1981 is a good example for the strong impact of late frost damages on apple yields in Europe. Thus it is very important to continue the plant monitoring in the future, to be prepared on impacts of climate changes on agriculture and horticulture.

The currently observed changes in the timing of phenological events are still moderate and mostly not more than a few days per decade, but the relationships between plant development and air temperature changes seems to be clear. The expected climate changes in this century will be much larger than those observed during the 20th century (Houghton et al. 2001). For Germany the increase in annual air temperature could range between 0.1 °C/decade (B1-scenario) and 0.45 °C/decade (A2-scenario, Hulme and Sheard 1999). According to this scenario, the strongest seasonal changes in air temperature will occur in winter and in summer. For the spring development of plants mainly the temperature changes in winter and early spring are important, which steer the period of dormancy and ontogenetic development. The threat of late spring frosts, combined with more frequent mild winters, pose a challenge for even frost hardy species (Burroughs 2002).

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