ORIGINAL ARTICLE

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Possible impacts of climate change on natural vegetation in Saxony (Germany)

Abstract Recent climate changes have had distinct impacts on plant development in many parts of the world. Higher air temperatures, mainly since the end of the 1980s, have led to advanced timing of phenological phases and consequently to an extension of the general growing season. For this reason it is interesting to know how plants will respond to future climate change. In this study simple phenological models have been developed to estimate the impact of climate change on the natural vegetation in Saxony. The estimations are based on a regional climate scenario for the state of Saxony. The results indicate that changes in the timing of phenophases could continue in the future. Due to distinct temperature changes in winter and in summer, mainly the spring and summer phases will be advanced. Spring phenophases, such as leafing or flowering, show the strongest trends. Depending on the species, the average timing of these phenophases could be advanced by 3–27 days by 2050. Phenophases in autumn show relatively small changes. Thus, the annual growth period of individual trees will be further extended, mainly because of the shift of spring phases. Frequent droughts in summer and in autumn can compensate for the earlier leafing of trees, because in this case leaf colouring and leaf fall would start some weeks earlier. In such cases, the growing period would not be really extended, but shifted to the beginning of the year.

Keywords Climate change · Climate scenario · Impacts · Tree phenology · Phenological models

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Introduction

Extremely warm years in the 1990s had distinct impacts on plant development in many parts of the world. There are reports on trends in the timing of spring events in mid- and high latitudes (Braslavska and Kamensky 1999; Ahas 1999; Schwartz and Reiter 2000; Rötzer et al. 2000; Defila and Clot 2001; Müller 2002) and on relationships between air temperature changes and variations in the timing of phenological phases (Bradley et al. 1999; Beaubien and Freeland 2000; Sparks et al. 2000; Schmerbach 2000; Chmielewski and Rötzer 2002). An indirect effect of increasing air temperatures is the extension of the general growing season in Europe (Menzel and Fabian 1999; Chmielewski and Rötzer 2001). Not only the natural vegetation responded to the strong warming in the 1990s, but also fruit trees and even annual crops like winter rye, maize and sugar beet (Chmielewski et al. 2004b). Therefore more research is necessary to estimate the impacts of future climate change on plant development.

This paper will focus on the impact of temperature rise on vegetation development in Saxony in the next decades up to 2050. Saxony is located in the south-eastern part of Germany and covers an area of 18,413 km^2. The altitude increases from north to south, with a maximum of 1,213 m. Simple phenological models (thermal time models, regression equations) were developed to estimate the shift of phenological phases due to climate change.
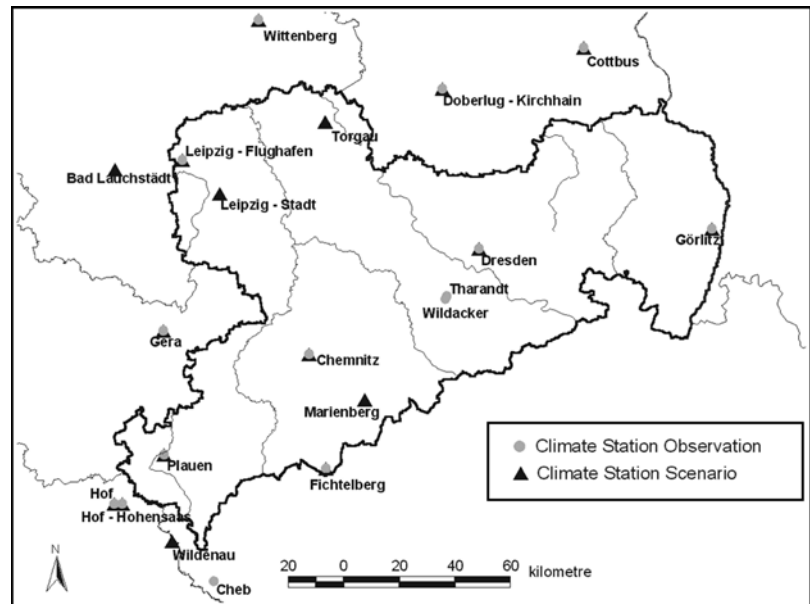
Materials and methods

Climate data and scenarios

To analyse relationships between climate and plant development in Saxony, climate data of the CLISAX study (Bernhofer and Goldberg 2001; Bernhofer et al. 2002) were used. This data set includes observations from all climate stations in Saxony as well as stations in the surrounding region (Fig. 1). The plant development in mid latitudes is

Fig. 1 Climate stations in and around Saxony

strongly driven by air temperature, so that in this study mainly temperature observations were considered. The investigation period was 1961–2000, because the phenological data were limited to these years. Altogether 15 climate stations with mean daily air temperature observations were available for this region. The lowest station is Cottbus at 69 m above sea level; the highest one is located on the peak of the Fichtelberg (1,213 m a.s.l.).

In order to estimate the impact of climate change on plant development in Saxony, a regional climate change scenario was used. It was developed within the REKLISA project (Enke 2003) and is based on a statistical weather-pattern downscaling method for individual climate stations in Saxony (Enke et al. 2005a). The input for the downscaling procedure comes from the SRES-B2 run (Houghton et al. 2001) of the coupled atmosphere and ocean model ECHAM4-OPYC3 of the Max-Planck-Institute for Meteorology and Deutsches Klimarechenzentrum in Hamburg, Germany (Roeckner et al. 1996).

In this study a climate change scenario for Saxony for the decades 2021–2030 (Sc I), 2031–2040 (Sc II) and 2041–2050 (Sc III) were used. The control run of the model (Ctrl) covers the years 1981–2000. For each scenario-decade and the Ctrl ten 20-year simulations were available. These time series were generated by Monte-Carlo simulations, so that for each scenario-decade 200 years (10x20-year simulations=200 years in total) exist which represent the variability of climate in this period (Enke et al. 2005b).

Phenological data

Phenological observations of different species in Saxony were derived from the German Weather Service (DWD). The phenological network of DWD consists of about 1,500 observers, who do the observations on a voluntary basis (Bruns 2001). Table 1 shows the natural vegetation species used and the observed phenophases. Generally, we can distinguish between the phases in spring (leaf unfolding, flowering, May shoot), in summer (general flower, first ripe fruits), and in autumn (autumn colouring). All phenophases are defined and observed according to the Biologische Bundesanstalt, Bundessortenamt, Chemische Industrie (BBCH) scale (BAHP 1991; Mayer 1997).

The number of phenological stations in Saxony varies from species to species (see below). For example, for the leafing of birch (*Betula pendula*) and for the flowering of Robinia (*Robinia pseudoacacia*) data from 89 and 30 stations were available, respectively. In the case of Robinia the limited number of stations was still sufficient to cover the whole area in terms of space and altitude.

The phenological observations were used to analyse recent trends in plant development (1961–2000) and to construct phenological models. On the basis of these models the impact of temperature change on plant development in Saxony was estimated.

Model construction

Phenological models are important tools to predict the impact of global warming on plant development (Schwartz 1990; Kramer 1996; Menzel 1997; Kramer et al. 2000). In phenology the use of heat and chilling units to model plant development is common (Chuine et al. 2003). It is known that trees in mid latitudes require a certain period with chilling temperatures, usually low temperatures of about 0–10°C, before they can react to higher temperatures, which force the development of buds and induce leaf unfolding and flowering in spring (Sarvas 1974; Hänninen 1990; Leinonen 1996a). Since dormancy release cannot be directly observed or measured, it is only possible to describe this stage using statistical model-fitting techniques, which makes the phenological model more complex.

Table 1 Species observed and phenophases of natural vegetation in Saxony

Species	Scientific name	Phenophase	Abbreviation
Goat willow	*Salix caprea*	Beginning of flowering	FL_{Wi}
Silver birch	*Betula pendula*	Beginning of leaf unfolding	LU_{Bi}
		Autumn colouring	AC_{Bi}
Horse chestnut	*Aesculus hippocastanum*	Beginning of leaf unfolding	LU_{Ch}
		Beginning of flowering	FL_{Ch}
		First ripe fruits	RF_{Ch}
		Autumn colouring	AC_{Ch}
Common oak	*Quercus robur*	Beginning of leaf unfolding	LU_{Ok}
		First ripe fruits	RF_{Ok}
		Autumn colouring	AC_{Ok}
Norway spruce	*Picea abies*	Beginning of May shoot	MS_{Sp}
Lilac	*Syringa vulgaris*	Beginning of flowering	FL_{Li}
Robinia	*Robinia pseudoacacia*	Beginning of flowering	FL_{Ro}
Black elder	*Sambucus nigra*	Beginning of flowering	FL_{El}
		First ripe fruits	RF_{El}
Orchard gras/Cocksfoot	*Dactylis glomerata*	General flowering	GF_{Gr}
Lime	*Tilia platyphyllos*	Beginning of flowering	FL_{Lm}

**Table 2** Number of days with temperatures effective for the release of dormancy in the buds ($0°C < T < 10°C$) between 1 September and 31 December for the control run (*Ctrl*) and the scenario decades [2021–2030 (*Sc I*), 2031–2040 (*Sc II*) and 2041–2050 (*Sc III*)]

	Ctrl	Sc I	Sc II	Sc III
Mean	69	72	71	69
SD	9.5	8.2	8.5	7.7
Maximum	90	92	91	88
Minimum	42	49	49	48

The simplest phenological model is the thermal time model (Robertson 1968; Cannell and Smith 1983), which does not take dormancy into account. It assumes that the release of dormancy is usually reached at the end of the year.

Since strong temperature changes in autumn and in early winter can influence the release of dormancy of trees, climate changes during this time of the year were examined. Specifically, the number of days with temperatures effective for the release of dormancy between September and December was calculated. The result shows that the conditions in the scenario hardly change (Table 2). Both in the control run and in the scenario decades, the number of days with temperatures between 0 and $10°C$ remains approximately 70 days. Thus, in this study, we supposed that chilling requirement is satisfied up to the end of the year (31 December), so that the plants can react to favourable temperatures starting from 1 January.

The higher the temperatures after the release of dormancy the earlier is the timing of phenophases. Figure 2 shows the relationship between monthly air temperature from October (previous year) to April and the leafing of birch trees (*B. pendula*) in Saxony. This example stands for all phenophases in spring for which the relationships between temperature and phenology are comparable (Table 3). Positive correlation coefficients are always found for November when the buds are still dormant. Lower temperatures in this month might be responsible for breaking
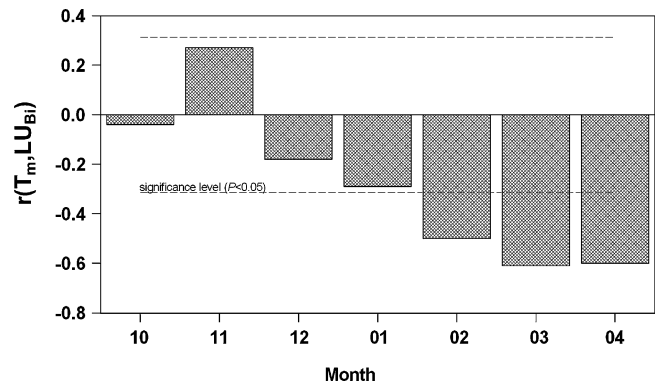
Fig. 2 Correlation coefficients (*r*) between leafing of birch trees (*Betula. pendula*; LU_{Bi}) and monthly air temperature (T_m) from October (*10*) (previous year) to April (*04*) for 1961–2000. *11* November, *12* December, *01* January, *02* February, *03* March

dormancy, so that in the following months the plant is able to react to forcing temperatures. Already beginning in December, the correlation coefficient is negative for all investigated species. This means that a mild December probably can force the development of buds. The first significant correlation coefficients between monthly air temperature and spring phenophases usually were found for February. Only for some very early spring phases did significant correlations already exist in January or even in December (FL_{Wi}: $r = 0.39$). Consequently, for the majority of plants the course of temperature between February and April is of great importance for the timing of spring phenological phases (Chmielewski and Rötzer 2001).

Different heat sums (T_S) exist for different species (sum of degree-days, growing-degree sums, forcing units). In the literature, diverse approaches are suggested to calculate the plant-specific forcing temperatures (e.g. Sarvas 1972; Hänninen 1995; Leinonen 1996b; Kramer 1996; Häkkinen et al. 1998; Snyder et al. 1999; Chuine et al. 1999; Cenci and Ceschia 2000; Kramer et al. 2000; Rötzer et al. 2004). In this study effective T_S were calculated for all species,

Table 3 Correlation coefficients between monthly mean air temperature from October (previous year) until May and timing of phenophases in Saxony, 1961–2000. For abbreviations, see Table 1

Phenophase	Mean$_{observed}$	October	November	December	January	February	March	April	May
FL$_{Wi}$	30 March	0.23	0.17	**−0.39***	**−0.46***	**−0.72***	**−0.80***	–	–
LU$_{Bi}$	23 April	−0.04	0.27	−0.18	−0.29	**−0.50***	**−0.61***	**−0.60***	–
LU$_{Ch}$	27 April	0.02	**0.31***	−0.23	**−0.35***	**−0.53***	**−0.60***	**−0.66***	–
LU$_{Ok}$	10 May	−0.01	**0.31***	−0.23	**−0.32***	**−0.44***	**−0.37***	**−0.79***	**−0.45***
FL$_{Ch}$	16 May	0.01	0.28	−0.24	**−0.31***	**−0.42***	**−0.31***	**−0.78***	**−0.52***
MS$_{Sp}$	16 May	0.08	0.28	−0.22	−0.22	**−0.47***	**−0.44***	**−0.77***	**−0.53***
FL$_{Li}$	17 May	0.05	0.29	−0.26	**−0.31***	**−0.46***	**−0.37***	**−0.77***	**−0.56***
FL$_{Ro}$	6 June	0.13	0.25	−0.18	−0.17	−0.27	**−0.31***	**−0.60***	**−0.81***
FL$_{El}$	9 June	0.15	0.29	−0.28	−0.20	**−0.38***	**−0.40***	**−0.66***	**−0.73***
GF$_{Gr}$	9 June	0.17	0.18	−0.21	−0.15	**−0.32***	**−0.38***	**−0.54***	**−0.84***
FL$_{Lm}$	30 June	0.14	0.16	−0.08	−0.11	−0.23	−0.29	**−0.57***	**−0.75***

*$P<0.05$

using daily mean temperatures (Eq. 1). "Effective" means that the daily mean temperature (T_i) has to be higher than a plant-specific base temperature (T_B), which was estimated for each species (Snyder et al. 1999; Wielgolaski 1999).

$$T_s = \sum_{t_1}^{t_2} \max{(T_i - T_B, 0)} \qquad (1)$$

The period of summation ranges from 1 January (t_1) to the timing of phenophase (t_2). All phenological models differ in their base temperature. In order to calculate this threshold, T_B was varied between 0 and 10°C in steps of 0.1°C. T_s is the heat sum which has to be reached before the phenophase can be observed.

If, additional to T_B, t_1 is also varied, then the root mean square error (RMSE) and mean absolute error (MAE) of the models are reduced slightly. For most species the best date for t_1 is sometime in February. However, according to the climate scenario we will have a distinct temperature increase in January (on average up to +3.4°C, Chmielewski et al. 2004a), so that the plants probably will react to these warmer conditions. In order to consider this fact in the models, t_1 was intentionally not changed.

To set up phenological models for Saxony the data base was split into two (fitting data, odd years; verification data, even years; 1961–2000). For the development of models the spatial daily mean air temperature (average of 15 stations) and the spatial mean annual timing of phenophases in Saxony were used. Starting with a base temperature of 0.0°C, the T_S between t_1 and t_2 was calculated for each year and afterwards averaged over all years. Then the mean T_S was used to estimate the annual timing of phenophases. To check the accuracy of the model, the RMSE between observed and estimated dates was calculated for the even years. In the next step, the base temperature was increased by 0.1°C and the whole procedure was repeated. The calculations were continued until the base temperature reached 10.0°C. Figure 3 shows the course of RMSE in relation to the variations in base temperature (T_B). The best model is always the model with the smallest RMSE. In this example the optimal base temperature for the beginning of
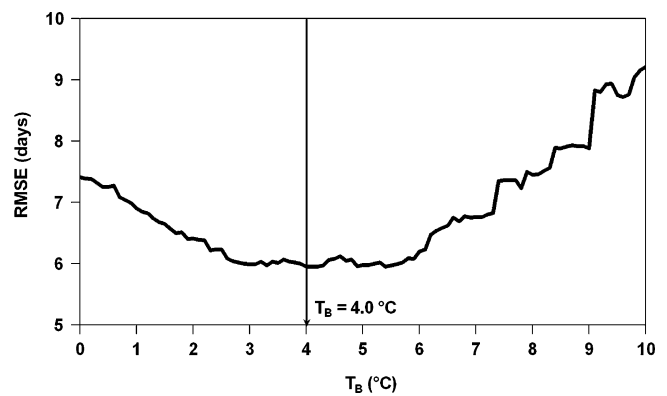

Fig. 3 Calculation of base temperature (T_B) in relation to the root mean square error (RMSE) between observed and estimated dates for the beginning of LU_{Bi}

leaf unfolding of birch (*B. pendula*) is 4.0°C. Between $T_B=3$ and 5°C the quality of the model is comparable. The average T_S for this phase is 110.6°C (MAE=3.9 days, RMSE=6.3 days). Figure 4 shows the observed and estimated dates for the leaf unfolding of *B. pendula*. Both time series indicate the same trend and about the same annual
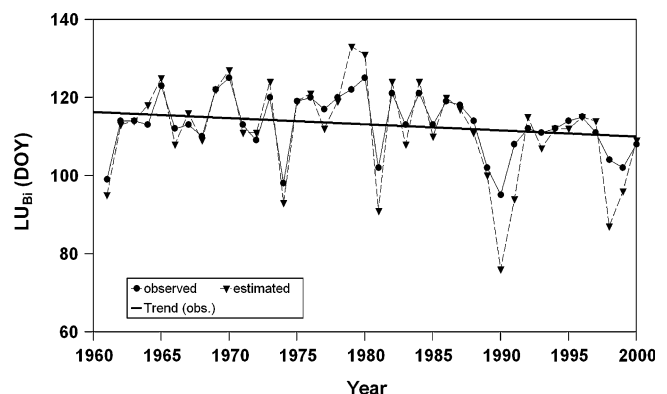

Fig. 4 Comparison between observed and estimated dates for LU$_{Bi}$ in Saxony between 1961 and 2000 on the base of a heat sum (T_S) model [T_B=4.0°C, T_S=110.6°C, mean absolute error=3.9 days, RMSE=6.3 days]. *DOY* Days of year; for other abbreviations, see Figs. 2 and 3

variability. Some larger deviations between observed and estimated data exist only for 1979, 1980, 1981, 1990, 1991, and 1998.

For phenophases in autumn the influence of temperature is not as decisive as for spring phases. Leaf colouring and leaf fall are induced by several factors, including the lack of light, decreasing temperatures, or frosts (Estrella 2000). The effect of temperature can turn during this time of the year, so that a mild autumn delays leaf colouring. For this reason it is not possible to use the same models as in spring.

For fruit maturity and leaf colouration multiple regression equations were used instead of thermal time models. In these equations we always considered a previous phenophase in spring or summer which is well correlated with the phase in autumn. The additional consideration of monthly mean temperatures between this phase and the phenophase in autumn increased the explained variance of the model. Using this approach it was possible to describe the autumn phases quite well.

Results

Recent air temperature changes in Saxony

The current mean annual air temperature in Saxony is 7.6°C (Table 4). Monthly mean temperatures below zero are only observed in January and February. The warmest month is July with a mean air temperature of 16.1°C. The majority of months show positive linear trends in the investigated

period. The strongest increase in air temperature was observed in winter, in spring, and in August. No trend was found in autumn. Altogether the increase in annual air temperature in Saxony is 0.3°C/decade ($P<0.01$). This means that in the last 40 years the temperature rose by 1.2°C.

Spatial differences of air temperature in Saxony are mainly determined by topography. The warmest areas are located in the northern lowlands and along the river Elbe (e.g. Dresden station). In the low mountains the temperature is reduced. The coldest regions can be found on the peaks of the Erzgebirge mountain range in southern Saxony. These spatial differences in temperature are well reflected in the timing of phenophases (Chmielewski et al. 2004a). The earliest dates in spring are usually observed in the Elbe Valley and in the northern lowlands.

Recent impacts on plant development

As described in previous studies, the temperature rise in the last years, mainly since the end of the 1980s, is well reflected in the plant development. Higher air temperatures led to an advanced timing of phenological phases, mainly in spring. The results which were found for Europe (Chmielewski and Rötzer 2001) and for Germany (Müller 2002; Chmielewski et al. 2004b) are transferable to Saxony without any restrictions. Generally, the very early spring phases show the strongest trend, because of the distinctive increase in air temperature in winter and in early spring (Table 5). For example, a strong trend was found for *Salix*

Table 4 Monthly and annual mean air temperature (°C) in Saxony 1961–2000, as well as trends (°C per decade)

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Mean	−1.2	−0.4	2.9	7.0	11.6	14.5	16.1	15.8	12.9	8.4	3.3	0.0	7.6
SD	3.0	3.0	2.3	1.4	1.5	1.1	1.6	1.2	1.5	1.5	1.7	2.4	0.8
Trend	+0.7	+0.4	+0.5	+0.2	+0.5	+0.0	+0.3	+0.5	+0.0	+0.0	−0.1	+0.6	+0.3
P	<0.10	–	<0.10	–	<0.01	–	–	<0.01	–	–	–	<0.10	<0.01

Table 5 Observed trends in the timing of different phenophases in Saxony 1961–2000. *BBCH* Biologische Bundesanstalt, Bundessortenamt Chemische Industrie scale; *T* trend per decade; for other abbreviations see Table 1

Species	Phenophases	BBCH[a]	No. of stations	Mean (date)	SD (days)	T
S. caprea	FL$_{Wi}$	60	77	30 March	12.2	−3.4*
B. pendula	LU$_{Bi}$	11	89	23 April	7.5	−1.5
	AC$_{Bi}$	94	66	5 October	2.9	+0.2
A. hippocastanum	LU$_{Ch}$	11	81	27 April	6.9	−1.8+
	FL$_{Ch}$	60	56	16 May	7.1	−1.6+
	RF$_{Ch}$	86	52	22 September	4.5	−1.5*
	AC$_{Ch}$	94	65	5 October	3.8	−0.6
Q. robur	LU$_{Ok}$	11	39	10 May	6.5	−1.9*
	RF$_{Ok}$	86	31	25 September	5.1	−1.2+
	AC$_{Ok}$	94	65	17 October	3.9	+0.6
P. abies	MS$_{Sp}$	10	49	16 May	6.2	−1.9*
S. vulgaris	FL$_{Li}$	60	67	17 May	7.7	−1.9+
R. pseudoacacia	FL$_{Ro}$	60	30	6 June	8.5	−3.6**
S. nigra	FL$_{El}$	60	39	9 June	8.0	−3.1**
	RF$_{El}$	86	62	8 September	7.9	−2.5*
D. glomerata	GF$_{Gr}$	65	58	9 June	6.0	−1.7*
T. platyphyllos	FL$_{Lm}$	60	50	30 June	7.0	−2.0*

*P<0.05, **P<0.01

+P<0.10

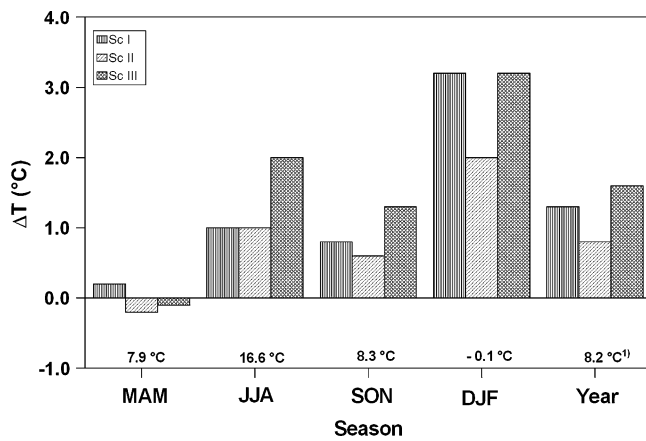[a]Developmental stages according to BBCH scale (Mayer 1997)

Fig. 5 Average deviations of air temperature (Δ*T*) in the climate scenario decades [2021–2030 (*Sc I*), 2031–2040 (*Sc II*), 2041–2050 (*Sc III*)] for different seasons and the whole year in relation to the control run. *1)* Means of the control run, *MAM* March April May, *JJA* June July August, *SON* September October November, *DJF* December January February

caprea which already starts to flower at the end of March. The flowering dates of *Robinia pseudoacacia* and *Sambucus nigra* are also strongly advanced because of the significant increase in May temperatures (Table 4). Usually, in the course of the year the negative trends decrease within a species (e.g. *Aesculus hippocastanum*). For some species the trend in autumn is positive (e.g. autumn colouring of birch and oak), but not significant. Higher temperatures in autumn (September, October) could maintain the plant physiological processes, so that autumn colouring starts some days later.

Future climate change in Saxony

According to the ECHAM4-OPYC3 climate scenario, the observed increase in air temperature will continue in the first half of the twenty-first century (Fig. 5). The temperature rise is not uniform from decade to decade and it clearly differs between the seasons. The annual average will increase by up to 1.6°C in the last decade of the scenario (2041–2050). The strongest changes will occur in winter (up to +3.2°C) and in summer (up to +2.0°C). In the transition seasons temperature changes are relatively weak. In spring (March, April, May) reverse trends are also possible (Table 6). The temperature rise between February and April, which is important for the timing of spring phases under current climatic conditions, is up to 1.3°C (Sc I). The period 2021–2030 is slightly colder than the previous and following decade. This effect is probably a result

of interactions in the coupled atmosphere–ocean model (ECHAM4-OPYC3).

Expected changes in plant phenology

In order to estimate possible impacts of temperature rise on plant development in Saxony, phenological models for all phenophases were calculated. As mentioned above, for spring and summer phases thermal time models were used, for the autumn phases multiple regression equations (Table 7). The average T_B of all models for the spring phases is 5.0°C. It ranges between the species from 3.9°C (leafing of chestnut) to 6.4°C (blossom of summer lime). Only the willow seems to react to all positive temperatures (T_B=0.0°C). Starting on 1 January, T_S 178.8°C is necessary to induce the beginning of flowering of *S. caprea*. The leafing of birches only starts when T_S reaches 110.6°C above a threshold of 4.0°C.

For the blossom of chestnut (FL_{Ch}) the calculation of the T_S was not started on 1 January, since an earlier phenophase was available for this species, so that it was possible to use the beginning of leaf unfolding (LU_{Ch}) as a starting date. The sum of degree-days which is necessary to induce flowering was 193.2°C. Changes in base temperature did not improve the model, because in mid May all daily temperatures are beneficial for the development of flowers.

In the models of fruit ripening, air temperature in the 2 months after the beginning of flowering or beginning of leafing is always considered. To estimate autumn colouring of chestnut and oak, the regression equation includes the date of first ripe fruits and September temperature. In all cases, above-average September temperatures delayed autumn colouring.

All plant-specific parameters and the goodness-of-fit of the models for the verification years (even years, 1961–2000) are given in Table 7. MAEs range between 1.3 and 6.2 days and are always distinctly below the SD of observations (Table 5). The largest MAE was calculated for the flowering date of *Salix caprea*, but compared to the SD of this very early phenophase (SD=12.2 days) the error is still acceptable. The autumn phases are also described by the regression equations very well. Generally, the MAE is in a range which is common for phenological models, even if they are much more sophisticated (Cannell and Smith 1983; Kramer 1996; Chuine et al. 1999). Since we have used average data (air temperature, phenological data) for all of Saxony, the models are relatively stable.

The phenological models were then applied to the scenario decades. As already mentioned, each decade is represented by 200 individual years. Table 8 shows the calculated

Table 6 Changes of monthly and annual mean air temperature (Δ*T*, °C) in Saxony in the different scenario decades. For other abbreviations, see Table 2

	January	February	March	April	May	June	July	August	September	October	November	December	Year
ΔT (Sc I)	3.1	3.4	0.2	0.3	0.2	1.0	0.9	1.1	0.9	0.9	0.5	3.0	1.3
ΔT (Sc II)	2.2	1.7	−0.2	−0.3	−0.2	0.7	1.1	1.2	0.6	0.8	0.3	2.1	0.8
ΔT (Sc III)	3.3	3.1	−0.3	0.0	0.0	2.1	1.8	2.2	1.3	1.6	0.9	3.1	1.6

Table 7 Phenological models for spring, summer (thermal time models), and autumn phases (multiple regression equations). t_1 Starting date, T_B base temperature, T_S heat sum, *DOY* days of year, *MAE* mean absolute error, *RMSE* root mean square error; for other abbreviations, see Table 2

Phenophase	t_1	T_B (°C)	T_S (°C)	Mean_observed (DOY)[a]	Mean_simulated (DOY)	MAE (days)	RMSE (days)
Spring/summer phases							
FL_{Wi}	1 January	0.0	178.8	91.0	88.0	6.2	8.2
LU_{Bi}	1 January	4.0	110.6	113.4	112.4	3.9	6.3
LU_{Ch}	1 January	3.9	132.2	117.4	115.4	4.4	8.1
LU_{Ok}	1 January	5.3	144.9	130.3	128.0	3.7	4.2
MS_{Sp}	1 January	5.1	191.7	135.7	134.4	3.3	3.8
FL_{Ch}	LU_{Ch}	0.0	193.2	135.9	134.5	1.9	2.7
FL_{Li}	1 January	4.9	212.8	137.5	136.2	2.4	3.1
FL_{Ro}	1 January	5.5	336.4	156.6	155.0	3.0	3.7
FL_{El}	1 January	5.2	383.9	159.2	157.9	3.2	3.8
GF_{Gr}	1 January	5.6	355.7	159.8	157.9	2.6	3.6
FL_{Lm}	1 January	6.4	527.1	181.0	183.5	3.6	4.8
Autumn phases							
RF_{El}	$RF_{El}=178.6+0.71$ $FL-1.87\,T_{06}-0.89\,T_{07}$			250.8	250.0	2.4	3.0
RF_{Ch}	$RF_{Ch}=267.8+0.24$ $FL-1.55\,T_{05}-1.17\,T_{06}$			265.0	265.3	1.7	2.2
RF_{Ok}	$RF_{Oa}=265.6+0.31$ $LU-1.30\,T_{05}-1.57\,T_{06}$			267.7	269.0	2.6	3.3
AC_{Ch}	$AC_{Ch}=93.0+0.63$ $RF+1.39\,T_{09}$			276.5	276.5	1.3	1.6
AC_{Bi}	$AC_{Bi}=279.3+0.03$ $LU-1.08\,T_{06}+0.90\,T_{09}$			277.5	276.6	2.5	3.2
AC_{Ok}	$AC_{Ok}=160.2+0.41$ $RF+1.45\,T_{09}$			288.1	288.9	2.2	2.8

[a]Even years

Table 8 Average starting days of different phenophases (in day of the year) in the control run (Ctrl: 1981–2000) and in the scenario decades and changes in these (Δ) in relation to the control run (in days). For abbreviations see Table 2

Phenophase	Ctrl	Sc I	Sc II	Sc III	ΔSc I	ΔSc II	ΔSc III
Spring/summer phases							
FL_{Wi}	84	57	69	57	−27.0	−15.0	−27.0
LU_{Bi}	107	97	104	98	−10.0	−3.0	−9.0
LU_{Ch}	110	103	110	104	−7.0	0.0	−6.0
LU_{Ok}	127	122	128	123	−5.0	1.0	−4.0
FL_{Ch}	127	121	127	123	−6.0	0.0	−4.0
MS_{Sp}	128	123	129	125	−5.0	1.0	−3.0
FL_{Li}	130	124	130	126	−6.0	0.0	−4.0
FL_{Ro}	151	148	152	149	−3.0	1.0	−2.0
FL_{El}	153	147	152	148	−6.0	−1.0	−5.0
GF_{Gr}	151	146	151	148	−5.0	0.0	−3.0
FL_{Lm}	178	174	178	173	−4.0	0.0	−5.0
Autumn phases							
RF_{El}	247	241	243	237	−6.0	−4.0	−10.0
RF_{Ch}	261	258	260	257	−3.0	−1.0	−4.0
RF_{Ok}	263	260	263	260	−3.0	0.0	−3.0
AC_{Ch}	275	274	275	274	−1.0	0.0	−1.0
AC_{Bi}	282	283	282	281	1.0	0.0	−1.0
AC_{Ok}	288	288	288	288	0.0	0.0	0.0

changes in plant development for the three decades up to 2050. The results are in accordance with the recent changes in plant development. The very early phases in March and April show the strongest shift (blossom of willow, leafing of birch and chestnut). In the observation period (1961–2000) the flowering of willows was already advanced by 14 days. Up to 2050 the timing of this phenophase could shift by another 27 days to the beginning of the year. In the control run (1981–2000) the date was 25 March (day 84); in the future this phase could be observed as early as the end of February. Also the leaf unfolding of birches would be accelerated, so that this phase could occur at the beginning of April (Ctrl: 17 April). The phenophases in May and June will also be advanced by 3–6 days.

The fruit ripening in autumn shows similar changes as the phases in summer. This phase is influenced by the shift of the previous phase and the course of air temperature in the two following months. The strongest change—of up to 10 days in the last decade of the climate change scenario—is calculated for the first ripe fruits of elder (*S. nigra*). Already in the observations, *S. nigra* showed a relatively strong temperature response. Compared to the other phenophases, autumn colouring will not change significantly, so that the individual growing periods of birch, chestnut, and oak would mainly be extended due to the earlier beginning of leafing in spring.

Conclusions

In the last 40 years the climate in Saxony has clearly changed. In nearly all months positive trends in air temperature were observed, which correspond well to the changes throughout Germany (Schönwiese et al. 1998). Phenological observations allow the investigation of the impact of temperature changes on plant development. This study shows that the species examined had already responded to the higher temperatures, which confirm findings in many parts of the world (e.g. Bradley et al. 1999; Schwartz and Reiter 2000; Beaubien and Freeland 2000; Defila and Clot 2001).

Mainly the very early spring phases show the strongest negative trends. There are a number of reasons for this. On the one hand, the temperature in winter and early spring is rising. On the other hand, air temperatures between January and April are always suboptimal for plant development, so that an increase in temperature noticeably accelerates plant development. With generally increasing temperatures in the course of the year, the observed trends within a species decline (chestnut, oak, and elder). Relatively high temperatures in autumn can delay leaf colouring and leaf fall.

According to the ECHAM4-OPYC3 climate scenario, air temperature will continue to rise up to 2050. The greatest increase is projected for winter and summer. Increasing temperatures in winter should cause earlier leafing or flowering (e.g. up to 27 days for the flowering of goat willow). This head start in spring will be partially compensated for by the higher summer temperatures, so that the period between leafing/blossom and fruit maturity is not clearly extended. The whole developmental stage is shifted to the beginning of the year, so that the general growing season starts earlier. This result is in accordance with observations, where changes in the beginning of the growing season have already been detected (Menzel and Fabian 1999; Chmielewski and Rötzer 2001). An earlier start to the growing season would have some beneficial aspects for carbon fixation and biomass increase, because during this time of the year insolation and soil water content are usually higher than in autumn. Thus, an earlier start to the growing season is more beneficial for tree growth than a later end of the growth period. On the other hand, the threat of late spring frosts, combined with more frequent mild winters, poses a challenge for even frost-hardy species (Burroughs 2002). Plant development in Saxony will mainly be forced due to increasing temperatures in January and February. Climate changes in spring seem to be relatively weak, so that the frost hazard for trees will probably increase. For fruit species the risk of late frost damage in Saxony will clearly rise (Chmielewski et al. 2004a).

In autumn, no strong changes in plant phenology are likely (e.g. autumn colouring for birch, chestnut, and oak). This means that the whole growing period for trees will be mainly extended, because of its earlier start in spring. For some other species, it is possible that the growing period will be shortened if leaf fall is more advanced than leaf unfolding (Kramer 1996).

In this study, the relatively simple phenological models were only driven by temperature. Many studies confirm that temperature is the most important factor in plant phenology if water is not the limiting factor (Lechowicz 1995; Zang 1995). Climate changes can also lead to more frequent droughts in summer. For Saxony, ECHAM4 projections in the last decade (2041–2050) show an increase in precipitation in winter (December–February), but a decrease in all other months (Chmielewski et al. 2004a). For the growing season from April until October it indicates an air temperature rise of $1.3°C$ and a precipitation decrease of >30 mm. This inevitably will lead to decreased soil water content and worse growing conditions for trees. The extreme summer temperatures of 2003 in Europe showed the impact of extremely limited soil moisture on vegetation. Most climate scenarios for mid latitudes point to an increase in precipitation in winter, but a decrease in summer (Houghton et al. 2001). Drought in early spring should not be the main problem, because in mid latitudes soil water content after winter is usually sufficient for plant growth. At this time of the year the plants will mainly react to the higher temperatures by an earlier leafing or flowering. High air temperatures combined with extensive drought in summer and autumn can lead to advanced fruit ripening as well as to earlier leaf colouring and leaf fall. For instance in Switzerland, 30% of the late spring and summer phenophases and still 20% of the autumn phases were extremely early in 2003 (Defila 2004). In south Germany a premature leaf and needle fall was observed at the forest climate stations in Bavaria (Raspe et al. 2004). This means that in warm and dry years the earlier start to the growing season can be compensated for by earlier leaf colouring or leaf fall. In any case, such extreme climate conditions are additional stresses for trees and they can still affect leafing and flowering in the following years. Trees probably can compensate for individual hot and dry years, but a succession of these extreme climate conditions would noticeably harm forest stands. In order to investigate such complex processes more detailed process-based forest growth models have to be used (Kramer 1996; Leinonen and Kramer 2002).

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