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Trends of spring time frost events and phenological dates in Central Europe

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With 12 Figures

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Summary

Over large parts of the Northern Hemisphere's continents temperature has been increasing during the last century. Particularly minimum temperatures show a more pronounced increase than maximum temperatures. Not only the phenological seasons, but also the potentially plant damaging late frost events are governed by the atmosphere. In case of a rise of minimum temperatures one would expect phenological phases and spring late frost events to occur earlier. In this work the question is elucidated whether plant phenology shifts at a higher or lower rate towards earlier occurrences than potential plant damaging events, like spring late frost events. Frost events based on the last occurrence of daily minimum temperatures below a certain threshold have been moving faster to earlier occurrence dates than phenological phases during the last decades at 50 climate stations in Central Europe. Trend values of frost time series range around −0.2 days/year and of phenological time series are between −0.2 and 0.0 days/year over the period from 1951–1997. '*Corylus avellana* beginning of pollination' is the only one of the 13 phases considered here with a lower trend value of −0.28 days/year. Early phases are more adapted to below zero temperatures and therefore follow more closely the temperature variability. Later phases seem to have more reason to be concerned about possible late frost events and react more cautiously towards higher spring temperatures and earlier last frost dates. The risk of late frost damage for plants should have been lower during the last decade as compared to the previous decades.

1. Introduction

The atmosphere not only governs the timing of seasonal plant development mainly through temperature, but represents also a potential risk to plants through late frost events, droughts or storms. With the latest warming trends in Europe one would expect for instance late frost events to shift also to earlier occurrence dates. The most interesting question here is, how plant phenology reacts to such trends of the climatic seasons, whether plant phenology shifts at a higher or lower rate towards earlier occurrences than potential plant damaging events, like spring late frosts. In case the plant phenology moves with a higher (lower) trend towards earlier occurrences then for instance spring late frosts, the risk of late frost damage should be enhanced (reduced). The short literature review will therefore concentrate on both, phenological observations and on analysis of temperature extremes.

Significant trends in the seasonal behaviour of plants and animals belong to the group of Global Change phenomena, which have unequivocally been observed in many regions of the world during the last decades (Walther et al., 2002). The length of the vegetation period of many plant species has been increasing through an advanced onset of spring phases and a forward shift of autumn phases in midlatitudes (e.g. Post and Stenseth, 1999; Menzel and Fabian, 1999; Menzel, 2000 and Menzel et al., 2001; Jaagus and Ahas, 2000; Chmielewski and Rötzer, 2001; Defila and Clot, 2001). Apart from recording changes in seasonal plant behaviour, there is a great interest in understanding the possible links with the climate variability of the midlatitudes. It has turned out that the seasonal cycle of plants is to a large degree influenced by the temporal and spatial variability of hemispheric scale atmospheric circulation patterns. The North Atlantic Oscillation (NAO) is thought to play a key role in governing the temporal variability of the lower atmosphere and thus phenological dates in Europe (Post and Stenseth, 1999; Chmielewski and Rötzer, 2001; Scheifinger et al., 2002). The latitudinal pressure gradient between Iceland and Southern Europe has been increasing during the last winters, causing an intensified westerly flow of mild maritime air from the Atlantic into continental Europe. An increase of the intensity of the west wind drift is thought to be the cause for the winter and early spring temperature increase during the last 15 years in Europe.

Apart from the link between the variability of the mean temperature with the seasonal development of plants, extreme events are also significant to phenology. A combination of early spring warming with succeeding low temperature events, for instance, can be detrimental to plant and animal species living at the margin of their climatic range (Parmesan, 2000). Meanwhile there is an increasing number of papers dealing also with lower and upper end of the probability distribution of temperature, like minimum and maximum daily temperature, diurnal temperature range and various frost/freeze indices (Folland et al., 1999).

Daily maximum and minimum temperatures have both been increasing over large parts of the world's land surface, but the rate of increase of the minimum temperatures for the 1950–1993 period is more than twice the increase of the maximum over large parts of the continents (1.8 °C/100 years versus 0.8 °C/100 years, Karl and Easterling, 1999). Similarly Horton (1995) finds a decrease of the daily temperature range (DTR) over a third of the earth's land surfaces connected with a strong increase of daily minimum temperatures especially since the 1970's. A pronounced trend towards higher daily minimum temperatures could be found often coincident with a decrease of the number of frost days over Australia and New Zealand (Plummer et al., 1999), the US (Cooter and LeDuc, 1995) and large parts of the earth's continents (Karl et al., 1993; Easterling et al., 1997, 2000). Combining the last and first freeze event (minimum temperature $\leq 0\,°C$) of a season to embrace the vegetation period, Skaggs and Baker (1985) found a general increase in growing season length. Between 1899 and 1982 last freeze events show a general trend towards earlier and last freeze events towards later occurrence in Minnesota. A similar trend towards an earlier occurrence of hard spring-freeze events (minimum temperature $\leq -2.2\,°C$) has been found by Cooter and LeDuc (1995) in North–Eastern USA for the period 1961–1990. Over the period 1906–1997 the growing season (the season without daily minimum temperatures $< 0\,°C$) has increased by nearly one week in Illinois (Robeson, 2002). The lower end of the probability distributions of daily minimum temperatures has been experiencing more warming during spring and less cooling during fall.

Also in Central and Northern Europe a reduction of the DTR has been recorded at many stations since mid of the 20th century. An increase of winter minimum temperatures has led to a significant decrease in the frequency of frost days since the 1930's of the last century (Heino et al., 1999). Investigating the temperature behaviour regional differences within Europe become apparent. Minimum daily temperature values have been significantly increasing at the western low elevation stations of Switzerland and Western Austria during all seasons and to a lesser degree in summer, autumn, and partly in spring at stations of Eastern Austria, the Czech Republic, the Slovak Republic and Croatia from 1901–1990 (Weber et al., 1997). In contrast daily minimum temperatures have been decreasing and daily temperature ranges have been increasing in parts of Central and Southeastern Europe (Brazdil et al., 1996).

It seems that in some mountain areas Global Change phenomena become more evident.

European mountain stations show significant changes in maximum and minimum daily temperatures in winter and spring from 1951–1990 (Weber et al., 1997). In many parts of the Alps the increase in mean annual temperatures has been about nearly twice the global average and minimum temperatures have been increasing at an even higher rate (Rebetez, 2001; Böhm et al., 2001). Investigations for the Swiss Alps reveal an increase in temperature anomalies during winter with increasing elevation for the period 1979 to 1994 (Beniston et al., 1997). From the middle of the last century onwards various periods with a strong increase in winter minimum temperatures have been observed in Switzerland, particularly at higher altitudes (Jungo and Beniston, 2001).

The day-to-day variability of temperature could be seen as an indicator of the short-term temperature stress for ecosystems. During the last century the day-to-day temperature variability has been decreasing in the Northern Hemisphere (Karl et al., 1995). As for Europe it has increased by 5% in southwest Europe, decreased by 0 to −5% in Northwestern and by −5 to −10% in Northeastern Europe over the period from 1880 to 1998. Additionally the frequency of extremely cold winter days in northern Europe has been lower in the 20th century than in the 18th and 19th centuries (Moberg et al., 2000). Similar results have been found by Rebetez (2001) for two stations in Switzerland. A reduction in day-to-day temperature variability has been caused by the loss of the coldest extremes and particularly the loss of the coldest extremes in winter.

2. Data and methods

For this investigation phenological data from Germany, Austria, Switzerland and Slovenia have been available with 13 phenological spring phases from 1951–1997 (e.g. Fig. 2). The species selected here do not necessarily represent typical late frost sensitive plants, like *Galanthu nivalis*, which is specifically adapted to endure low temperatures. Nevertheless the phases will serve to generally elucidate the relationship between phenology and frost climatology. Daily minimum, maximum and mean temperatures from 50 stations have been available from Germany, Austria and Switzerland ranging also from 1951 to 1997.

Phenological time series have been checked for consistency. As second procedure a multiple regression model with station longitude, latitude and elevation as independent variables and phenological dates as dependent variable is fit to the data of each year. Station data beyond 1.5 standard deviations from the model value are rejected for further analysis. In order to increase the number of climate stations for analysis, a single missing year (except the first or last year) has been allowed for the time series of daily minimum, maximum and mean temperatures (Fig. 1). The missing year has been interpolated linearly. Because homogenised time series of daily data are still scarce and have therefore not been available for this study, the results are to some extent tentative. Nevertheless they aim at a consistent picture, which creates some trust in the conclusions.

Minimum temperatures are difficult to interpolate statistically because of their high local scale variability, especially in complex terrain. Therefore, in order to have temperature and phenological data combined at a station, phenological time series are interpolated to climate station coordinates. Height reduced inverse distance weighting is applied as interpolation method based on long term mean slopes of the elevation – phenological date relationships.

The fundamental difficulty in dealing with the question of frost risk for plants is that there are no time series with observed plant damaging late frost – events at hand. Late – frost events themselves do not occur on a regular basis are therefore very heterogeneously distributed in time and space. Any investigation has therefore to work with a surrogate for the actual late frost events. This investigation is based on the last occurrence dates of minimum temperatures below a number of threshold values. The advantage of this parameter is its regular occurrence and that a range threshold values can be observed each year. The time series of last occurrence dates can directly be compared with time series of phenological events.

Minimum temperatures in spring do not show a continuous linear seasonal trend towards higher temperatures. Their daily variability is influenced by a number of factors, which makes the time

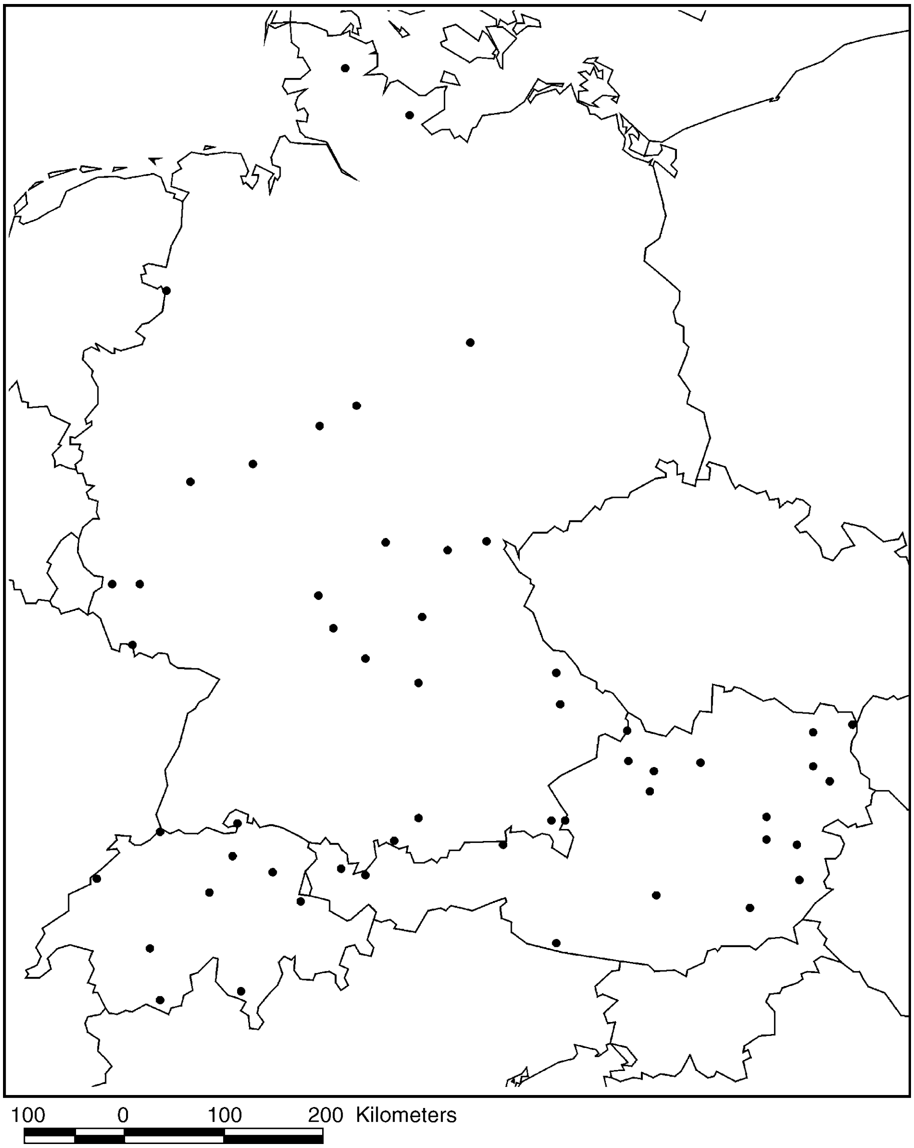

Fig. 1. Geographical position of the 50 climate stations used for this study

series appear noisy. In order to reduce the random component, the last occurrence date time series of thresholds have been calculated in half degree steps for 0, -1, -2, -3 and $-4\,°C$. Each time series of last occurrence dates is then a mean of three half-degree time series. The $0\,°C$ time series for instance is a mean of the 0.5, 0 and $-0.5\,°C$ time series.

3. Results

On average most last frost events at various threshold values overlap to a large degree with the phenological spring phases (Fig. 2). Only the latest phases do not coincide with the daily minimum temperatures $< -4\,°C$ and '*Sambucus nigra* beginning of flowering' hardly experiences any frost events. Most trend values of phenological and frost events are negative, both indicating a general warming from 1951 to 1997 (Fig. 3). Trends of the frost events appear more negative than those of the phenological phases. The trend values between the various frost events do not differ much. Therefore in the analysis to follow the frost time series with a threshold value of $-1\,°C$ is thought of being representative for the frost events and selected for comparison with the phenological phases.

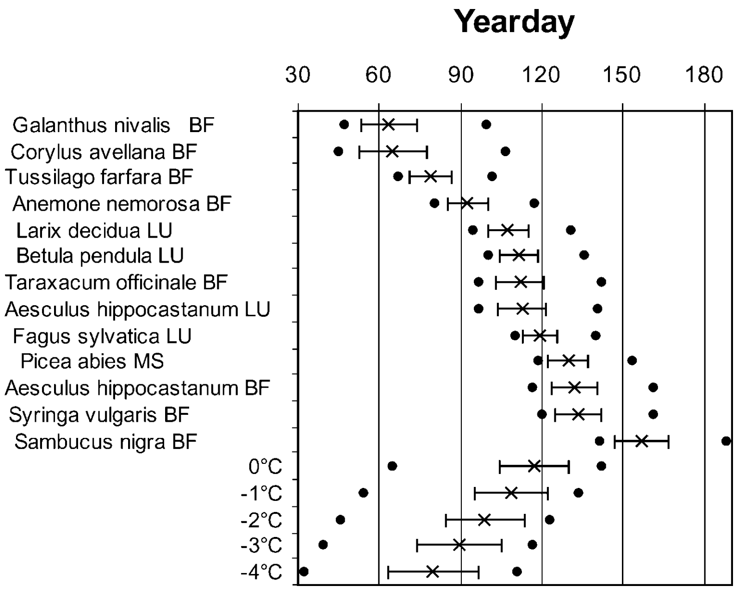

Fig. 2. Mean occurrence dates of phenological and frost events at 50 stations in Central Europe over the time period from 1951–1997. Frost events are indicated by their respective threshold values. The acronyms at the end of the plant names mean: LU = leaf unfolding, BF = beginning of flowering, MS = May sprouting, BP = beginning of pollination, NU = needle unfolding. The cross designates the mean value over all stations, the bars the standard deviation and the dots the minimum and maximum values. Phenological phases are sorted according to their occurrence dates

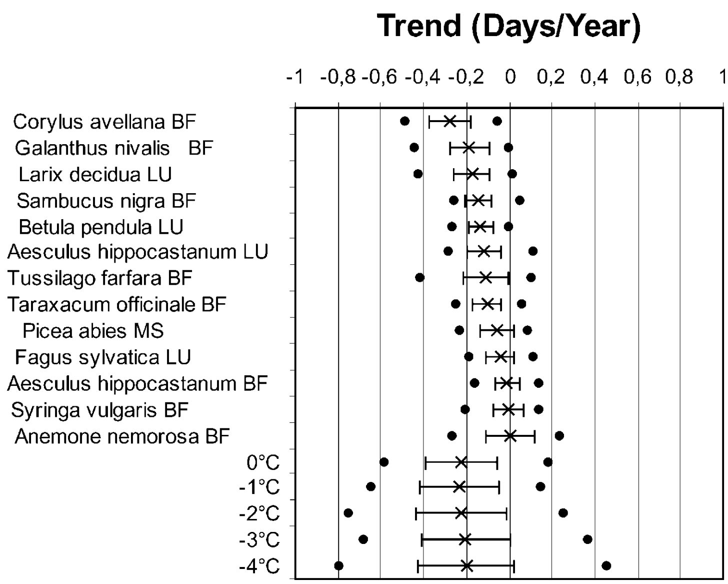

Fig. 3. Linear trends of phenological and frost events at 50 stations in Central Europe over the time period from 1951–1997. Frost events are indicated by their respective threshold values. The cross designates the mean value over all stations, the bars the standard deviation and the dots the minimum and maximum values. Phenological phases are sorted according to their trend values

Sample time series from 2 stations (Luzern and Wien Hohe Warte) are to provide an idea how phenological time series and time series of last occurrence dates of daily minimum temperatures do relate to each other (Fig. 4). In both cases the trends of the temperature time series are more negative than the phenological trends, which produce positive trends for the difference time series ‘phenological – temperature dates’. A positive trend of the difference time series means that dates of phenological events and temperature events are moving further apart. The intersection of both trend lines lies in the past. The correlation between phenological and temperature time series is generally low and insignificant.

Trends of phenological and last occurrence dates of daily minimum temperatures below $-1\,°C$ are compared in Fig. 5. Only 83 from 650 cases (13%) show significant trends for phenological and temperature time series at the same

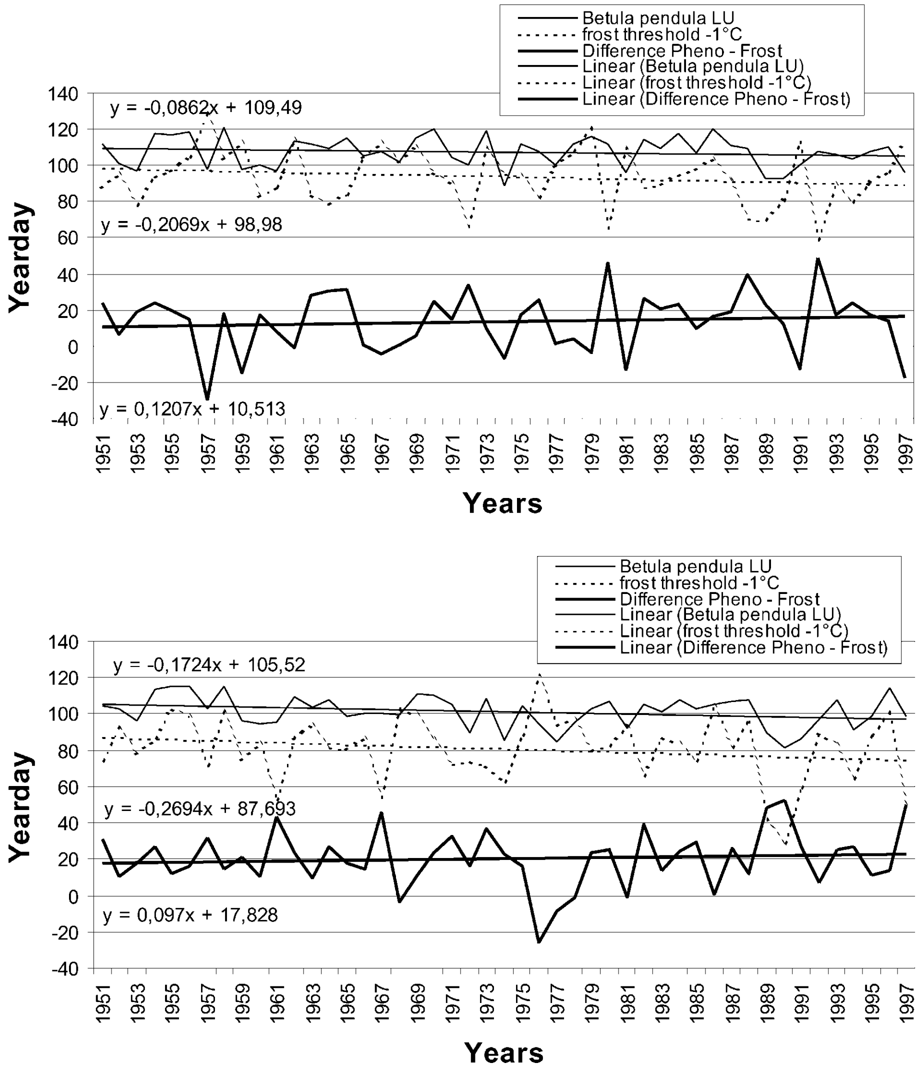

Fig. 4. Time series of phenological dates of '*Betula pendula* leaf unfolding' at Luzern (top) and Wien Hohe Warte (bottom), of last occurrence dates of daily minimum temperatures lower equal $-1\,°C$ and of the difference phenological – temperature dates. The respective regression equations are inserted. Time series begin in 1951 and end in 1997

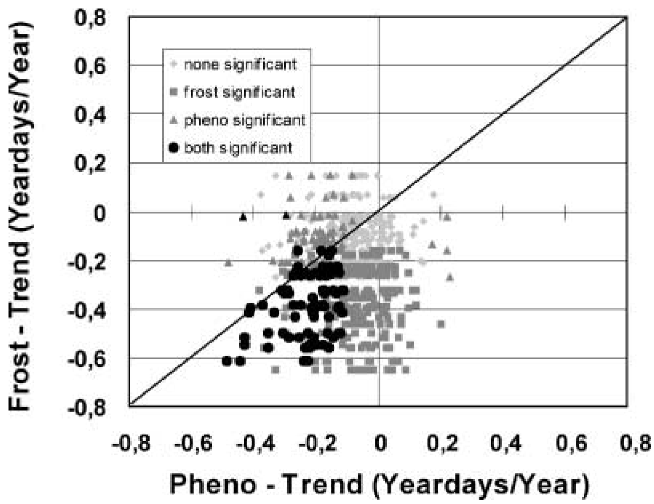

Fig. 5. Trends of phenological and last occurrence dates of daily minimum temperatures below $-1\,°C$ based on all 13 phenological phases. Trend values have been differentiated according to their significance ($p < 0.1$), which results in 4 groups with trends of both, phenological and temperature time series, significant respectively not significant and either trend value significant or not significant

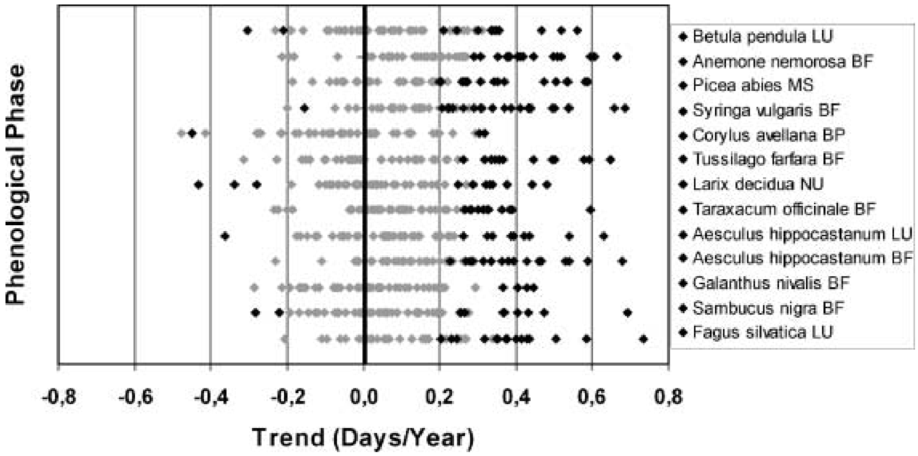

Fig. 6. Trends of difference time series (phenological occurrence dates – last occurrence dates of daily minimum temperatures below $-1\,^{\circ}$C) according to the 13 selected phenological phases at each of the 50 climate stations. Black dots indicate significant trends ($p < 0.1$), grey dots otherwise

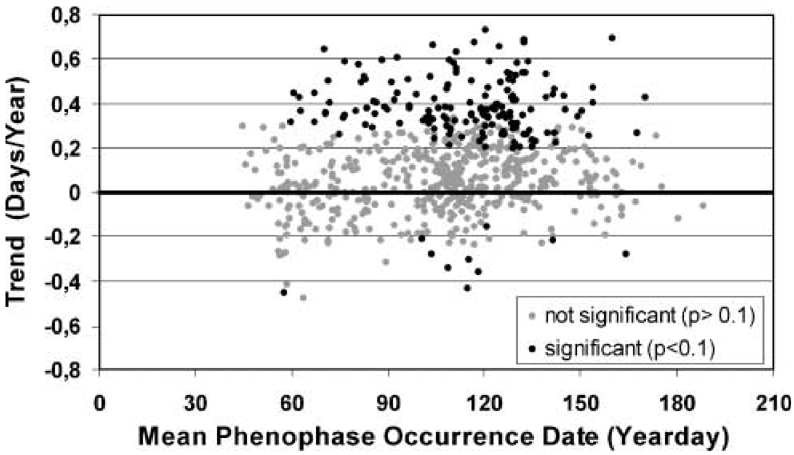

Fig. 7. Trends of difference time series (phenological occurrence dates – last occurrence dates of daily minimum temperatures below $-1\,^{\circ}$C) of 13 selected phenological spring phases at each of the 50 climate stations plotted according to the mean occurrence date of the phase

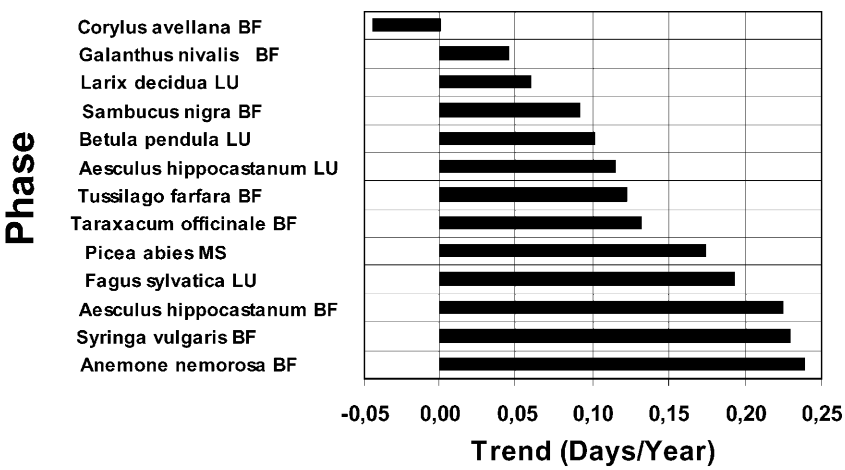

Fig. 8. Mean trends of difference time series (phenological occurrence dates – last occurrence dates of daily minimum temperatures below $-1\,^{\circ}$C) for each of the 13 selected phenological phases averaged over all 50 climate stations

time. The majority of trends of temperature time series are larger than those of the phenological time series.

The trends of the difference time series (phenological – temperature dates) illustrate the relation between the trends of phenological phases and the temperature dates (Fig. 6). Most of the phases show a distribution of the dots, which is inclined towards the right hand side of the graph, indicating that the timing of phenological and temperature events is moving apart. Only in case of early phases, like '*Corylus avellana* beginning of pollination' or '*Galanthus nivalis* beginning of flowering', the trend values are distributed differently. Although there is no obvious relation between the mean occurrence dates of the

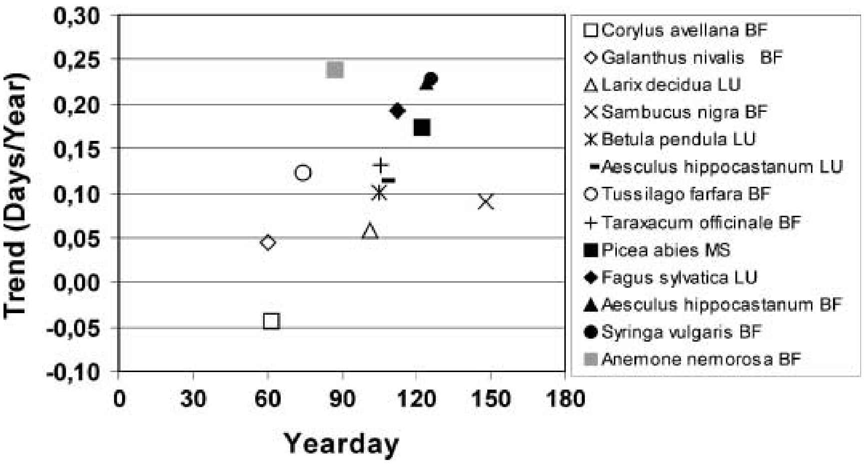

Fig. 9. Trends of difference time series (phenological occurrence dates – last occurrence dates of daily minimum temperatures below $-1\,°C$) for each of the 13 selected phenological phases averaged over all 50 climate stations and plotted according to the mean occurrence date of the phase

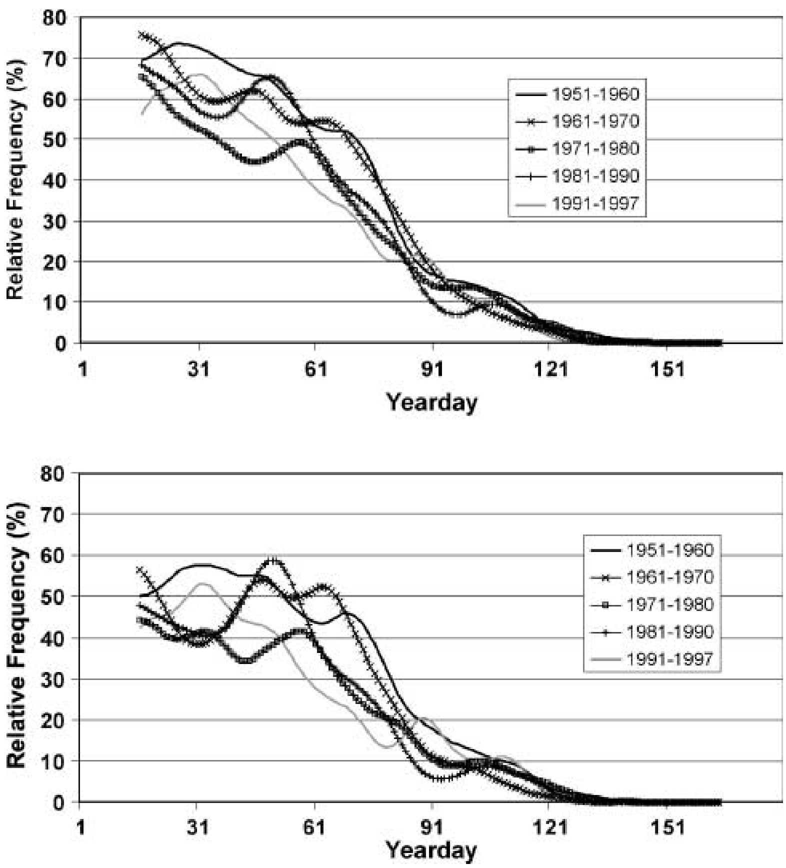

Fig. 10. Seasonal distribution of daily minimum temperatures below $-1\,°C$, calculated as relative frequency over all stations ($< 49°$ N top, $> 49°$ N bottom) for each decade

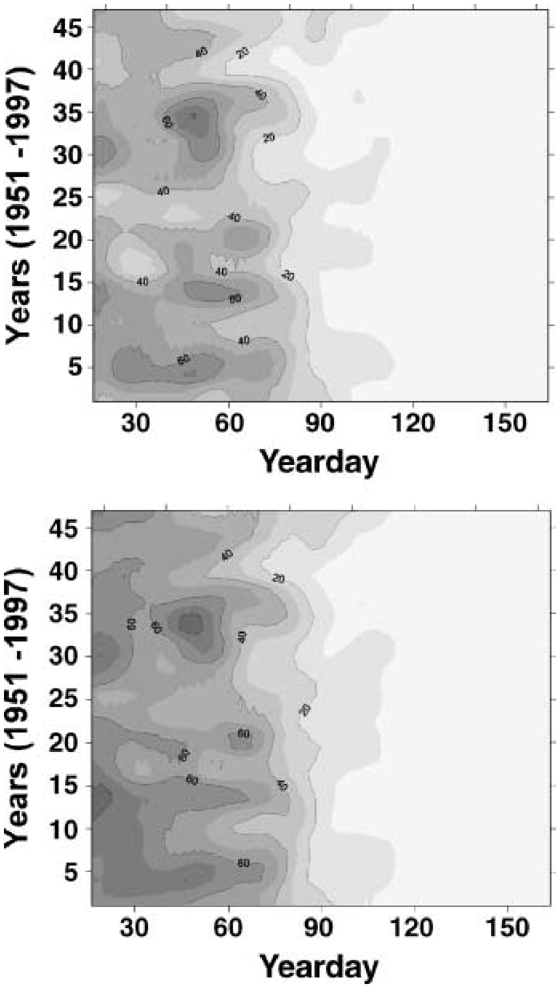

Fig. 11. Seasonal distribution of daily minimum temperatures below $-1\,°C$, calculated as relative frequency over all stations ($< 49°$ N top, $> 49°$ N bottom)

phenophase and the trends of the difference time series (Figs. 7 and 8), one finds in case of the mean trend over all stations for each phase that later phases are connected with stronger trends of the difference time series (Fig. 9).

The frequency of stations with frost occurrences drops with increasing yearday resulting in the curves of Fig. 10. The variability from decade to decade indicates a discontinuous warming since the fifties (Figs. 10 and 11). The last 'decade' (1991–1997) shows the lowest frequencies of minimum temperatures below $-1\,°C$ during February and March. End of March the seasonal drop seems to be halted for a few weeks and in April all decades merge and show a narrow range of deviation from each other. Southerly stations show a much more pronounced seasonal drop in frequency of frost events. On the other hand the frequencies are lower at the northerly stations and the reduction in frequency during the last decade is more pronounced.

The history of the temperature record preceding frost events might be more significant for ecosystems than single days with temperatures below a certain threshold. In the Northern Hemisphere a general decrease of the day-to-day temperature variability has been observed over the recent decades (Karl et al., 1995; Moberg et al., 2000). In order to see, whether this is of any significance for spring time frost events, a fixed sequence of events has been defined with a 5 day warm phase (mean daily temperature $\geqq 2\,°C$, daily minimum $\geqq 0\,°C$) followed on the 6th day by a daily mean value of $\leqq 0\,°C$ and a daily minimum $\leqq -3\,°C$. Although it is difficult to deduce any reliable trend in case of such a highly variable event, it seems to show a reduction in frequency from 1951 to 1997 (Fig. 12).

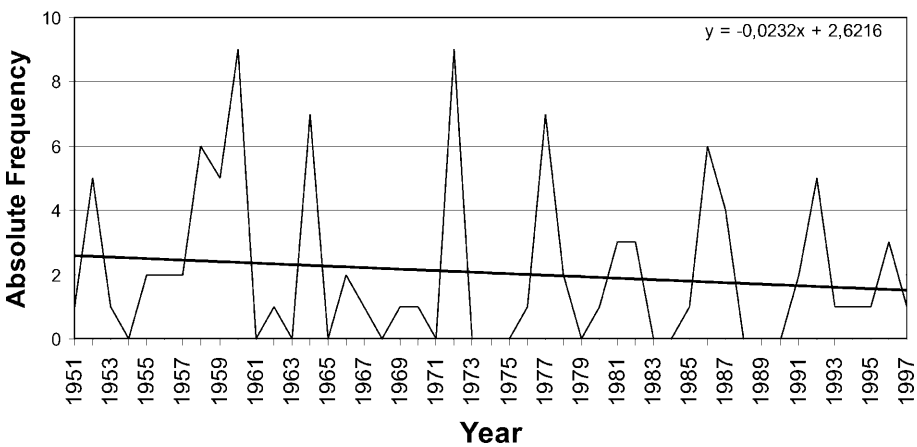

Fig. 12. Time series of absolute frequency of events with a 5 day warm phase (mean daily temperature $\geqq 2\,°C$, daily minimum $\geqq 0\,°C$) followed on the 6th day by a daily mean value of $\leqq 0\,°C$ and a daily minimum $\leqq -3\,°C$

4. Conclusions

Frost events based on the last occurrence dates of daily minimum temperatures below a certain threshold have been moving faster to earlier occurrence dates than phenological phases during the last decades in Central Europe. Trend values of time series of last frost occurrence dates range around -0.2 days/year and that of phenological time series are between -0.2 and 0.0 days/year. '*Corylus avellana* beginning of pollination' is the only one of the 13 phases considered here with a higher absolute trend value of -0.28 days/year. Early phases are more adapted to below zero temperatures and therefore follow more closely the temperature variability. Later phases seem to have more reason to be concerned about possible late frost events and react more cautiously towards higher spring temperatures and earlier last frost dates. The real risk of late frost damage for plants should therefore have been lower during the last decade as compared to the previous decades.

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