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Modelling of weather variability effect on fitophenology

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ABSTRACT

Phenology models are useful tools for various sectors of human activity, particularly for all environmental studies. An historical, 46-year phenological record, and meteorological data set for period 1955–2000 were used to analyse the abilities of the statistical models to predict flowering and leaf unfolding time for a set of wild and cultivated plants in Slovenia. With single *phenological* model, we have predicted timing of phenophase for particular plant on the base of previous phenological data of the same plant or on the base of previous phenological data of the other plants. The most frequently included independent variables in such models were common silver birch, dandelion and horse-chestnut. It was stated that these plants may be used as phenological indicators in given conditions. Correlation analysis and linear multiple regression were applied to establish the relationship among phenological development and climatic variables (temperature, rainfall, North Atlantic Oscillation, day length). Different thresholds temperatures have been selected for eight different locations with the smallest standard deviation in growing degree day's method to calculate thermal time. Various plant species responded differently to the same climatic factors and were best fitted to certain geographic region. The timings of spring phenophases strongly correlated with temperature of the precedent months, on the other hand rainfall and North Atlantic Oscillation explained smaller part of phenological variability. Photothermal time significantly improved results of *phenoclimatic models* when taken into account instead of thermal time. The validity of the results was tested with cross validation method and using independent data set for the year 2000, respectively. Considering the high year-to-year variability of phenological events, the models presented provide satisfactory estimations of the leaf unfolding and flowering dates. Formal equations presented in this study could be powerfully extended and applied to other sites and plants, provided that a sufficiently long time series of phenological and meteorological data were available.

1. Introduction

Phenology is the study of the timing of recurring biological phases, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species (Lieth, 1974). Early forecasting of the phenological phases of plant species is of great support to various sectors of human activity, particularly for all agricultural practices.

The aim of this paper was to predict leaf unfolding and flowering dates of different cultivated and wild plants linked with original data sample of meteorological variables and phe-

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nological dates. Such knowledge would provide a better understanding of plant development and improve the description of plant phenology in relation to climatic variability. In this study, climatic parameters, introduced into models with different methods including thermal and photothermal time calculations were used as the predictive parameters to obtain the best-forecast model.

Phenology models are needed in many studies that are relevant for agriculture, horticulture and silviculture: suitability for production and yield potential, length of growing season and frost free days, frost damage prevention, epidemiology of diseases and pests, timing of sowing, sprinkling, harvesting, pesticide use, irrigation and many others. Predicting the onset of pollen season is of particular importance to people allergic to given pollen, which can on the base of forecast start anti-allergic treatment several days before pollination, and thereby optimizing its effectiveness (Rodriguez-Rajo et al., 2003). Distinct changes in air temperatures since the end of the 1980s have led to clear response in plant phenology in many parts of the world. Since then many phenological papers report on trends in the timing of spring events (Menzel, 2000; Chmielewski et al., 2004). Phenological phases were proposed by the European Environment Agency as climatic difference and global change indicators (Menzel, 2003). Phenology models are also needed for estimation of past climate conditions, improvement of primary productivity models, support of ecologists in biodiversity studies and bioclimatic zonations (Häninnen, 1994). The timing of phenological events is clearly correlated with different climatic factors including air temperature, soil temperature, precipitation, solar radiation, evapotranspiration, day length, snow cover, etc. (Wielgolaski, 2001). In mid- and high latitudes, with a vegetation rest in winter and an active growing period in spring-summer time, plant phenology is mainly driven by temperature and photoperiod (Galan et al., 2001; Rodriguez-Rajo et al., 2003; Chmielewski et al., 2004). In many studies, accumulated temperature is recognized as the main factor influencing year-to-year variation in phenology (Galan et al., 2001; Schaber and Badeck, 2003). Phenological models have been also published for the impact of photoperiod on phenophase appearance (Masle et al., 1989; Kramer, 1994; Huang et al., 2001). However, photoperiod without interaction with temperature cannot explain the annual variability of phenology at a given location because photoperiod is the same each year.

The North Atlantic Oscillation (NAO) as major driving force of the climate system of the northern hemisphere determines the major part of the inter-annual variation of winter temperatures in North Atlantic region (Hurrell and van Loon, 1997). A simple index of the NAO (NAOI) is defined as the difference of normalized air pressures between centre of high pressure across the subtropical Atlantic and centre of low pressure across the region of the Iceland (Hurrell, 1996). Winters with a positive NAOI reflect in the warm and wet conditions in Northern and Central Europe. During the last few years an increasing number of studies have been revealing correlations between NAOI and phenological spring phases (Piovesan and Schirone, 2000; Črepinšek et al., 2002; Menzel, 2003).

Two main types of phenology models exist: dynamic and statistical. The first ones describe known or assumed cause–effect relationships between biological processes and driving variables in the plant's environment. Parameters of dynamic models have physical dimensions that can be measured directly instead of being estimated by fitting. Statistical phenology models relate the timing of phenological events to different environmental factors, mainly climatic. Model parameters are estimated from empirical data using various statistical fitting methods, some are simple correlations with air temperature (Galan et al., 2001), and some are more complex, including numerous input parameters (Schwartz, 1999).

According to input data, the forecasting mathematical models can be distinguished as *phenological* and *phenoclimatic*. The *phenological* models are based on the correlations between the phenophases of species other than that under consideration. These models are empirical and their formulation requires statistical analyses of long series of observational data to identify the marker species. The *phenoclimatic* models are based on the relationships between the phenological phases of the treating species and the various climatological parameters. The most important assumption in plant phenoclimatic modelling is that differences between years and locations in the date of phenological event could be explained by differences in daily temperatures from an arbitrary date to the date of the phenophase considered (Gárcia-Mozo et al., 2002).

2. Data and methods

The data base includes the phenological dates for a set of the wild and cultivated plants observed at eight different locations in Slovenia between 1955 and 2000 by the Environmental Agency of the Republic of Slovenia (ARSO). All the meteorological data for the entire period come from the very same locations representing different climatic regions across Slovenia.

2.1. *Phenological data*

Indicator plants and phenophases are presented in Table 1 locations are at the same time phenological and meteorological stations providing complete records for the entire period. Six different phenophases and 17 plants, respectively, were chosen to represent four groups of phenological objects: wild herbaceous plants (ox-eye daisy, snowdrop, dandelion, spring-saffron), forest trees and shrubs (common silver birch, beech, common elder, horse-chestnut, goat willow, hazel, large-leaved lime, black locust, Norway spruce, common lilac), grasses (cock's-foot) and fruit trees (plum tree, apple tree). The phenological data used were verified by the ARSO, no gaps were filled up. The statistical analysis of phenological data was carried out with the standard tools of Statgraphics Plus; averages, standard deviations, minima and maxima were calculated. Phenological data set was used to calculate four phenological indices: *leaf unfolding index* (the annual mean of the leaf unfolding dates for beech, common silver birch, large-leaved lime and horse-chestnut), *early spring flowering index* (the annual mean of the flowering dates for common silver birch, dandelion, goat willow, hazel and snowdrop), *late-spring flowering index* (the annual mean of the flowering dates for black locust, common elder, common lilac and large-

Table 1 – Phenological data: indicator plants, phenophases, locations

Indicator plants: Species (Engl.)	Species (Latin)	Phenophases, selected for analysis
Apple tree	*Malus domestica* Borkh	LU, F1, F2, FR, M
Beech	*Fagus sylvatica* L.	LU, LC
Black locust	*Robinia pseudacacia* L.	F2
Cock's-foot	*Dactylis glomerata* L.	F1
Common elder	*Sambucus nigra* L.	F2
Common lilac	*Syringa vulgaris* L.	F2
Common silver birch	*Betula pendula* Roth.	LU, F1, LC
Dandelion	*Taraxacum officinale* Weber/Wiggers	F1
Goat willow	*Salix caprea* L.	F1
Hazel	*Corylus avellana* L.	F1
Horse-chestnut	*Aesculus hippocastanum* L.	LU, F1
Large-leaved lime	*Tilia platyphyllos* Scop.	LU, F1, LC
Norway spruce	*Picea abies* (L.) Karsten	LU
Ox-eye daisy	*Leucanthemum ircutianum* Turcz.	F1
Plum tree	*Prunus domestica* L.	LU, F1, F2, FR, M
Snowdrop	*Galanthus nivalis* L.	F1
Spring-saffron	*Crocus napolitanus* Mordant&Loisel.	F1

Phenophases
Leaf unfolding, needle emergence (LU)
Beginning of flowering (F1)
Full flowering (F2)
First ripe fruits (FR)
Maturity (M)
Autumnal leaf colouring (LC)

Locations (represent at the same time phenological and meteorological stations)

Station	Geographic coordinates	Elevation
Celje	46°15′N, 15°15′E	242 m a.s.l.
Ilirska Bistrica	45°34′N, 14°15′E	414 m a.s.l.
Lesce	46°22′N, 14°11′E	515 m a.s.l.
Ljubljana	46°04′N, 14°31′E	299 m a.s.l.
Maribor	46°32′N, 15°39′E	275 m a.s.l.
Murska Sobota	46°39′N, 15°12′E	190 m a.s.l.
Novo mesto	45°48′N, 15°11′E	220 m a.s.l.
Rateče	46°30′N, 13°43′E	864 m a.s.l.

leaved lime) and *growing season index* (the mean value of the above mentioned phenological indices for 11 species at 8 locations). Analysis of variance was performed to test variation in phenological dates between stations and linear trend analysis was used to investigate time series of phenological data.

2.2. Climate data

Altogether eight stations (Table 1) were considered which are well distributed across Slovenia and their climate varies considerably. Dry and warm region, such as the Northeast of Slovenia (Murska Sobota with altitude 190 m) with annual mean temperature of 9.2 °C and precipitation sums of approximately 800 mm is included, as well as Alpine climate station (Rateče, NW-Slovenia, with altitude 864 m) with annual mean temperature of 5.7 °C and yearly total rainfall of nearly 1600 mm. Daily maximum, minimum, monthly minimum, mean and maximum temperatures, and the monthly total rainfall were used to obtain predictive models for forecasting leaf unfolding and flowering by multiple regression analysis, 2- and 3-monthly running means of temperature and rainfall were calculated. We used also 1955–2000 monthly and seasonal NAO-indices (Jones et al., 1997) as additional variables to be considered in equations.

2.3. Methods

2.3.1. Development of the statistical model

Multiple linear regression (Wilks, 1995; von Storch and Zwiers, 1999) was used to relate the occurrence dates of selected phenophases (*predictand*) with meteorological variables and previously observed occurrence dates of phenophases of other plants (*predictors*) at selected location. *Predictands* were: *beginning of flowering* of apple tree, plum tree, dandelion, cock's-foot, common silver birch and large-leaved lime, *full flowering* of apple tree, plum tree, hazel, black locust and common elder, and first leaf unfolding of beech, common silver birch and large-leaved lime.

If vector **y** contains a set of predictand values observed in the past, and the columns of matrix **X** contain simultaneously observed values of relevant predictors together with a column of ones, the empirical model can be written as:

$$\hat{\mathbf{y}} = \mathbf{X} \cdot \boldsymbol{b}, \qquad \boldsymbol{b} = (\mathbf{X}' \cdot \mathbf{X})^{-1} \cdot \mathbf{X}' \cdot \mathbf{y} \tag{1}$$

In the Eq. (1), vector $\hat{\mathbf{y}}$ presents the model estimates of observed $\boldsymbol{y}$, $\boldsymbol{b}$ the vector of regression coefficients estimated on the base of observed $\mathbf{y}$ and $\mathbf{X}$, and $\mathbf{X}'$ denotes transposed matrix (Krzanowski, 1998).

Stepwise selection (Wilks, 1995; von Storch and Zwiers, 1999) was used to select the relevant predictors within the entire set of available predictors. The prediction performance of developed statistical models was evaluated by leave-one-out cross-validation approach (Wilks, 1995; von Storch and Zwiers, 1999). Pearson's correlation coefficient (r) between original values y_i and cross-validation estimates $y_{(i)}$ was used as a measure of prediction performance. Beside commonly used determination coefficient (R^2), showing percentage of predictand variability explained by the model, Studentized residuals and Cook's distance (Krzanowski, 1998) were used as an additional measure of the quality of statistical models.

2.4. *Estimating parameters for models*

2.4.1. *Growing degree days*

Degree days (DD) models assume a linear relation between temperature and rate of development, and that an event occurs when a certain number of 'heat units' above a lower threshold or base temperature (T_b) have accumulated (McMaster and Wilhelm, 1997). Heat units are expressed in °D, where 1 °D is equal to 1 °C above T_b over 24 h (Snyder et al., 1999). Growing degree days (GDD) were calculated according to the Eq. (2) proposed by McMaster and Wilhelm (1997):

$$\mathrm{GDD} = \sum((T_{i,\max} + T_{i,\min}) \times 0.5 - T_b) \tag{2}$$

where $T_{i,\max}$ is the daily maximum air temperature and $T_{i,\min}$ is the daily minimum air temperature. T_b is the temperature below which the process of interest does not progress, and if $\lfloor (T_{i,\max} + T_{i,\min}) \times 0.5 \rfloor < T_b$, then $\lfloor (T_{i,\max} + T_{i,\min}) \times 0.5 \rfloor = T_b$. The comparison to T_b occurs after calculating average temperature (T_{avg}) from $T_{i,\max}$ and $T_{i,\min}$. We have tested two additional methods for thermal time calculation within sight of simplicity: GDD was calculated from the difference between T_{avg} and uniform lower threshold ($T_b = 0$ °C) and between $T_{i,\min}$ and $T_b = 0$ °C, respectively, (Masle et al., 1989; Snyder et al., 1999). In the present study, GDD were calculated following the method proposed by Snyder et al. (1999) from the 1st January to the particular phenological event. The selection of an appropriate T_b is critical to the GDD or any heat unit model.

2.5. *Base temperatures*

In order to estimate the most significant lower T_b for single phenophase at each site a wide range of possible *threshold temperatures* were tested (from −5 °C to 10 °C by step 1 °C) with the smallest standard deviation of GDD method proposed by Yang et al. (1995). The standard deviation from the mean observed GDD (SD_{GDD}) for different threshold temperatures was calculated as:

$$SD_{GDD} = \sqrt{\frac{\sum \mathrm{GDD}_i - \mathrm{GDD}_{mean}}{n-1}} \tag{3}$$

Here, GDD_i is the GDD for the ith case, GDD_{mean} the mean of the cumulative GDD for the whole period and n is the number of years. In this method, GDD is calculated using a series of candidate base temperatures, each one resulting in a set of GDDs and standard deviations. The temperature that generates GDDs with the smallest standard deviation is selected as the most accurate base temperature.

2.6. *Photothermal time*

Many modifications to enhance the biological meaning of the Eq. (2) have been suggested, among them also GDD converting to photothermal units by adding a photoperiod variable. Photothermal time (PT) was summed according to the equation proposed by Masle et al. (1989) as:

$$\mathrm{PT} = \sum l_i \cdot (T_{l,i} - T_b) \tag{4}$$

where l is the light period as a proportion of a day, T_l is the average temperature in the light period and T_b is the base temperature. T_l is obtained from $T_{\min}$ and $T_{\max}$ using $T_l = T_{\min} + k \cdot (T_{\max} - T_{\min})$, where k can be estimated empirically or from a physical model (Masle et al., 1989). Method after Fernhout and Kurtz (2001) was used for the light period calculations.

3. Results

3.1. *Basic statistics and trends*

In order to build the statistical models properly, the basic statistical parameters were tested for each phenophase. The extreme dates of phenophase appearance for leaf unfolding of birch, beech, horse chestnut, linden and spruce differed on the average from 29 to 39 days. Similar values were determined also for autumnal leaf colouring for birch, beech and linden, where the interval between the earliest and the latest date of leaf colouring was in average 33–40 days. Inter-annual variability was highest for phenophases appearing in early spring. For spring-saffron, the earliest and the latest dates of flowering differed for about 50 days, for pussy willow and snowdrop about 60 days and for hazel even 80 days. For late-spring phases of flowering the interval between extreme dates was not so spacious, the magnitude was the same as for leaf unfolding and leaf colouring.

The temporal trends of mean phenological phenomena were calculated by linear regression against time to check for effects of temperature changes in the environment to plant development timing. All but one of the trends of the spring records were significant negative indicating an earlier onset of leaf unfolding and flowering during the past decades. The mean linear trends (days/decade) ranged from −1.4 for leaf unfolding, −2.2 for late-spring flowering and −3.1 for early

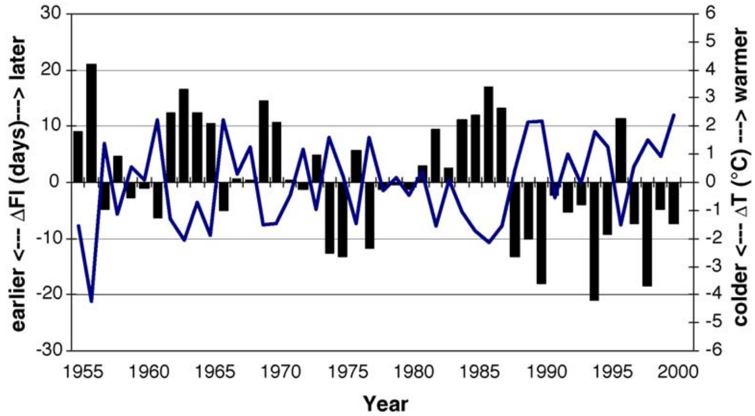

Fig. 1 – Deviations in early spring flowering index (ΔFI in days) and in the average air temperature (Δ*T* in °C). The regression equation is $\Delta FI = 7.83 - 0.32\Delta T$. Vertical bars represent the annual early spring indexes (the mean of flowering dates for: *Betula pendula*, *Taraxacum officinale*, *Salix caprea*, *Corylus avellana* and *Galanthus nivalis*) expressed as deviations in days from the mean value. The line represents the annual deviations of temperature (°C) from the spring mean temperature (February–April), 1955–2000.

spring flowering (Fig. 1). This represents movement forward of 6 days in the timing of leafing and of 10–14 days in the timing of flowering. Growing season index showed a significant negative trend of 2.2 days per decade, corresponding to 10 days earlier beginning of growing season over the last five decades in Slovenia.

3.2. *Relation to air temperature and NAO*

The correlation analyses were carried out to establish the relationships between phenophases appearance and some meteorological variables. Mean monthly air temperatures corresponded more to spring flowering phenophases (correlation coefficients between −0.6 and −0.85, $P < 0.001$) than to leaf unfolding. Correlation was weaker and positive for autumnal phases, which means higher temperatures, delayed the end of growing season. In most cases, both flowering and leaf unfolding was accelerated by 3–5 days per °C increase in mean monthly or bimonthly temperature from the starting date. Flowering of hazel seemed to be most strongly accelerated by higher temperatures—nearly 8 days earlier per °C increment within the period January–February (Fig. 2). Flowering of the apple and plum tree, as an additional example, was less influenced (about 4–6 days earlier per °C in the period February–March). Recently, similar observations were made for plants along a Norwegian fjord (Wielgolaski, 2003), and trees, shrubs, fruit trees and field crops in Germany (Menzel, 2003; Chmielewski et al., 2004).

We have analyzed also the influence of NAO on spring phenology in Slovenia. The correlation between winter NAOI ($NAOI_{win}$) and temperature was highly significant for all stations for the months from December to March, the average correlation coefficient was +0.58. High $NAOI_{win}$ promoted the most early–spring plant development (Fig. 3), correlations were weaker for late-spring phenophases.

3.3. *Base temperatures*

Lower threshold temperature was determined statistically (Eq. (3)) to estimate parameters for predictive models. For plants flowering in early spring, most of calculated T_b were negative; the lowest T_b were defined for flowering of hazel (average on all stations was about −3 °C), for the rest of the plants T_b were between −3 °C and +2 °C. These findings agree with results of other studies (Larcher, 1995; Snyder et al., 1999). Calculated T_b of −2.6 °C for hazel, −4.5 °C for goat willow, and −5.9 °C for

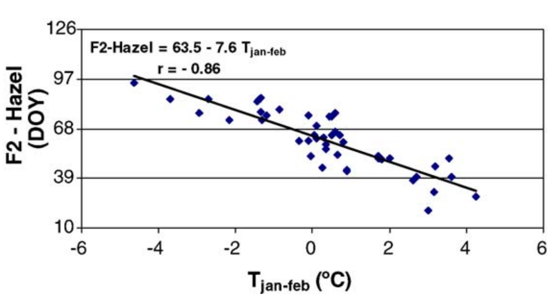

Fig. 2 – Correlation between full flowering of hazel (F2-Hazel) and the average temperature from January to February in Ljubljana, 1955–2000. The correlation coefficient of $r = -0.86$ is significant with $^{***}P < 0.001$. DOY: day of the year.

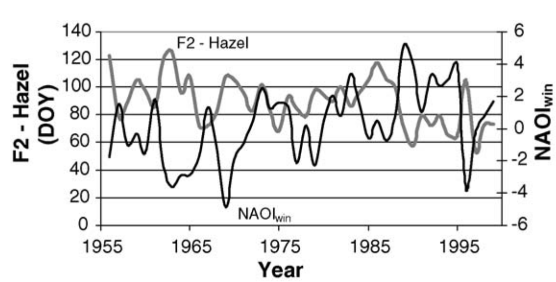

Fig. 3 – Inversely proportionality of curves of full flowering of hazel (F2-Hazel) and winter North Atlantic Oscillation Index ($NAOI_{win}$) in Rateče, 1956–1999. The correlation coefficient of $r = -0.63$ is significant with $^{**}P < 0.05$. DOY: day of the year.

Table 2 – Average growing degree days above the statistical selected base temperature for leaf unfolding of large-leaved lime and the relative coefficient of variation for the studied years data set

Location	Selected base temperature (°C)	Average growing degree days (GDD_{stat})	Coefficient of variation (%)
Celje	3	241	15
Ilirska Bistrica	2	321	12
Lesce	5	102	11
Ljubljana	3	258	11
Maribor	3	251	19
Murska Sobota	3	234	11
Novo mesto	3	254	21

The base temperature was chosen according to the smallest standard deviation (Eq. (3)) of GDD method (Eq. (2)).

bird cherry were reported by Wielgolaski (1999). T_b between +3 °C and +4 °C were adequate to calculate thermal time for leaf unfolding of birch, beech and linden. For later phases (flowering in the period May–June) determined T_b was somewhat higher: between 5 °C and 7 °C on average. Selected T_b varied among sites, results for large-leaved lime unfolding as an example are shown in Table 2.

3.4. *Thermal and photothermal time*

Thermal time was calculated according to the Eq. (2) in the first place on the base of statistically determined T_b (GDD_{stat}) and after that above unified $T_b = 0$ °C (GDD_{uni}). GDD_{uni} were lower in Rateče, compared to the other stations; largest sums were mostly reached in Ilirska Bistrica and Ljubljana (Fig. 4), confirming that the same plant species needs larger amount of heat unit accumulation for its development on warm locations than in colder areas (Arnold, 1959; Perry et al., 1986).

Coefficients of variability (Cv) of GDD_{uni} among years were relatively high (from 10% to 25%), higher for earlier phases. Average correlation coefficients (Cc) between GDD_{uni} and phenophase appearance were relatively low (less than 0.5). For GDD_{stat}, calculated on the base of statistically determined T_b for every single phenophase and location, variability was

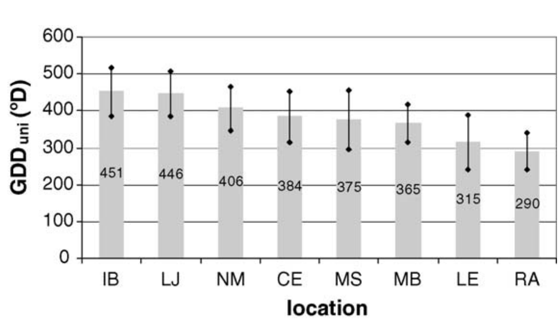

Fig. 4 – Average growing degree days above $T_b = 0$ °C (GDD_{uni} in D°) for silver birch unfolding at different locations (IB, Ilirska Bistrica; LJ, Ljubljana; NM, Novo Mesto; CE, Celje; MS, Murska Sobota; MB, Maribor; LE, Lesce; RA, Rateče), 1955–1999.

also high; Cv was between 12% and 30%. Describing phenological progress with GDD_{stat} instead with GDD_{uni}, resulted in higher Cc (from 0.5 to 0.65). We calculated photothermal time for location Ljubljana only; we took into consideration the temperature for the light part of the day only (Eq. (4)). For all phases, Cc was higher when we used photothermal instead of thermal time; and Cv was lower (on the average 8% compared to 14%).

3.5. *Models and validation*

In detailed analysis of phenophases dependence on meteorological parameters we used multiple linear regression to make phenological and phenoclimatic models. We formed models for 10 different plants and 14 phenophases, respectively, where forecasting could be useful for particular measures in agrometeorology (flowering of apple and plum tree, dandelion), medical meteorology (flowering of hazel, birch, cock's-foot), pharmacy (flowering of large-leaved lime, common elder, black locust) or in climate change researches (first leaf unfolding of beech, birch and large-leaved lime).

With single *phenological* model individual phenological phenomenon was predicted for particular plant on the base of previous phenological data of the same plant or on the base of previous phenological date of other plants, provided that predictions should be possible at least 3 days ahead to assure applicability. Because of large number of developed models we will present precisely only two of them. As an example of pure phenological models, Table 3 shows forecasting models for the beginning of flowering of dandelion and plum tree, obtained from multiple regression analysis, taking into account the period 1955–1999. Only models with the explained variance equal or greater than 50% (adjusted $R^2 > 0.5$) are presented here. Seven different plants (birch, dandelion, hazel, horse-chestnut, linden, spring-saffron and willow) were included as independent variables in plum flowering models with a determinant coefficient ranged from 0.72 for Celje and Lesce to 0.87 for Rateče. Predictive formulae to be applied for dandelion flowering used previous phenological dates of birch, hazel, snowdrop, spring-saffron and willow (maximal R^2 for Maribor was 0.73).

In combined *phenoclimatic* models (Table 4), monthly, 2- and 3-monthly average air temperatures, monthly amount of precipitations, thermal time (GDD_{uni} and GDD_{stat}), North Atlantic Oscillation Index (NAOI) and photothermal time (PT) for the Ljubljana location only, were included as the independent variables. In all *phenoclimatic* models thermal time respectively photothermal time for Ljubljana was presented as independent variable.

Cross validation method was used to test the models, average correlation coefficient between observed and predicted phenophase data amounted above 0.90 which indicates that models represent actual conditions well.

Analysis of residuals at cross validation has shown that maximal deviations occurred during extremely warm and cold years; the same pattern appeared on all locations. The calculated mean absolute error values of the *phenoclimatic* regression models between 3.4 days and 7.6 days, as well as the explained variance: 42–93%, are similar to those obtained with other phenology models (Snyder et al., 1999; Menzel, 2000;

Table 3 – Predictive formulae for the beginning of flowering of dandelion and plum tree (date from 1st January), based on the previous phenological data of wild species (1955–1999)

	Predictors ($X_1, X_2, \ldots, X_n$) (phenological phases)	Intercept (a)	Slope ($b_1, b_2, \ldots, b_n$)	R^2
$F1_{dandelion}$				
Celje	$F1_{snowdrop}$; $F1_{willow}$	63.4	0.16; 0.40	0.72
Ilirska Bistrica	$F1_{willow}$	47.3	0.65	0.50
Lesce	$F1_{snowdrop}$; $F1_{s.saffron}$	70.7	0.30; 0.20	0.53
Maribor	$F1_{snowdrop}$; $F1_{willow}$; $F1_{birch}$	37.3	0.16; 0.19	0.73
Novo mesto	$F2_{hazel}$; $F1_{s.saffron}$	62.6	0.25; 0.29	0.54
$F1_{plum}$				
Celje	$F1_{dandelion}$	−6.4	1.1	0.72
Ilirska Bistrica	LU_{birch}; $LU_{h.chestnut}$; $F1_{dandelion}$	4.5	0.37; 0.34; 0.33	0.84
Lesce	LU_{linden}; $F1_{s.saffron}$; $F1_{dandelion}$	34.6	0.40; 0.23; 0.16	0.72
Maribor	LU_{birch}; $F1_{dandelion}$	15.8	0.56; 0.37	0.80
Murska Sobota	$LU_{h.chestnut}$; $F1_{birch}$; $F2_{hazel}$	0.66	0.50; 0.45; 0.16	0.84
Novo mesto	LU_{birch}; $F2_{hazel}$	18.0	0.77; 0.15	0.76
Rateče	$F1_{h.chestnut}$; $F1_{dandelion}$; $F1_{willow}$	−7.2	0.90; 0.35; 0.15	0.87

R^2, adjusted coefficient of determination; F1, beginning; F2, full flowering; LU, first leaf unfolding.

Table 4 – Predictive formulae for the beginning of flowering of dandelion and plum tree (date from 1 January), based on the phenological and meteorological data (1955–1999)

	Phenological predictors ($X_1, X_2, \ldots, X_{n-1}$)	Meteorological predictors ($X_n, X_{n+1}, \ldots, X_k$)	Intercept (a)	Slope ($b_1, b_2, \ldots, b_k$)	R^2
$F1_{plum}$					
Celje	$F1_{dandelion}$; $F2_{hazel}$	GDD_{uni}; T_{mar}	7.6	0.09; 0.71; 0.07; −1.54	0.88
Ilirska Bistrica	LU_{brich}; $LU_{h.chestnut}$; $F1_{dandelion}$		4.5	0.37; 0.34; 0.33	0.84
Lesce	LU_{linden}; $F1_{s.saffron}$; $F1_{dandelion}$	GDD_{uni}	0.37	0.43; 0.38; 0.16; 0.04	0.84
Maribor	LU_{brich}; $F1_{dandelion}$	GDD_{uni}; $NAOI_{win}$	−9.7	0.57; 0.37; 0.69; 0.05	0.84
Murska Sobota	$LU_{h.chestnut}$; $F1_{birch}$; $F2_{hazel}$	GDD_{uni}	−16.6	0.43; 0.49; 0.19; 0.04	0.87
Novo mesto	LU_{brich}; $F2_{hazel}$	GDD_{stat}; T_{mar}	23.3	0.52; 0.19; 0.02; −1.14	0.88
Rateče	$F1_{h.chestnut}$; $F1_{dandelion}$	GDD_{uni}; T_{apr}	23.0	0.53; 0.29; 0.05; −1.91	0.93
$F1_{dandelion}$					
Celje	$F1_{snowdrop}$; $F1_{willow}$	GDD_{uni}; T_{mar}	72.0	0.15; 0.26; 0.03; −1.83	0.83
Ilirska Bistrica	$F2_{hazel}$	GDD_{stat}; T_{feb}; T_{mar}	63.5	0.16; 0.07; −1.61; −3.22	0.89
Lesce		T_{feb}; T_{mar}	118.3	−1.67; −2.75	0.69
Ljubljana	$F1_{willow}$	GDD_{uni}; T_{feb}; T_{mar}; PT	65.1	0.17; −0.08; −0.8: −1.94: 0.24	0.92
Maribor	$F1_{snowdrop}$; $F1_{brich}$; $F1_{willow}$	GDD_{uni}; T_{mar}	23.3	0.15; 0.21; 0.35; 0.07; −1.17	0.84
Novo mesto	$F2_{hazel}$	GDD_{stat}; T_{feb}; T_{mar}	67.3	0.15; 0.06; −1.11; −2.68	0.86
Rateče		GDD_{uni}; T_{feb}; T_{mar}	95.5	0.16; −1.67; −3.07	0.72

R^2, adjusted coefficient of determination; F1, beginning; F2, full flowering; LU, leaf unfolding; T_{feb}, T_{mar}, T_{apr}—average temperature February, March, April; $NAOI_{win}$, Winter North Atlantic Oscillation Index; GDD, growing degree days; PT, photothermal time.

Table 5 – Observed and predicted dates for selected phenophases for the year 2000 (not included in the model) at the station Celje

Phenophase	Observed date	Predicted date	Difference (days) (observed–predicted)	Mean absolute error (days)
$F1_{brich}$	99	96	−3	4
LU_{brich}	103	103	0	5
LU_{beech}	104	102	−2	7
$F1_{plum}$	101	98	−3	5
$F2_{plum}$	104	106	+2	6
$F1_{apple}$	110	114	+4	5
$F2_{apple}$	115	115	0	7
$F2_{hazel}$	49	51	+2	7
$F1_{linden}$	139	143	+4	6
LU_{linden}	108	106	−2	6
$F1_{cock's\text{-}foot}$	128	128	0	7
$F1_{dandelion}$	94	92	−2	4
$F2_{b.locust}$	129	134	+5	4
$F2_{lilac}$	111	107	−4	5

Rötzer et al., 2004). Analysis was also performed using data from 1955/1999 in order to test the models on independent data set (year 2000) for Celje, the only location with data for all treating phenophases. Predictions of all models were very good (Table 5), maximal difference between observed and predicted values was 5 days for flowering of black locust, otherwise the differences had both positive values (model gives later date than the actual) and negative values (model gives earlier date than the actual).

4. Discussion

The timing of spring events such as flowering and leaf unfolding of plants varied greatly among the years and different locations in Slovenia. The phases occuring earliest in the year, such as flowering of *G. nivalis* or *C. Avellana*, show a higher inter-annual variability than phases observed in late spring or summer. These findings agree with results of other studies across the Europe (Wielgolaski, 1999; Menzel, 2003; Rötzer et al., 2004). Because this phenological variability is mainly caused by temperature-induced variations (Chmielewski et al., 2004), diverse temperature oscillations regarding seasons could be among the reasons for differences. In the present study, month of February displayed the greatest year-to-year variation in mean monthly temperatures for studied locations. We ascertained also differences among the spring trends of different phenophases observed, the higher trends were found for early spring flowering of hazel, goat willow and snowdrop, indicating that changes of events occurring in the early spring are more distinct and related to considerable change in late-winter and early spring temperatures. Phenophases of flowering appear to be more sensitive to air temperature variability than leaf unfolding. The results of our paper confirm findings of other authors, concerning the influence of air temperature on the timing of spring events (Chmielewski and Rötzer, 2001; Črepinšek and Kajfež-Bogataj, 2003; Menzel, 2003; Chmielewski et al., 2004).

On the basis of the simple correlations between climatic factors and phenological phases, temperature seems to be the major driving force for the onset of spring phenophases. These results of a strong correlation between the onset of spring phenological phases and spring temperatures broadly agree with results of other studies (Bergant et al., 2002; Rodriguez-Rajo et al., 2003; Wielgolaski, 2003). However, for some plants flowering seemed to be accelerated most strongly (for hazel about 8 days earlier flowering per °C increase in mean 2-monthly temperature) while flowering of others was less influenced (for plum tree 4 days earlier per °C). Different responses of various plants species (or even cultivars of the same species) means that there might be rather large changes in biodiversity because of global warming (Kramer et al., 2000). Beside air temperature many other climatic parameters like precipitation, air humidity, soil temperature or radiation can have an influence on phenology (Wielgolaski, 1999). The correlation analysis between monthly amount of precipitations and phenological dates has shown that on average water availability was not a problem for plants in springtime in Slovenia. The amount of monthly precipitation in discussed conditions was not significant correlated to the date of flowering and leaf unfolding, although it could be of importance in extremely dry years (locations) and for other plants respectively. The NAO as major driving force of the climate system of the northern hemisphere determines most of the inter-annual variation of winter temperatures in the broad Atlantic region (Hurrell, 1996; Menzel, 2003) and to a certain extent also in Slovenia (Črepinšek et al., 2002). Our results also support findings of a strong seasonal variation of NAO, especially with earlier spring phases being more sensitive to NAO (Post and Stenseth, 1999; Črepinšek, 2002; Menzel, 2003).

To predict plant development with air temperature, GDD or a similar linear unit system is widely used, where the selection of an appropriate T_b is critical to calculate the GDD (Yang et al., 1995). In our study, T_b appeared to vary from −3 °C for flowering of hazel to 7 °C for flowering of lilac and lime tree. Negative T_b were also estimated by others researchers (Snyder et al., 1999; Wielgolaski, 1999). Although there is nothing wrong with using negative threshold temperatures in terms of modelling phenological development, the question is about physiological meaning of so lower thresholds (Snyder et al., 1999). However, some authors pointed out that there may be some physiological activity of the plants in some parts of the day even at mean T_b below 0 °C (Wielgolaski, 1999). T_b may vary not only among locations (Gárcia-Mozo et al., 2002) but also in the same species and cultivar throughout the season and with the plant age (Wielgolaski, 1999). The phenological characteristics of each species are adapted to climate conditions of its own geographical area. Our results show that for each location a different T_b provided the best fitted predictive models. On this basis, the calculated GDD for leaf unfolding and flowering also varied among locations; however differences between calculated GDD for different year at the same locations were not significant. It can be seen from Table 2 that in Rateče and Lesce, sites with more alpine climate, the selected threshold for leaf unfolding of large-leaved lime was the same, 5 °C and the calculated GDD was quite similar, 74 °D and 102 °D, respectively. Thermal time was significant lower comparing with other sites having higher annual mean air temperatures. This and the rest of the estimations indicate that the same plant species are best fitted to a certain climatic location and seem to have sufficient adaptability to the present temperature changes.

According to input data, predictive models of plant development can be distinguished as *phenological* or *phenoclimatic* (Cenci and Ceschia, 2000). *The phenological* models are based on the possible correlations between the phenophases of species other than that under consideration. We applied *phenological* models with the intention to establish a reference species close to the plants for which the phenological timing has to be predicted. These marker species can be employed for predictions when climatic data for some locations are not available. Eventually only about two thirds of all phenological models could explain more than 50% of variance with phenological predictors. Taken as a whole, the most frequently included independent variable in *phenological* models was birch, the next were dandelion and horse-chestnut. We can characterize these plants as good phenological indicators in given conditions. Mainly one or two independent variables were included in a particular *phenological* model (Table 3), the largest number of independent variables in model were five. We are of the opinion that application of models with more than three independent phenological variables is not justified because additional variables do not explain essentially higher part of variability. We obtained the highest part of explained variability with models of full flowering of domestic plum and apple tree. These models contained as independent variables previous phenophases of the same plants. That is why the predictions were possible only 3–4 days in advance, however from agrometeorological point of view this is early enough. Phenological predictions on the base of previous phenological data of other plants have explained on average most variability for leaf unfolding of birch and flowering of lilac and plum tree.

On the other hand, the *phenoclimatic* models are based on the assumed relationships between the phenological phases of the involved species and the various meteo-climatological variables, such as temperature, rainfall, insolation, etc. In *phenoclimatic* modelling, the GDD and mean monthly temperatures appeared to be the best parameters, although the coefficient of determination increased when the other variables (precipitation, PT, NAOI) were taken into account. In described models (Table 4), thermal time was mostly expressed as GDD_{uni} (above unified $T_b = 0\,^\circ C$) or GDD_{stat} (above statistical determined T_b) indicating that both methods are convenient for usage. Sums of GDD, calculated from minimum daily temperatures, were statistically significant correlated with appearance of phenophases in smaller number of models. We could not ascertain general principle that minimum temperatures were more significant for appointed phenophase or plant. Calculated PT for Ljubljana was included in all *phenoclimatic* models for this location. Comparison between explained variability for Ljubljana with models, including thermal time and those with photothermal time, has shown that we could explain more variability in phenophase occurrences in all models with photothermal time. In terms of R^2 for model testing, the maximal improvement – an increase of 13% explained variance – was achieved for flowering of birch and black locust. For the other phenophases this increase ranged from 1% (flowering of apple tree and hazel) to 11% (leaf unfolding of birch and flowering of dandelion). Even though this has been known for a long time and often proved by experiments, day length has only rarely been used in phenological modelling (Menzel, 2003); temperature was thought to be sufficient. However, in this study the inclusion of day length significantly improved the models.

Variables of monthly amount of precipitation and NAOI were included in smaller number of models. Comparatively small part of the whole variability can be explained by those two independent variables. This may be also a result of intercorrelations between temperature, NAO, precipitations and other climatic factors like radiation, evapotranspiration and soil temperature, for example.

The validation of the regression models showed results similar to those obtained with others phenology models. The calculated mean absolute error values of the regression of 3.4–7.6 days (Table 5) are close to the mean absolute errors values of 4.4–5.0 days for the bud burst models presented by Rötzer et al. (2004) or 5.5 days obtained for *Quercus* pollination start models by Gárcia-Mozo et al. (2002). The explained variance ranged from 42% to 93% (Tables 3 and 4) is within values for models estimated by many authors (Snyder et al., 1999; Galan et al., 2001; Chuine et al., 2003; Rötzer et al., 2004). Reasons for deviations of simulated values from observations are various. The microclimatic conditions of the phenological site and the climate station can differ so that the temperature data do not exactly describe the phenological site (Snyder et al., 2001). The genotype and the age of plant species influence its phenology (Chmielewski and Rötzer, 2001) as well as the presence of other plant species (Kramer, 1994). Non-climatic parameters such as soil type, water content or nutrient supply can also affect phenological appearance (Wielgolaski, 2001). The regression models presented perform satisfying estimations of the flowering and leaf unfolding for general applications. However, to analyze the contribution of all the influences mentioned above and their interrelations on phenology more precisely, further investigations have to be carried out.

5. Conclusions

Plant phenology models are important tools in a wide range of issues such as agricultural practices, forestry, prediction of the impact of global warming, and aerobiology. Possibilities of predicting flowering and leaf unfolding time for wild and cultivated plants were studied based on meteorological and phenological variables in Slovenia. With single phenological model we have predicted individual phenological phenomenon for particular plant on the base of previous phenological data of the same plant or on the base of previous phenological date of other plants. The most frequently included independent variables in phenological models were common silver birch, dandelion and horse-chestnut. It was stated that these plants may be used as phenological indicators in given conditions. Phenological events in Slovenia varied greatly among the years. This variation is highly influenced by climate factors. Phenoclimatic models showed temperature to be the major driving force for the onset of leaf unfolding and flowering phases. Different thresholds temperatures have been selected for different locations for computing GDD with the smallest SD_{GDD} method, however, simply using $T_b = 0\,^\circ C$, provided also good predictions. Rainfall and NAOI explained smaller part of variability of models. The same species in different localities show adaptation to different environmental conditions. Considering the high year-to-year variability of phenological events, the models presented provide satisfactory estimations of the leaf unfolding and flowering dates. Formal equation presented in this study could be powerfully extended and applied to other sites and plants, provided that a sufficiently long time series of phenological and meteorological data were available.

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