Modelling of weather variability effect on fitophenology

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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 INTERRELATIONS among phases of the same or different species (Lieth, 1997)

Early FORECASTING of the PHENOLOGICAL PHASES of WILD and CULTIVATED PLANTS is of great SUPPORT to VARIOUS SECTORS OF HUMAN ACTIVITY, particulary for all agricultural practices:

- SUITABILITY FOR PRODUCTION AND YIELD POTENTIAL
- LENGHT OF GROWING SEASON AND FROST FREE DAYS
- FROST DAMAGE PREVENTION
- EPIDEMIOLOGY OF DISEASES AND PESTS
- TIMING OF SOWING, SPRINKLING, HARVESTING, IRRIGATION...
- PREDICTING THE ONSET OF POLLEN SEASON
- CLIMATE CHANGE STUDIES (FUTURE AND PAST CLIMATE)
- ECOLOGICAL STUDIES (BIODIVERSITY, BIOCLIAMTIC ZONATIONS)
- AND MANY OTHERS...

WHY IS IMPORTANT TO STUDY WEATHER VARIABILITY EFFECT ON PLANTS (PHENOLOGY) ?

We should make

the best of favourable weather conditions

and **try to avoid unfavourable ones**

to achieve optimal yield (quality and quantity)

as far as food production is concerned

The aim of study was to

- **EXPLAIN WEATHER VARIABILITY EFFECT ON PHENOLOGY**
- **WORKING OUT STATISTICAL MODELS** that are able **TO PREDICT LEAF UNFOLDING AND FLOWERING DATES** of differents plants

The preconditions for the models were that the model developed must

- **Considering PRINCIPLE OF PARSIMONIOUS**
- **Represent the EFFECT OF ENVIRONMENTAL FACTORS on specific phenological event**
- **Predict APPLICABLE PHENOLOGICAL EVENT at least three days ahead**

According to INPUT DATA, the forecasting mathematical models can be distinguished as

- **PHENOLOGICAL models: are based on the correlations beetwen defined phenophase and the phenophases of species other than that under consideration**

  *** these models are empirical**

  *** their formulation requires statistical analysis of long series data to identify the ‘marker species’**

- **PHENOCLIMATIC models: are based on the relationships beetwen the specific phenophase and the various CLIMATOLOGICAL PARAMETERS**

MATERIALS AND METHODS

PHENOLOGICAL and CLIMATE DATA were provided by

ENVIRONMENTAL AGENCY OF THE REPUBLIC OF SLOVENIA (ARSO) for the period 1955-2000

Six different phenophases and 17 plants were chosen to represent FOUR GROUPS of phenological objects:

WILD HERBACEOUS PLANTS

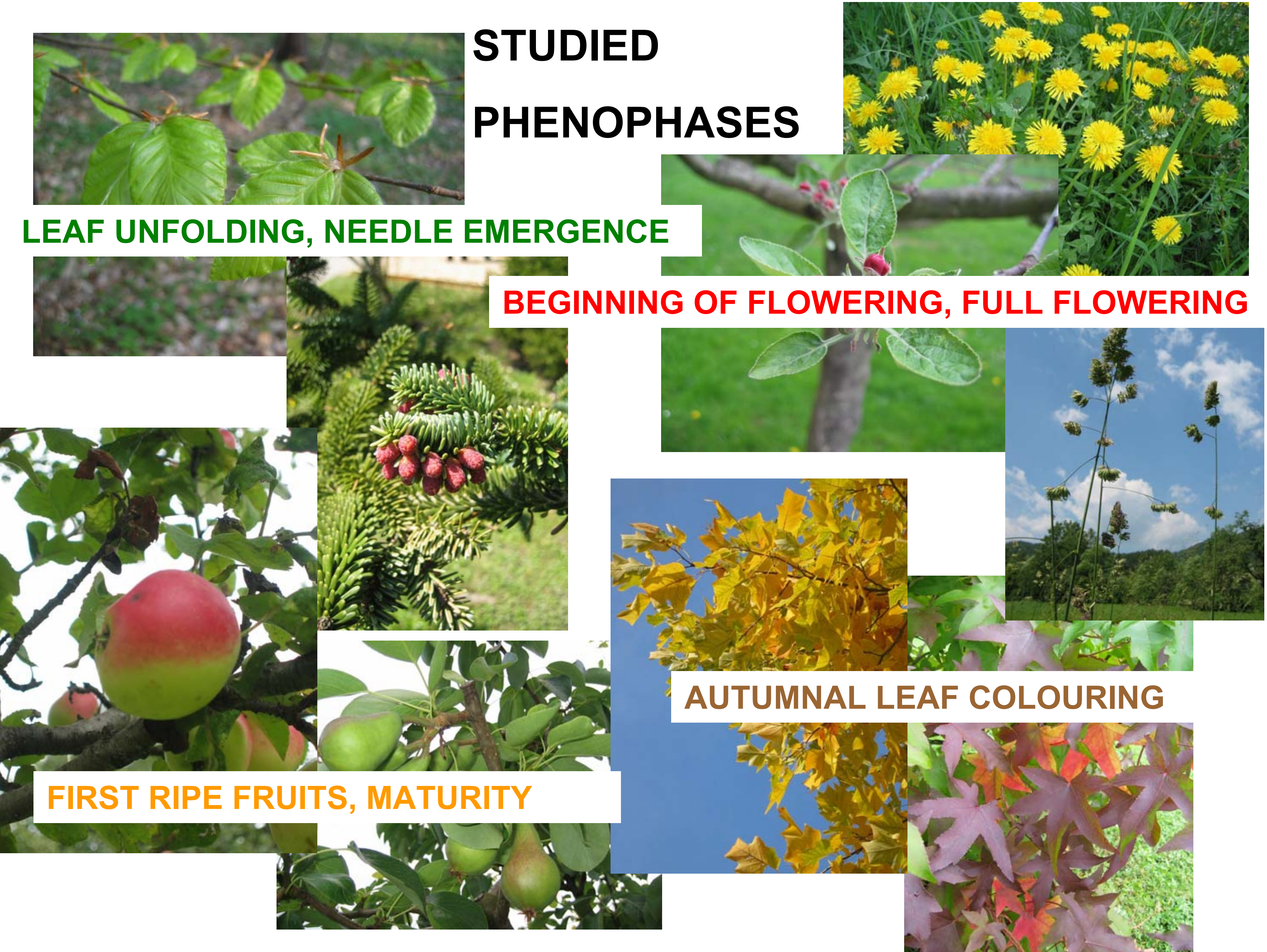
FOREST TREES AND SHRUBS

GRASSES

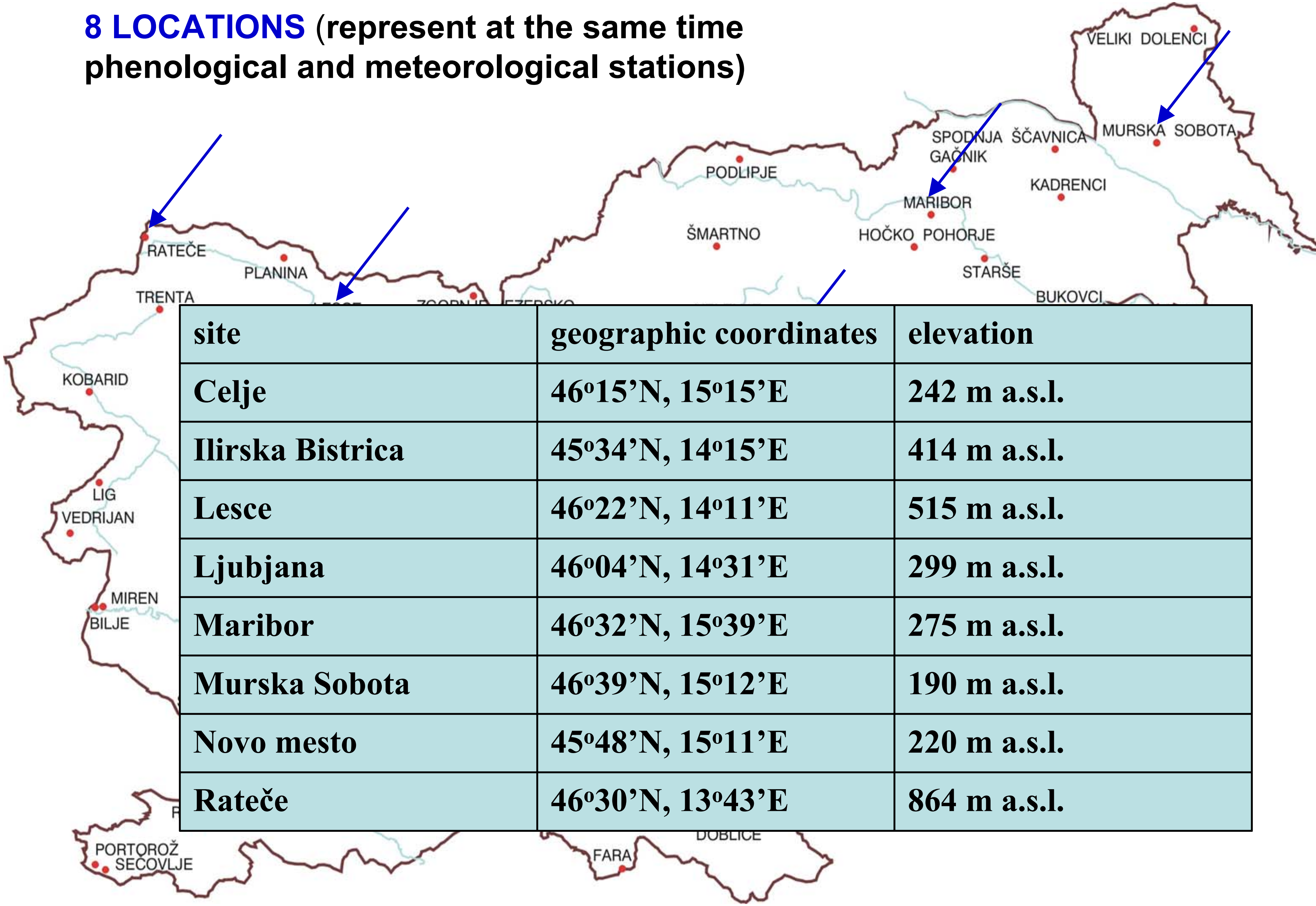
FRUIT TREES

INDICATOR PLANTS

Species (Engl.)	***Species (Latin)***
- **apple tree**	*Malus domestica* Borkh
- beech	*Fagus sylvatica* L.
- black locust	*Robinia pseudacacia* L.
- cock's-foot	*Dactylis glomerata* L.
- common elder	*Sambucus nigra* L.
- common lilac	*Syringa vulgaris* L.
- **common silver birch**	*Betula pendula* Roth.
- dandelion	*Taraxacum officinale* Weber/Wiggers
- goat willow	*Salix caprea* L.
- hazel	*Corylus avellana* L.
- horse-chestnut	*Aesculus hippocastanum* L.
- large-leaved lime	*Tilia platyphyllos* Scop.
- **Norway spruce**	*Picea abies* (L.) Karsten
- ox-eye daisy	*Leucanthemum ircutianum* Turcz.
- **plum tree**	*Prunus domestica* L.
- snowdrop	*Galanthus nivalis* L.
- spring-saffron	*Crocus napolitanus* Mordant&Loisel.


STUDIED
PHENOPHASES
LEAF UNFOLDING, NEEDLE EMERGENCE
BEGINNING OF FLOWERING, FULL FLOWERING
AUTUMNAL LEAF COLOURING
FIRST RIPE FRUITS, MATURITY

8 LOCATIONS (represent at the same time phenological and meteorological stations)



site	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.
Ljubjana	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.

METEOROLOGICAL DATA

TEMPERATURE
Daily maximum
Daily minimum
Monthly minimum
Monthly mean
Monthly maximum
2- an 3-monthly running means

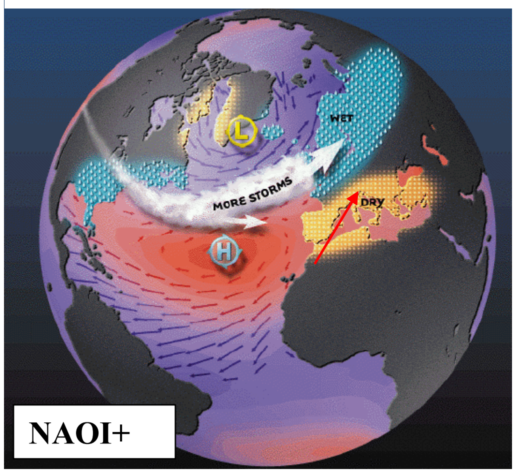
THERMAL TIME
PHOTOTHERMAL TIME

RAINFALL
Monthly total amount
2- an 3-monthly running means

NAOI
monthly
seasonal

(North Atlantic Oscillation Index – NAOI)

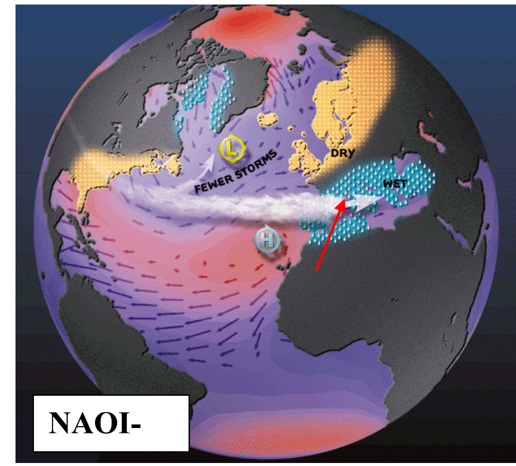
warm, dry winters



$$NAOI = SLP_1 - SLP_2$$

$$SLP_{1,2} = \frac{(X_{SLP_{1,2}} - \overline{X}_{SLP_{1,2}})}{\sigma_{SLP_{1,2}}}$$

cold, wet winters



- The NAO index - the difference of normalized sea-level pressure (SLP) between 2 stations situated close to the "centres of action" over Iceland and the Azores. Stykkisholmur (Iceland) is invariably used as the northern station, whereas either Ponta Delgada (Azores) Lisbon (Portugal) or Gibraltar are used as the southern station

(Jones et al., 1997; http://www.cru.uea.ac.uk/cru/data/nao.htm)

- **MULTIPLE LINEAR REGRESSION** (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,
>
> ***first leaf unfolding*** of beech, common silver birch and large-leaved lime.

- **stepwise selection** was used to select the relevant predictors within the entire set of available predictors

- **measures of the quality of statistical models**: Pearson's correlation coefficient, Coefficient of determination, Studentized residuals (Krzanowski, 1998)

- **CROSS VALIDATION METHOD, independent data set for 2000**

GROWING DEGREE DAYS (GDD)

Degree-day **(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).**

$$GDD = \sum \left[\left(T_{i,\max} + T_{i,\min} \right) \times 0.5 \right] - T_b$$

base temperature

daily maximum air temperature

daily minimum air temperature

If $\left[\left(T_{i,\max} + T_{i,\min} \right) \times 0.5 \right] < T_b$, then $\left[\left(T_{i,\max} + T_{i,\min} \right) \times 0.5 \right] = T_b$

-GDD were calculated following the method proposed by Snyder (1999) **from the 1 January** to the particular phenological event

BASE TEMPERATURES (T_b) were calculated with

- THE SMALLEST STANDARD DEVIATION OF GDD method

(Yang et al., 1995):

In order to estimate the most significant lower Tb for single phenophase at each site a wide range of possible **T_b** were tested (from -5°C to 10°C by step 1°C). The smallest standard deviation from **the mean observed GDD** (**SD_{GDD}**) was calculated as:

$$SD_{GDD} = \sqrt{\frac{\sum GDD_i - GDD_{mean}}{n-1}}$$

mean of the cumulative GDD

GDD for the i^{th} case

number of years

- **UNIFIED T_b** (**0°C)** as proposed by some researchers to simplify thermal time caculations

PHOTOTHERMAL TIME (PT) was summed according to the **equation proposed by Masle et al.** (1989) as:

average temperature in the light period

$$PT = \sum l_i \cdot \left(T_{l,i} - T_b\right)$$

base temperature

light period as a proportion of a day

T_l was obtained from T_{min} and T_{max} using

$$T_l = T_{\min} + k \cdot (T_{\max} - T_{\min})$$

where **k** was estimated empirically (Masle et al., 1989).

RESULTS

- All but one of the **trends of the spring** records were significant negative - earlier onset of leaf unfolding and flowering during the past decades.
- Autumnal phases of **leaf colouring** tented to be **DELAYED**

The mean linear trends (days/decade) were

-1.4 for leaf unfolding

-2.2 for late-spring flowering

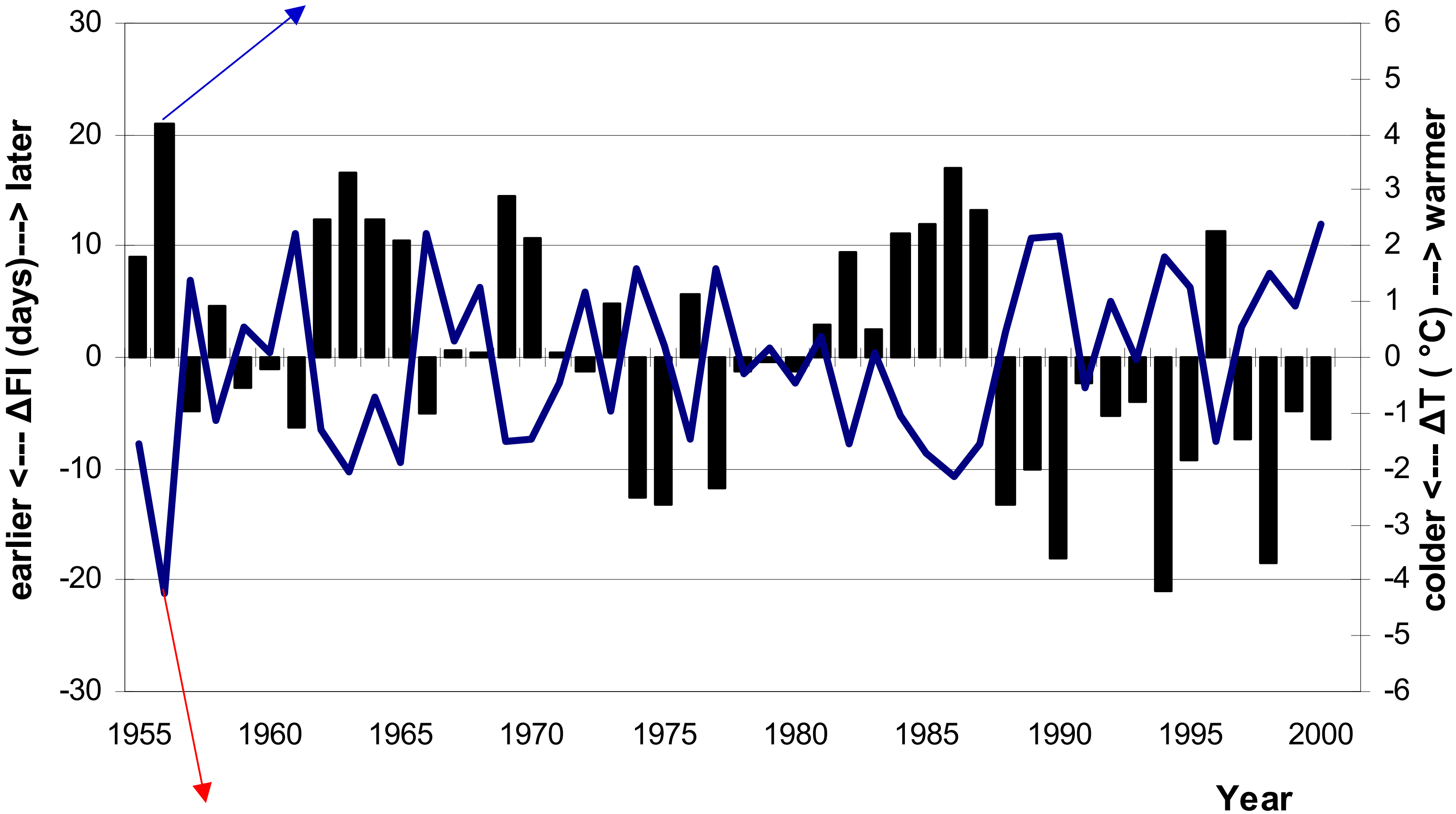
-3.1 for early-spring flowering

+2 for leaf colouring

GROWING SEASON EXTENDED!

GROWING SEASON INDEX a significant negative trend of 2.2 days per decade ($P<0.001$), corresponding to **10 days earlier beginning of growing season** over the last five decades

- Vertical bars represent the **annual early-spring flowering index** (the mean of flowering dates for: *Betula pendula*, *Taraxacum officinale, Salix caprea, Corylus avellana* and *Galanthus nivalis*) **expressed as deviations from the mean value**



- The line represents the **annual deviations of temperature** (°C) from the spring mean temperature (February-April), 1955-2000.

- The average defined **correlation coefficients** between flowering dates and mean monthly air temperatures were strong and negative, from –0.6 to –0.85 on the average; values for leaf unfolding phases were a little lower.

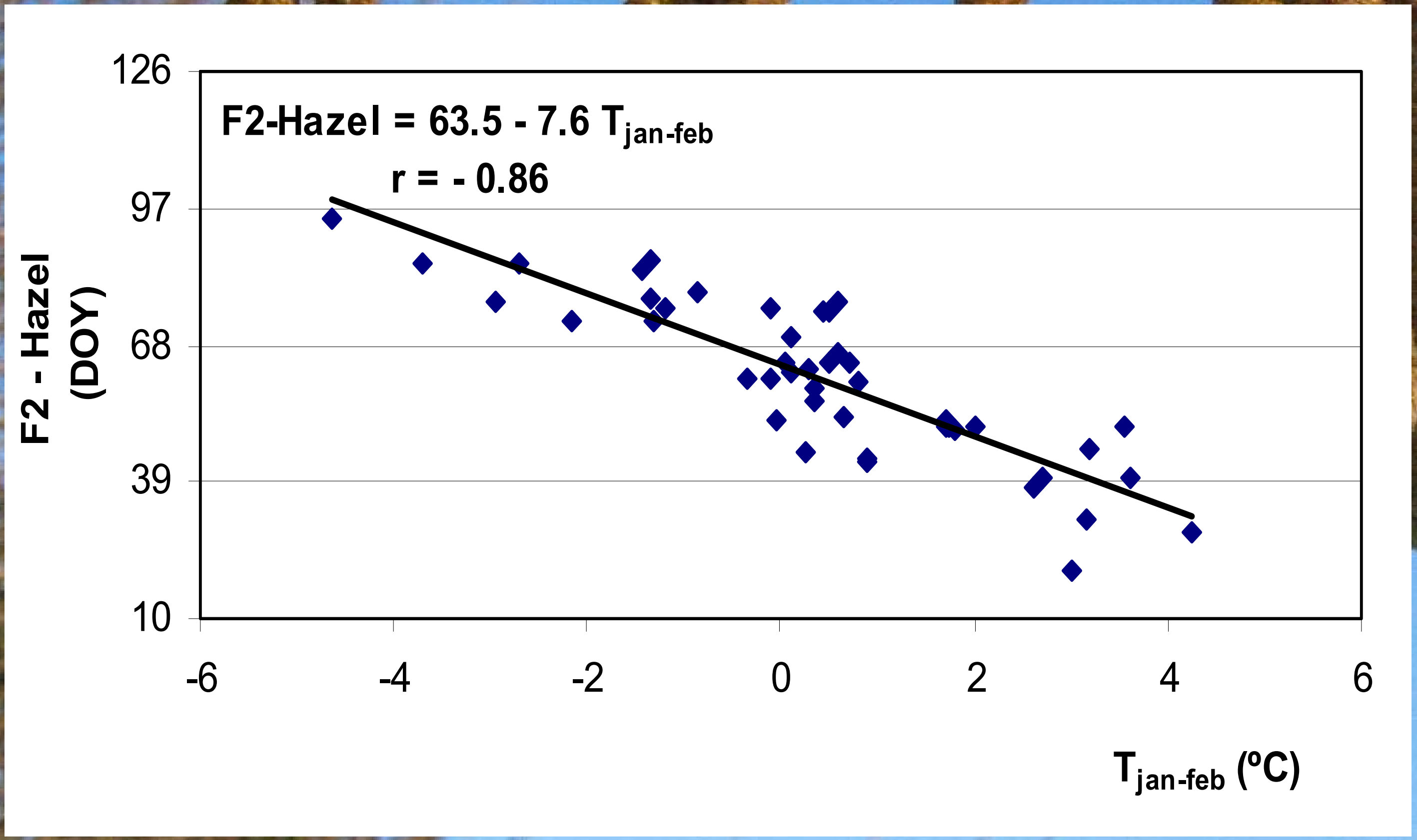
- Correlation was weaker and positive for autumnal phases, which means higher temperatures delay the end of growing season.

- In most cases both flowering and leaf unfolding were accelerated by **3-5 days per 1°C increase** in mean monthly or bimonthly temperature from the starting date.

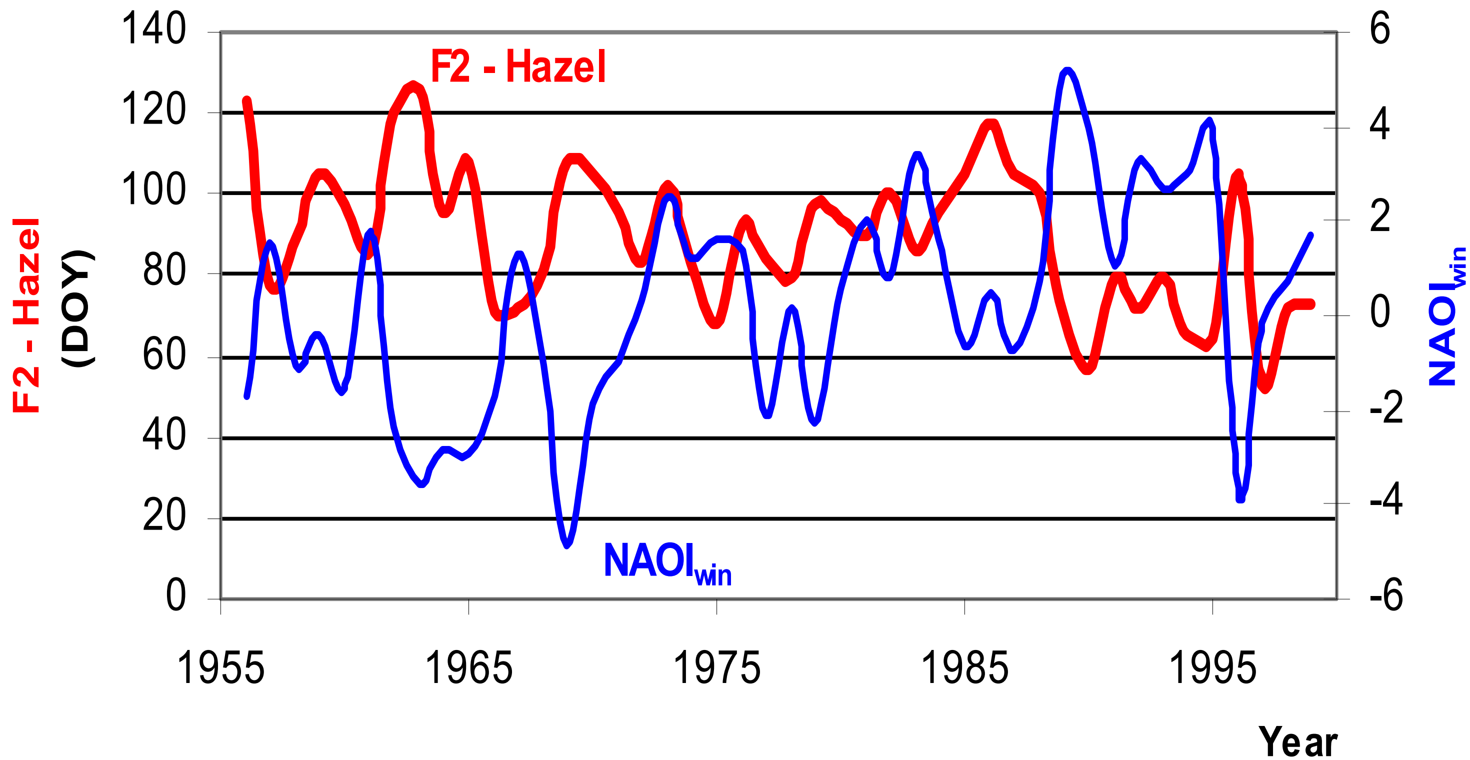
Correlation between full flowering of hazel (F2–Hazel) and **the average temperature from January to February** in Ljubljana, 1955-2000.

The correlation coefficient of r = - 0.86 is significant with ***P<0.001.

DOY: day of the year



- The correlation between winter North Atlantic Oscillation Index ($NAOI_{win}$) and temperature was highly significant for all stations for the months from December to March, the average correlation coefficient was +0.58.
- With $NAOI_{win}$ variability we explained the large part of variation in flowering phases of early-spring plants like dandelion, pussy willow and hazel
- Correlations were weaker for late-spring phenophases and no correlations were found for autumn phenological phases



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.

The amount of monthly **precipitation** in concrete conditions was NOT significantly correlated to date of flowering and leaf unfolding, although it could be of importance in extremely dry years,

IN SPRING TIME THE WATER IN SLOVENIA IS USUALLY NOT LIMITATION PLANT DEVELOPMENT

Average **GROWING DEGREE DAYS (GDD)** above the statistical selected **base temperature (T_b)** for leaf unfolding of large-leaved lime and the relative coefficient of variation

Location	**Selected base temperature – T_b (°C)**	**Average growing degree days (GDD_{stat} in °D)**	**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
Rateče	5	74	14

GDD were **lower** in Rateče and Lesce (altitude!), compared to other stations; largest sums were mostly reached in Ilirska Bistrica and Ljubljana, 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).

Example of *PHENOLOGICAL* MODEL- Beginning of flowering of plum tree

PREDICTORS: PHENOLOGICAL DATA of wild species

-Only about two thirds of all phenological models could explain more than 50% of variance with only phenological predictors

-On the whole, the MOST FREQUENTLY INCLUDED independent variables in PHENOLOGICAL models were **BIRCH, DANDELION and HORSE-CHESTNUT**

-These plants are **PLANT PHENOLOGICAL MARKERS** in given conditions.

- Mainly **two or three independent variables** were included in a particular *phenological* model, the largest number of independent variables in model were five; application of models with more than three independent phenological variables is not justified, because **additional variables do not explain essentially higher part of variability**

P		R²
Celje		72
Ilirska		84
Lesce		72
Marib		80
Mursk		84
Novo		76
Rateč	h.chestnut, dandelion, willow	87

R^2 adjusted coefficient of determination

F1 beginning of flowering; **F2** full flowering; LU **first leaf unfolding**

Example of *PHENOCLIMATIC* MODEL- Beginning of flowering of dandelion

PREDICTORS: PHENOLOGICAL AND CLIMATOLOGICAL DATA

Location	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
CE	$F1_{snowdrop}$; $F1_{willow}$	GDD_{uni}; T_{mar}	72.0	0.15; 0.26; 0.03; -1.83	0.83
IB	$F2_{hazel}$	GDD_{stat}; T_{feb}; T_{mar}	63.5	0.16; 0.07; -1.61; -3.22	0.89
LE		T_{feb}; T_{mar}	118.3	-1.67; -2.75	0.69
LJ	$F1_{willow}$	GDD_{uni}; T_{feb}; T_{mar}; PT	65.1	0.17; -0.08; -0.8: -1.94: 0.24	0.92
MB	$F1_{snowdrop}$; $F1_{birch}$; $F1_{willow}$	GDD_{uni}; T_{mar}	23.3	0.15; 0.21; 0.35; 0.07; -1.17	0.84
NM	$F2_{hazel}$	GDD_{stat}; T_{feb}; T_{mar}	67.3	0.15; 0.06; -1.11; -2.68	0.86
RA		GDD_{uni}; T_{feb}; T_{mar}	95.5	0.16; -1.67; -3.07	0.72

PT: photothermal time (only for location Ljubljana)

Calculated PT for Ljubljana was included in all *phenoclimatic* models for this location. Even thought this has been known for a long time and often proved by experiments, day length has only rarely been used in phenological modelling (Menzel, 1997), temperature was thought to be sufficient. However, in this study the inclusion of **day length significant improved the models**

- Precipitations 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 and precipitations.
- 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 (precipitations, PT, NAOI) were taken into account

CONCLUSIONS

- **PHENOLOGY models are IMPORTANT TOOLS** in a wide range of issues such as AGRICULTURE, FORESTRY, CLIMATE CHANGES, AEROBIOLOGY...

- **PHENOLOGICAL EVENTS VARIED greatly among years, this variation is highly INFLUENCED by CLIMATE factors, particularly TEMPERATURE**

- **The MOST FREQUENTLY included INDEPENDENT VARIABLES in PHENOLOGICAL MODELS were: birch, dandelion and horse-chestnut, these plants may be used as PHENOLOGICAL MARKERS IN GIVEN CONDITIONS**

- **PHENOCLIMATIC MODELS** showed **TEMPERATURE** and its derivatives to be THE MAJOR DRIVING FORCE for the onset of leaf unfolding and flowering

- **Different thresholds temperatures have been selected for different LOCATIONS for computing GDD with the smallest SD_{GDD} method, the SAME SPECIES in DIFFERENT LOCATIONS showed 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 equations presented in this study could be powerfully EXTENDED AND APPLIED TO OTHER SITES AND PLANTS, if sufficiently LONG TIME SERIES OF PHENOLOGICAL AND METEOROLOGICAL DATA are available.**