New frontiers in plant phenological research

H. Scheifinger [1], E. Koch [1], P. Cate [2] and C. Matulla [1]

[1] Central Institute for Meteorology and Geodynamics, Hohe Warte 38, A - 1190 Vienna, Austria
[2] AGES, Institut für Pflanzengesundheit, Spargelfeldstr. 191, A - 1220 Vienna, Austria
Email: Elisabeth.Koch@zamg.ac.at / Tel.: +43 1 36026 2205 / Fax.: +43 1 36026 72

Keywords: *Phenology, climate change impact*

EXTENDED ABSTRACT

In recent years phenology has emerged as highly valuable source of information in the field of climate impact assessment. An increasing number of studies report that plants and animals of the mid- and higher latitudes of the northern hemisphere have been responding to the temperature increase of the last decades.

Here a few selected results of an extended analysis (project named CLIMPHEN) of the Austrian phenological data set are presented. Entry dates of 244 phases (of which about 50 to 100 can be used for analysis, depending on the time section), have been observed continuously since 1951 in Austria including the Alps at 284 stations, where the station elevation ranges from 150 to 1400 m MSL.

One section explores the relationship between the spatial gradients of the phenological phases and temperature. As summary of this relationship the spatial gradient law is proposed. The basis of the spatial gradient law of phenology is the observation that a specific temperature sensitivity can be attributed to each phase. It says that the spatial gradient of the phenological phases is the product of the spatial gradient of the temperature corresponding to the phenological phase and the spatial sensitivity of the phenological phase. The spatial structure of the temperature field is mirrored in the spatial structure of the field distribution of phenological entry dates, while being scaled via the spatial temperature sensitivity of the phenological phase. The validity and significance of this relationship has to be explored with spatially more extended data sets.

Another topic concerns the spatial variation of the long term mean occurrence dates of a phenological phase as function of station longitude, latitude and elevation, which can be described by a Multiple Linear Regression (MLR) model to a great degree (> 70% for many phases), but not completely. Long term phenological occurrence dates reveal in fact residual patterns of spatial variation not described by the MLR model. These residual patterns display a great similarity among different phases. They seem to be related with climatic deviations of a greater region. This unexpected result warrants a deeper look into the physical background governing the spatial variations of the phenological occurrence dates and their related temperature sums.

1. INTRODUCTION

Within the last decade the scientific community's view of phenology as a harmless pastime of natural historians has changed dramatically, because the value of phenological data in climate change research has been recognised (Rosenzweig et al., 2007). Faced with the prospect of a possible global warming, information is needed about how natural systems may respond to a warming climate. The study of the observed response to the warming during the last 4 to 5 decades may provide a hint on a possible future response. An increasing number of studies report that plants and animals of the mid- and higher latitudes of the northern hemisphere have been responding to the temperature increase of the last decades (Walther et al., 2002; Root et al., 2003; Parmesan and Yohe, 2003). More specifically most phenological data sets reveal an advancing of flowering and leaf unfolding in Europe and North America by 1.2 to 3.8 days/decade, a delay of autumn phases by about 0.3 to 1.6 days/decade, which results in a lengthening of the vegetation period by about 1.5 to 5.2 days/decade during the last 40 to 50 years (Menzel, 2002; Menzel at al., 2006). In Western Europe a shift to earlier first and peak appearances of butterflies have been recorded and flight periods have been lengthened in multi-brooded species. Bird migration timing and breeding times in Europe and North America have been responding to changes in temperature, predominantly shifting towards earlier dates in spring (Sparks and Menzel, 2002).

Here a few selected results of an extended analysis (project named CLIMPHEN) of the Austrian phenological data set are presented. Entry dates of 244 phases (of which about 50 to 100 can be used for analysis, depending on the time section) have been observed continuously since 1951 in Austria including the Alps, which are specifically sensitive to climate variability. The network (Figure 1, red dots) spans about 7° longitude, 2.5° latitude and station elevations range from about 150 to 1400 m MSL. Since 1951 all together 284 stations reported phenological observations. Data from up to about 80 stations may be available for one phase in a year.

Temperature is seen as the main atmospheric variable governing the spatial and temporal variability of the phenological phases. In order to get a temperature, which is specifically related to each phase, the HISTALP (Historical Instrumental climatological Surface Time series of the Greater ALPine region, Auer et al., 2006; Figure 1 blue dots) temperature time series were interpolated with height reduced Inverse Distance Weighting (IDW) to the coordinates of each phenological station. Station elevation was taken into account with a mean monthly temperature slope, calculated from long term mean monthly temperature distribution over the area. Based on the 12 monthly temperature time series at each phenological station and a Multiple Regression Model (MLR) a phenological temperature T_p was calculated for each phase.

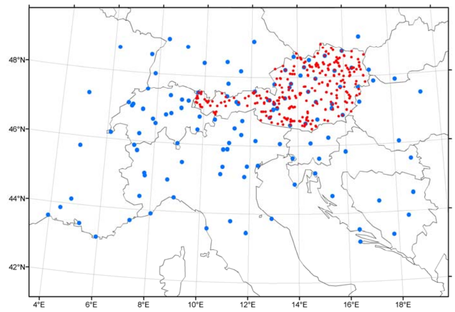

Figure. 1: Station networks used in this work: the red dots indicate the phenological station network of the ZAMG and the blue dots the HISTALP temperature station network.

2. THE SPATIAL GRADIENT LAW

In this section it is investigated how the phases and their related temperatures T_p move through the space spanned by the Austrian phenological station network and if and in which way T_p is able to explain that movement through space. The spatial gradients of the phenological entry dates are derived from the following MLR model

$$p = c_1 + c_2\lambda + c_3\phi + c_4 z\,, \qquad (1)$$

where p are the long term mean phenological entry dates at the stations, λ, ϕ the station coordinates, z station elevation and c_2 (days/deg longitude), c_3 (days/deg latitude) and c_4 (days/m) the relevant regression coefficients or 'spatial gradients'. The higher the values of the coefficients, the slower move the entry dates through space. The analogue model was constructed for temperature T_p.

Figure 2 shows the spatial gradients of the long term mean phenological occurrence dates (black) and that of their related temperature T_p (red) as function of the mean long term occurrence dates of the phases.

The most prominent feature of Figure 2 is the large scatter of the spatial gradients from phase to phase. The earliest spring phases commence in the west (phenological gradients > 0, Figure 2 top), whereas later spring phases may also commence at the eastern stations (phenological gradients < 0). Much more clear cut are the latitudinal and elevation gradients (Figure 2 medium and bottom panel), where all the spring and summer phase occurrences move from south to north and from low to high elevations.

The temperature T_p (red) displays a seasonal variation, which is roughly similar to that of the phenological phases, although with a much more reduced scatter. So temperature can explain the seasonal cycle of the phenological gradients to some extent, but not the scatter. Comparing both data sets, the spatial gradients of temperature T_p and those of the phenological phases in the scatter plots, one finds no correlation between them. Here arises following question: is the scatter of the gradients of the phenological phases a random phenomenon, related with observational inaccuracy or is it something more systematic?

The spatial temperature sensitivity (days/°C) is a measure of how the long term mean phenological occurrence dates change with spatial temperature changes within a station network (Figure 3). The temperature sensitivities go through a characteristic seasonal cycle, where 3 periods can be discerned. Early phases show a high temperature sensitivity. Then the temperature sensitivity decreases from early to mid spring phases and warm season phases show the highest temperature sensitivity of all phases and autumn phases the least temperature sensitivity. The most sensitive phases are summer ripening phases and the least temperature sensitive phases are autumn phases.

The minimum and maximum temperatures, the daily temperature amplitudes and the way, temperature sums accumulate over the relatively long ripening period might be factors responsible for the different spatial temperature sensitivities among the plant phases.

The key to understand the differences between the spatial gradients of the phenological phases and those of temperature T_p is the relationship between the spatial sensitivity as function of station coordinates and the spatial sensitivity of the phenological entry dates as function of temperature, because both are strongly linked with each other.

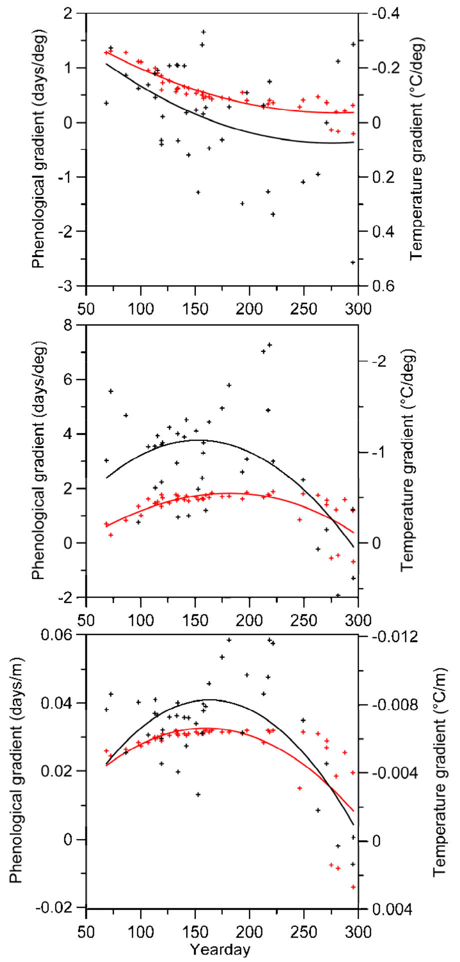

Figure 2: Spatial gradients of phenological phases (black) compared with spatial gradients of the long term mean monthly temperature T_p (red). Presented here are coefficients of the spatial MLR with station longitude (top), latitude (medium panel) and elevation (bottom).

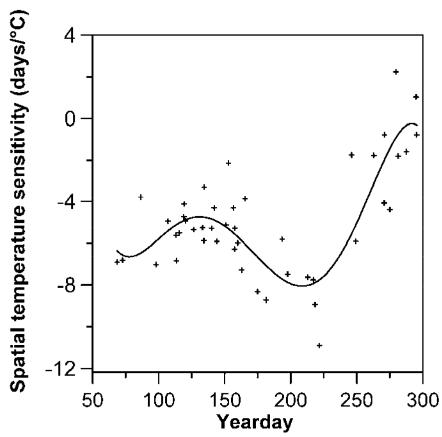

Figure 3: Spatial temperature sensitivity of the mean Austrian phenological time series.

Figure 4 shows scatter plots of spatial temperature (T_p) sensitivity of the phenological phases versus their spatial phenological gradients or spatial sensitivity (station longitude top, station latitude middle and station elevation bottom). The link with station elevation is very strong (RSQ = 0.94), with station latitude mediocre (RSQ = 0.39) and with station longitude not visible. The spatial sensitivities of the phases for temperature, station elevation and station latitude appear strongly linked.

From the above discussion the following relationships, also termed spatial gradient law of phenology, are proposed:

$$\frac{dT_p}{d\lambda} * \left(\frac{dp}{dT_p}\right)_{space} = \frac{dp}{d\lambda} \qquad (2)$$

$$\frac{dT_p}{d\phi} * \left(\frac{dp}{dT_p}\right)_{space} = \frac{dp}{d\phi} \qquad (3)$$

$$\frac{dT_p}{dz} * \left(\frac{dp}{dT_p}\right)_{space} = \frac{dp}{dz} \qquad (4)$$

where T_p is the long term mean temperature, λ, ϕ and z station longitude, latitude and elevation, p is the long term mean occurrence date of the phenophase.

Figure 5 demonstrates that it is in fact possible to reconstruct the spatial sensitivity of the phenological phases via (2-4), at least for the station elevation (bottom panel) and to some extent for station latitude (medium panel). Hence the large scatter of the spatial gradients of the phenological phases of Figure 2 can be explained and modelled.

The spatial gradient law of phenology says that the spatial gradient of the phenological phases is a combined effect of the spatial temperature gradient and the spatial temperature sensitivity of the phenological phase. The spatial structure of the temperature field is mirrored in the spatial structure of the field distribution of phenological entry dates, while being scaled via the spatial temperature sensitivity of the phenological phase. The general validity and significance of this relationship has to be explored in future.

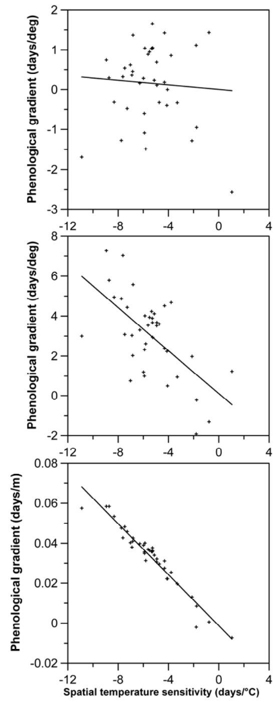

Figure 4: Scatter plots of spatial temperature (T_p) sensitivity of the phenological phases versus their spatial phenological gradients or spatial sensitivity

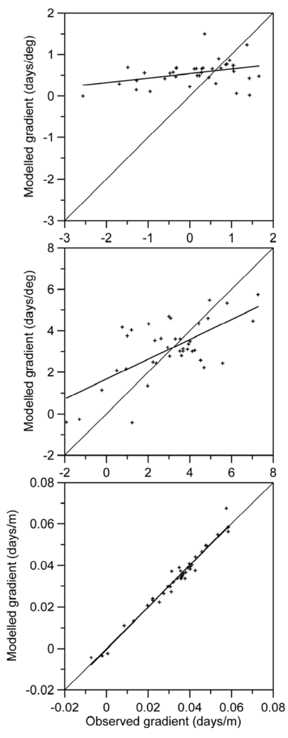

Figure 5: Scatter plot of the right hand side of (2 – 4, ‘observed’) versus the left hand side of (2 – 4, ‘modelled’) spatial gradients (station longitude top, station latitude medium panel and station elevation bottom) of phenological phases.

3. SPATIAL RESIDUALS

Another topic concerns the spatial variation of the long term mean occurrence dates of a phenological phase as function of station longitude, latitude and elevation, which can be described by a MLR model to a great degree (> 70% for many phases), but not completely. There remains a fraction of variance, which can not be explained by the station position. If the spatial patterns of the residuals turn out to be not chaotic, but result in contiguous subregions of similar residual values, this can be seen as a hint to the dominance of topographical features combined with atmospheric mechanisms shaping the climate of such subregions.

For comparison purposes the spatial residual patterns of temperature were first calculated based on the temperature data set of the ECSN/HRT – GAR (European Climate Support Network/High Resolution Temperature – Greater Alpine Region) data set with mean monthly long term temperature values from 386 Austrian stations (1961 – 1990) (Figure 6). The spatial patterns of the temperature residuals are in fact non – chaotic and can be linked with the regional climate.

Areas with a high incidence of clouds and precipitation upwind of the main Alpine ridge can be found for instance at the northern rim of the Alps, which are linked with lower than expected temperatures (blue areas in Figure 6 top, measured values are lower than modelled values). The red areas in the east downwind of the Bohemian mountains and the Eastern Alps in summer (Figures 6 top, measured values are higher than modelled values) indicate a low incidence of clouds and precipitation and much sunshine to warm this region.

The spatial residual patterns of the long term mean phenological occurrence dates show in fact a great similarity with the residual patterns of temperature (Figure 6, bottom). From this result one can conclude that the microclimate at the phenological stations plays a subordinate role compared to topographical and atmospheric factors of a larger region, which govern the temperature distribution. This unexpected result warrants a deeper look into the physical background governing the spatial variations of the phenological occurrence dates and their related temperature sums.

The above results can be applied to support the mapping of long term mean phenological entry dates. Interpolation procedures, like the height detrended IDW (Inverse Distance Weighting), interpolate the residuals of the height regression and then recalculate the value at a point (on the

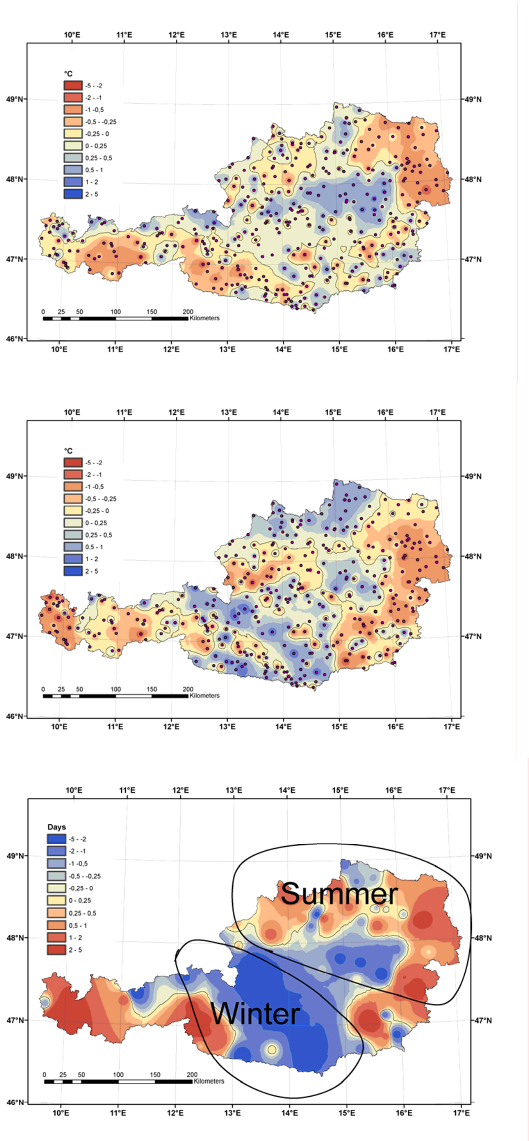

Figure 6: Residuals of the MLR model of the long term mean temperature resp. phenological occurrence dates as function of station coordinates of the ECSN (European Climate Support Network) temperature data set from Austria (386 stations), 1961- 1990, winter (top) and summer (medium panel), residuals of 21 selected phases, 1951 - 2005 (bottom).

DEM = Digital Elevation Model for instance) via the height regression. As an example the phase 'snow drop beginning of flowering' has been selected and the residuals (Fig. 7 top), the field interpolated with MLR only (Fig. 7 medium panel) and the combined MLR and residual field interpolation (Fig. 7 bottom) plotted. The elevation gradient of the occurrence dates of 'snow drop beginning of flowering' is 35 days/1000 m, whereas the residuals show a range of +-10 days, which is equivalent to an elevation range of about +-300 m. The residuals represent a factor, which can not be neglected.

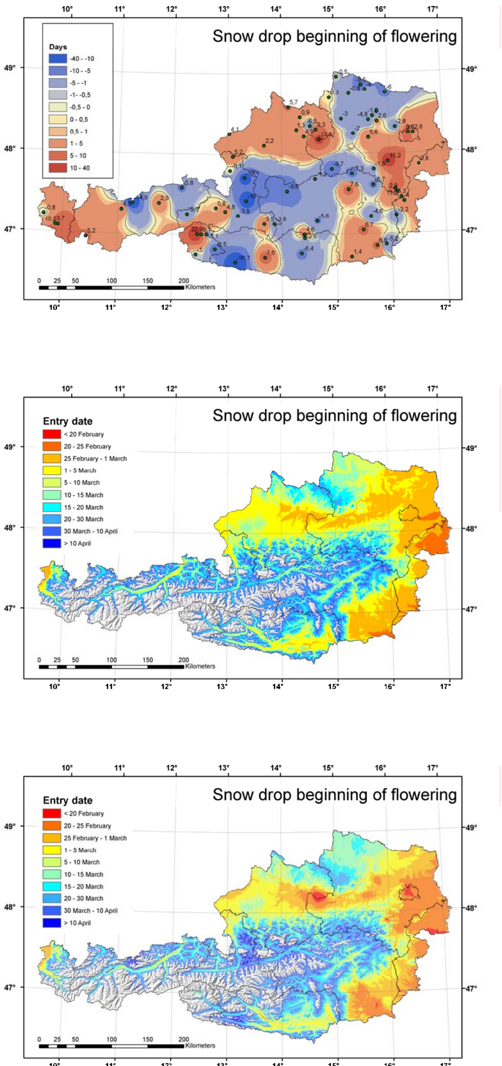

Figure 7: Residual map (left), map of the occurrence dates modelled with the MLR (Multiple Linear Regression) only (medium panel) and map of the occurrence dates modelled with the MLR combined with interpolated residuals (right) of 'snow drop beginning of flowering', 1951 - 2005.

4. CONCLUSIONS AND SUMMARY

From the above study we draw the following conclusions:

- Each phase has its specific spatial temperature sensitivity and there exists a large range of temperature sensitivities among the phases.
- The spatial temperature sensitivity of a number of phases goes through a characteristic seasonal cycle with a maximum temperature sensitivity during early spring and summer.
- The spatial temperature sensitivity and the spatial sensitivity of phenological phases are linked via the proposed gradient law of phenology, which underlines the dominant role of temperature for the spatial behaviour of the phenological phases.
- The analysis of the spatial residuals of long term phenological entry dates demonstrates that regional topographical and atmospheric factors cause contiguous subregions of similar residual values. Microclimate at individual stations play a subordinate role with respect to spatial residuals.

5. REFERENCES

Auer, I., R. Böhm, A. Jurkovic, W. Lipa, A. Orlik, R. Potzmann, W. Schöner, M. Ungersböck, C. Matulla, K. Briffa, P. Jones, D. Efthymiadis, M. Brunetti, T. Nanni, M. Maugeri, L. Mercalli, O. Mestre, J. Moisselin, M. Begert, G. Müllerwestermeier, V. Kveton, O. Bochnicek, P. Stastny, M. Lapin, S. Szalai, T. Szentimrey, T. Cegnar, M. Dolinar, M. Gajic-Capka, K. Zaninovic, Z. Majstorovic and E. Nieplova (2007), HISTALP – Historical Instrumental climatological Surface Time series of the greater ALPine region 1760 – 2003. *International Journal of Climatology*, 27(1), 17-40.

Menzel, A. (2002), Phenology: its importance to the Global Change community – An Editiorial Comment. *Climatic Change*, 54, 379 – 385.

Menzel A., T. H. Sparks, N. Estrella, E. Koch, A. Aasa, R. Ahas, K. Alm-Kübler, P. Bissolli, O. Braslavska, A. Briede, F. M. Chmielewski, Z. Crepinsek, Y. Curnell, A. Dahl, C. Defila, A. Donnelly, Y. Filella, K. Jatczak, F. Mage, A. Mestre, Ø. Nordli, J. Penuelas, P. Pirinen, V. Remisova, H. Scheifinger, M. Striz, A. Susnik, A. J. H. Van Vliet, F. Wielgolaski, S. Zach and A. Zust (2006), European phenological response to climate change matches the warming pattern. *Global Change Biology*, 12 (10), 1969 - 1976; doi:10.1111/j.1365-2486.2006.01193.xVolume 12 Issue 10

Parmesan, C. and G. Yohe (2003), A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, 421, 37-42.

Root, T. L., J. T. Price, K. R. Hall, St. Schneider, C. Rosenzweig and A. Pounds (2003), Fingerprints of global warming on wild animals and plants. *Nature*, 421, 57-60.

Rosenzweig, C., G. Casassa, D.J. Karoly, A. Imeson, C. Liu, A. Menzel, S. Rawlins, T.L. Root, B. Seguin, P. Tryjanowski, (2007), Assessment of observed changes and responses in natural and managed systems. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 79-131.

Sparks, T. H. and A. Menzel (2002); Observed Changes in Seasons: an Overview. *Int. J. Climatol*., 22, 1715-1725.

Walther, G.-R., E. Post, P. Convey, A. Menzel, C. Parmesan, T. J. C. Beebee, J.-M. Fromentin, O., Hoegh-Guldberg and F. Bairlein (2002), Ecological responses to recent climate change. *Nature*, 416, 389-395.

6. ACKNOWLEGDEMENTS

This work has been supported by the ÖAW (the Austrian Academy of Sciences) and the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management, (UW.1.3.2/0377-V/4/2005).