

RESEARCH
PAPER

Representativeness of point-wise phenological *Betula* data collected in different parts of Europe

Pilvi Siljamo^{1*}, Mikhail Sofiev¹, Hanna Ranta², Tapio Linkosalo³, Eero Kubin⁴, Rein Ahas⁵, Eugene Genikhovich⁶, Katarzyna Jatczak⁷, Victoria Jato⁸, Jiří Nekovář⁹, Alexander Minin¹⁰, Elena Severova¹¹ and Valentina Shalaboda¹²

OnlineOpen: This article is available free online at www.blackwell-synergy.com

¹Finnish Meteorological Institute, P.O. Box 503, 00101 Helsinki (Erik Palménin aukio 1), Finland, ²University of Turku, Finland, ³University of Helsinki, Finland, ⁴Finnish Forest Research Institute, Finland, ⁵University of Tartu, Estonia, ⁶Main Geophysical Observatory, Russia, ⁷Institute of Meteorology and Water Management, Poland, ⁸University of Vigo, Spain, ⁹Czech Hydrometeorological Institute, Czech Republic, ¹⁰Ecological Centre Pasva, Institute of Global Climate and Ecology, Russia, ¹¹Moscow State University, Russia, ¹²Institute of Geochemistry and Geophysics, Belarus

ABSTRACT

Aim We examine issues of uncertainty regarding the spatial and temporal representativeness of phenological observations using a newly compiled Europe-wide data base of phenological observations for *Betula* species.

Location Europe.

Methods A new data base was compiled from national phenological observations covering 15 European countries, with the longest observational periods exceeding several decades for some sites. From this, the spatial and temporal representativeness of phenological observations were evaluated via statistical analysis.

Results The results showed that there was a significant and irreducible uncertainty related to the use of data of a single station, which varied from 3 to 8 days depending on the station location. In more continental and northern climatic zones the uncertainty was lower, probably due to faster spring-time weather developments. In mild climatic conditions, the uncertainty of dates of the phenological phases registered by a single station exceeded 1 week. The considerable number of data allowed us to preliminarily estimate the features of some stations, marking them as 'late', 'early', 'representative' or 'random', depending on the dates reported by these sites and the corresponding regional means.

Main conclusions The uncertainties discovered in single-site phenological observations are significant for virtually any potential application. Possible approaches for handling the uncertainty problem are station pre-averaging and spatial regularization of the data set, pre-selection (down-sampling) or changing the description of the phenomena from deterministic to probabilistic.

Keywords

Betula, Europe, flowering, leaf unfolding, phenological observations, phenological stages, station representativeness, sub-grid variability.

*Correspondence: Pilvi Siljamo, Meteorological Research, Finnish Meteorological Institute, P.O. Box 503, FI-00101 Helsinki (Erik Palménin aukio 1), Finland. E-mail: pilvi.siljamo@fmi.fi

Re-use of this article is permitted in accordance with the Creative Commons Deed, Attribution 2.5, which does not permit commercial exploitation.

INTRODUCTION

Phenological observations – the dates of leaf bud burst, leaf unfolding, start of flowering, etc. – are one of the most important (and sometimes the only) sources of information on the physiological condition of plants and their reactions to external forcing (Sparks & Carey, 1995; Sparks & Menzel, 2002; Menzel *et al.*, 2006). Consequently, the number of studies in which these data are used for evaluation of the integrated characteristics of climate, and its changes during recent decades, is growing rapidly

(Heikinheimo & Lappalainen, 1997; Parmesan & Yohe, 2003; Chen *et al.*, 2005; Črepinšek *et al.*, 2006). These data have also been used for the development, parametrization and evaluation of various (semi-)empirical models of phenological phases (e.g. Häkkinen *et al.*, 1998; Linkosalo, 2000; Rötzer & Chmielewski, 2001; Schaber & Badeck, 2003). Many national and international phenological networks provide monitoring data for such investigations. An extensive list of these networks is presented at the website of the European Phenological Network (<http://www.dow.wau.nl/msa/epn>).

A significant limitation of phenological archives is that their features vary between different countries. As a result, many European regions are represented by just a few monitoring sites. This raises questions of the spatial representativeness of existing networks for the corresponding regions and, in particular, the representativeness of a single observational point for its neighbourhood. Such types of problems are well known in meteorology and air pollution, where the cost of measurements is often high and thus problems concerning the optimal number of stations and their optimal locations are important (e.g. Berg & Schaug, 1994). However, the phenomena related to meteorology and air quality have different features from those of phenological processes. First of all, they are much more dynamic and have much wider variability than the slowly progressing phenological developments. The spatial scales of meteorological changes are mainly affected by synoptic processes that are hundreds of kilometres in size. A similarity, however, between these two types of processes, is that the observations of a station are largely affected by its surroundings (WMO, 1996). Therefore, although the practices accepted in meteorology cannot be automatically applied to phenological networks, they can give important guidelines for the assessment of phenological observations.

There are several mechanisms limiting or promoting the synchronization of space-separated biological systems and, consequently, the representativeness of single-site observations. One of the most important mechanisms is large-scale forcing by meteorological and geophysical factors. From the theory of differential equations, it is known that the evolution of linear systems under external forcing will generally follow the evolution of the forcing, which works as a synchronizing agent for these systems. In population dynamics and ecology it is referred to as the Moran effect (after the pioneering study of Moran, 1953). Numerous studies (e.g. Blasius & Stone, 2000; Ripa, 2000; Sparks & Braslavská, 2001; Engen & Sæther, 2005) have shown that the Moran effect plays a crucial role in the spatial synchronization of biological systems. For the pollen and seed production of trees, Koenig & Knops (1998, 2000) demonstrated that synchronous seed reproduction over large areas in the Northern Hemisphere is caused by a common environmental fluctuation, such as rainfall and temperature.

However, the situation is more complicated and there are other processes in play. Thus, Satake & Iwasa (2000, 2002) indicated that in the case of pollen limitation, coupling of trees through pollen exchange may synchronize reproduction with a scale a few times larger than the range of direct pollen exchange, which is assumed to be limited in forest trees (Smouse & Sork, 2004). In the case of pollen coupling, the synchronization of flowering intensity could be connected to the resource allocation of trees (Satake & Iwasa, 2000, 2002). The effects of small-scale pollen-induced coupling in comparison with large-scale climate forcing were compared in the follow-up work by Satake (2004).

From an evolutionary point of view, effective pollination of anemophilous plants requires adaptations that cause scattered individuals to release pollen at the same time over large areas. For wind-pollinated Betulaceae trees, the benefits of releasing a great amount of pollen at the same time seem obvious: an exponential

positive relationship exists between the amount of pollen produced, pollination efficiency and seed viability (Sarvas, 1952; Shibata *et al.*, 1998).

One of the ultimate practical outcomes of coupling between biological systems is that observations made at any phenological station have a limited representativeness over the surrounding region. The term 'representativeness' reflects the uncertainty introduced by an extrapolation of data in time and/or space beyond the time period and area when/where they were obtained. Specific quantitative measures can vary depending on the application. For instance, representativeness can be quantified via the spatial correlation radius (as done in kriging analysis), via the pair-wise correlation coefficient and its dependence on the distance between the correlated points, via the standard deviation of a spatially averaged field, spatial structure functions, etc. More quantitative descriptions of representativeness can be found, for example, in the classic textbook of Yaglom (1987).

The purpose of the current paper is to provide the first quantitative assessment of spatial representativeness of phenological observations in Europe using the birch (*Betula*) taxon as an example. We also demonstrate how the assessments of representativeness can be used as quantitative indicators of variability of the phenological processes and their spatial and temporal scales.

The study was performed within the scope of the POLLEN project (<http://pollen.fmi.fi>), which has developed a grid-based numerical model combining meteorological, phenological and other types of information (Sofiev *et al.*, 2006). We therefore focused our attention on a grid-based type analysis of the spatial station representativeness. In particular, we discuss how the local-scale or point-wise data of phenological station(s) correspond to grid-cell medians, and how the observations from single stations compare with each other if the sites are located in the same grid cell (assuming that some grid is imposed over the domain of interest).

MATERIAL AND METHODS

The collected phenological data base and its quality control

A main pre-requisite for the assessment of the spatial variability of plant processes over Europe is a comprehensive phenological data base. There are many national data bases in Europe, but they have not yet been combined. The ongoing COST (European Co-operation in the Field of Scientific and Technical Research) action 725 'Establishing a European Phenological Data Platform for Climatological Applications' is collecting Europe-wide phenological data but has not yet produced the data base. The information for the current study was therefore collected on a country-by-country basis with subsequent conversion to a common format. The current status of the *Betula* data base is presented in Table 1 and the station locations are shown in Fig. 1(a).

The data base PhenoData contains observations of *Betula* from 15 countries from various sources. The taxonomy of *Betula* in Europe is disputed, but of the four species in *Flora Europaea* (Tutin *et al.*, 1993) the observed trees are known or assumed to

Table 1 Current status and content of the phenological data base PhenoData.

Country	No. of stations	Years	Species	Data provider
Belarus	5	1967–98/2002–05	<i>Betula</i>	University of Tartu, Institute of Geochemistry and Geophysics
Czech Republic	206	1955–2004, a few older	<i>Betula pendula</i>	Czech Hydrometeorological Institute
Estonia	19	1947–2003	<i>Betula</i>	Estonian Meteorological and Hydrological Institute
Finland 1	39	1997–2005	<i>Betula pendula</i> , <i>Betula pubescens</i>	Finnish Forest Research Institute
Finland 2	547	1773–2004, station specific	<i>Betula</i>	Finnish Society of Science and Letters
Germany	2119	1985–2004	<i>Betula pendula</i>	German Weather Service DWD
Latvia	2	1958–93	<i>Betula</i>	University of Tartu
Lithuania	3	1962–96	<i>Betula</i>	University of Tartu
Norway	1	1927–2004, holes	<i>Betula pubescens</i>	Planteforsk Holt
Poland	20	1980–92, 2005	<i>Betula pendula</i>	Institute of Meteorology and Water Management
Russia	89	1951–2004	<i>Betula</i>	Ecological Centre Pasva, University of Tartu, Moscow State University
Slovakia	4	1986–2004	<i>Betula pendula</i>	Slovak Hydrometeorological Institute
Spain	4	2002–03	<i>Betula pendula</i> , <i>Betula alba</i>	Galician Aerobiological Network
Switzerland	138	1996–2004	<i>Betula pendula</i>	Meteoswiss
Ukraine	5	1951–98	<i>Betula</i>	Moscow State University
UK	3414	1999–2004, station specific	<i>Betula pendula</i>	UK Phenological Network
Total	6595			

represent the two tree-like species, silver birch (*Betula pendula* Roth.) and downy birch (*Betula pubescens* Ehrn.), both common and with natural distributions extending from the mountainous regions of southern Europe to northernmost Fennoscandia, and through Siberia to the east coast of Asia (Atkinson, 1992).

The data base includes observations of three plant parameters: date of bud burst, date of leaf unfolding and the first flowering day. The total number of the data points (all stations, all years) considered for the study was: 6215 for bud burst, 58,755 for leaf unfolding and 27,519 for the first flowering day. Most of the observations were made after 1980, but some date back to the middle of the 19th century, e.g. the data set of the Finnish Society of Science and Letters covers more than 150 years. The longest single-site time series in the analysis covers the period 1970–2005 (36 years) but some stations in the PhenoData reported for even longer.

The methodologies of the observations and definitions of the phenological phases vary somewhat from country to country (Tables 1 & 2) (Elagin & Lobanov, 1979; Kubin *et al.*, 2004). Also the number of trees monitored and the frequency of monitoring varies, depending on the country. In several countries the birch types are not reported, which has to be treated as an internal uncertainty of the particular subsets. This is consistent with the absence of quantitative information about the geographical distribution of the birch taxa mentioned by Sofiev *et al.* (2006), who compiled a map of 'general birch' without a split into individual species.

The definition of phenological phases based on BBCH methodology (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie, after Meier, 1997) is widely used within

the agricultural sector; all participants in the COST 725 action have therefore adopted the use of BBCH methodology (<http://www.cost725.org>), and the European Phenological Network (EPN) recommend, that (new) phenological networks should adopt it as the basis for setting up or updating their monitoring programmes (Bruns & van Vliet, 2003). However, until now, not all national networks have adopted the Europe-wide unified definitions of the phenological phases, nor a single procedure of observations describing the number of trees to be looked at, minimal area covered, etc.

Organizational details can also affect the data. Professional networks monitor objects regularly at least twice a week. For amateur observers the frequency may differ, although during transition phases it is at least the same as for professionals. The densest networks in the UK and Germany are operated by amateurs, as well as the newly established network in the Netherlands (not in the data base). Therefore, the phenological observations by non-professionals should not be underestimated, as they provide the bulk of the currently available information in Europe.

While compiling the data base, a pre-screening was made to ensure its self-consistency, but this was reduced to a minimum in order not to disturb the data by excessive filtering. The pre-screening was done to all data, independent of the potential national practices of same type performed to data before delivery. The requirements for the final data set were: (1) it should be internally consistent, i.e. the discrepancies between the national sub-sets should be smaller than their internal variability; and (2) it should be free of crude errors due to misprints or misprocessing of the data. The pre-screening therefore included the following:

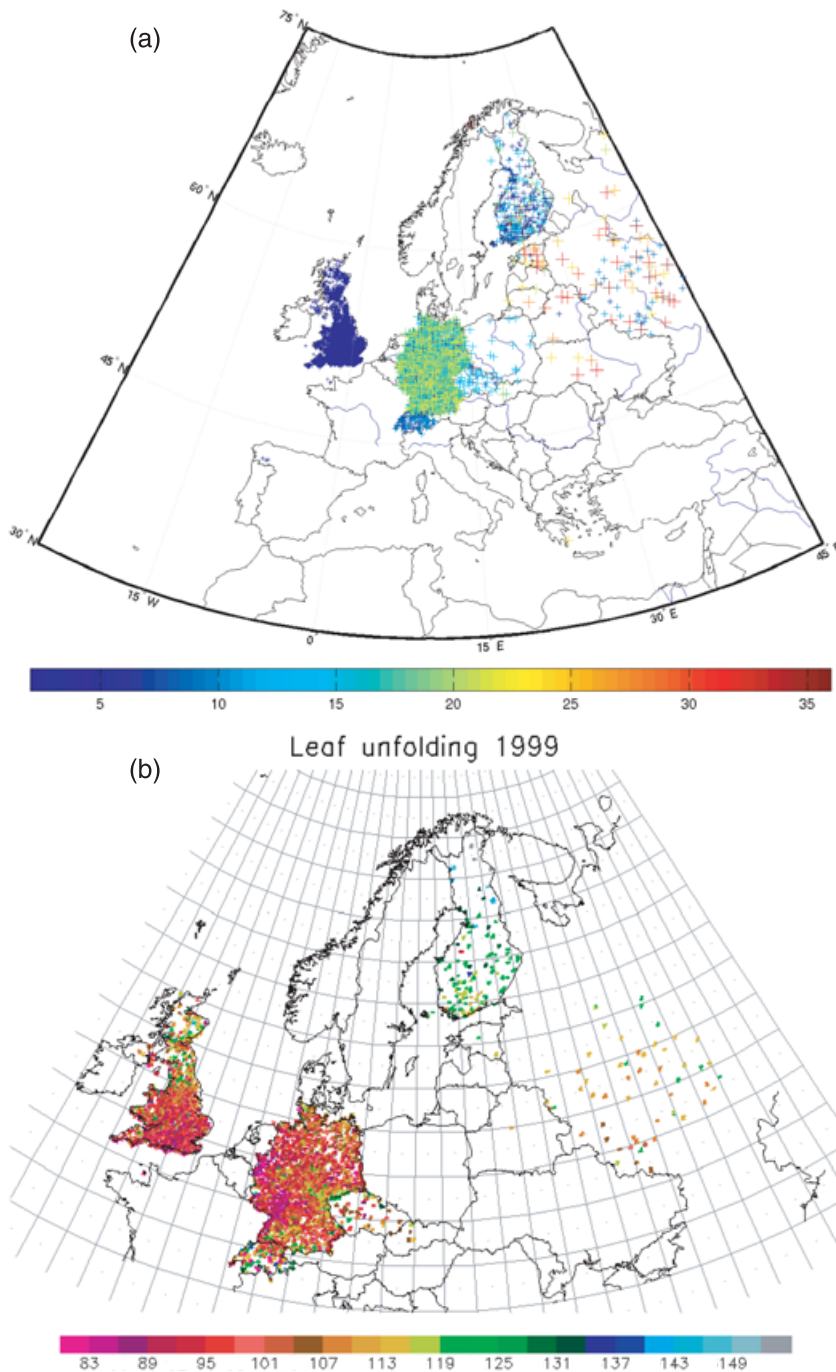


Figure 1 (a) Locations of the phenological stations. Colours show the length of the time series for each station (years). (b) *Betula* leaf unfolding in 1999 (Julian days). The grid shown has a resolution of 2.250°.

(1) at the methodological level, comparisons of the definitions of the phenological stages and assessment of the contribution to overall uncertainty from the discrepancies; (2) at the processing level, checks for the normal order of the phenological phases for all stations and all years; and (3) at the final stage, a qualitative check performed for the absence of visible country borders on a printed map (see Fig. 1b as an example).

From Table 2, it can be seen that the largest discrepancy in the definitions of the phenological phases is 10% versus 50% of unfolded leaves as a criterion for leaf unfolding. Its impact can be estimated using the results of Rousi & Heinonen (2007), who

studied the temporal distribution of leaf unfolding of a mixed birch stand (*B. pendula* and *B. pubescens*) at Punkaharju, Central Finland (61.8° N, 29.3° E). They found the variance in timing between individual plants to be 2.24 days. Assuming a normal distribution, we estimated that the systematic bias between the 10% and 50% criteria is about 1.9 days. This bias was already smaller than the uncertainties deriving from the limited frequency of observations (Table 2). Taking into account the other internal uncertainties in each subset (e.g. mixed birch species, unknown microclimate of each station, individual plant characteristics, etc.) the overall impact of this bias was believed to

Table 2 Characteristics of the monitoring system and criteria for a phenological phenomenon to take place at an observation site.

	Type of network	No. of trees	Frequency of monitoring	BBCH used	Leaf unfolding (BBCH 11)	Start of flowering (BBCH 60); when takes place at one site?
Belarus 1 (Aeroteam)	Professional	1	Every day/second day during transition phases	No	Leaves at several sites of the object have unfolded	First time when pollen falls out when the catkins are touched
Belarus 2	Professional	1	2 to 3 times per week	No	10% of leaves unfolded	First time when pollen falls out when the catkins are touched
Estonia	Professional	n/a	2 to 3 times per week	No	10% of leaves unfolded	First time when pollen falls out when the catkins are touched
Finland 1	Professional	5	2 to 3 times per week	No	50% of leaves of 5 trees unfolded	No data
Finland 2	Amateur		Daily	No	No information	No data
Germany	Amateur	1	Own consideration, but frequently during transition phases	Yes	Leaves have unfolded at least at three sites of the tree	3 flowers of selected tree are open
Latvia	Professional	5	2 to 3 times per week	No	10% of leaves unfolded	No data
Lithuania	Professional	5	2 to 3 times per week	No	10% of leaves unfolded	No data
Russia 1	Professional	5	2 to 3 times per week	No	10% of leaves unfolded	First time when pollen falls out when the catkins are touched (Moscow)
Slovakia	Professional	1	Several times a week during transition phases	Yes	Leaves have unfolded at least at three sites of the tree	No data
Spain	Professional	1	Twice a week	Yes	Leaves have unfolded at least at three sites of the tree	3 flowers of selected tree are open
Switzerland	Amateur	1	2 to 3 times per week	Partly	50% of leaves have unfolded	3 flowers of selected tree are open
Czech Rep.	Professional	3 to 5	Every second day	No, but similar	Mode of days the phase has appeared in 10% of leaves of individual trees	Mode of days the phase has appeared in 10% of catkins of individual trees
UK	Amateur	1	Own consideration, but frequently during transition phases	Yes	Leaves have unfolded at least at three sites of the tree	3 flowers of selected tree are open

BBCH number refers to BBCH methodology number (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie, after Meier, 1997).

be small, for which reason we did not apply any bias correction in the current study.

We analysed the widest possible range of spatial scales. The density of stations in several countries allowed for consideration of a wide range of spatial scales down to a few kilometres (Fig. 1a). There was also one data set from Spain with tree-specific information given for several trees at a single station, which corresponded to a spatial scale of a few tens of metres and reflects the variability in the behaviour of a single tree. The largest-scale consideration covered the whole of Europe.

Factors influencing the representativeness of a single phenological station

There are three main sources of objective uncertainty in the determination of a phenological phase at a station and its extrapolation to the surrounding region: local microclimate, meteorological variability and plant-specific variability. Non-ideal observations also contribute to the overall uncertainty: a non-daily monitoring frequency, a mixture of different taxa, subjective inaccuracies in determining the phases, etc. However, such irregularities in the data gathering and processing, being subjective, are essentially irreducible and thus have to be treated as an underlying basic source of uncertainties common to all the data.

The first contributor is the local microclimate. The immediate surroundings of the site, such as the southward slope of a hill or the proximity of a lake to the forest, play an important role in the phenological stages. The local microclimate has a very small characteristic spatial scale – well below 1 km. Its impact at larger scales can be considered random in space, but the bias in the dates of the phenological stages observed at the station is stable in comparison with the grid averages. Indeed, the effect of, for example, the northern slope of a valley is stable from year to year. Its influence can be somewhat reduced if observations at a station cover at least a few hundred metres (e.g. a botanical garden or a forest). It can also be treated during data preparation, for example, as by Häkkinen *et al.* (1995) who have combined several point-wise phenological observations into a single regional time series by adjusting observations with a station-specific, temporally fixed bias correction.

The second contributor is the meteorological variability. Presumably, it should be more important at larger scales, because plant processes have a considerable ‘memory’ of past weather conditions and thus are not sensitive to small-scale short-term events, such as a single rainfall event (Sarvas, 1955, p. 21). In contrast to microclimate, meteorological variability does not create a temporally stable bias for a specific station but is rather seen as random fluctuations in the dates of the phenological phases from year to year. These fluctuations should be spatially synchronized over synoptic-scale areas (at least a few tens of kilometres) and will thus disappear when the data are treated at a higher spatial resolution. In the analysis, that should be seen as a reduction of the variability with increasing resolution.

The contribution of the third source of uncertainty – the plant-specific variability (Rousi & Pusenius, 2005) – is practically indistinguishable from the impact of observational errors, differences

in methodology and practice (at both country and station levels), etc. The contribution of all these factors to the overall uncertainty should be largely random (except for some specific aspects of methodology, which, as shown above, are believed to be small) in both time and space. In a few cases (e.g. frequency of observations) some part of it can be quantified, but in most cases only an overall estimate can be obtained via the procedures described below.

Importantly, the meteorological factors play both synchronization and de-synchronization roles depending on the spatial scale. They are one of the sources of uncertainties at large scales when the synoptic structures (cyclones, fronts, etc.) are not resolved. For smaller scales the Moran effect starts to dominate; plants that are under the same meteorological stress respond in a similar way, their phenological stages thus becoming closer to each other.

Quantitative characterization of the uncertainty and delineation of its sources

The methodology described below is largely based on grids with varying resolutions defined for the domain, onto which grids the stations were projected directly, without any interpolation between the sites or other gridding techniques (see Appendix S1 in Supplementary Material for the details).

In many cases (especially at a high spatial resolution) the number of stations falling into a single grid cell was small. As a protective measure against outliers, we always used statistically robust measures, such as the median and percentiles, instead of sensitive parameters, such as the arithmetic average and variance. We also required at least five stations to fall into a grid cell for it to be included in the analysis. For the analysis of temporal variability, an additional requirement of at least 5 years of common reporting period was made.

Three types of statistical measures were selected for the analysis:

Grid-based estimate of spatial uncertainty

The spatial variability V of the date of a phenological phase within a grid cell was defined as: $V = P_{84} - P_{16}$ where P_{84} and P_{16} are the 84th and 16th percentiles, respectively, of the single observations made by the stations located within this grid cell. The variability V was thus a robust estimate of the double-standard-deviation 2σ uncertainty interval, which contains about 64% of the observations. For example, for seven observations in a grid cell, V was the difference between the second earliest and the second latest observed dates. To reveal the scale dependence of the variability, we considered several grids with resolution varying from a few tens of metres up to a few thousand kilometres.

Grid-based estimate of temporal uncertainty

The temporal stability of the data of a single station was estimated as the probability for the station to report dates earlier/close-to/ later than the median over the corresponding grid cell. A single observation was classified as ‘early’ (or ‘late’) if its deviation from

the grid-cell median date exceeded 2 days. This threshold was selected to be close to a typical synoptic time-scale of 3 days. For each station, we computed in how many cases the station reported the date within the median ± 2 days, later than 2 days or earlier than 2 days from the median. Finally, we marked the station as 'early/late' if more than 70% of its observations were 'early' or 'late', respectively. The sites with more than 70% of dates reported within 2 days of the median were labelled as 'representative'. Stations not counted in any of the above groups were considered as 'random' as they did not demonstrate any regularity in year-to-year behaviour regarding the grid-cell median. For example, if the station was within 2 days of the median in 50% of years, 'late' in 25% and 'early' in 25% of cases, it was called 'random'.

Grid-free spatial uncertainty analysis via structure functions

To support and double-check the grid-based analysis, the method of structure functions was brought into use as a complementary tool. It is an independent method for the analysis of space-distributed stochastic fields, which is neither based on any imposed regular grids nor involves any other regularization techniques. It is widely used for the analysis of meteorological fields and observations. Its formal definition and main features are explained in Appendix S2. From a physical point of view, the structure function $S_f(r_1, r_2)$ of a field f quantifies the decorrelation of the subregions of the field r_1 and r_2 depending on the distance between these sub-regions $|r_1 - r_2|$. The higher $S_f(r_1, r_2)$, the more independent these regions are. Vice versa, if $S_f = 0$ then the processes in these regions perfectly coincide. In our case, the S_p of the phenological phase p showed decorrelation of the observing stations depending on the distance between them. The 'distance' here also included the direction from one station to another, because decorrelation along longitude was evidently different from that along latitude.

RESULTS OF THE REPRESENTATIVENESS ANALYSIS AND DISCUSSION

General characteristics of spatial variability

The key result of the study (Fig. 2) was that the variability V for practically all resolutions was between 7 and 16 days (i.e. the standard deviation σ varied from 3 to 8 days) and behaved quite similarly for all considered phenological parameters. The variability tended to decrease at higher resolutions but this trend was not strong: (1) for very high-resolution grids with a cell size from < 1 km to 10–20 km, the increasing resolution reduced the uncertainties in the first flowering day but seemingly did not affect the leaf unfolding; (2) for a wide range of meso-to-regional (20–500 km) scales no clear dependency of variability on resolution existed; and (3) extra-coarse resolution – over thousands of kilometres – lead to a clear increase in the variability.

Analysis via the structure functions for leaf unfolding (Fig. 3) did not include the subkilometre range because of an insufficient number of data. The rest of the spectrum was very well seen, providing more insight into the above observation and refining

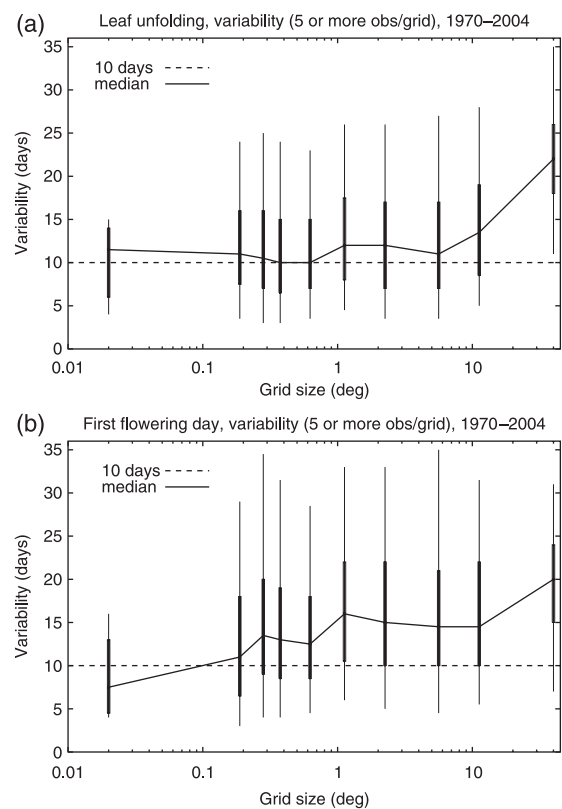


Figure 2 Variability of selected plant parameters within quadrants (all stations in 1970–2004 with five or more observations per grid) aggregated into grids of different resolution: (a) leaf unfolding, (b) first flowering day. Shown are the median, upper and lower quartiles and 5th and 95th percentiles of variability.

some of the conclusions. As the separation distance (a direct analogy of grid resolution) approached 2 km (the minimum computed distance), the unified European structure function S_E (built using the whole data set) approached the limit of 5–6 days. With increasing scale, it grew to 6.5 days for ~50 km and then continued to grow slowly to reach 7 days for a resolution of about 500 km. At this scale – but not earlier – the difference between north–south and east–west directions became visible, so that the decorrelation of stations located far from each other in a north–south direction grew faster (an evident footprint of a different climate). A further scale increase resulted in widening the variability, which grew fastest across climatic zones, i.e. in a north–south direction.

Structure functions built for individual regions revealed further peculiarities of site representativeness in each part of Europe. Thus, the maximum decorrelation between sites at all distances was observed in the UK. There, even co-located sites (at a distance of ~2–4 km) showed a variability between 6.5 and 7.5 days. For larger scales, it grew faster than in other regions and reached 9 days for a scale of 500 km. After that, the analysis became inaccurate due to the limited size of the UK.

The decorrelation of German sites largely resembled that of the whole of Europe, but was slightly lower – by about 1 day.

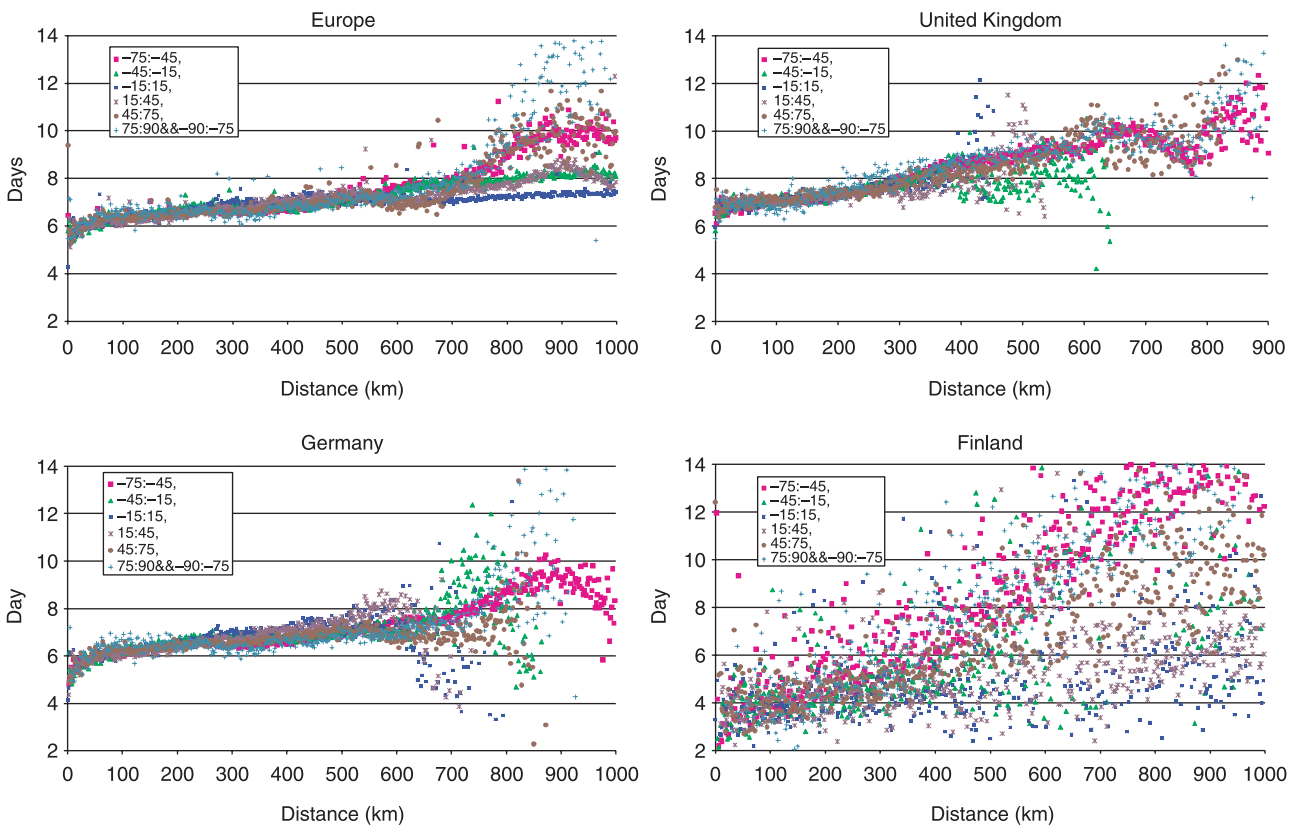


Figure 3 Structure functions for leaf unfolding in Europe, the UK, Germany and Finland. The series represents the sectors with regard to longitudinal direction (0° is along a west–east parallel). Structure function reflects the variability in data between two points located at given distance along given direction. The strongest growth is in the cross-climate north–south direction. See Appendix S2 for methodological details.

Structure functions built from Finnish sites were noisier due to the limited number of stations, but still revealed the main feature of the region; the sites were correlated much more strongly than in the other considered areas. Closely located stations tended to deviate by less than 4 days with a very slow growth towards 5 days for a scale of 300 km. Larger scales became too noisy due to the limited size of the domain; the only conclusion that could be drawn was that the north–south separation of the sites already plays an important role for distances of about 200–300 km.

In all regions, the finest scales partially resolved the local microclimate structures. The main irreducible variability for such scales was therefore the individual fluctuations of the plants and observation-specific noise. The seemingly different behaviour of leaf-unfolding data (Fig. 2a showed no reduction of uncertainty for subkilometre scales) may have been artificial because the variability estimate for the highest resolution was computed from the data for just four stations in Spain, which provided information for single trees. With all the specifics of birch in Spain, this four-site data set was clearly insufficient for deriving general conclusions on the small-scale variability of birch phenophases. Conclusions based on structure functions seemed to be more reliable – and clearly showed a decrease of variability with increasing resolution.

Averaging over larger spatial scales (20–500 km) smoothed out the small-scale fluctuations and individual specifics of the stations. For all these scales, the microclimate was unresolved, while the meteorological processes did not contribute to the variability because their scales are larger. From the opposite point of view, the Moran effect should have been in full force here, eventually synchronizing the dates from different stations. As a result, the dependence of variability and resolution was broken and the variability became nearly constant (10–12 days for leaf unfolding and 14–16 days for the first flowering day) up to a grid cell size of ~500 km.

Very coarse grids with averaging over more than 1000 km almost always covered several climatic zones with a single grid cell, a fact that contributes to the subgrid variability. For structure functions (Fig. 3), this range corresponds to the right-hand part of the curves where the variability depended on direction, showing the strongest growth in the cross-climate north–south direction. The variability of the first flowering day (Fig. 2b) showed a moderate increase because of the relatively high contribution of short-term meteorological fluctuations to the underlying phenological processes. The leaf unfolding (Fig. 2a) variability, or the contrary, increased strongly to ~15 days for a grid cell size of ~1000 km. This corresponded to the typical synoptic (or large) scale in meteorology (500–5000 km and 1–5 days).

The above results look very discouraging due to the very large variability between the sites at all scales and in almost all regions. In some years the difference in bud burst, leaf unfolding or first flowering date between the earliest and the latest birch individuals standing in the same garden could be as large as 1 month — as was observed at one station in Spain (42.3° N, 7.5° W).

Influence of local micro-climate and topography

The second part of the study was dedicated to a separation of the influence of local microclimate and topography from that of meteorological processes. This analysis required long time series and a dense network, and was thus almost solely based on German observations. The working hypothesis was that the local microclimate should create a spatially random but temporally synchronized bias for the specific station whereas the influence of meteorological processes would be much more synchronized in space and random in time. Indeed, a microclimate caused by local geographical specifics, such as a hilly surface with northern–southern slope differences or a freezing lake that takes long to thaw in spring, would affect the trees every year in a similar way. Meteorological effects, such as a late, rainy spring, would affect large regions synchronously, but would vary strongly from year to year. The microscale noise from the tree specifics and imperfect observations were independent additional components to the above, and were assumed to have similar features for all stations within a specific grid cell.

The above two factors could be separated by an analysis of the ability of single stations to follow the regional averages year by year (see Appendix S1 for details). For areas having a sufficient network density and a long observational history, it appeared possible to ‘label’ each station in accordance with its behaviour – ‘early’, ‘representative’, ‘late’ or ‘random’ – and to perform this labelling for all grid resolutions. The expectation was that the fraction of ‘representative’ stations increases for a finer resolution. This trend would reveal the impact of microclimate. For example, if some station was ‘late’ at coarse resolutions but became ‘representative’ for a sufficiently small grid cell size Δx , this station was affected by a local microclimate with a characteristic scale Δx .

The result of the analysis – the fraction of stations in each category in relation to the grid resolution – is shown in Fig. 4(a,b). As expected, the smaller grid cell sizes corresponded to a higher fraction of ‘representative’ stations because the corresponding microclimate processes were resolved by these grids. The number of ‘early’ and ‘late’ stations decreased proportionally, which also pointed to the local microclimate specifics as the primary reason for such systematic bias. The number of ‘random’ stations did not change, indicating that their uncertainties were not connected with spatially regular phenomena. Such stations tended to deviate randomly from any neighbouring site, regardless of the distance between them.

The numbers of ‘early’ and ‘late’ stations were nearly equal to each other for all resolutions, with a slightly larger fraction of ‘late’ sites. This additionally illustrates an asymmetry in the temporal distribution of phenological phases: the probability of long delays is higher than the chance of starting a phase very early.

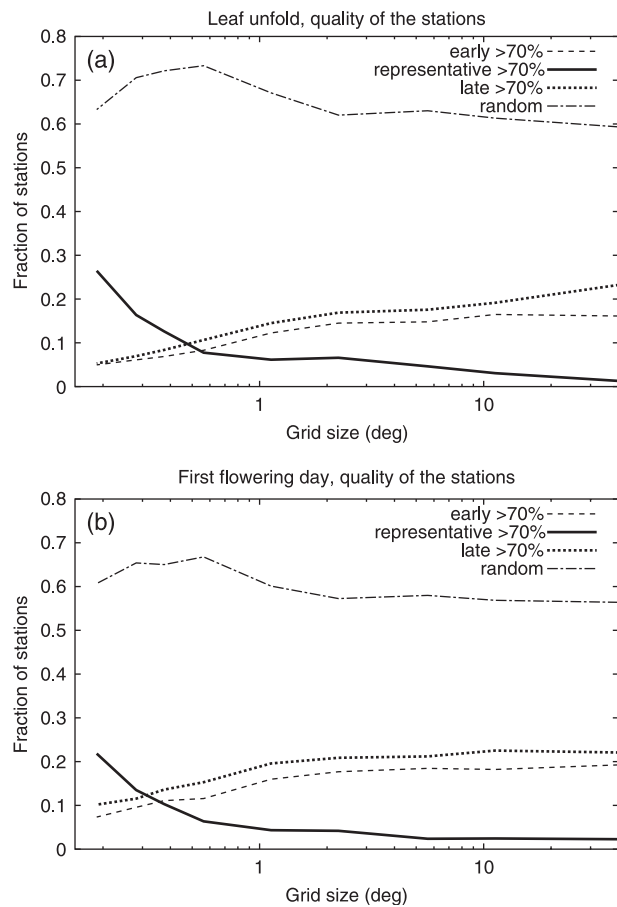


Figure 4 Fractions of ‘early’, ‘late’, ‘representative’ and ‘random’ stations in relation to the grid cell mean as a function of resolution: (a) leaf unfolding, (b) first flowering day.

To evaluate the sensitivity of the analysis to the above thresholds in the station classification, we repeated the analysis with 3 days being taken as the threshold for a ‘large’ deviation of an observation from the grid median (rather than 2 days as explained in Appendix S1 and used above). For the small grid sizes, the number of ‘representative’ stations increased from under 30% (for ± 2 days) to over 40% (for ± 3 days) and even at a grid size of 11.25° there were still over 10% of stations that could be designated as ‘representative’ (compared with 2% for a threshold of ± 2 days). The fractions of ‘late’ and ‘early’ stations did not differ markedly, although were decreasing. However, the fraction of ‘random’ sites dropped to 50% for high-resolution grids (vs. 62% for ± 2 days threshold). When the grid size was larger than 2.250°, the differences were negligible.

The other sensitivity test was to call a station ‘representative’ with just 50% of the observations falling close (± 2 days) to the grid cell median – instead of the 70% used above. The fraction of ‘random’ stations then dropped to 25%, and tended to decrease towards large grid cell sizes. The fractions of the other classes changed accordingly – the ‘representative’ class increased while the ‘early’ and ‘late’ classes became thinner. For example, for a high-resolution grid cell size of 0.187° all four fractions were

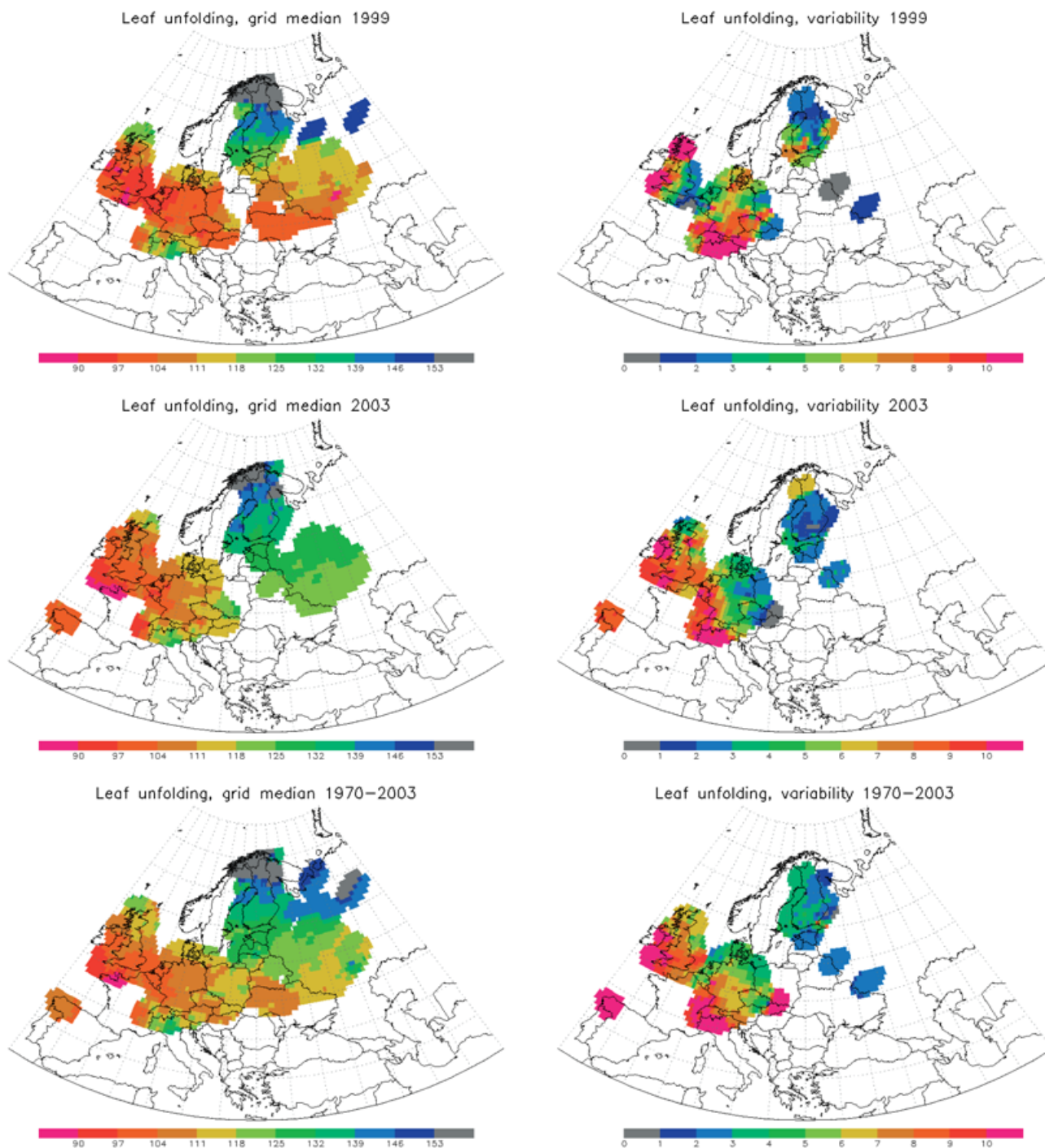


Figure 5 Maps of the median date (Julian days) of *Betula* leaf unfolding and its variability (days) for the ERA-40 grid, ($1.125^\circ \times 1.125^\circ$ resolution) in 1999, 2003 and mean 1970–2003. Variability is computed for grid cells with more than three stations.

close to 25%. Their dependence on resolution was similar to that of the base case.

Regional peculiarities of the variability

Analysing structure functions, we have already seen that the largest uncertainty was in the UK, while stations in the northern regions

were the most representative. As an additional illustration of the regional specifics and spatial trends of the variability, Figure 5 presents examples of maps of median dates of leaf unfolding and their variability for the reference grid having a 1.125° resolution. A comparison of Fig. 5 with the structure functions in Fig. 3 confirms the tendency towards a much higher uncertainty in the south-west of the studied region – in addition to the evident

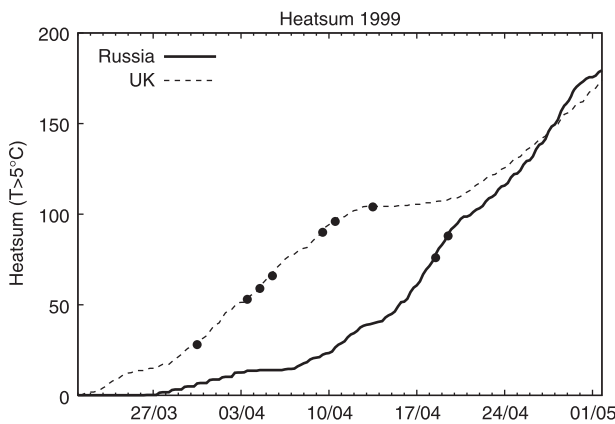


Figure 6 Accumulation of the heat sums (degree-days) in Russia (35° E, 53° N) and the UK (2° W, 53° N) in ERA-40 grid cells in spring of 1999, 21 March to 1 May. Dots mark the *Betula* leaf unfolding dates reported in 1999 by stations located in the corresponding grid cells.

south-to-north trend in the dates themselves and the pronounced year-to-year fluctuations. Variability in mountainous regions was very high, as expected.

Interpretation of the east–west and north–south gradients of the variability (Fig. 5) can again involve the Moran effect of meteorological forcing. It is well known that in continental climates the rise of temperature is rapid in spring in comparison with the slow and non-monotonic pace in a marine climate. This means that forcing by the rising temperature is much stronger in the east than in the UK and western Europe. As an illustration, we compared two typical time series of the accumulated heat sum (low threshold of 5 °C, accumulation started on 22 March) in the UK and in Russia. Both points were taken at the same latitude of 53 ° N and the meteorological data were picked from the two corresponding grid cells of the ERA-40 reanalysis (Uppala *et al.*, 2005; resolution of 1.125°) for 1999. As seen in Fig. 6, in Russia the heat sum starts accumulating late but advances very fast in comparison with the UK, finally arriving at even slightly larger values. All small-scale fluctuations are suppressed when large areas warm up rapidly; this rapid rise synchronizes the phenological processes.

From Fig. 6 it is seen that the seven and two stations that reported leaf unfolding in 1999 in the selected ERA-40 grid cells in the UK and Russia, respectively (black dots on the lines, dates correspond to reported phenological phase), actually showed that the trees in these two regions are not much different. Indeed, in both areas the critical heat sum appeared to be between 60 and 100, except for one site in the UK. However, this range of 40 degree-days projects to a time uncertainties of more than 2 weeks in the UK but less than 1 week in Russia.

An indirect confirmation of the above interpretation was given by Leinonen & Hänninen (2002), who studied the adaptation of Norway spruce in continental and maritime climates. One of their conclusions was that the risk of frost damage in a continental climate has probably led to a better synchronization between the

trees, in particular leading towards a more uniform critical heat sum level in a continental than in a maritime climate. As expected, such environmental stress affects not only trees but other biosystems. For example, Tryjanowski *et al.* (2006) observed, too, that dog violet and horse chestnut records were significantly more variable in the UK than in Poland.

The mechanisms of synchronization of the phenophases in the northern regions are probably somewhat different from those in the continental climate of Russia, and have a stronger connection with the shorter vegetation period and risk of late-spring and early-autumn frost damage in addition to a faster rise of temperature in spring.

Influence of uncertainties in the phenological data on their applications

The analysis of spatial representativeness of the phenological sites presented here follows the general procedure of pre-evaluation of observational data used in numerical modelling. The key assumption imposed on the data when using them in such grid-based systems is that the variations within the grid cells (the non-resolved part of a phenomenon) are much smaller than the simulated part of the signal. Similar assumptions are generally true for all of applications; the noise in the data must be small compared with the signal.

The uncertainties discussed above, however, are quite large. Even for a grid size of 30 km, the variability is from 6–14 days, depending on the region, with a significant reduction seen only in continental and northern climates. These correspond to a standard deviation of from 3–7 days. Depending on the application and strength of the signal, such variability can be acceptable or not. In the latter case, certain measures are needed before the data become usable.

A primary goal of the current study was to support the POLLEN project by evaluating the possibility and suggesting a methodology for using the phenological data for the pollen release model within the scope of an atmospheric dispersion model. According to experience with similar model types, the subgrid variability should not exceed the synoptic time scale of ~3 days. This means that the uncertainty in the starting date of pollen emission should not exceed 2 days (the above threshold for ‘representative’ observations). The large objective uncertainties in the phenological data therefore require special measures before these observations can be used for pollen forecasting (Estrella *et al.*, 2006).

For another popular use of phenological data – climatological studies (e.g., Chuine *et al.*, 2000; Sparks *et al.*, 2000; Ahas *et al.*, 2002; Menzel *et al.*, 2003; Studer *et al.*, 2005) – the variability also seems to be high, because the expected signal is just a few (1–3) days per decade, which is again comparable with the variability itself, and makes the conclusions vulnerable to the limited representativeness of the station data, especially for ‘random’ stations.

Seemingly the simplest way is to filter out the ‘random’ stations and to correct the bias in the ‘early’ and ‘late’ ones. However, this leads to a substantial reduction of the volume of the data set and strong changes in its features. It may be acceptable in some

applications and entirely wrong in others. In our view, the variability discovered above is objective and is mainly natural in origin rather than originating from observational artefacts, which certainly contribute but do not dominate. If this is true, the filtered data set will no longer reproduce reality; it will become nice-looking, but in many senses useless.

An alternative approach might be to switch from a deterministic approach, which requires a minimum of internal uncertainty in the input data, to a probabilistic one, which takes this uncertainty into account. This can be comparatively straightforward in pollen dispersion modelling but more difficult in some other applications. Numerical weather predictions and air-quality forecasts to an increasing extent already use probabilistic ensemble forecasts (e.g. Molteni *et al.*, 1996; Galmarini *et al.*, 2004a,b) and it would be interesting to apply a similar treatment to phenological time series.

One of the important problems arising from the high uncertainty of phenological observations is that their treatment requires a large abundance of data to provide reliable results. Therefore high-density networks with the longest possible time series become a matter of the utmost importance. In most cases, such networks can be maintained only with the help of amateur observers, which in turn raises the problem of the quality assurance of the data, training for the observers, etc.

CONCLUSIONS

A unique phenological data base has been compiled for birch species, bringing together long-term observations from 15 countries over the European continent. A crude pre-screening of the data base has been performed and has confirmed the usability of the data set after a minor reduction. The data were used for quantifying the spatial representativeness of phenological observations.

The analysis highlighted the problem of the limited spatial and temporal representativeness of the phenological data, and showed that representativeness may strongly affect their usage and require treatment appropriate for the application in hand.

The variability of a single observation expressed as the difference between the 16th and 84th percentiles (a robust estimate, corresponding to double the standard deviation for a normal distribution) with regard to the regional median date appeared to range from 6 to 16 days depending on the size of the region and location. The uncertainty was generally smaller for regions of smaller size (corresponding to a higher resolution.).

The representativeness of the eastern and northern sites appeared to be substantially higher than that of those in the western part of the domain. Sites located in mountains normally had poor representativeness.

A reasonable explanation for the observed dependence of the representativeness on the geographical location relies on the Moran effect due to meteorological forcing. Shorter springs in the continental and northern climates and shorter vegetation periods with a high frost risk would generally force the plants to act more synchronously, following the cause of the weather developments. However, this matter requires further investigation

of the biological mechanisms behind it and cannot be confirmed within the scope of the current study.

Station-specific analysis showed that only 10–30% of sites (depending on the grid resolution) stably report dates close to the regional averages (within 2 or 3 days). Another 20–40% of the sites are either stably 'early' or 'late' in comparison with the regional median. Practically regardless of the spatial resolution, a large fraction of the sites (~60% for a threshold of 2 days and 25% for 3 days) fluctuate widely and randomly around the regional mean dates.

The study showed that direct utilization of the phenological observations for constructing a pollen atmospheric dispersion model is not feasible. Special measures should be implemented in the emission module to reflect the objective variability of the dates of the phenological phases.

These findings also call for appropriate treatment of the phenological data in other studies relying on the spatial and temporal representativeness of the data, most of all in climate research.

Methods of pre-processing the data depend on the specific application, but could include filtration of noisy parts of the data set (a potentially dangerous action disturbing the data features), or a switch to probabilistic description of the phenomena.

ACKNOWLEDGEMENTS

The current study is part of the Academy of Finland POLLEN project on 'Evaluation and forecasting of atmospheric concentrations of allergenic pollen in Europe' (<http://pollen.fmi.fi>).

The phenological data were provided by: Belarus Aerobiology team, Meteo Swiss (Switzerland), Czech Hydrometeorological Institute, German Weather Service DWD, Estonian Meteorological and Hydrometeorological Institute EMHI, Tartu University (Estonia), Moscow State University (Russia), Galician Aerobiological Network (Spain), Finnish Forest Research Institute, The Finnish Society of Sciences and Letters, UK Phenological Network, Centre for Ecology and Hydrology (UK), Plante Forsk (Norway), Institute of Meteorology and Water Management (Poland) and the Slovak Hydrometeorological Institute.

REFERENCES

- Ahas, R., Aasa, A., Menzel, A., Fedotova, V.G. & Scheifinger, H. (2002) Changes in European spring phenology. *International Journal of Climatology*, **22**, 1727–1738.
- Atkinson, M.D. (1992) *Betula pendula* Roth (*B. verrucosa* Ehrh.) and *B. pubescens* Ehrh. *Journal of Ecology*, **80**, 837–870.
- Berg, T. & Schaug, J. (eds) (1994) *EMEP Workshop on the Accuracy of Measurements*. EMEP/CCC-Report 2/94, Norwegian Institute for Air Research, Kjeller, Norway.
- Blasius, B. & Stone, L. (2000) Ecology: nonlinearity and the Moran effect. *Nature*, **406**, 846–847.
- Bruns, E. & van Vliet, A.J.H. (2003) *Standardisation and observation methodologies of phenological networks in Europe*. Wageningen University, German Weather Service, Wageningen, Offenbach.

- Chen, X.Q., Hu, B. & Yu, R. (2005) Spatial and temporal variation of phenological season and climate change impacts in temperate eastern China. *Global Change Biology*, **11**, 1118–1130.
- Chuine, I., Cambon, G. & Comtois, P. (2000) Scaling phenology from the local to the regional level: advances from species-specific phenological models. *Global Change Biology*, **6**, 943–952.
- Črepinšek, Z., Kajfež-Bogataj, L. & Bergant, K. (2006) Modelling of weather variability effect on fitophenology. *Ecological Modelling*, **194**, 256–265.
- Elagin, A.I. & Lobanov, A.I. (1979) *Atlas-opredelitel' fenologicheskikh faz u rastenii*. Nauka, Moscow.
- Engen, S. & Sæther, B.E. (2005) Generalizations of the Moran effect explaining spatial synchrony in population fluctuations. *The American Naturalist*, **166**, 603–612.
- Estrella, N., Menzel, A. & Krämer, U. (2006) Integration of flowering dates in phenology and pollen counts in aerobiology: analysis of their spatial and temporal coherence in Germany (1992–1999). *International Journal of Biometeorology*, **51**, 49–59.
- Galmarini, S., Bianconi, R., Addis, R., Andronopoulos, S., Astrup, P., Bartzis, J.C., Bellasio, R., Buckley, R., Champion, H., Chino, M., D'Amours, R., Davakis, E., Eleveld, H., Glaab, H., Manning, A., Mikkelsen, T., Pechinger, U., Polreich, E., Prodanova, M., Slaper, H., Syrakov, H., Terada, H. & Van der Auwera, L. (2004a) Ensemble dispersion forecasting – part II: application and evaluation. *Atmospheric Environment*, **38**, 4619–4632.
- Galmarini, S., Bianconi, R., Klug, W., Mikkelsen, T., Addis, R., Andronopoulos, S., Astrup, P., Baklanov, A., Bartniki, J., Bartzis, J.C., Bellasio, R., Bompay, F., Buckley, R., Bouzom, R., Champion, H., D'Amours, R., Davakis, E., Eleveld, H., Geertsema, G.T., Glaab, H., Kollax, M., Ilvonen, M., Manning, A., Pechinger, U., Persson, C., Polreich, E., Potemski, S., Prodanova, M., Saltbones, J., SlapeR, H., Sofiev, M.A., Syrakov, D., Sørensen, J.H., Van der Auwera, L., Valkama, I. & Zelazny R. (2004b) Ensemble dispersion forecasting – part I: concept, approach and indicators. *Atmospheric Environment*, **38**, 4607–4617.
- Häkkinen, R., Linkosalo, T. & Hari, P. (1995) Methods for combining phenological time series; application to bud burst in birch (*Betula pendula*) in Central Finland for the period 1896–1955. *Tree Physiology*, **15**, 721–726.
- Häkkinen, R., Linkosalo, T. & Hari, P. (1998) Effects of dormancy completion and the environmental factors on timing of bud burst in *Betula pendula*. *Tree Physiology*, **18**, 707–712.
- Heikinheimo, M. & Lappalainen, H. (1997) Dependence of the flower bud burst of some plant taxa in Finland on effective temperature sum: implications for climate warming. *Annales Botanici Fennici*, **34**, 229–243.
- Koenig, W.D. & Knops J.M.H. (1998) Scale of mast-seeding and treeing growth. *Nature*, **396**, 225–226.
- Koenig, W.D. & Knops, J.M.H. (2000) Patterns of annual seed production by northern hemisphere trees: a global perspective. *The American Naturalist*, **155**, 59–69.
- Kubin, E., Poikolainen, J., Hokkanen, T., Karhu, J. & Pasanen, J. (2004) Field instructions for plant-phenological observations. The Finnish Forest Research Institute, Muhos Research Station.
- Leinonen, I. & Hänninen, H. (2002) Adaptation of the timing of bud burst of Norway Spruce to temperate and boreal climates. *Silva Fennica*, **36**, 697–701.
- Linkosalo, T. (2000) Mutual regularity of spring phenology of some boreal tree species: predicting with other species and phenological models. *Canadian Journal of Forest Research*, **30**, 667–673.
- Meier, U. (1997) *Growth stages of plants*. BBCH-Monograph. Blackwell Wissenschafts verlag, Berlin and Wien.
- Menzel, A., Jakobi, G., Ahas, R., Scheifinger, H. & Estrella, N. (2003) Variations of the climatological growing season (1951–2000) in Germany compared with other countries. *International Journal of Climatology*, **23**, 793–812.
- Menzel, A., Sparks, T.H., Estrella, N. & Roy, D.B. (2006) Altered geographic and temporal variability in phenology in response to climate change. *Global Ecology and Biogeography*, **15**, 498–504.
- Molteni, F., Buizza, R., Palmer, T.N. & Petroliagis, T. (1996) The ECMWF ensemble prediction system: methodology and validation. *Quarterly Journal of The Royal Meteorological Society*, **122**, 73–119.
- Moran, P.A.P. (1953) The statistical analysis of the Canadian lynx cycle. II Synchronization and meteorology. *Australian Journal of Zoology*, **1**, 291–298.
- Parmesan, C. & Yohe, G. (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, **421**, 37–42.
- Ripa, J. (2000) Analysing the Moran effect and dispersal: their significance and interaction in synchronous population dynamics. *Oikos*, **89**, 175–187.
- Rötzer, T. & Chmielewski, F.M. (2001) Phenological maps of Europe. *Climate Research*, **18**, 249–257.
- Rousi, M. & Heinonen, J. (2007) Temperature sum accumulation effect on within-population variation and long-term trend in date of bud-burst of European white birch (*Betula pendula*). *Tree Physiology*, **27**, 1019–1025.
- Rousi, M. & Pusenius, J. (2005) Variations in phenology and growth of European white birch (*Betula pendula*) clones. *Tree Physiology*, **25**, 201–210.
- Sarvas, R. (1952) On the flowering of birch and the quality of seed crop. *Communicationes Instituti Forestalis Fenniae*, **40**, 1–38.
- Sarvas, R. (1955) Investigations into flowering and seed quality of forest trees. *Communicationes Instituti Forestalis Fenniae*, **45**, 1–37.
- Satake, A. (2004) Modelling spatial dynamics of episodic and synchronous reproduction by plant populations: the effect of small-scale pollen coupling and large-scale climate. *Population Ecology*, **46**, 119–128.
- Satake, A. & Iwasa, Y. (2000) Pollen-coupling of forest trees: forming synchronized and periodic reproduction out of chaos. *Journal of Theoretical Biology*, **203**, 63–84.

- Satake, A. & Iwasa, Y. (2002) Spatially-limited pollen exchange and a long-range synchronization of trees. *Ecology*, **83**, 993–1005.
- Schaber, J. & Badeck, F.W. (2003) Physiology based phenology model for forest tree species in Germany. *International Journal of Biometeorology*, **47**, 193–201.
- Shibata, M., Tanaka, H. & Nakashizuka, T. (1998) Causes and consequences of mast seed production of four co-occurring *Carpinus* species in Japan. *Ecology*, **79**, 54–64.
- Smouse, P.E. & Sork, V.L. (2004) Measuring pollen flow in forest trees: an exposition of alternative approaches. *Forest Ecology and Management*, **197**, 21–38.
- Sofiev, M., Siljamo, P., Ranta, H. & Rantio-Lehtimäki, A. (2006) Toward numerical forecasting of long-range transport of birch pollen: theoretical considerations and a feasibility study. *International Journal of Biometeorology*, **50**, 392–402.
- Sparks, T.H. & Braslavská, O. (2001) The effect of temperature, altitude and latitude on arrival and departure dates of the swallow *Hirundo rustica* in Slovak Republic. *International Journal of Biometeorology*, **45**, 212–216.
- Sparks, T.H. & Carey, P.D. (1995) The responses of species to climate over two centuries: an analysis of the Marsham phenological record, 1736–1947. *Journal of Ecology*, **83**, 321–329.
- Sparks, T.H. & Menzel, A. (2002) Observed changes in seasons: an overview. *International Journal of Climatology*, **22**, 1715–1725.
- Sparks, T.H., Jeffree, E.P. & Jeffree, C.E. (2000) An examination of the relationship between flowering times and temperature at the national scale using long-term phenological records from the UK. *International Journal of Biometeorology*, **44**, 82–87.
- Studer, S., Appenzeller, C. & Defila, C. (2005) Inter-annual variability and decadal trends in alpine spring phenology: a multivariate analysis approach. *Climatic Change*, **73**, 395–414.
- Tryjanowski, P., Panek, M. & Sparks, T. (2006) Phenological response of plant temperature varies at the same latitude: case study of dog violet and horse chestnut in England and Poland. *Climate Research*, **32**, 89–93.
- Tutin, T.G., Burges, N.A., Chater A.O., Edmondson, J.R., Heywood, V.H., Moore, D.M., Valentine, D.H., Walters, S.M. & Webb, D.A. (eds) (1993) *Flora Europaea*, 2nd edn, Vol 1. Cambridge University Press, Cambridge.
- Uppala, S.M., Källberg, P.W., Simmons, A.J., Andrae, U., da Costa Bechtold, V., Fiorino, M., Gibson, J.K., Haseler, J., Hernandez, A., Kelly, G.A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R.P., Andersson, E., Arpe, K., Balmaseda, M.A., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B.J., Isaksen, I., Janssen, P.A.E.M., Jenne, R., McNally, A.P., Mahfouf, J.F., Morcrette, J.J., Rayner, N.A., Saunders, R.W., Simon, P., Sterl, A., Trenberth, K.E., Untch, A., Vasiljevic, D., Viterbo, P. & Woollen, J. (2005) The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society*, **131**, 2961–3012.
- WMO (1996) Guide to meteorological instruments and methods of observations, WMO-No. 8, 6th edn. World Meteorological Organization, Geneva.
- Yaglom, A.M. (1987) *Correlation theory of stationary and related random functions*. Springer Verlag, Berlin.

SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article:

Appendix S1 Details of grid definition and processing.

Appendix S2 Definition, main features of structure functions and their application to phenological analysis.

This material is available as part of the online article from: <http://www.blackwell-synergy.com/doi/abs/10.1111/j.1466-8238.2008.00383.x>

(This link will take you to the article abstract).

Please note: Blackwell Publishing is not responsible for the content or functionality of any supplementary materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

BIOSKETCHES

Pilvi Siljamo is a researcher (meteorology) at the Finnish Meteorological Institute. Specific areas of interest are atmospheric dispersion models, modelling pollen long-range transport and dispersion calculation during emergency-type short-term releases of various air pollutants.

Mikhail Sofiev is a physicist and adjunct professor at the Finnish Meteorological Institute. Specific areas of interest are mathematical modelling of atmospheric pollution by various compounds, model verification and comparison with measurements, statistical methodology for model evaluation, analysis of the measurement data, inverse and adjoint dispersion modelling.

Hanna Ranta is a lecturer and aerobiologist at the University of Turku. Specific areas of interest are pollen research, development, evaluation and application of pollen long-range transport modelling and official pollen forecasts in Finland.

Tapio Linkosalo is a phenologist at the University of Helsinki. Specific areas of interest are studying the annual rhythm of boreal forests and the impact of climatic warming on it, phenology of boreal forests and applied mathematics.

Editor: Matt McGlone