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THE INFLUENCE OF ATMOSPHERIC CIRCULATION ON PLANT PHENOLOGICAL PHASES IN CENTRAL AND EASTERN EUROPE

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ABSTRACT

The objective of this study is to analyse relationships between the start dates of spring phenological phases and large-scale atmospheric circulation patterns. The timing of phenological phases in temperate zones is driven by temperature, and temperature regime is generally determined by atmospheric circulation. The database analysed consists of the first dates of flowering of coltsfoot (*Tussilago farfara* L.), of birch (*Betula pendula* Roth.) leaf unfolding and of flowering of lilac (*Syringa vulgaris* L.); the North Atlantic oscillation (NAO) and the Arctic oscillation (AO) indices, frequencies of the circulation forms classified by Vangengeim and Girs, and of the groups of *Grosswetterlagen* presented by Hess and Brezowsky. The study area covers central and eastern Europe, and the period considered is 1951–98.

The results show that the influence of the westerly airflow is more pronounced in the winter half-year, and weakens and even disappears as spring advances. Phases have the highest correlation with NAO and AO indices during winter (December–March) and the first three months of the year (January–March), which have correlations stronger than −0.5 in the Baltic Sea region. Among the phenological phases, flowering of coltsfoot is the most strongly correlated with the NAO and AO indices, followed by leafing of birch and flowering of lilac. Airflow from the north and from the east has a greater influence in springtime, particularly in the northernmost and southernmost regions of the study area. Copyright © 2004 Royal Meteorological Society.

KEY WORDS: central Europe; eastern Europe; correlation; phenology; atmospheric circulation; coltsfoot; birch; lilac

1. INTRODUCTION

The investigation of interactions between biosphere and atmosphere has been an essential avenue of research. Variations in weather conditions are the main cause of annual differences in the seasonal development of nature. The beginning of plant phenological phases in spring depends strongly on overwintering conditions and the temperature regime in the spring period. Atmospheric circulation is one of the main factors affecting the weather and temperature regime in Europe at this time. Depending on the prevalence of certain airflow patterns, wintertime weather can vary widely. The preceding winter, in turn, largely determines whether the spring will be warm and early or late and cold.

We can assume that the onset dates of phenological phases are associated with the temperature changes, which are caused by atmospheric circulation. Circulation parameters describe the impingement of warm or cold air into the study area. The spatial relationships between phenophases and atmospheric circulation patterns provide essential information for the description of the factors affecting phenological phenomena and the changes in these factors.

Central and eastern Europe is located in the transition zone between a maritime and a continental climate. In this region, air masses of different origin result in particularly large climatic fluctuations from year to year. We can presume that the effects of circulation on plant phenology will be most pronounced in our study area.

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The aim of the current study is to investigate the dependence of atmospheric circulation on the seasonal development of plants in spring in central and eastern Europe. The strength of the relationships between some general descriptive measures of atmospheric circulation and some phenological phases, as well as their geographical distribution, is investigated. An assessment is made regarding which of the circulation indices or classifications used in the current study best describes the long-term changes in the onset dates of phenophases.

Correlation analysis is used to relate the start dates of three plant phenological phases with a wide spatial distribution (flowering of coltsfoot, leafing of birch, flowering of lilac) to the circulation characteristics that influence the area.

2. DATA

2.1. Phenological data

The phytophenological data set originates from the European plant phenology database, which is compiled under the European Union 5th Framework Programme project POSITIVE (Phenological Observations and Satellite Data (NDVI): Trends in the Vegetation Cycle in Europe) in 2001 (Ahas *et al*., 2002). The period under observation is 1951–98. The relationships between the start dates of three spring phases (i.e. the flowering of coltsfoot (*Tussilago farfara* L.), birch (*Betula pendula* Roth.) leaf unfolding, the flowering of lilac (*Syringa vulgaris* L.)) and atmospheric circulation is analysed. The species selected are good phenological indicators and they have a broad geographical distribution in the study area. The locations of the observation stations used in the study are shown in Figure 1.

On average, in the 1951–98 period, the flowering of coltsfoot begins the earliest in Matrei (47.0 °N, 12.5 °E), on 7 March, and the latest in Ust-Kulom (61.8 °N, 53.7 °E), on 2 May. The time interval between the earliest and the latest average dates of the onset of flowering was 56 days (Figure 2). The phase does not spread in an exact south–north direction, being slightly shifted towards the southwest–northeast direction. The standard deviation describing the variance of the onset of flowering is greater in the western part of the study area, and generally is within the range of 1–2 weeks.

In the observation period, unlike the spatial spread of the onset of flowering of coltsfoot, the birch leaf unfolding spreads predominantly in the south–north direction (Ahas *et al*., 2002). The phase begins earliest (28 March) in the Ukraine (Nelipino, 48.6 °N, 37.5 °E), spreading from there to the northern edge of the study area (Njandoma, 61.5 °N, 40.0 °E) by 25 May. The period between the average earliest and latest dates of onset of leafing is similar to that for the flowering of coltsfoot, at 58 days. The standard deviation for the

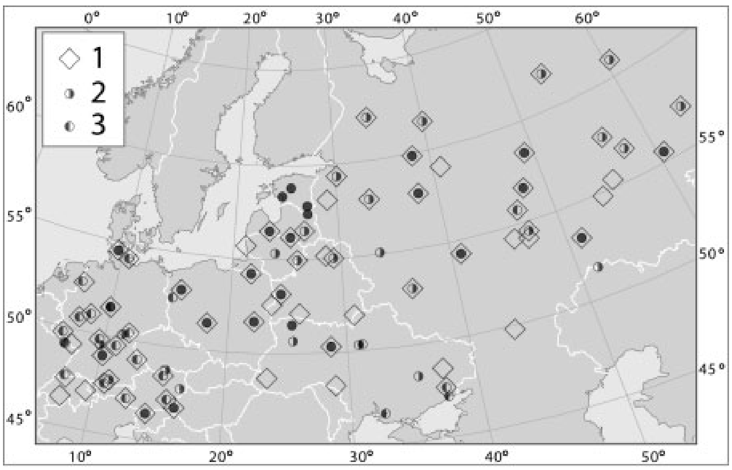

Figure 1. The location of the observation stations used in the study: (1) flowering of coltsfoot; (2) birch leaf unfolding; (3) flowering of lilac

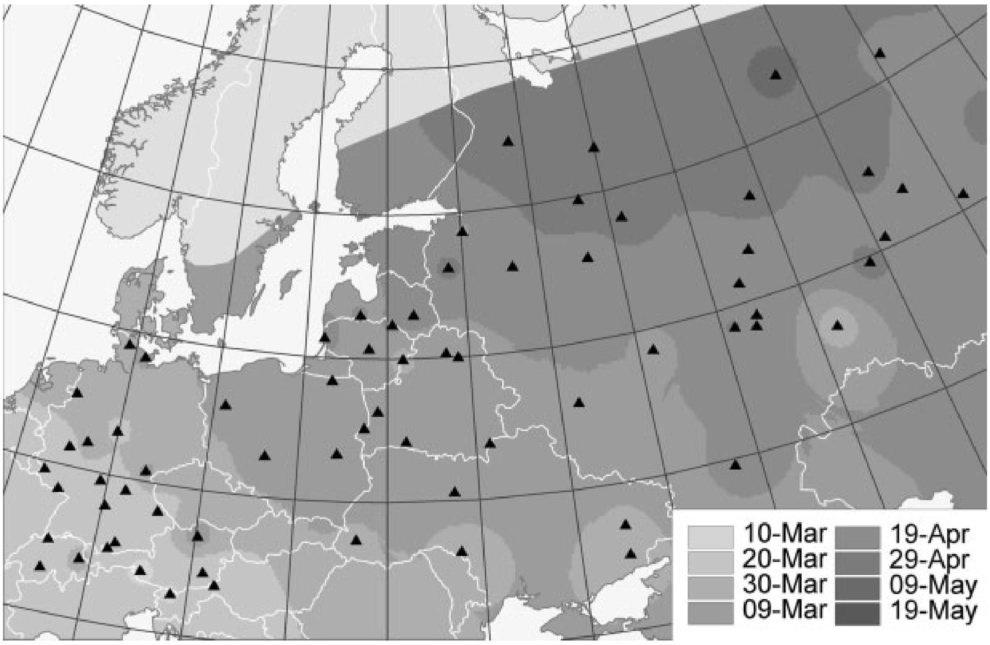

Figure 2. Date of average onset of flowering of coltsfoot (the legend gives the upper class boundaries)

onset of leaf unfolding of birch is in the range 1–2 weeks and the spatial distribution is also similar to that of the onset of flowering of coltsfoot: the variance is greater in the west.

Within the study period, the earliest average onset of the flowering of lilac is on 24 April in southwest Germany (Weil, 47.6 °N, 7.6 °E), and the latest is on 4 June in Kirillov (59.9 °N, 38.2 °E) in northern Russia. The onset of flowering of lilac spreads, on average, in the south–north direction. The phase spreads from the earliest to the latest location in 41 days on average. The temporal variance is similar to that of the phases already discussed, with the standard deviation in the range 7–12 days. The spatial spreading patterns of the average onset date of both birch leaf unfolding and lilac flowering are similar to that of the flowering of coltsfoot.

2.2. Atmospheric circulation data

Atmospheric circulation is characterized both by circulation indices and by monthly frequency of circulation types distinguished by two classifications (Table 1). Both the North Atlantic oscillation (NAO) index and the Arctic oscillation (AO) index characterize the westerly airflow or the intensity of the zonal circulation. The NAO index is defined as the difference in normalized sea-level pressure between the Azores high and the Icelandic low. Positive values denote a large air pressure gradient and a strong westerly airflow, and negative values indicate a small pressure gradient in the North Atlantic, which leads to a weakening of the westerlies.

In this study, the indices are calculated using measurements made at Ponta Delgada (Azores) and Stykkisholmur (Iceland) (Hurrell and van Loon, 1997). The AO index describes atmospheric circulation over a much larger area, indicating the intensity of the circumpolar vortex (Thompson and Wallace, 1998). The NAO can be viewed as an expression of the AO in the North Atlantic.

The atmospheric circulation classification that was constructed in the Arctic and Antarctic Research Institute in St Petersburg by Vangengeim and Girs was initially designed for making long-term weather forecasts for the Arctic Ocean shipping lane (Vangengeim, 1952). According to this, atmospheric circulation patterns are classified into three basic circulation forms W, E and C, mainly according to the thermobaric wave position in the upper troposphere. A simplified diagram of sea-level pressure fields and the predominating directions of air mass transfers for each of the circulation forms is presented in Figure 3. Studies have shown that the

Table I. Characteristics used in this study to describe atmospheric circulation

Characteristic	Description
NAOI, monthly/seasonal	North Atlantic oscillation index: north–south difference in pressure between Iceland and Azores (Hurrell and van Loon, 1997)
AOI, monthly/seasonal	Arctic oscillation index: the intensity of the wind circulating counter clockwise around the Arctic at about 55 °N (Thompson and Wallace, 1998)
Circulation forms	Subjective circulation classification by Vangengeim–Girs (Kozuchowski and Marciniak, 1988)
C	Airflow from northerly direction
E	Airflow from south, southeast and east
W	Prevalence of westerlies
Circulation types	Large-scale airflow classification by Hess–Brezowsky (Gerstengarbe and Werner 1999)
H	Half-meridional: southwesterly and northwesterly flow
M	Meridional: all other directions between north, east and south
Z	Zonal: westerly airflow

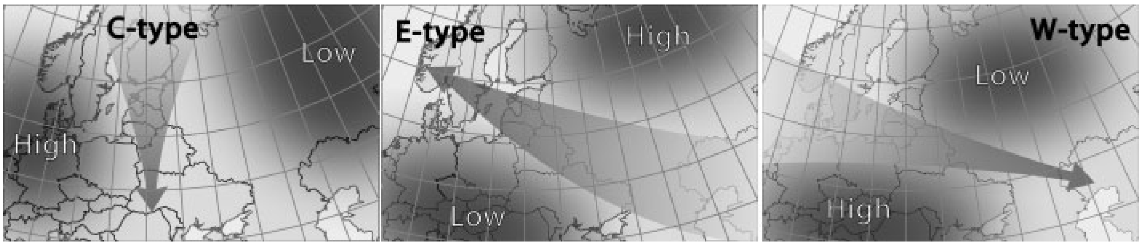

Figure 3. Simplified diagrams of Vangengeim–Girs circulation types. 'High' and 'Low' mark location of main air pressure centres

frequencies of these circulation forms are closely correlated with weather fluctuations in northern and eastern Europe (Kozuchowski and Marciniak, 1988; Sepp and Jaagus, 2002). The frequency of the circulation patterns varies quite widely between months (Figure 3).

The Hess and Brezowsky classification system, also known as the *Grosswetterlagen*, reflects the atmospheric circulation in central Europe. The classification is based on circulation types that are distinguished on the basis of (1) the position of large pressure centres (Azores high/Icelandic low), (2) the position of frontal zones, and (3) the cyclonicity or anticyclonicity of the circulation (Bardossy and Caspary, 1990; Gerstengarbe and Werner, 1999). In this classification, individual circulation types are divided into three groups: zonal (Z), half-meridional (H), and meridional (M). The generalized atmospheric circulation motions in each case are shown in Figure 4 and their annual frequency is depicted in Figure 5.

3. METHODS

3.1. Correlations between phases and climate parameters studied

The timing of phenological phases is influenced by different environmental factors, such as temperature of the external environment, moisture and radiation regime, soil conditions and landscape features. The dynamics of climatic factors are mostly determined by atmospheric circulation. Atmospheric circulation controls the temperature regime, which is the most important trigger of phenological phases in temperate ecosystems (Hopkins, 1918; Schnelle, 1955; Schults, 1981; Schwartz, 2003). Air temperature data (daily

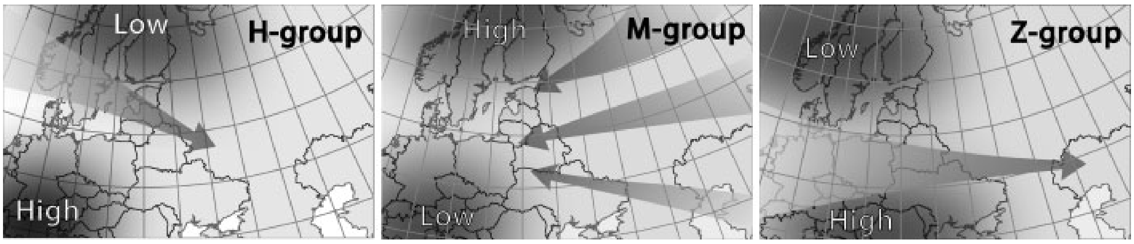

Figure 4. Simplified diagrams of Hess–Brezowsky circulation groups. ‘High’ and ‘Low’ mark location of main air pressure centres

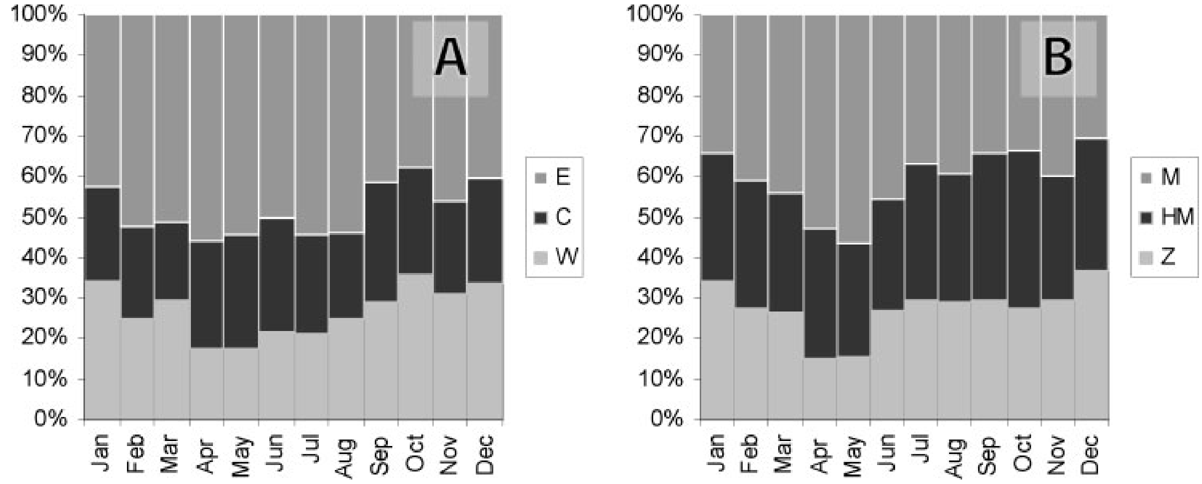

Figure 5. Average relative frequency per month of (A) Vangengeim–Girs weather forms and (B) *Grosswetterlagen* circulation groups

minimum and maximum measures) are normally used for assessment of plant phenology as this is the standard observation methodology in the world and has good correlations with soil and water temperature. For phenological studies, very different indicators have been calculated on the basis of daily minimum and maximum measurements: mean temperature of day for different periods; cumulative sums of positive or negative temperatures; temperatures crossing certain thresholds. Different life forms and species have different temperature dependencies and, therefore, a wide list of temperature indicators has been used in assessments and models (Podolsky, 1984; Chuine *et al*., 2003; Schwartz, 2003).

For reference, in our database we studied correlations between the start dates of phenophases and mean air temperatures for the 30 preceding days. In all of the study area, the mean correlations stay in the range 0.4–0.7 and are statistically significant at the 0.05 level. For example, correlation coefficients at the German station Trier-Petrisberg (49.75 °N, 6.65 °E) for flowering of coltsfoot and lilac are 0.5 and that for birch leaf unfolding is 0.6. At Dunajevo (58.42 °N, 49.13 °E) station, in the eastern part of Europe, the correlation coefficients for flowering of coltsfoot and lilac are 0.7 and 0.8 respectively, and that for birch leaf unfolding is 0.7.

Variations in atmospheric circulation, as a determiner of local temperature regime, have been studied by different workers (Kozuchowski and Marciniak, 1988; Bardossy and Caspary, 1990; Kozuchowski, 1993; Jönsson and Bärring, 1994; Hurrell, 1995; Chen, 2000; Slonosky *et al*., 2001; Sepp and Jaagus, 2002). It has been ascertained that a strong westerly airflow in winter carries the warming effect of the Atlantic Ocean far into the east, to the Baltic Sea region and eastern Europe. For instance, in the East European Plain there is a strong negative correlation between the beginning of the climatic seasons and the circulation indices describing westerly airflow (Jaagus *et al*., 2003). The influence of the NAO index on the amount of rainfall, the duration of snow cover, and air temperature has been proved in Europe as a whole (Jacobeit *et al*., 2003;

Pozo-Vázquez *et al*., 2001), as well as in its separate regions (Chen and Hellström, 1999; Keevallik *et al*., 1999; Ottersen *et al*., 2001; Stenseth *et al*., 2002).

A relationship between atmospheric circulation and air temperature in winter is clearly expressed (Sepp and Jaagus, 2002). Characteristics of the intensity of westerlies — the frequencies of the circulation form W (according to Vangengeim–Girs) and of zonal circulation group Z (Hess–Brezowsky) are positively correlated with temperature in northern and central Europe. The weakening of westerlies and the prevalence of the meridional circulation are related to cooler than normal weather in most of continental Europe. The highest correlation between air temperature and the variables of the meridional circulation were revealed during the transition seasons. A northerly airflow (form C) in spring and in autumn causes an intense cooling in eastern Europe. At the same time, a southerly and easterly circulation (form E) brings warmth to northern Russia and Scandinavia. The zonal circulation has less influence on temperature during the transition seasons.

The dependence of seasonal plant development on the weather of the preceding months (primarily on the temperature regime (Chmielewski and Rötzer, 2002), but also on the atmospheric circulation (Scheifinger *et al*., 2002)) has also been shown. In aquatic ecosystems, the effect of the NAO on water temperature, ice phenomena, and the phenology of water bodies has been demonstrated (Blenckner and Chen, 2003).

In addition to its direct ecological effects, atmospheric circulation can also have indirect and contradictory effects (Ottersen *et al*., 2001; Stenseth *et al*., 2002). Nevertheless, the relationships between circulation indices and phenological phases have been investigated in narrow fields and in regard to just a few parameters.

3.2. Study methods

Linear correlation analysis was used to assess the strength and direction of the relationships between the beginning of phenological phases and atmospheric circulation. The correlation coefficients were calculated separately for each phase. We used correlation analyses in our study as the objective was to study the influence of atmospheric circulation on the timing of phenological phases.

The results were mapped using spatial interpolation according to the Kriging method (Legendre and Legendre, 1998). The statistical significance of the correlation coefficients was checked at random and, as a result, relationships stronger than ± 0.3 proved to be statistically significant.

For the Vangengeim–Girs and Hess–Brezowsky classifications the parameters of the following months/seasons were used: January, February, March, April, May; spring (March–May), winter (December–February), the cold half-year (November–March). The NAO indices for January, February, March, April, May, December–February, January–March, February–April and March–May were considered. Of the AO indices, in addition to those of the first 3 months of the year, the values for December–February, March–May and November–March were also used. The circulation parameters of June and later months were excluded from further analysis, since all three phases begin before June. The latter is also apparent from the sudden weakening of correlation from June onwards.

4. RESULTS

4.1. Influence of winter circulation

The results of the correlation analysis demonstrate significant relationships between the parameters of large-scale atmospheric circulation and start dates of the three phenological phases in central and eastern Europe. Correlation maps for some typical cases are presented in Figures 7–9. Table 2 summarizes the correlation coefficients between circulation and phenological variables at six locations situated in different parts of the study area: Schleswig characterizes phenology in northern Germany, Weiz (47.22 °N, 15.63 °E) in Austria, Dobele (56.52 °N, 23.32 °E) in Latvia, Zhitomir (50.33 °N, 28.67 °E) in the Ukraine, Borok (57.88 °N, 38.13 °E) in central Russia, and Kuznetskoye (55.50 °N, 60.50 °E) in the Ural Mountains area. Statistically significant correlation coefficients at the $P < 0.05$ level are marked in bold. Circulation parameters without any significant correlation are omitted from Table 2.

Table II. Correlations between phenological phases studied and selected circulation characteristics. Significant ($P < 0.05$) correlations are in bold

	Tussilago farfara beginning of flowering						*Betula pendula* leaf unfolding						*Syringa vulgaris* beginning of flowering					
	Schleswig	Weiz	Dobele	Zhitomir	Borok	Kuznetskoye	Schleswig	Weiz	Dobele	Zhitomir	Borok	Kuznetskoye	Schleswig	Weiz	Dobele	Zhitomir	Borok	Kuznetskoye
NAO_{Jan}	**−0.54**	−0.28	**−0.53**	**−0.57**	**−0.40**	−0.17	**−0.35**	−0.16	**−0.49**	**−0.39**	−0.28	−0.21	**−0.38**	**−0.35**	**−0.33**	−0.23	−0.09	−0.19
NAO_{Feb}	**−0.45**	**−0.47**	**−0.54**	**−0.46**	−0.32	**0.42**	**−0.44**	**−0.35**	**−0.49**	−0.28	0.01	−0.11	**−0.43**	**−0.34**	**−0.44**	−0.16	−0.14	−0.18
NAO_{Mar}	**−0.40**	**−0.43**	−0.35	**−0.36**	−0.17	0.06	−0.16	**−0.30**	**−0.35**	**−0.34**	−0.19	−0.21	**−0.36**	−0.28	**−0.51**	−0.16	−0.02	0.03
NAO_{JFM}	**−0.65**	**−0.57**	**−0.65**	**−0.64**	**−0.45**	0.15	**−0.44**	**−0.37**	**−0.62**	**−0.45**	−0.24	−0.26	**−0.55**	**−0.46**	**−0.60**	−0.26	−0.14	−0.18
NAO_{NDJFM}	**−0.58**	**−0.48**	**−0.62**	**−0.54**	**−0.39**	−0.05	**−0.36**	−0.25	**−0.43**	−0.32	−0.31	−0.21	**−0.43**	**−0.40**	**−0.38**	−0.18	−0.13	−0.27
AO_{Jan}	**−0.55**	−0.23	**−0.61**	**−0.50**	**−0.46**	0.04	**−0.34**	−0.01	**−0.44**	−0.26	−0.25	−0.05	**−0.34**	−0.26	**−0.35**	−0.15	−0.16	−0.19
AO_{Feb}	**−0.54**	**−0.47**	**−0.53**	**−0.62**	−0.19	**0.33**	**−0.53**	**−0.35**	**−0.54**	**−0.39**	−0.07	−0.11	**−0.53**	**−0.44**	**−0.53**	−0.19	−0.21	−0.19
AO_{Mar}	**−0.48**	**−0.33**	**−0.49**	**−0.50**	−0.05	0.07	**−0.32**	**−0.40**	**−0.50**	**−0.50**	−0.32	−0.25	**−0.49**	**−0.31**	**−0.58**	−0.24	−0.14	0.05
AO_{Dec}	**−0.34**	−0.19	−0.31	−0.21	**−0.47**	0.02	−0.18	0.09	0.07	0.02	−0.14	0.16	−0.13	−0.08	−0.02	0.10	0.07	0.05
AO_{MAM}	**−0.44**	−0.24	**−0.44**	**−0.52**	−0.02	0.18	**−0.33**	**−0.42**	**−0.56**	**−0.47**	−0.27	−0.12	**−0.42**	−0.27	**−0.49**	−0.26	−0.07	0.13
AO_{DJF}	**−0.63**	**−0.42**	**−0.60**	**−0.59**	**−0.49**	0.19	**−0.47**	−0.14	**−0.45**	−0.29	−0.21	−0.02	**−0.47**	**−0.37**	**−0.43**	−0.12	−0.16	−0.16
AO_{NDJFM}	**−0.66**	**−0.48**	**−0.67**	**−0.63**	**−0.46**	0.22	**−0.42**	−0.24	**−0.54**	**−0.38**	−0.29	−0.14	**−0.52**	**−0.38**	**−0.54**	−0.15	−0.18	−0.16
W_{Jan}	**−0.36**	−0.15	−0.31	−0.22	−0.13	0.11	−0.14	−0.02	−0.30	−0.06	−0.30	−0.04	**−0.33**	**−0.31**	−0.15	0.01	−0.15	−0.19
W_{Feb}	**−0.36**	**−0.51**	−0.28	**−0.59**	−0.02	**0.36**	**−0.49**	−0.28	**−0.48**	−0.29	−0.07	0.02	**−0.44**	**−0.39**	**−0.33**	−0.18	−0.20	0.04
W_{Mar}	−0.22	−0.17	**−0.39**	**−0.49**	0.17	0.09	**−0.35**	**−0.40**	**−0.49**	**−0.44**	−0.12	−0.12	**−0.53**	**−0.45**	**−0.43**	**−0.42**	−0.08	0.02
W_{MAM}	−0.15	−0.25	−0.27	**−0.39**	0.06	0.17	−0.26	**−0.29**	**−0.39**	**−0.33**	−0.10	−0.10	**−0.42**	**−0.41**	−0.23	**−0.35**	0.00	0.06
W_{DJF}	**−0.49**	**−0.40**	−0.32	**−0.51**	−0.18	0.25	**−0.44**	−0.15	**−0.46**	−0.12	−0.17	0.04	**−0.48**	**−0.53**	**−0.33**	−0.11	−0.22	−0.09
W_{NDJFM}	**−0.45**	**−0.44**	**−0.44**	**−0.59**	−0.15	0.31	**−0.46**	−0.21	**−0.53**	−0.20	−0.10	0.04	**−0.51**	**−0.58**	**−0.41**	−0.28	−0.25	−0.07
E_{Jan}	0.16	−0.03	0.29	0.14	0.06	**−0.43**	0.12	−0.12	0.24	−0.05	0.25	0.04	0.24	0.15	0.10	−0.01	0.08	0.15
E_{Feb}	**0.34**	**0.42**	0.18	**0.56**	−0.06	−0.30	**0.34**	0.17	**0.44**	0.15	**0.39**	0.05	**0.40**	**0.39**	0.25	0.19	**0.41**	0.05
E_{Mar}	0.14	−0.04	0.29	**0.43**	−0.14	−0.13	**0.40**	**0.31**	**0.48**	**0.45**	0.23	0.09	**0.38**	**0.39**	**0.37**	**0.45**	0.30	0.06
E_{MAM}	0.19	0.03	0.36	0.29	−0.15	−0.25	**0.35**	0.26	**0.41**	0.25	0.11	0.08	**0.49**	0.26	0.07	0.24	−0.06	0.02
E_{DJF}	0.25	0.24	0.26	**0.38**	0.10	**−0.39**	0.28	−0.03	**0.36**	0.00	0.20	−0.07	**0.34**	**0.30**	0.26	0.10	0.16	0.02
E_{NDJFM}	0.25	0.22	**0.37**	**0.52**	0.10	**−0.42**	**0.37**	−0.02	**0.45**	0.09	0.17	−0.11	**0.34**	**0.31**	**0.33**	0.25	0.27	0.02

(*continued overleaf*)

Table II. (*Continued*)

	Tussilago farfara beginning of flowering						*Betula pendula* leaf unfolding						*Syringa vulgaris* beginning of flowering					
	Schles-wig	Weiz	Dobele	Zhito-mir	Borok	Kuznets-koye	Schles-wig	Weiz	Dobele	Zhito-mir	Borok	Kuznets-koye	Schles-wig	Weiz	Dobele	Zhito-mir	Borok	Kuznets-koye
C_{Jan}	0.25	0.19	−0.07	0.05	0.08	**0.44**	−0.03	0.18	0.04	0.12	−0.02	0.03	0.06	0.19	0.06	0.04	0.07	0.04
C_{Apr}	−0.02	0.11	−0.14	−0.04	0.02	−0.01	−0.09	−0.01	0.16	0.16	**0.41**	0.25	−0.14	−0.02	0.12	0.30	0.26	0.19
C_{Dec}	0.21	−0.06	−0.05	0.03	−0.09	0.22	0.08	0.13	0.00	0.03	0.22	0.23	0.02	0.19	−0.10	0.00	0.26	0.30
C_{NDJFM}	0.18	0.20	−0.08	−0.11	0.06	**0.41**	−0.06	**0.32**	−0.06	0.10	−0.14	0.21	0.05	0.24	−0.01	−0.05	−0.07	0.07
Z_{Jan}	**−0.37**	−0.27	−0.12	−0.29	−0.25	−0.11	−0.04	−0.12	**−0.34**	−0.29	−0.27	−0.15	−0.23	**−0.32**	**−0.31**	−0.21	−0.20	−0.11
Z_{Feb}	**−0.32**	**−0.50**	−0.10	−0.28	−0.18	0.32	−0.12	**−0.40**	−0.28	−0.22	0.07	−0.09	−0.11	−0.23	−0.19	−0.24	−0.19	−0.08
Z_{Mar}	−0.27	**−0.34**	−0.06	−0.16	−0.13	0.14	−0.04	**−0.30**	**−0.33**	−0.13	−0.07	−0.10	−0.15	−0.17	**−0.31**	−0.15	0.17	0.17
Z_{Dec}	**−0.38**	**−0.41**	−0.09	−0.20	−0.23	0.00	−0.11	−0.22	−0.04	−0.08	−0.05	0.13	−0.27	**−0.36**	−0.14	−0.04	−0.23	−0.03
Z_{DJF}	**−0.55**	**−0.64**	−0.16	**−0.40**	**−0.36**	0.11	−0.13	**−0.40**	**−0.35**	−0.31	−0.14	−0.06	**−0.33**	**−0.50**	**−0.35**	−0.25	**−0.34**	−0.12
Z_{NDJFM}	**−0.62**	**−0.67**	−0.20	**−0.44**	**−0.44**	0.11	−0.14	**−0.45**	**−0.42**	**−0.35**	−0.14	−0.22	**−0.35**	**−0.48**	**−0.35**	−0.25	−0.27	−0.11
M_{Jan}	**0.66**	**0.40**	**0.38**	**0.54**	0.31	0.18	0.26	0.27	**0.41**	**0.35**	0.17	0.15	**0.42**	**0.43**	**0.32**	0.03	0.25	0.27
M_{Feb}	**0.50**	**0.56**	0.27	**0.53**	0.26	−0.14	**0.37**	**0.38**	**0.36**	**0.36**	−0.02	0.03	0.26	**0.38**	**0.36**	0.10	**0.34**	0.12
M_{Mar}	**0.32**	**0.42**	0.06	0.32	−0.03	−0.17	0.06	**0.35**	**0.38**	0.14	0.25	0.18	0.16	**0.38**	0.30	**0.36**	0.19	−0.16
M_{Apr}	−0.20	0.04	−0.16	−0.01	−0.02	**−0.37**	−0.03	0.03	0.13	−0.11	0.14	−0.08	−0.11	−0.05	−0.07	0.03	−0.02	−0.23
M_{MAM}	0.10	**0.31**	−0.10	0.29	−0.08	**−0.40**	0.06	0.14	0.28	0.07	0.20	0.04	0.02	0.27	0.14	0.29	0.09	−0.31
M_{NDJFM}	**0.71**	**0.61**	**0.38**	**0.61**	**0.42**	−0.08	0.29	**0.32**	**0.49**	**0.33**	0.23	0.20	**0.36**	**0.53**	**0.43**	0.20	**0.44**	0.16
H_{Jan}	**−0.40**	−0.18	−0.36	−0.28	−0.09	−0.07	−0.28	−0.19	−0.11	−0.09	0.10	0.01	−0.26	−0.16	−0.04	0.20	−0.07	−0.20
H_{Feb}	−0.25	−0.13	−0.25	**−0.35**	−0.17	−0.15	**−0.32**	−0.01	−0.16	−0.20	−0.04	0.07	−0.20	−0.20	−0.25	0.15	−0.19	−0.07
H_{Mar}	−0.22	−0.29	−0.04	−0.31	0.15	0.10	−0.07	−0.25	−0.23	−0.10	−0.26	−0.17	−0.13	**−0.38**	−0.16	**−0.34**	**−0.35**	0.05
H_{Apr}	0.15	−0.17	0.03	0.04	−0.16	**0.45**	0.19	0.04	−0.10	0.08	−0.14	−0.03	0.13	0.10	−0.08	0.03	−0.13	0.09
H_{Dec}	−0.06	0.05	−0.10	−0.14	−0.22	0.01	−0.12	0.26	−0.08	−0.05	−0.19	−0.15	0.12	0.01	−0.02	−0.02	−0.09	−0.07
H_{MAM}	−0.11	**−0.37**	−0.03	−0.29	0.03	**0.48**	0.02	−0.09	−0.26	−0.04	−0.29	−0.14	−0.06	−0.23	−0.22	−0.25	−0.28	0.12
H_{NDJFM}	**−0.49**	−0.26	**−0.43**	**−0.53**	−0.22	0.04	**−0.34**	−0.03	−0.31	−0.16	−0.22	−0.08	−0.19	**−0.30**	−0.29	−0.07	**−0.37**	−0.13

The first and the most important result is that atmospheric circulation during the previous winter is closely related to phenological phases during the following spring. This relationship is expressed most strongly in the case of early phases. The flowering of coltsfoot is determined most of all by the nature of the atmospheric circulation during the previous winter. As a general rule, a mild winter is followed by an early spring, and coltsfoot, being quite an early flowerer, responds rapidly to this. Following a cold winter the ground thaws more slowly and the growth and development of plants is retarded.

Mild winters in central and eastern Europe are associated with a zonal circulation. A strong westerly airflow carries warm air from the Atlantic far towards the east. Zonal circulation indicators, NAO and AO indices, and the frequency of circulation forms W and the zonal circulation group (Z) are negatively correlated with the onset of flowering of coltsfoot (Figures 6 and 7). This means that flowering begins earlier following a mild winter and later following a cold winter.

The beginning of the phase has the highest correlation with NAO_{JFM} index (Figure 7(1)), for which the correlation coefficient in the study area falls in the range −0.7 to 0.2. Approximately the same correlation pattern was also obtained for winter AO indices (Figure 7(2)). The areas with higher correlation are the Baltic countries, Ukraine, northern Russia and some regions in Germany and Austria. The correlation of the onset of flowering of coltsfoot with the indices of individual months has a much greater spatial variance and is generally weaker than the correlation with the index averaged over several months.

A rather similar pattern is also present for frequencies of zonal circulation types W and Z (Figure 7(3)). The negative correlation of the start date of coltsfoot with the frequency of the circulation form W is highest in northern Ukraine, and with zonal circulation group Z in central Europe ($r > |-0.6|$).

At the same time, frequencies of meridional circulation types (E and M) in winter have a significant positive correlation with the beginning of flowering of coltsfoot (Figure 7(4)). These circulation parameters are closely related to the cold weather conditions in winter, to the prevailing cold continental air mass and extended anticyclones, in northern Europe. Thus, in Schleswig the correlation between the frequency in winter of the meridional type (M) and the onset of flowering of coltsfoot almost reaches the 0.7 level. Although the spatial variance of the correlation coefficient is large (−0.1 to 0.7), the correlation is higher than 0.5 at 15 observation stations. The half-meridional circulation group in winter is negatively correlated with flowering of coltsfoot, but the correlation is mostly low.

The influence of winter circulation is also evident on birch leaf unfolding and on flowering of lilac, but of a lesser magnitude. The spatial pattern of the correlations has the same general distribution (Figures 8(1) and (2) and 9(1), (2) and (4)). The highest negative correlation coefficients, $r > |-0.6|$, are located in the Baltic Sea region. The frequency of meridional circulation group M, according to Hess and Brezowsky, has

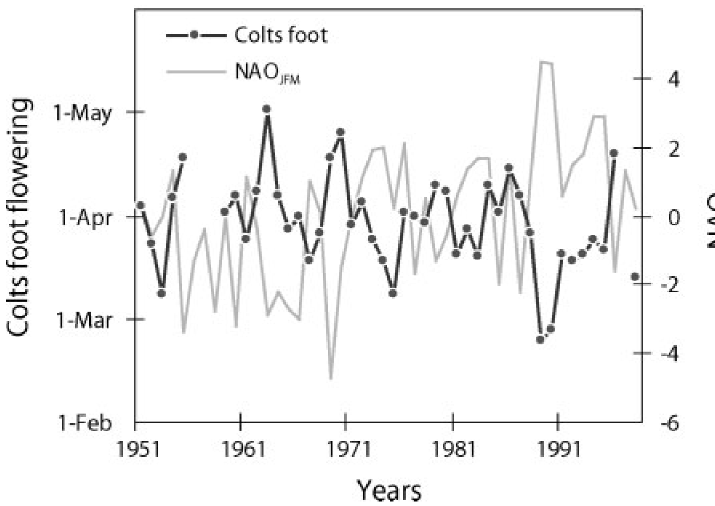

Figure 6. Temporal variation of NAO_{JFM} and flowering of the coltsfoot in Schleswig, northern Germany ($r = -0.65$)

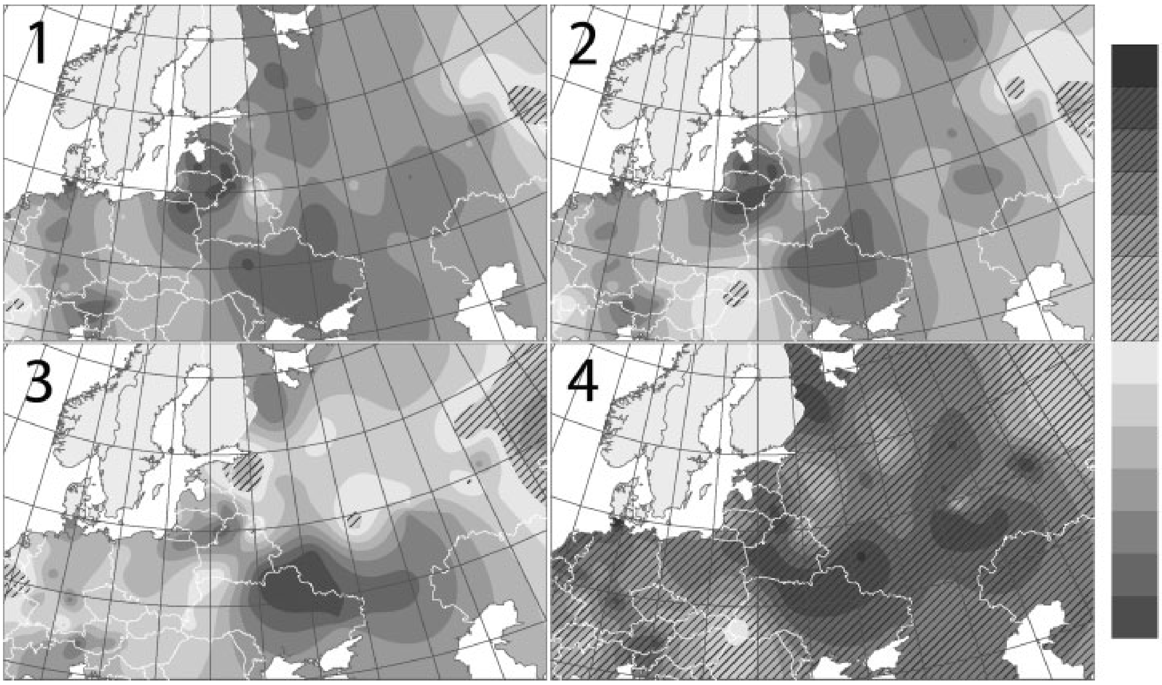

Figure 7. The spatial distribution of the correlation coefficients between the onset of flowering of coltsfoot and different circulation characteristics: (1) NAO_{JFM}; (2) AO_{DJFM}; (3) W_{winter}; (4) M_{winter}

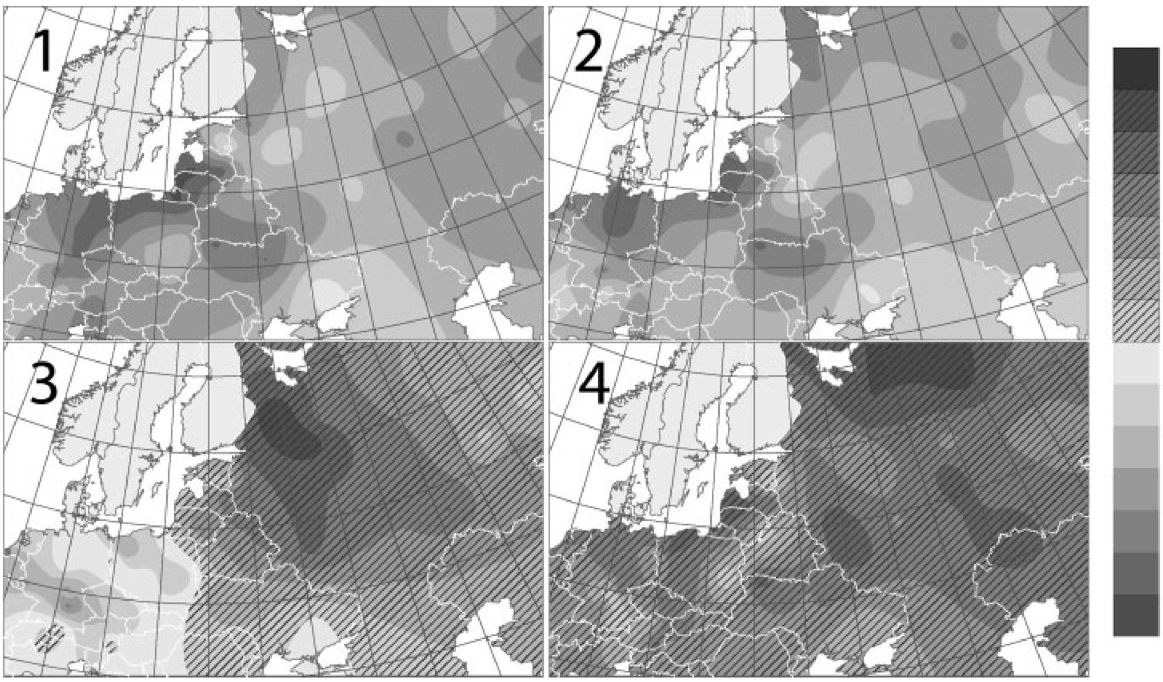

Figure 8. The spatial distribution of correlation coefficients between the beginning of birch leaf unfolding and different circulation characteristics: (1) NAO_{JFM}; (2) AO_{DJFM}; (3) C_{Apr}; (4) M_{NDJFM}

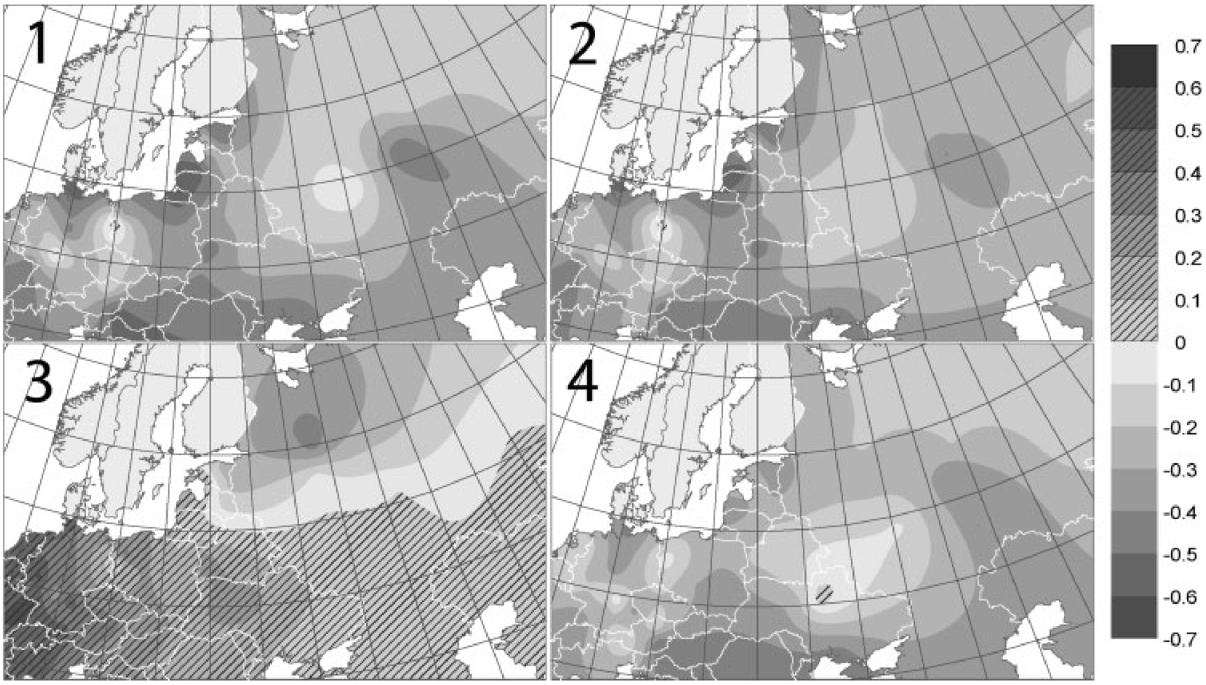

Figure 9. The spatial distribution of correlation coefficients between the onset of flowering of lilac and different circulation characteristics: (1) NAO_{JFM}; (2) AO_{NDJFM}; (3) E_{MAM}; (4) Z_{NDJFM}

a high positive correlation with birch leaf unfolding (Figure 8(4)). The maximum correlation is located in the East European Plain, and also in Poland, Germany and Austria. The influence of meridional circulation, i.e. cold winter, is also evident on the flowering of lilac, especially in central Europe and in the Baltic area.

Different correlations with phenophases are observed in Kuznetskoye. There is a significant positive correlation between flowering of coltsfoot and the characteristics of zonal circulation, and a negative correlation with meridional circulation in February (Table 2). There are no significant correlations at all in Kuznetskoye between birch leaf unfolding and flowering of lilac and the parameters of atmospheric circulation. This can be explained by the fact that the circulation indices and classifications designed for Europe are not valid for describing atmospheric circulation in places located so far to the east. Probably, in the mountainous area, local conditions play a very important role in climate formation.

4.2. Influence of spring circulation

Large-scale atmospheric circulation in spring influences the beginning of plant phenological phases. Correlation between them is highest in the case of later phases. Flowering of coltsfoot has a significant correlation with circulation parameters until March. This phase is entirely dependent on winter conditions. However, birch leaf unfolding and flowering of lilac have some remarkable relationships with circulation parameters in April, and even in May (Table 2).

The correlation between westerlies and leaf unfolding of birch weakens from March onwards, and by April it has disappeared altogether. The main circulation factor in April is northerly airflow, bringing cold Arctic air to southern regions and retarding the phenological development of nature. Northerly advection is described by the frequency of circulation form C. It has a close relationship with birch leaf unfolding in the East European Plain, especially in northern Russia (Figure 8(3)).

The onset of flowering of lilac is directly influenced by spring (March–May) circulation patterns, with form E having the stronger correlation and more clearly defined spatial distribution (Figure 9(3)). The greater the frequency of form E in spring, the later the onset of flowering of lilac in the western part of the study area

($r > 0.5$) and the earlier the onset in the northern part ($r > |-0.4|$). Of the individual months, the frequency of the E and W forms in March has the greatest influence on the onset of flowering of lilac, particularly in the southern part of the study area. A greater frequency of the W form and a corresponding smaller frequency of the E form triggers an earlier onset of flowering of lilac ($r > |0.5|$). There are no significant correlations in April and May.

5. CONCLUSIONS AND DISCUSSION

Compared with correlation between air temperature and circulation (Sepp and Jaagus, 2002), the correlations between the onset of different phenological phases and atmospheric circulation patterns have considerably larger spatial variances. This is partially due, no doubt, to the fact that, in the case of air temperature, gridded data were used, whereas this study uses the raw observation data of selected stations. Phenological data are much more site specific, i.e. dependent on local climatic and landscape conditions. Phenological data are also more biased, as the observation methodology is not as uniform in all countries and networks as it is with meteorological stations.

In the eastern part of the study area (Kuznetskoye station, near the Ural Mountains) the correlations with atmospheric circulation are, in many cases, opposite to the rest of the study area (Table 2). This may be caused by different circulation patterns influencing weather in western Siberia, but the current database does not have enough stations in the area to study those influences properly.

The seasonal development of the plants studied in spring is best described by the NAO and AO indices, which are themselves interlinked and, therefore, give very similar results (Thompson and Wallace, 1998; Jaagus *et al.*, 2003). The NAO_{JFM} index produces the strongest correlation with the spring phenophases, which gave correlations greater than -0.5 in the Baltic Sea region for all the phases. For the AO, the previous wintertime index also gives the strongest correlations ($r > |-0.5|$). The spatial pattern of influence was also similar to that of the NAO indices. Of the individual months, the NAO and AO indices for March gave the strongest correlations.

Although the correlations with the March indices also exceed the $|-0.5|$ level in the Baltic Sea region, the spatial variance of the correlations is considerably larger and the spatial patterns, therefore, less clear. The strongest correlations of both indices reach -0.7 at a few stations. Of the NAO indices of individual months, the March index has the highest correlation with air temperature, just as it has with the beginning of the phenophases (Chen and Hellström, 1999). Of the different phases, the flowering of coltsfoot is most strongly correlated with the NAO and AO indices, followed by the onset of leafing of birch and flowering of lilac. Thus, the weakening of correlations reflects the temporal sequence of the phases.

The correlations between the Vangengeim and Girs classifications (C, E, W) and the onset of phenophases generally give results that are similar to those obtained from the previous indices. The onset of flowering of coltsfoot and leafing of birch are most closely correlated with the circulation form (W), which describes the strength of the westerly airflow in winter, for which $r > |-0.6|$. Of this classification, the frequency of form W in March most accurately describes the onset of flowering of lilac ($r > |-0.6|$). If the influence of the westerly air flow (form W) is more pronounced in the winter half-year and weakens and disappears as spring advances, then form C (from the north) and E (from the east) have a greater influence in springtime, particularly in the northernmost and southernmost regions of the study area (Figure 10).

Of the Hess-Brezowsky classifications (H, M, Z), the frequency of the meridional (M from the north) type in the cold half-year is the best descriptor of the onset of all three phases. The correlation coefficients between both onset of flowering of coltsfoot and leafing of birch and the M_{winter} index exceed the $|-0.5|$ level; the spatial variance of the correlations is relatively large, and regional patterns are difficult to distinguish. The zonal (Z from the west) type is correlated most closely with the onset of flowering of coltsfoot, with the wintertime correlations exceeding the $|-0.5|$ level in places. The correlation of type Z with the onset of leafing of birch is generally weaker than -0.4. For the onset of flowering of lilac, a certain inverse correlation ($r > |-0.4|$) with the cold half-year has been observed in the southern part of the study area. The half-meridional (H from northwest/southwest) type does not yield any significant correlations with the onset of the phenological phases.

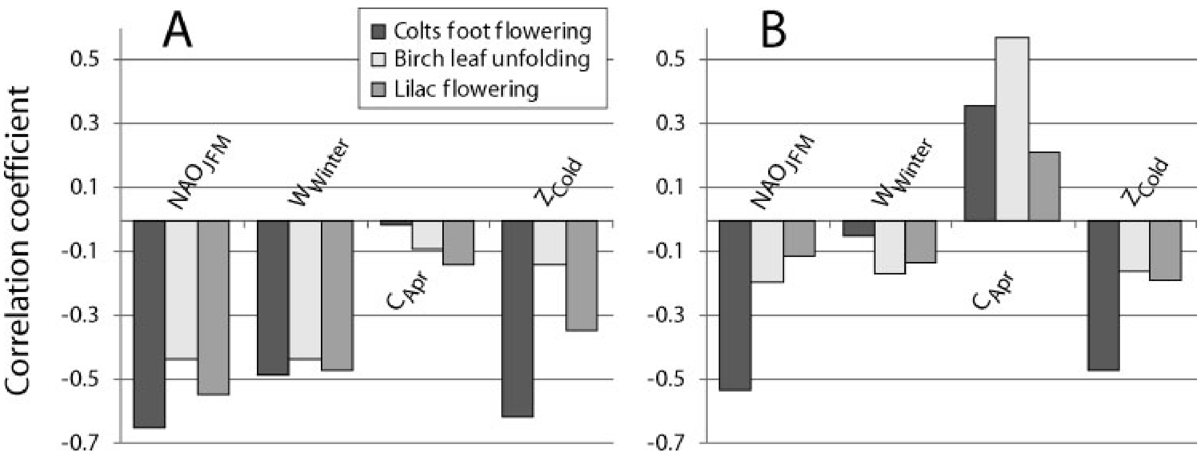

Figure 10. Distribution of correlations studied in (A) Schleswig (54.5 °N, 9.6 °E) northern Germany and (B) Kirillov (59.9 °N, 38.2 °E) in northern Russia

The correlations between circulation types and phenophases weaken in March and April because the observed scale changes from a climatological to synoptic. This means that the geographic effects of individual baric formations are smoothed out when values averaged over several months are used. In monthly averages, however, the effects of individual cyclones or anticyclones predominate. In the case of zonal circulation, for instance, particularly in the spring months, the air temperature and, as a result, the start date of phenophases in every individual location depends on the trajectory of the cyclone with respect to that location. This trajectory determines whether zonal circulation in spring brings warm weather or, conversely, allows cold air to push in. Such synoptic-scale processes can be observed on a sub-type level. The main types, which are also used for comparisons in this study, are, however, made up of the sum of the sub-types, which results in the smoothing out of the opposing effects.

As a consequence of the above it can be asserted that none of the circulation parameters used in this study universally describes the onset of phenological phases in central and eastern Europe. Each circulation characteristic has certain specific regions in which it most closely describes the variation in plant phenological phases individually.

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