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Spatial and temporal variability of the frost-free season in Central Europe and its circulation background

Agnieszka Wypych,[a*] Zbigniew Ustrnul,[a] Agnieszka Sulikowska,[a] Frank-M. Chmielewski[b] and Bogdan Bochenek[c]

[a] *Department of Climatology, Jagiellonian University, Krakow, Poland*
[b] *Institute of Agricultural and Horticultural Sciences, Humboldt-University of Berlin, Germany*
[c] *Institute of Meteorology and Water Management – National Research Institute, Krakow, Poland*

ABSTRACT: The aim of the study was to investigate the temporal and spatial variability of last spring and first autumn frost events as well as the length of the frost-free season (FFS) in Central Europe in relation to atmospheric circulation. Studies were conducted for the period 1951–2010 using gridded, daily minimum air temperature data obtained from the E-OBS dataset at 0.25° spatial resolution. To assess the possible impact of air temperature variability on plants, late spring frost events and severe frost events were also examined with respect to the beginning of the thermal growing season. The role of atmospheric circulation was described using Grosswetterlagen circulation types and NAO index, and finally estimated using empirical orthogonal function analysis (EOF). The results confirm a significant increase in the length of the FFS, up to 10 days per decade in the western parts of Europe. This is mostly a result of earlier occurrence of last spring frost in the west up to 5 days. The occurrence of first autumn frost shows no significant trend in most of the studied regions. The obtained spatial pattern of the trends reflects oceanic (west) and continental (east) climatic conditions of the study area. Detailed analysis of circulation types favouring the occurrence of frost in Central Europe indicates that anti-cyclonic situations are mainly responsible. EOF analyses for the springtime confirm that the first mode, which accounts for 56% of total variance, is related to an extensive high pressure system over eastern Ukraine and Belarus, which brings an inflow of cold, continental air masses to Central Europe. The results provide a broaden information on the region climatologically important due to its transitional location, which may be relevant for investigating past and future trends in spring freeze risk for perennial crops, as changes in the frequency of these airflow patterns will result in changes in the risk of frost damage.

KEY WORDS frost dates; frost-free season; atmospheric circulation; Central Europe

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1. Introduction

Due to both oceanic and continental climatic influences, Central Europe is particularly vulnerable to frequent changes in the weather and occurrence of weather extremes. This key feature of local and regional climatic conditions, particularly thermal conditions, is vital to the functioning of human society in the region, especially in climate-related fields of endeavour such as agriculture. Perennial crops such as fruit trees are very sensitive to fluctuating temperatures. Most damage at mid-latitudes occurs during the spring bloom season when below-freezing temperatures harm flower buds following the loss of cold hardiness (Rigby and Porporato, 2008; Kreyling *et al.*, 2012; Winkler *et al.*, 2013; Matzneller *et al.*, 2016).

Variations in minimum air temperature, length of the frost-free season (FFS), as well as the timing of frost events are not reflected in a simple analysis of main climate elements (Robeson, 2002; Jönsson and Bärring, 2011). All three characteristics are economically important, and are studied extensively in Europe and throughout the world (Robeson, 2002; Fernández-Long *et al.*, 2013; Winkler *et al.*, 2013; Yu *et al.*, 2014). Researchers generally agree that global trends of rising air temperatures are reflected in the decline in the number of frost days and in the lengthening of the FFS, where there exists a clear spatial and seasonal variation of the intensity of these changes. In Europe, there is practically no region in which the described changes would not be observed. For areas in the central and eastern parts of the continent, spring trends are more important, because of an increase in air temperature and the early-commencing FFS (Scheifinger *et al.*, 2003; Auer *et al.*, 2005; Jylhä *et al.*, 2008; Goergen *et al.*, 2013; Potop *et al.*, 2014; Ustrnul *et al.*, 2014). Regions under the influence of maritime air masses and the southern part of the continent recorded more pronounced changes in autumn (Matzneller *et al.*, 2010; Fernández-Montes and Rodrigo, 2012; Prior and Perry, 2014; Harding *et al.*, 2015). Similar trends were observed by Auer *et al.* (2005) in the higher parts of the Alps, which confirms the oceanic character of mountain climate.

The observed increase in air temperature in the northern hemisphere, especially in recent decades (IPCC, 2013),

* Correspondence to: A. Wypych, Department of Climatology, Jagiellonian University, 7 Gronostajowa Street, 30-387 Krakow, Poland. E-mail: agnieszka.wypych@uj.edu.pl

has led to significant modifications in plant phenology. A number of studies have shown that the growing season lengthens by approximately 5 days per 1 °C increase in mean annual air temperature (Chmielewski and Rötzer, 2001) and up to 12 days per 1 °C increase in mean spring air temperature (Chmielewski and Rötzer, 2001; Scheifinger *et al.*, 2003; Menzel *et al.*, 2006). A significant temperature rise in early spring (February–April) results in earlier plant growth, which may lead to increased exposure of plants to damage due to late season frost events (Goergen *et al.*, 2013). Moreover, a warmer climate can lead to an earlier loss of cold hardiness of flower buds, and consequently potentially greater risk of late spring frost events (Chmielewski *et al.*, 2004; Jönsson and Bärring, 2011).

However, recent trends in risk patterns observed for spring frost damage have been complex. While some analyses suggest that the last date of spring frost has moved forward in time – synchronously with plant development (Scheifinger *et al.*, 2003), analyses from Finland (Kaukoranta *et al.*, 2010) and Canada (Rochette *et al.*, 2004) suggest that the risk of frost damage has increased with warmer temperatures. Not surprisingly, considerable uncertainty also exists regarding the future susceptibility of perennial crops to springtime frost damage.

An inaccurate estimate of the timing of flowering periods, due to unrealistic parameter values used in phenological models could become a source of erroneous conclusions (Chmielewski and Götz, 2016). In these models, the date of dormancy release, which strongly depends on the chilling requirements of the crop, is usually the most uncertain model parameter. Increasing autumn and winter temperatures can cause a delay in the date of dormancy release (Luedeling *et al.*, 2009; Chmielewski *et al.*, 2012), so that under warmer climatic conditions, the blooming period may also become slightly delayed, compared with current conditions. Hence, non-physiological models can overestimate the earliness of plant development, and frost risk is thereby increased.

The aim of this purely climatological study was to investigate the temporal and spatial variability of the dates of last spring and first autumn frost events as well as to measure the length of the FFS in Central Europe in relation to atmospheric circulation patterns.

2. Data and methods

The analysis was performed for the period 1951–2010 using two independent data sets. Daily minimum air temperature values from gridded E-OBS data v.10 (Haylock *et al.*, 2008) with a spatial resolution of 0.25° × 0.25° as well as *in situ* measurements (selected meteorological stations) were used to evaluate the differences in the spatial occurrence of spring and autumn frost events and the length of the FFS in Central Europe. The study area stretches between 4.75° and 45.50°E and 43.75° and 56.75°N, including parts of Germany, Poland, Hungary, and Ukraine, i.e. leading regions in fruit production (Figure 1).

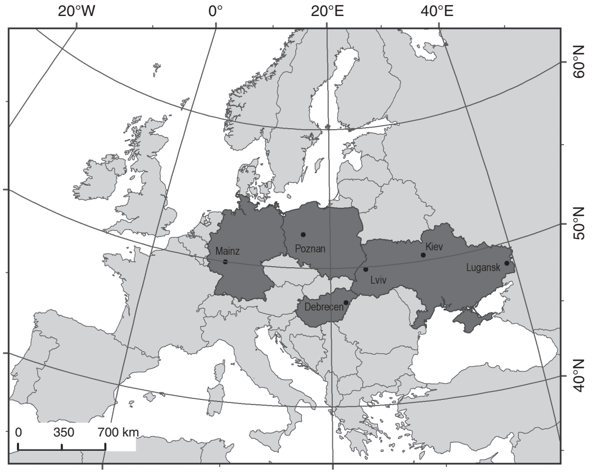

Figure 1. Study area.

Every day of every spring (March–May) and autumn (September–November), in which minimum air temperatures dropped below 0 °C was designated a day with frost. In order to assess the possible impact of temperature variability on plant development, late spring frost and severe frost events TN < −2.2 °C (WMO, 1963) were also examined with respect to the beginning of the thermal growing season. For each year studied, dates of the last spring frost (LSF) and first autumn frost (FAF) were extracted from the data set and the resulting FFS length was calculated for each grid point separately.

The long-term variability of the analysed variables and indices was tested using the nonparametric Mann–Kendall test used to assess the statistical significance of changes (von Storch and Zwiers, 2003). To assess the intensity of the detected tendencies, the resulting linear model was employed and least squares linear fitting was then used to calculate the slope of the studied trends.

Detailed analyses were performed for six measurement sites located in the selected orchard regions. (Figure 1, Table 1). *In situ* measurement data were used at first. Four statistical tests were used to analyse the data: (1) standard normal homogeneity test (SNHT) for a single break, (2) Buishand range test, (3) Pettitt test, (4) von Neumann ratio test (Wijngaard *et al.*, 2003). The four tests were carried out independently to assess the homogeneity of data. These tests were applied to time series of annual and seasonal mean minimum temperatures. A 1% significance level was used to identify 'breaks'. Following the procedure provided by Wijngaard *et al.* (2003), less than 47% of the studied series may be regarded as useful, 10% as doubtful, and in the remaining 43%, three or even four tests rejected the null hypothesis at the 1% level. Due to the non-uniform periods of observation available for the aforementioned measurement sites, and the results of homogenization tests, we decided to carry out the main analysis with the use of nearest E-OBS grid-points as representative values of the selected measurement sites. The correlation coefficient for raw *in situ* data and E-OBS data for the observation time period available average 0.98. Nevertheless, following an additional weather-dependent

Table 1. Basic characteristics of selected variables at examined stations (nearest grid-point locations) (1951–2010)

Selected climatological characteristics			Stations latitude (°N); longitude (°E); elevation (m a.s.l.)					
			Mainz 50.0; 8.2;140	Poznan 52.4; 16.8;75	Debrecen 47.5; 21.6;117	Lviv 49.8; 23.9;319	Kiev 50.4; 30.5;138	Lugansk 48.6;3 9.2;49
Air temperature (1951–2010)	TG (year) (°C)		10.2	8.7	10.5	7.8	8.7	8.7
	Tendency (°C (10 years)$^{-1}$)		**0.27**	**0.25**	**0.13**	**0.20**	**0.25**	**0.24**
	TG ($_{MAM}$) (°C)		10.0	8.3	10.9	7.8	8.9	8.9
	Tendency (°C (10 years)$^{-1}$)		**0.31**	**0.31**	**0.25**	**0.34**	**0.39**	**0.29**
Frost-free season (FFS) characteristics (1951–2010)	LSF date (mean)		9 April	28 April	8 April	23 April	8 April	18 April
	Tendency (days (10 years)$^{-1}$)		**−3.6**	**−1.9**	**−3.2**	−1.3	−1.2	1.4
	FAF date (mean)		30 Oct.	16 Oct.	23 Oct.	15 Oct.	19 Oct.	10 Oct.
	Tendency (days (10 years)$^{-1}$)		**2.9**	1.2	0.3	0.2	−0.3	1.3
	FFS length (mean)		203	170	197	174	194	176
	tendency (days (10 years)$^{-1}$)		**6.6**	**3.1**	**3.5**	1.4	0.9	−0.1
Frost-free season (FFS) extremes (1951–2010)	LSF date		11 May 1953	28 May 1957	21 May 1952	23 May 1980	29 April 1954	22 May 1990, 2002
	FAF date		5 October 1957	8 September 1991	28 September 1977	17 September 1952	28 September 1977, 1986	17 September 1958
	FFS length (days, year)	Min	148 1957	118 1973	150 1952	119 1952	165 1959	134 1990
		Max	286 2000	221 1961, 2000	244 2004	220 1996	223 1960, 1983, 2008	209 1991

Statistically significant values ($\alpha = 0.05$) are given in bold.

analysis, the measurement site data were used as a reference in assessing the incidence of extreme climate cases since minimum air temperature is extremely sensitive to local conditions and gridded data have the tendency to underestimate the tails of the distribution (Wibig *et al.*, 2014). It is especially significant in low temperatures so over-smoothing is stronger in winter time and may also influence the number of spring and autumn frost days.

The role of atmospheric circulation was estimated for both the spatial and temporal scale using Grosswetterlagen (GWL) circulation types (Werner and Gerstengarbe, 2010; Die Großwetterlagen Europas, 2014, http://www.dwd.de/GWL). It is based on work by Hess and Brezowsky on large-scale weather systems with a focus on the direction of air mass advection and location of key pressure systems, available for Central Europe (Werner and Gerstengarbe, 2010). For each given grid point, dominant types of circulation favouring the occurrence of frost and severe frost events were determined. To examine the impact of circulation on long-term variability zonal and meridional indices were calculated using the GWL classification (Werner and Gerstengarbe, 2010) and seasonal North Atlantic Oscillation (NAO) values provided by Jones *et al.* (1997) and University of East Anglia, 2000 (https://crudata.uea.ac.uk/cru/data/nao/), which is a measure of zonal circulation intensity in the Atlantic-European sector. In a final step, an empirical orthogonal function (EOF) was used to identify circulation patterns accompanying frost occurrence. To determine the synoptic situations during the frost events analysed, daily mean sea level pressure (SLP) fields were used.

Special attention was paid to springtime as the most important time period for late frost events. EOF analysis was conducted for all days with frost in the examined region for each month separately. To focus on the role of atmospheric circulation and to avoid incidental frost events with possible impact of local conditions, final calculations were performed for days with widespread frost, i.e. noted over more than 75% of the study area (Müller *et al.*, 2000).

Initial cluster analysis identified three main clusters with frost occurrence: (1) mountain areas found at over 500 m of elevation (Alps, Carpathians), (2) western and (3) eastern regions with the boundary line running along approximately 20°E. The derived zones were subsequently used for detailed circulation pattern studies. In this study, only the first three EOF modes, which together explain more than 75% of the variance, were analysed.

3. Results

The observed increase in air temperature in the northern hemisphere in recent decades is undeniable, especially in Europe. Since 1951, the average annual temperature (TG_{AV}) in the study area increased by 0.2 °C (10 years)$^{-1}$, with the strongest warming (up to 0.5 °C (10 years)$^{-1}$) in the continental part – i.e. Poland and areas located further east. Less intensive changes are observed in Western

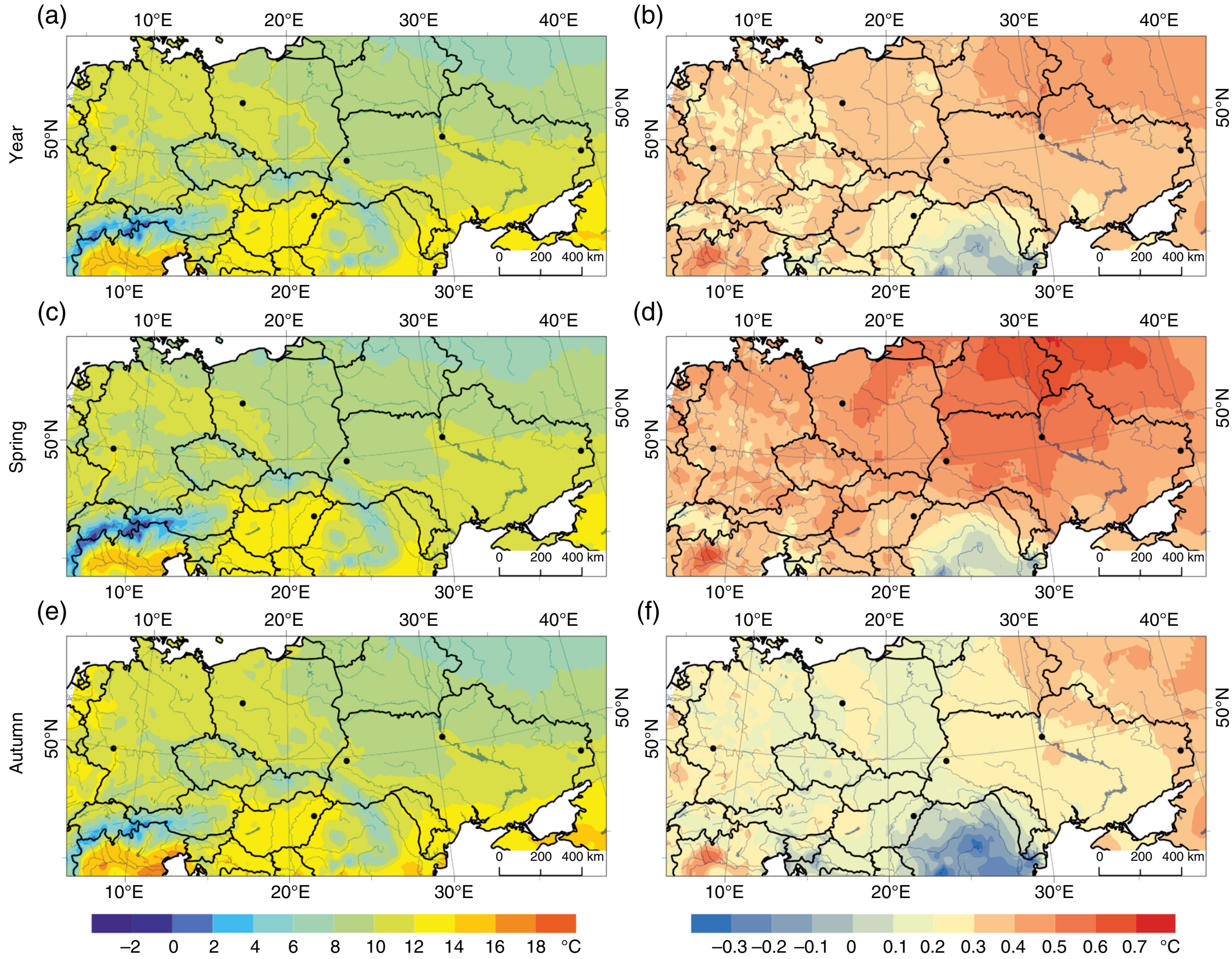

Figure 2. Spatial differentiation of annual and seasonal mean air temperature (a, c, e) and its tendency per 10 years (b, d, f) (1951–2010).

Europe and the south-eastern extremities, which marks a slightly negative trend (Figure 2). The presented tendencies are statistically significant at the level of $\alpha = 0.05$ for 95% of the study area.

The intensity of changes has a strong impact on the temperature trend in the transitional seasons, which was the most relevant time period for this study. The spatial differentiation of seasonal trends corresponds with the noted trend of TG_{AV} changes. In Central Europe, one may note boundaries between the intensely warming areas of the continental and western regions, which are affected by oceanic effects (Figure 2). Changes are clearly visible and statistically significant in spring (TG_{MAM}) (Figure 2), whereby clear differences are also noted in the subsequent months of the spring season (not shown in Figure 2). In March, the temperature increase is primarily significant in the eastern part of the study area (up to 0.6 °C (10 years)$^{-1}$), while the remaining part of the study area had a temperature rise not exceeding 0.2–0.3 °C (10 years)$^{-1}$. In April and May, respectively, the studied warming effect also affects the northern and central parts of the study area (up to 0.4 °C (10 years)$^{-1}$). Thermal changes occurring in autumn are much weaker (TG_{SON}) (Figure 2). For most parts of the studied region, these values reach 0.2 °C (10 years)$^{-1}$, which is statistically insignificant. The only area where the changes were significant was situated between 15° and 25°E. Trends in seasonal mean air temperature values mirror minimum temperature trends, which are equally significant from the point of view of the occurrence of frost (TN). In spring (TN_{MAM}), trends range from 0.2 °C (10 years)$^{-1}$ in the west to 0.5 °C (10 years)$^{-1}$ in the east, whereas in autumn statistically insignificant change, not exceeding 0.2 °C (10 years)$^{-1}$, dominates in the eastern region.

3.1. Spatial variability

The trends in spring and autumn temperature described above are reflected in both the frequency and spatial diversity of the occurrence of frost in Central Europe (Figure 3). Last spring frost (LSF) appears, on average, between 1 and 30 April. The minimum air temperature below 0 °C persists the longest in the northern part of the region (including Germany and Poland), its north-eastern extremities (until the first ten days of May), and in mountain areas, which are not considered in this particular study because of their minor importance from an agricultural point of view. The FFS begins in the south-eastern region first. It occurs at earliest in the last 10 days of March due to the

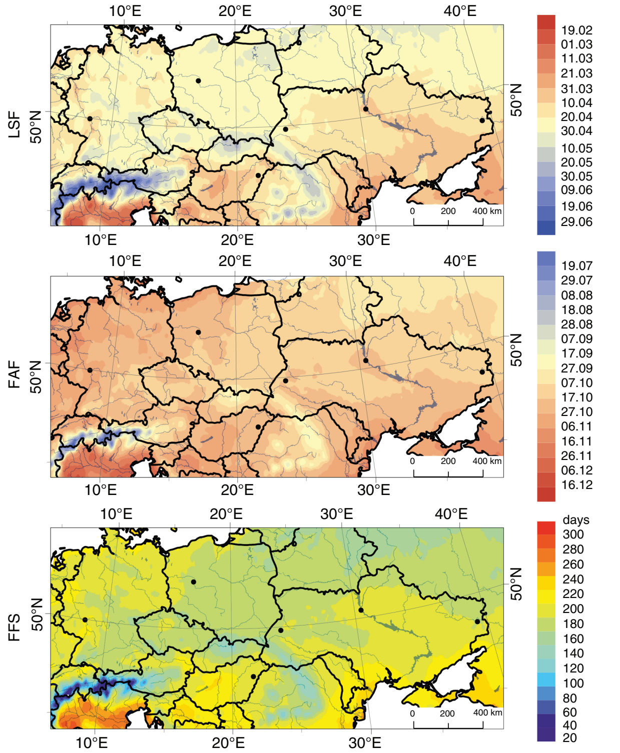

Figure 3. Spatial differentiation of the date of last spring frost (LSF), the date of first autumn frost (FAF) and the length of frost-free season (FFS) (1951–2010).

region's geographical location (Figure 3). The first autumn frost (FAF) enters the analysed area from the east, where it occurs at the earliest on 3–4 October. The longest minimum temperature above 0 °C remains in coastal regions, i.e. in northern Germany and on the Black Sea coast at the beginning of the second 10-day period of November (Figure 3).

As a result, the FFS lasts the longest (almost 230 days) in the south of Ukraine (Figure 3), and slightly less time (just over 200 days) in north-western, coastal Germany. Most of the area is characterized by FFS persisting 160–180 days, i.e. on average from May to October.

The FFS and LSF and FAF dates are characterized by large fluctuations from year to year. The standard LSF deviation ranges from 7 to 30 days and is also comparable with the standard deviation range for FAF (8–33 days), with 90% of the area having a deviation of 10–15 days for both LSF and FAF. The standard deviation for the length of the FFS ranges from 11 to 41 days; however, a standard deviation over 20 days is only typical for 5% of the area, and these are mostly mountain areas. The spatial variations of the standard deviation for both LSP and FFS reflect the regional divide between oceanic and continental conditions. The western part of Central Europe is marked by a definitely greater deviation. Interannual variability of the date of the first frost in spring is characterized by large fluctuations with no clear spatial trend (not shown).

The number of days with frost is characterized by spatial differences, reaching more than 80 in spring and 60 in autumn in the mountains, while on the Adriatic coast there is only 1 day with frost per year, which can be seen in Figure 4 (both regions are located outside the area of interest). However, in the study area, days with frost range from 10 in western Germany to almost 40 in the eastern part of Central Europe in spring, and from 5 to 30 in autumn (Figure 4).

3.2. Long-term variability and trends

The previously described spatial differentiation of the standard deviation of LSF, FAF, and FFS gives a certain picture of interannual variation of these variables, which reflect thermal changes in Central Europe between 1951 and 2010. The FFS has become significantly prolonged (Figure 5) in the western parts of Europe, up to 10 days in southern Germany, Slovakia, and the Czech Republic. Regions situated east of central Poland are characterized by either a lack of trends, or even by an insignificant shortening of the FFS. Changes in FFS are the result of spatial trends in LSF and FAF. LSF occurs earlier only in the west – up to 5 days at sites in Germany and western Poland. In turn, the occurrence of the first autumn frost (FAF) shows no significant trend in most of the areas studied herein. In some regions, FAF occurs early (e.g. north-east Poland), while in some places, it appears later – up to 4 days in southern Germany, Slovakia, and the Czech Republic (Figure 5).

Figure 4 shows the tendency in the occurrence of days with frost (TN < 0 °C). In spring, a decrease in the number of days with frost of up to 4 days (10 years)$^{-1}$ can be observed in most parts of the area studied, while in autumn in Central Europe, there is a slight increase in their frequency to 2 days (10 years)$^{-1}$ in the north-western and southern regions.

The tendencies shown in Figures 4 and 5 are statistically significant primarily for the spring time; however, for last spring frost, they are appropriate only for the area located to the west of 20°E. The same pattern can be observed for the variability of FFS length.

An analysis of the long-term variability of selected variables, carried out for six measurement sites located approximately along east–west cross-sections of the investigated area revealed additional important characteristics of the FFS and the occurrence of frost in Central Europe. Warming in spring (TG_{MAM}) ranges from 0.25 °C (10 years)$^{-1}$ in the city of Debrecen in Hungary to 0.39 °C (10 years)$^{-1}$ in Kiev in Ukraine, whereby at all measurement sites, the temperature increase is statistically significant.

However, there are no statistically significant changes in the duration of FFS, LSF, and FAF at measurement sites located in the eastern part of the area (Figure 6 and Table 1), which confirms the previously described spatially different trends.

In the investigated period, there were no clearly warmer periods, with few frost events and few long frost-free periods or clearly cooler periods. Most extremes represented by the extreme LSF date occurred in the first decade of the aforementioned six decades, reaching no later than 28 May

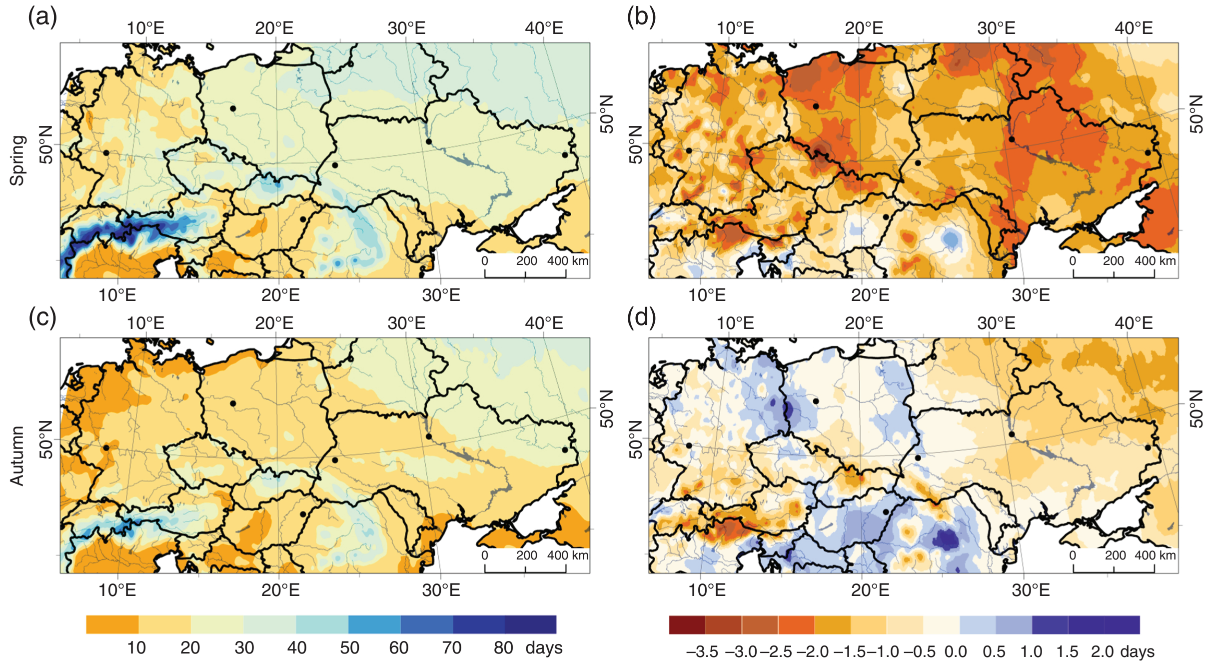

Figure 4. Spatial differentiation of the number of frost days (a, c, e) and its tendency per 10 years (b, d, f) (1951–2010).

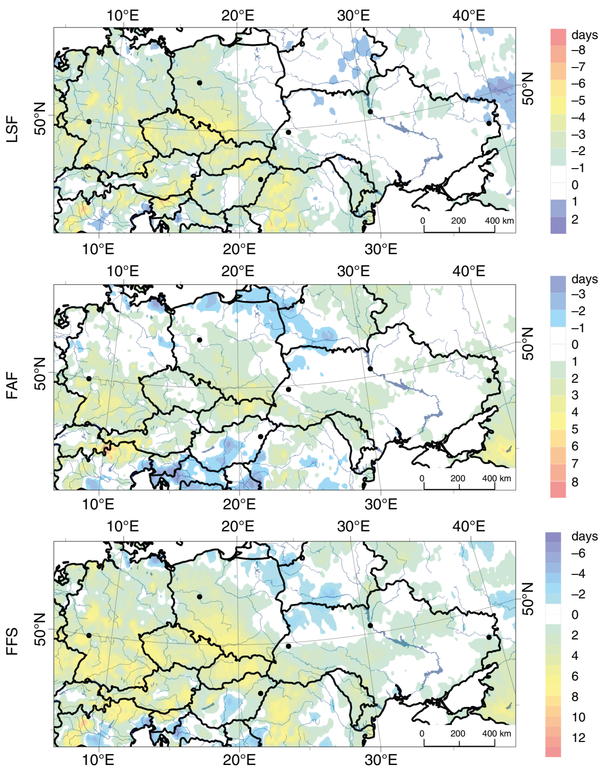

Figure 5. Tendencies (per 10 years) in the date of last spring frost (LSF), the date of first autumn frost (FAF) and the length of frost-free season (FFS) (1951–2010).

in Poznan (1957). The earliest frost was also recorded in Poznan on 8 September 1991. In the case of FAF, there is no period with a significantly larger number of extremes. The shortest FFSs at most measurement sites occurred in the 1950s, but only in Debrecen 1952 was the year in which the latest frost occurred at the same time (Table 1). However, in the beginning of the 21st century, frequently short periods of frost were noted, while at all measurement sites, the longest FFS was recorded in the last two decades.

Despite a significant decline in the number of days with frost, up to a maximum of 5 days (10 years)$^{-1}$ in Kiev (Figure 7), the risk associated with the occurrence of frost, mainly in spring, remains a serious problem, especially in the central and eastern parts of Central Europe. Once the thermal growing season begins earlier, a small increase in the number of days with frost can be observed, with a special focus on days with severe frost (TN $< -2.2\,^{\circ}$C), which are characterized by a statistically significant tendency during this time (Figure 7). For this reason, frost damage such at bud burst in April or May is possible.

3.3. Role of atmospheric circulation

Atmospheric circulation is of great importance for thermal conditions in Europe. One of the most important circulation measures for Europe is the NAO index (Hurrell and van Loon, 1997; Trigo *et al.*, 2002; Beranová and Huth, 2007, 2008; Moore and Renfrew, 2012). The peak effect of NAO on air temperature can be observed at high NAO index values (Beranová and Huth, 2007). Previous studies have emphasized the role of zonal circulation in shaping air temperature in the winter (Scaife *et al.*, 2008) or mainly in the cooler half of the year (Aasa *et al.*, 2004). The correlations between NAO and air temperature are positive and were found to be statistically significant, especially for Western Europe; however, they weaken towards the far north and far south-east, reaching negative values in the Mediterranean region (Scheifinger *et al.*, 2002; Aasa *et al.*, 2004; Menzel *et al.*, 2005; López-Moreno *et al.*, 2011; Fernández-Montes and Rodrigo, 2012). The impact

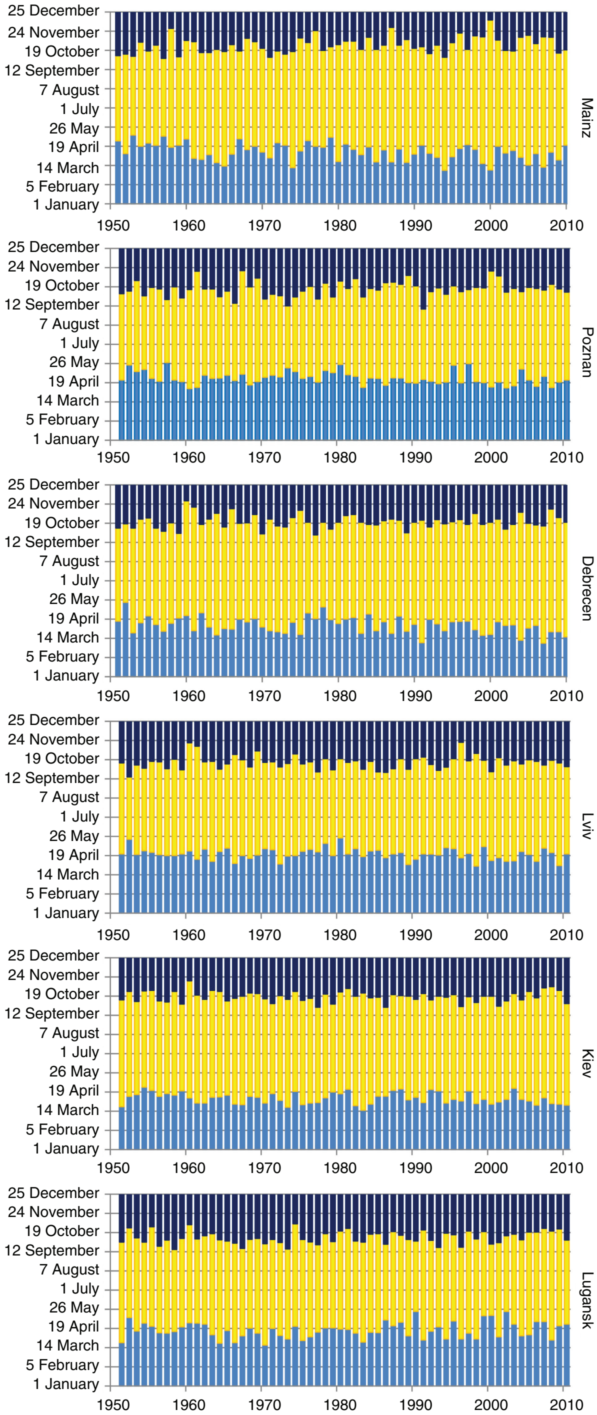

Figure 6. Variability of frost-free season characteristics (LSF date, FAF date, FFS length) at selected stations (1951–2010). [Colour figure can be viewed at wileyonlinelibrary.com].

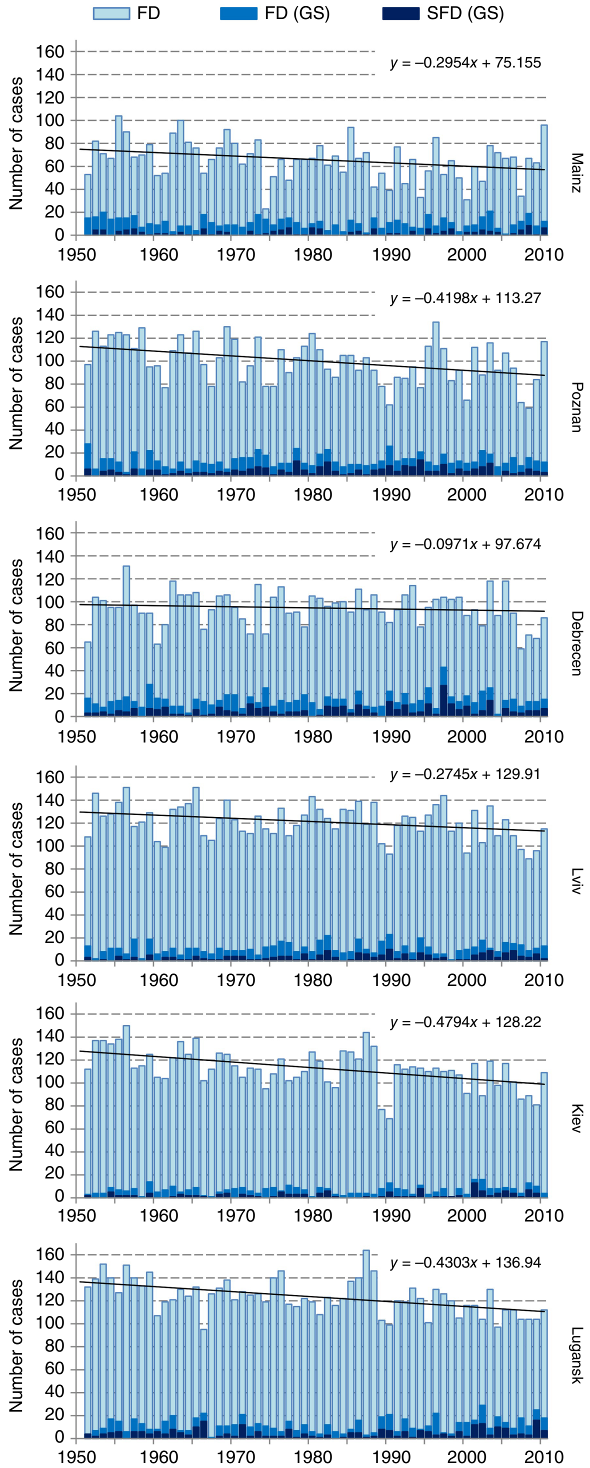

Figure 7. Variability of the number of frost days (FD), days with spring frost in the thermal growing season FD (GS) and days with severe spring frost in growing season SFD (GS) at selected stations (1951–2010). Straight line – linear trend (FD). [Colour figure can be viewed at wileyonlinelibrary.com].

of NAO on the timing of phenological events has also been proven (Chmielewski and Rötzer, 2001; Ahas *et al.*, 2002; Menzel *et al.*, 2005). Following a mild winter related to the positive phase of NAO, subsequent phases of plant development occur earlier in the western part of the continent. The NAO is much less important in areas found in the eastern and south-eastern parts of Europe experiencing the influence of a seasonal high-pressure centre and advection from the north (Sepp and Jaagus, 2002; Aasa *et al.*, 2004; Menzel *et al.*, 2005; Jaagus, 2006).

The role of atmospheric circulation in the temporal and spatial occurrence of frost was investigated by determining the dependence of air temperatures in spring on the intensity of NAO. The results confirm the importance of zonal circulation in the formation of thermal conditions in the western and north-western parts of the study area.

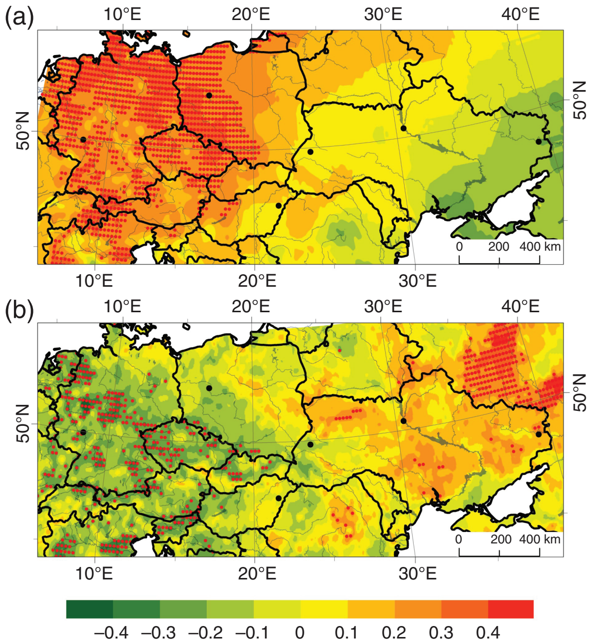

Figure 8. Spatial differentiation of Pearson's correlation coefficient between spring NAO index values and (a) spring temperature (TG_{MAM}), (b) number of spring frost days (1951–2010). Red dots indicate statistically significant relationship.

The Pearson correlation coefficient achieved statistically significant values of up to 0.40 for Germany and western Poland, which decrease in the south-easterly direction down to −0.20 in eastern Ukraine (Figure 8(a)). Similar spatial heterogeneity was identified in the frequency of frost events. The positive phase of NAO caused a clear decline in the number of days with frost only in the west ($R < -0.30$, statistically significant at $\alpha = 0.05$); however, this relationship was not confirmed for the remaining area (Figure 8(b)). Moreover, the simultaneous lack of correlation between air temperature in spring and NAO (Figure 8(a)) suggests that this particular region experiences different circulation conditions. Here the temperature differentiation and variability also depend on regional atmospheric conditions such as the East Atlantic pattern (Moore and Renfrew, 2012), Siberian anticyclone (Bednorz, 2002; Bukantis and Bartkeviciene, 2005), and even local factors.

Similar inferences can also be made after a detailed analysis of the circulation types favouring the occurrence of frost events in Central Europe (Figure 9). In most of the study area, the lowest air temperature on record in spring is associated with the presence of the Scandinavian High and the Central European Ridge (HFa) (Figure 9(c)). Similarly, the largest number of days with frost and severe frost accompany anti-cyclonic situations (20% of all cases): Zonal Ridge across Central Europe (BM) and HFa (Figure 9(a) and (b)). The one exception is eastern Ukraine, where the most common types of circulation are western types (Wz, Ww), which are associated with the advection of warm air masses. This is confirmed by the fact that the GWL calendar was created primarily for Central Europe; it is not fully representative of the continent's eastern extremities (Hoy *et al.*, 2013). While Western Europe is under strong advection from the west, the weather conditions in the east may be influenced by the western edge of the continental Siberian high-pressure zone with its low temperatures. Pressure patterns for days with BM and WZ circulation types during spring are presented in Figure 10(a) and (b), and show clearly the differences in circulation conditions between the western and eastern parts of the study area. A high pressure centre blocking western advection (Figure 10(b)) is the main factor in the confirmed temperature contrasts.

Further results were obtained via EOFs. EOF analyses were performed to identify dominant spatial patterns of SLP across Central Europe. They were distinguished only for days with frost defined as days with a minimum air temperature below 0 °C recorded across more than 75% of the study area, excluding mountain areas as especially prone to low temperatures and normally not used for cultivation purposes (no frost risk detected). Although a set of EOF modes was produced for each month separately, according to the frost climatology of the region (e.g. frost event frequency, LSF dates), the analysis for April was adopted as the most representative of springtime (Figure 11).

The leading modes of SLP for days with frost are shown in Figure 12. The first mode (EOF 1) explains 56% of total variance (Figure 11(a)). The anomalies are positive for the study area as a whole, and exhibit the largest variability over western Ukraine, Belarus, and eastern Poland (more than 9 hPa), and the smallest fluctuations at the west German border.

This type of pressure pattern brings anti-cyclonic eastern advection of cold air masses towards the western part of the study area and produces an advection-free situation with atmospheric subsidence of cold air in the central part of the studied system. The second mode (EOF 2) accounts for 27% of total variance (Figure 11(a)). The spatial variability of pressure anomalies ranges from +6 hPa in the western part of the investigated area or Germany to −6 hPa in north-eastern Ukraine, creating two opposing pressure centres. The herein described baric field leads to the advection of cold air masses from the north intensifying frost occurrence over the entire studied area (Figure 12). Given that the two leading EOF modes explain more than 80% of total variance, the third mode seems to be of minor importance. It accounts for only 7% of total variance and the fluctuations are in-phase only in the studied eastern regions (Figure 12) responsible for frost event occurrence over the Black Sea coastal region (small positive anomalies).

Since climatological analyses of frost event occurrence confirmed by cluster analysis distinguished two frost regions in Central Europe, the EOF modes were produced also for these regions separately (Figure 13). The first two modes for the western part explain together 82% of total variance, which is 10% more than that for the eastern part (Figure 11(b) and (c)). Moreover, SLP spatial patterns over the western region are similar to those described for the entire studied area, also in terms of the percentage of total variance, whereas the eastern patterns

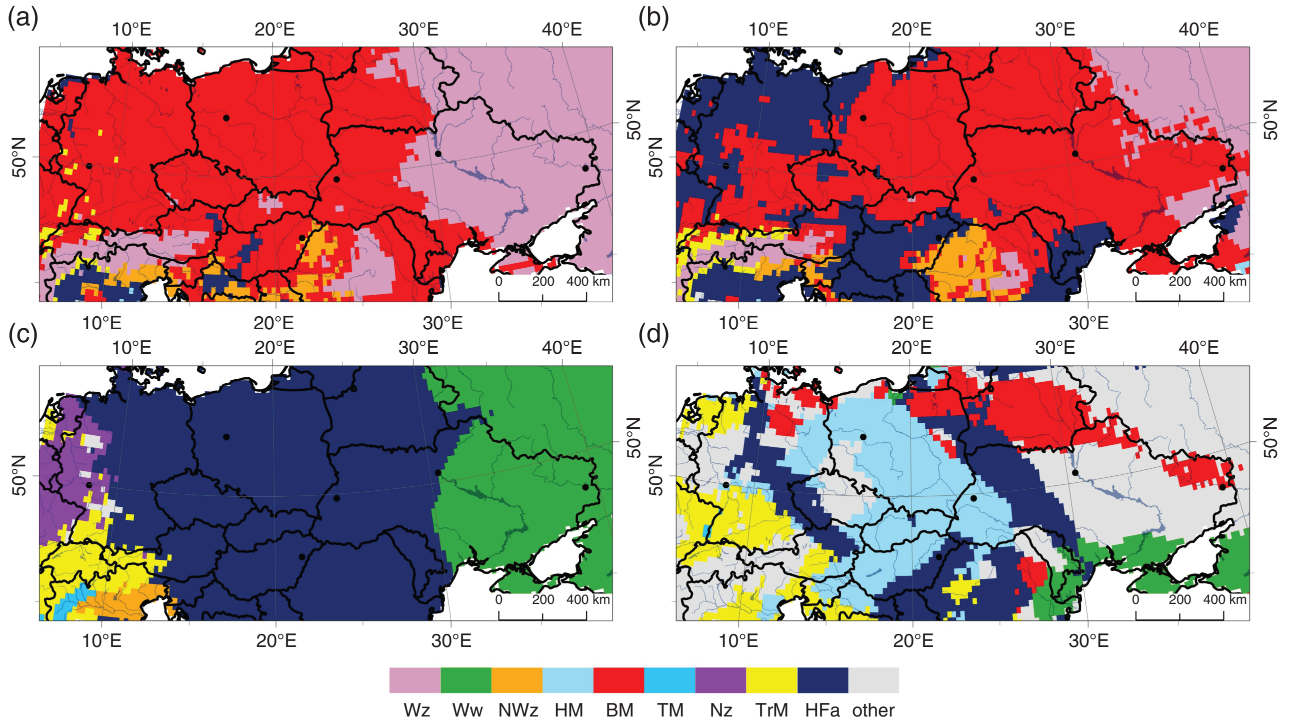

Figure 9. Circulation types (GWL calendar) accompanying (a) the highest number of spring frost days, (b) the highest number of severe spring frost days, (c) the lowest average minimum spring temperature, (d) the absolute minimum spring temperature Explanations: Wz – Cyclonic westerly, Ww – Maritime westerly (block Eastern Europe), NWz – Cyclonic north-westerly, HM – High over Central Europe, BM – Zonal ridge across Central Europe, TM – Low over Central Europe, Nz – Cyclonic northerly, TrM – Trough over Central Europe, HFa – Fennoscandian high, anticyclonic, other – any other circulation type.

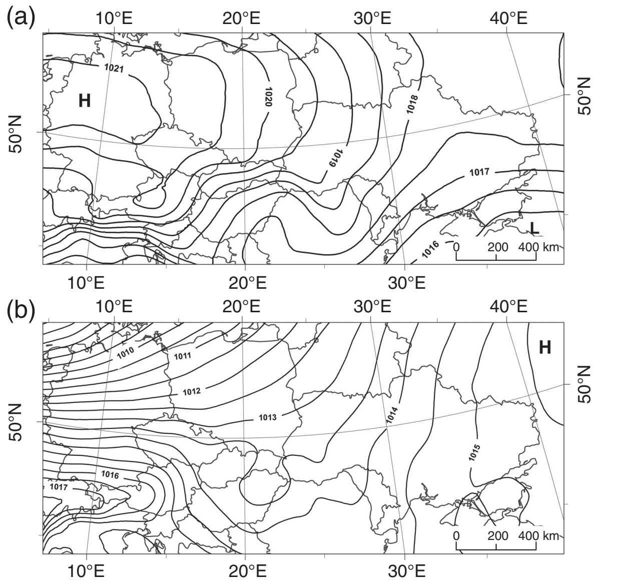

Figure 10. Spatial pattern of sea level pressure (SLP) on days with BM (a) and Wz (b) circulation types (GWL classification) in Spring (1951–2010).

are opposite. This can be seen especially with the second mode (EOF 2). Pressure anomalies range from +8 hPa over the north-east to −5 hPa in the western part of the study area, which results in eastern advection of cold air masses over Ukraine, Belarus, and eastern Poland. The third mode (EOF 3) for both regions is of lesser importance, and explains 7 and 11% of total variance, respectively (Figure 11(b) and (c)).

EOF analysis illustrated the important role of atmospheric circulation in spring frost occurrence in Central Europe. There exists a limited number of air pressure patterns that are responsible for cold air mass advection or subsidence leading to low minimum air temperatures. The mesoscale pattern is often affected by local conditions.

Hence, particularly noteworthy is the fact that the occurrence of extremes of absolute minimum air temperature in Central Europe is not related to the presence of a specific type of circulation (Figure 9(d)). Under a large variety of synoptic conditions, anticyclonic (high-pressure) non-advective situations dominate by far, which favours the occurrence of air temperature inversion, thus generating local minimum thermal extremes, further intensified by environmental conditions such as relief (Whiteman *et al.*, 1999; Trigo *et al.*, 2002; del Río *et al.*, 2007; Beranová and Huth, 2008; Ustrnul *et al.*, 2010; López-Moreno *et al.*, 2011; Ustrnul *et al.*, 2014).

4. Conclusions

Future climate projections for Europe point towards a reduced risk of frost events, due to a significant decrease in the number of days with frost as well as a much longer FFS and less severe frost intensity (Jylhä *et al.*, 2008). Moreover, in the northern and eastern parts of the continent, frost periods with only individual freeze events are also

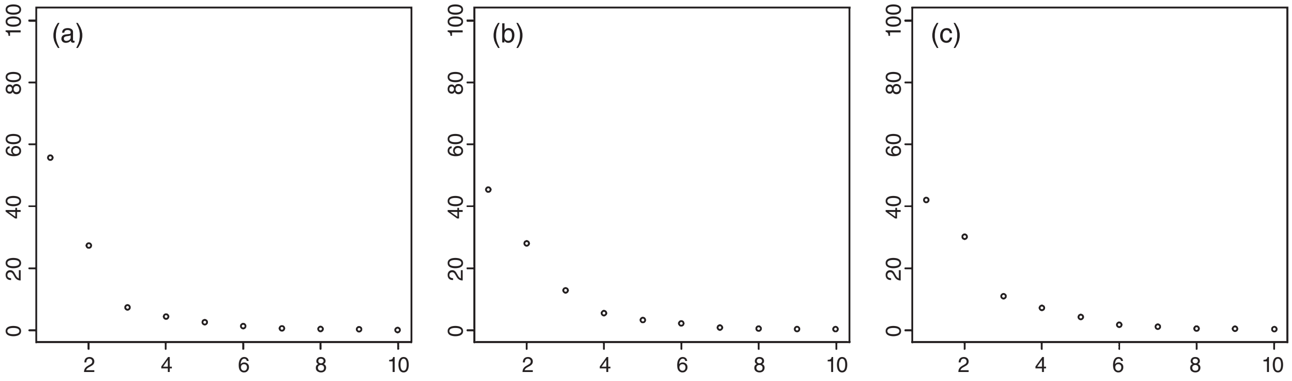

Figure 11. Amount of variance (%) explained by EOF modes 1–10 (April, 1951–2010) (a) whole research domain, (b) western subdomain, (c) eastern subdomain.

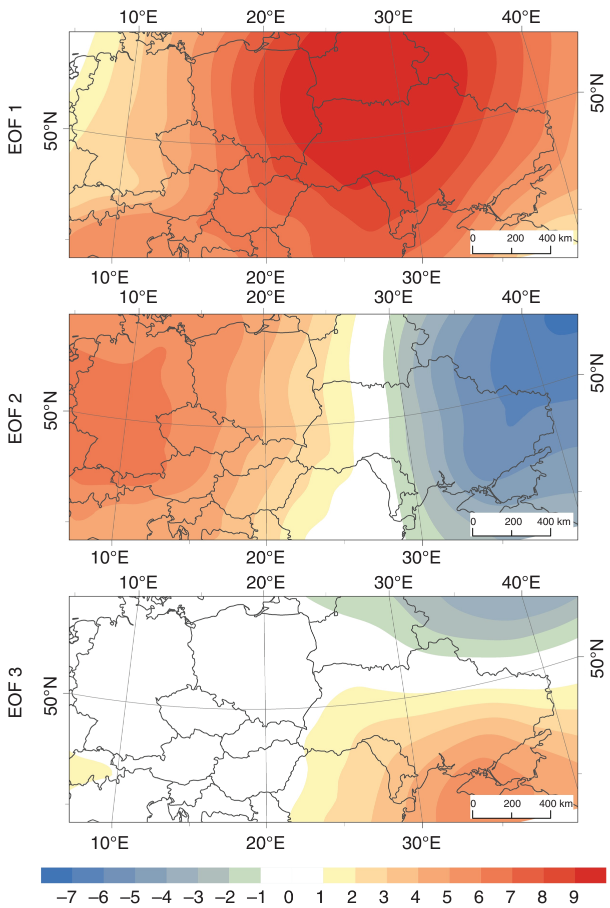

Figure 12. Spatial patterns of pressure anomalies (hPa) in April for three leading EOF modes (1951–2010).

expected to occur. Nevertheless, early autumn frost and more importantly from an agricultural point of view early spring frost remain problematic. The earlier timing of phenological events due to rising air temperatures may prompt the occurrence of more harmful spring frost events because of the closer timing to the beginning of budburst (Eccel *et al.*, 2009). This scenario is possible in Central and Eastern Europe, where there exists a risk of an inflow of cold air masses from the north or the east and for extensive radiative cooling under cloud-free anticyclones related to the seasonal Siberian high-pressure zone. Moreover, due to global warming in the Arctic, more polar air masses are likely to be transported to lower latitudes and the cold spell risk will remain despite the increasing air temperatures (Petoukhov and Semenov, 2010).

The results of this study confirm the warming of the climate in Central Europe via a statistically significant increase in minimum air temperature and a decreasing number of days with frost in most of the studied area as well as a clear trend towards an extension in the FFS. An very important aspect of this study is the significant spatial differentiation of these changes. The analysis of atmospheric circulation responsible for frost events clearly shows the influence of regional disparities in circulation impact and divides the study area into a western part, which lies in the transitional seasons of the year and experiences the effects of oceanic air circulation, and a south-eastern and eastern part, where continental circulation effects dominate. The earlier timing of plant development in the eastern regions increases the risk of severe frost damage, given that the possibility of sudden frost episodes in the spring there is high. Detailed analyses of data obtained at selected test sites confirm a statistically significant increase in severe frost events during the thermal growing season in the study area.

The relationship between atmospheric circulation and frost occurrence potentially provides an alternative approach to investigate past and future trends in frost risk under the assumption that only a small number of airflow patterns are associated with severe frost events and that changes in the frequency of these airflow patterns will result in changes in the risk of frost damage. To achieve this end, it is necessary to conduct a detailed analysis of the conditions of air circulation at each grid point separately, with a special focus on the direction of advection and their consequences in specific synoptic situations. Only then, in conjunction with future circulation models and the detailed analysis of local environmental conditions favourable to frost event occurrence, will it be possible to develop a method designed for their projections.

In order to investigate the occurrence of frost events on a plant-specific level, the study would need to be much more complex, because different plants react differently

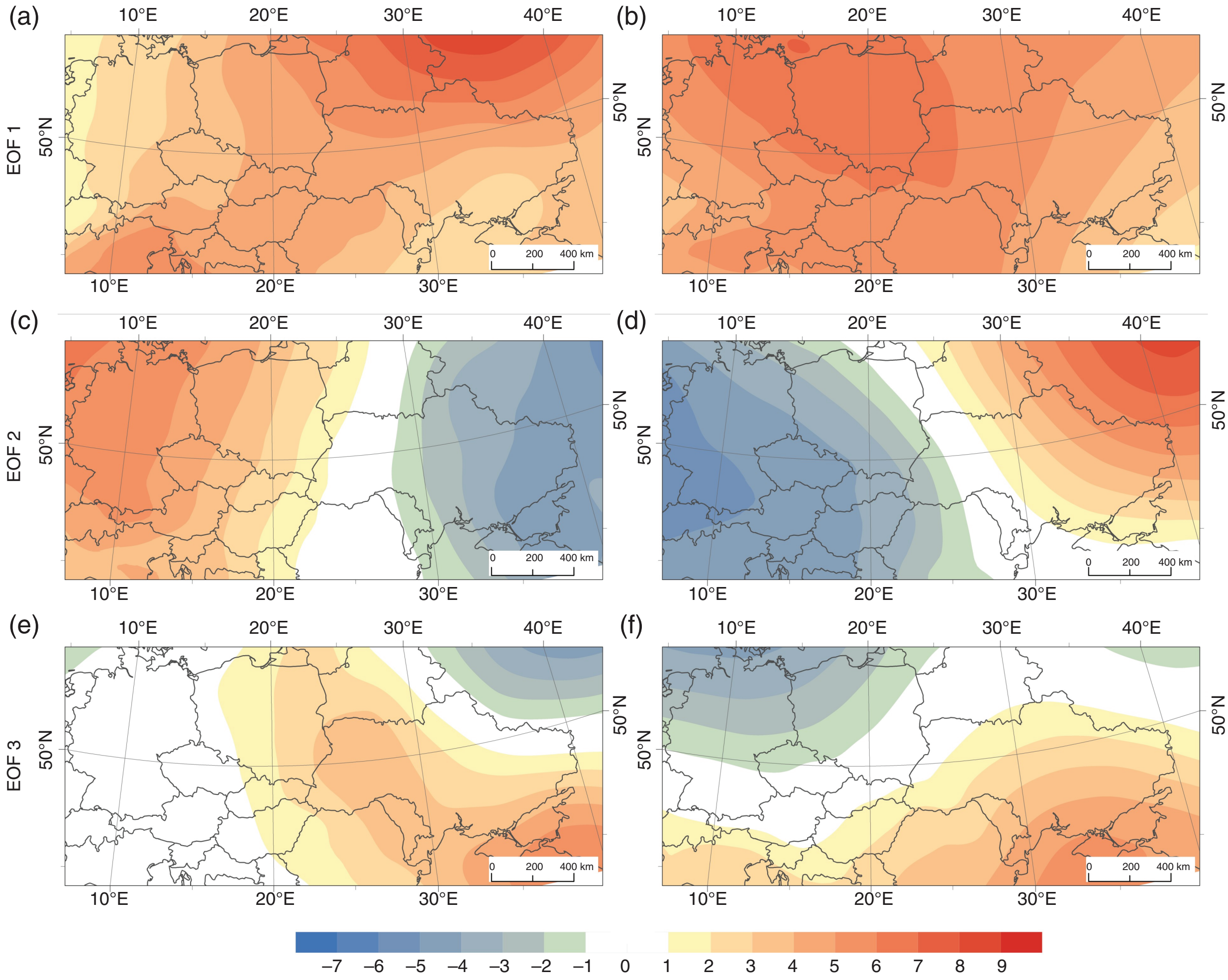

Figure 13. Spatial patterns of pressure anomalies (hPa) in April for three leading EOF modes in distinguished research domains: West (a,c, e) and East (b, d, f) (1951–2010).

to frost, depending on their developmental stage. The precondition for this type of impact study consists of reliable phenological models, which are capable of calculating the timing of phenological events (e.g. beginning of fruit tree blossom) for current as well as future (warmer) climatic conditions with the same accuracy. Currently, such models are still hard to find, so that a plant-specific analysis remains an important task for the future.

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