



If not NAO then what?—regional circulation patterns governing summer air temperatures in Poland

Ewa Bednorz¹ · Bartosz Czernecki¹ · Arkadiusz M. Tomczyk¹ · Marek Półrolniczak¹

Received: 22 November 2017 / Accepted: 4 July 2018 / Published online: 14 July 2018
© The Author(s) 2018

Abstract

The correlation between the daily/monthly North Atlantic Oscillation (NAO) index and the daily/monthly anomalies of the summer (JJA) surface air temperatures in Poland is close to 0.00, being positive in most of the country (but hardly exceeding 0.15) and negative in the southeast. Therefore, the regional scale circulation patterns other than NAO were determined using principal component analysis (PCA) to establish the relationship between the air circulation and the daily anomalies of the mean, maximum and minimum air temperatures in Poland. Regression and correlation analysis were applied to define the strengths and spatial distributions of these relationships. The best results were obtained for the mean and maximum daily temperature anomalies, for which the Pearson correlation coefficient (r) between the modelled and observed values exceeded 0.75 in the vast areas of central and southeastern Poland, while, over the rest of the country, it amounted to 0.7. The weaker influence of the circulation on air temperatures is observed in the northwestern part of the country, along the Baltic Sea shore ($r < 0.65$). The weakest results were obtained for the anomalies of the daily minimum temperatures (r equals 0.5–0.6 over most of the country and drops below 0.4 in the northwest). Furthermore, the influences of each PCA-based regional circulation pattern on the variabilities of the surface temperatures were analysed. The circulation pattern recognized as the second principal component, distinguished in the positive phase by the high-pressure conditions with the anticyclonic centre located right over central and southeastern Poland, revealed the strongest positive relationship with the air temperature.

1 Introduction

Atmospheric circulation is one of the most important factors that influences weather and climate conditions, and its changes significantly determine short- and long-period temperature variabilities (Yarnal 1993). In the North Atlantic–European sector, this theorem is most true in the winter, for which the paradigm of the macroscale circulation pattern called the North Atlantic Oscillation (NAO) is most often used to explain the variability of the air temperature and other meteorological factors. However, there is much less recognition of the circulation's impact on European weather and climate in the summer (Folland et al. 2009).

The NAO is the most prominent and recurrent circulation pattern over the middle and high latitudes of the Northern Hemisphere. It depicts the redistribution of atmospheric mass and therefore, the heat and moisture transport between the subtropical Atlantic and the Arctic. Therefore, it has most often been used to describe the relationships between macroscale circulation and the climate in Europe (e.g., Shabbar et al. 2001; Hurrell et al. 2003; Trigo et al. 2004; Scherrer et al. 2006; Beranová and Huth 2007, 2008). The NAO is observed at any time of the year; however, its influence on the weather over the Atlantic and its neighbouring continents is most pronounced in the cold season. This is mainly because of the seasonal variation of the oscillation strength and partly because of the seasonal changes in the spatial patterns of the NAO dipole centre locations (Barnston and Livezey 1987; Portis et al. 2001; Folland et al. 2009; Pokorná and Huth 2015). In the eigenvector analysis of the North Atlantic–European sea level pressure, the NAO pattern explains 36.7% of the variance in the winter, but only 22.1% in the summer; similar differences appear at the 700 hPa level (Barnston and Livezey 1987; Hurrell et al.

✉ Ewa Bednorz
ewabedno@amu.edu.pl

¹ Department of Climatology, Institute of Physical Geography and Environmental Planning, Adam Mickiewicz University, Krygowskiego 10, 61–680 Poznań, Poland

2003). Furthermore, the summer NAO has a smaller spatial scale than its winter counterpart and both centres are shifted north, which means that the summer southern dipole is located over northwestern Europe rather than over the Azores–Spain region (e.g. Hurrell et al. 2003, Folland et al. 2009). Nevertheless, not only winter but also summer fluctuations of the NAO phases and their intensity are said to influence the weather and climate in Europe, mainly due to the changing frequencies, positions and intensities of blocking events and storm tracks over the extratropical North Atlantic (e.g. Shabbar et al. 2001; Trigo et al. 2004; Scherrer et al. 2006; Folland et al. 2009; Pokorná and Huth 2015). However, in the first part of this study, it has been proven that the influence of the summer NAO on the surface air temperature does not encompass Poland, which is located in central Europe. In this case, it was assumed that circulation patterns other than the NAO, possibly at a regional scale, determine the variability of the summer air temperatures in this region. To this end, the classification of regional atmospheric circulation types occurring in the summer over central Europe was performed, and the influences of the produced circulation patterns on the surface air temperature variabilities in Poland were investigated.

Classifications of atmospheric circulation types are a useful and important tool that are often applied to synoptic climatological analyses concerning the influences of circulation dynamics on local and regional surface climate variables (Beck et al. 2007). There are different methods used to assign circulation patterns, such as the threshold based methods (e.g. Grosswetterlagen by Hess and Brezowsky 1952), clustering techniques (e.g. Esteban et al. 2005; Bednorz 2011; Beck et al. 2015), and the most often used principal component analysis (PCA)-based methods (e.g. Barnston and Livezey 1987; Huth 1993, 1996; Philipp 2009; Huth et al. 2008; Huth 2010). The resulting circulation types are related to various climatic variables, i.e., air temperature and precipitation (Beck et al. 2007), the occurrence of droughts (Vicente-Serrano and López-Moreno 2006; Fleig et al. 2010; Beck et al. 2015), snowfall (Esteban et al. 2005), storminess (Leckebusch et al. 2008) and others.

Many studies concerning the influence of circulation patterns on the summer temperature conditions in Europe focused on extreme events, in particular on the occurrences of heat waves (e.g. Kysely 2002, 2007, 2008; Porebska and Zdunek 2013; Tomczyk and Bednorz 2016). These works have proven that extreme temperatures in Europe are triggered by the stable circulation conditions that develop under blocking systems that persist over the Euro–Atlantic sector and drive warm air from Africa. Such blocking anticyclones induce the most devastating heat waves, including the 2003 heat wave in western and southwestern Europe, the 2010 heat wave in Russia, and the 2015 heat wave in Central Europe (Katsafados et al. 2014; Tomczyk and Bednorz 2016; Tomczyk et al. 2017).

The first aim of this study is to verify the influence of NAO on the surface air temperature in Poland during the summer season. Furthermore, the purpose is to determine other than NAO circulation patterns at the regional scales that appear in the summer over central Europe and to construct the regression models showing, how the obtained circulation types influence the surface air temperature variability in Poland.

2 Data and methods

This study is based on the daily data from the years 1966–2015, including the mean, maximum and minimum air temperatures (T_{mean} , T_{max} , T_{min}) at 44 meteorological stations in Poland (Fig. 1). These data were obtained from the records of the Polish Institute of Meteorology and Water Management. Anomalies of all variables were computed as the differences between the value in a particular day and the 50-year mean value for this day.

In the first step, in order to evaluate the influence of the NAO on the summer (JJA) surface air temperature variabilities in Poland, the correlations (Pearson's correlation coefficient) between the air temperature anomalies and NAO index were computed for each station used in this analysis; the computation was performed for both daily and monthly time scales. The NAO indices were derived from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Centre (CPC) datasets (historical monthly NAO indices available at ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/nao_index.tim; daily NAO indices available at <ftp://ftp.cpc.ncep.noaa.gov/cwlinks/norm.daily.nao.index.b500101.current.ascii>). The procedure used to identify the Northern Hemisphere teleconnection patterns recognized in this database is the PCA applied to the Northern Hemisphere monthly mean standardized 500 hPa height anomalies (Barnston and Livezey 1987). Alternatively, two other monthly NAO indices were used, namely the NAO index by Li and Wang (2003) (available at <http://ljp.gcess.cn/dct/page/65610>) and the Hurrell's index (NCAR 2017) (available at <https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based>). The NAO index by Li and Wang (2003) is defined as the difference in the normalized monthly sea level pressure (SLP) regionally zonal-averaged over the North Atlantic sector from 80° W to 30° E between 35° N and 65° N and it is considered as a measure of the intensity of zonal winds across the central North Atlantic between 35° N to 65° N. (Li and Wang 2003). The Hurrell's index is a PCA-based index of the North Atlantic Oscillation (NAO) and it reveals the time series of the leading Empirical Orthogonal Function of SLP anomalies over the Atlantic sector, 20°–80° N, 90° W–40° E.

Fig. 1 The locations of the meteorological stations used in the analysis



In the next step, the statistical relationships between the daily air temperature anomalies in Poland and the large-scale pressure fields were developed. To this end, the daily mean sea level pressure (SLP) and 500-hPa geopotential height (z500) reanalysis data were used. The reanalysis data for the Euro–Atlantic area encompassing the region of 35° W–65° E by 25°–75° N with a $2.5^\circ \times 2.5^\circ$ resolution were derived from the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis data (Kalnay et al. 1996), available from the NOAA ESRL PSD (National Oceanic and Atmosphere Administration, Earth System Laboratory, Physical Sciences Division) resources (www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.shtml). Data from the same source was used to establish the same relationships in the vertical tropospheric profile; to this end, the geopotential heights along the 52.5° N parallel at 11 levels (1000, 850, 700, 600, 500, 400, 300, 250, 200, 150, and 100 hPa) were correlated with the surface air temperature anomalies in Poland. To establish the relationships between the continuous and normally distributed variables, used in this study, the Pearson's correlation coefficient was employed, which is a

most often used method. The statistical significance of the correlation indices were tested using Student's *t*-distribution for probability level $p = 0.05$ and for an appropriate degree of freedom ($n - 2$). Nevertheless, we assumed that if the absolute value of correlation coefficient is smaller than approximately 0.3 it is not relevant which is justified from the climatological point of view.

To develop the daily regional circulation patterns distinctive to the summer season, the PCA was applied to the S-mode data matrix where the grid points made up the variables and the daily z500 values (1966–2015, JJA) acted as the observations (Barnston and Livezey 1987; Wilks 2011; NCAR 2015). The PCA is the most widely used multivariate statistical technique in the atmospheric sciences which reduces a data set containing a large number of variables to a data set containing fewer new variables (e.g. Barnston and Livezey 1987; NCAR 2015). In this case, the mean daily gridded ($2.5^\circ \times 2.5^\circ$) standardized values of z500 in the area of 5°–45° E by 35°–70° N (255 variables) were reduced to a set of new variables, namely principal components (PCs), which express the variability of the z500 field. In the analysis, several new data are obtained: (1) first of all, new variables (PCs) which stand for circulation

types with the percentage of explained z500 variance by each of them, (2) new daily time series of eigenvalues for each PC, which are used as daily indices of each circulation type; these indices give information on the strength and sign (positive/negative) of a particular circulation type, and (3) loadings of each PC, which show the spatial pattern of correlation between the old variables (standardized gridded daily z500 values in this case) and the new ones (daily indices of each PC). The geopotential height z500 and the spatial range of data taken to PCA were chosen based on the former correlation analysis. A pre-processing of the data was first performed, scaling the daily values, namely standardizing the observations from a spatial point of view. This procedure allowed to deseasonalize the observations, keeping the fields' intensities in the analysis, and maintains the daily temporal scale of the original data (Esteban et al. 2005). Standardizing the z500 data amounted to applying a correlation matrix in the analysis. An important issue while performing the PCA is the decision whether to rotate the obtained PCs or not. Rotation of PCs is commonplace in the atmospheric science; however, there has been extensive discussion of its advantages and disadvantages (i.e. Richman 1986; Jolliffe 1987, 2002; Rencher 1995; Wilks 2011). The main argument for rotation is that it simplifies the physical interpretation of PCs, but it has also a number of drawbacks. The first difficulty consists in a subjective choice of the rotated PCs number and then arbitrary choice from a large number of possible rotation criteria (Cattell 1978; Richman 1986). Moreover, while PCA successively maximizes variance accounted for subsequent PC, rotation redistributes it among the rotated components more uniformly, which means that information about the nature of the dominant components may be lost. Rotation means also loss either the orthogonality, or the uncorrelatedness of the resulting PCs, which constricts the interpretation of their meaning. Considering all the arguments, rotation of the PCs was abandoned in this study and despite this, the physical interpretation of the unrotated PCs appeared to be simple and apparent.

The number of principal components (PCs), namely, the circulation patterns that were used for further analysis were established considering the total amount of variability represented by obtained PCs (Jolliffe 2002; Wilks 2011).

Finally, the regression and correlation analyses were applied to define the strengths and spatial distributions of the relationships between the determined daily regional circulation types and the daily anomalies of the T_{max}, T_{min} and T_{mean}. To this end, the circulation indices have been utilized as predictors within multiple linear regression models. The cross-validation procedure based on the 10-fold cross-validation approach repeated 10 times using bootstrap resampling was used to verify the model. This was performed for each of the 44 stations used in this analysis, and the results were visualized using maps to show the correlation fields.

3 Results

The influence of the NAO on the surface air temperature variability in Poland is significant in the winter and very weak in the summer. The Pearson's correlation coefficient between the monthly air temperature anomalies and the CPC monthly NAO index is statistically significant in each winter month over the entire country, except over southeastern Poland in February. The relationships are stronger in the western and northern areas, where the correlation coefficients (r) exceed 0.65 in December, 0.70 in January and 0.55 in March (for $n = 50$ $r > 0.354$ is statistically significant at $p = 0.05$). The influence of the macroscale circulation on the air temperature weakens considerably in the transitional seasons, and in the summer, the correlation coefficient is close to 0.0, being positive in most of the country (but hardly exceeding 0.15) and negative in the southeast (Fig. 2). Even worse results were obtained at the daily time scale as the correlation coefficient computed between daily air temperature anomalies and NAO index for summer months hardly exceeded $|0.1|$. Alternatively, two other SLP-based NAO indices were used to evaluate the influence of the oscillation on the surface air temperature variability in Poland. Both Hurrell's (NCAR 2017) and Li and Wang's (2003) indices are weakly correlated with monthly temperature anomalies and r does not exceed $|0.15|$ in the majority of stations taken to the analysis.

The thermodynamic state of the atmosphere at any point is determined by the values of pressure, temperature, and density (or specific volume) at that point and it is described by the equation of state for an ideal gas (Holton 2004). To establish the simple linear statistical relationships in the dynamic atmosphere between the distant variables such as surface air temperature variabilities in Poland and the pressure fields, the correlation coefficients between the daily anomalies of T_{mean}, T_{max} and T_{min} (averaged for 44 stations taken to the analysis) and the fields of SLP and z500 were computed and mapped (Fig. 3). The strongest correlations occurred at z500 over Poland where the correlation of T_{mean} and T_{max} exceeded 0.65. The correlation fields limit the areas of statistically significant positive values to the region between the geographical coordinates of 5° to 35° E and 40° to 65° N. Weaker relationships were found at ground level, where the correlation amounted to 0.4 and the centre of the positive values was located east to the centre of positive values at the z500 level. The anomalies of the daily T_{min} values are less dependent on the pressure fields than the mean and maximum values, which suggests that the daily minimum temperature is more associated with local factors than with the regional circulation patterns. Having established that the surface air temperature variability is more associated with the middle- than low-tropospheric pressure field, the correlation between the surface temperature anomalies in the vertical profile for the entire troposphere along the 52.5° N parallel was computed

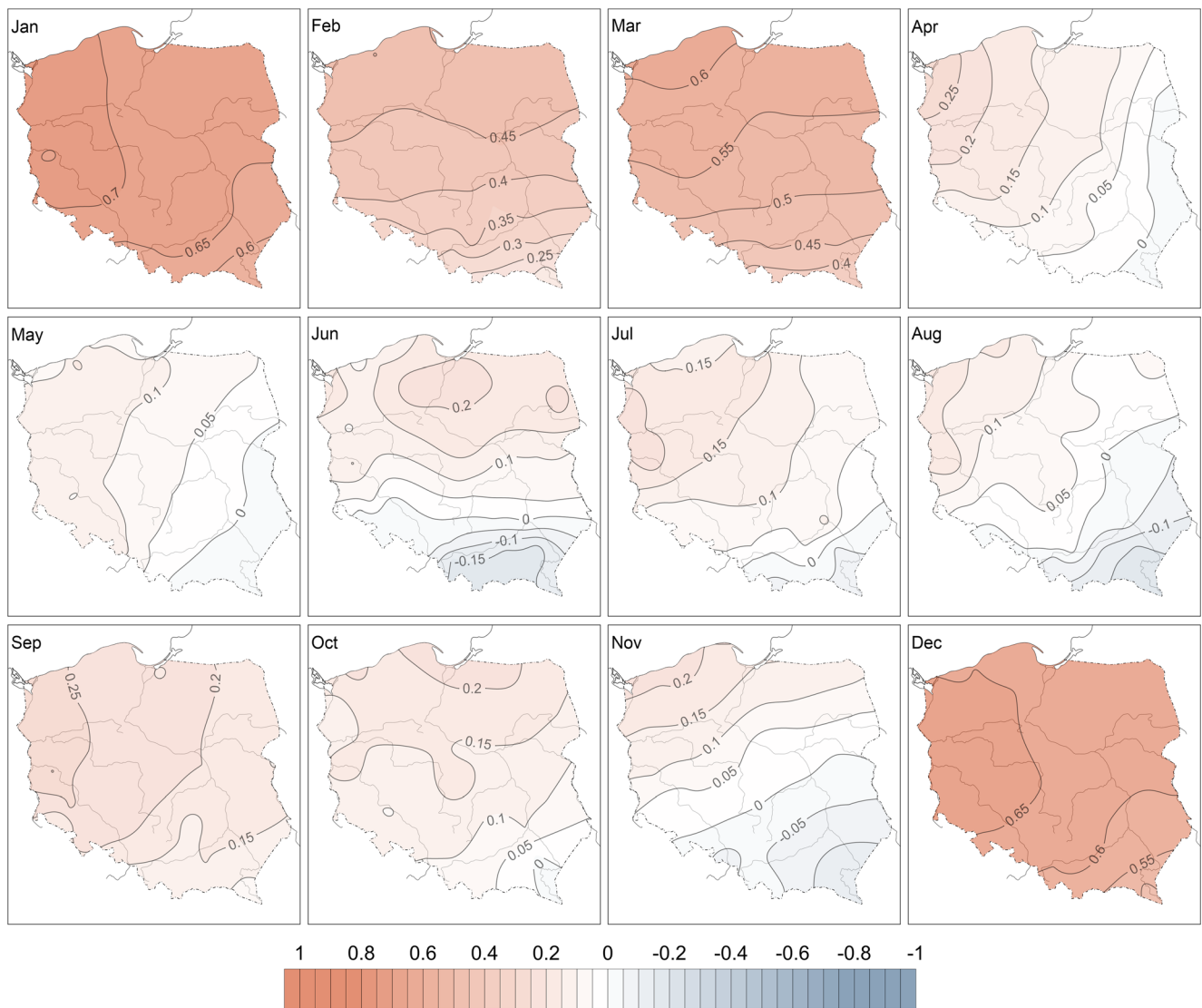


Fig. 2 Correlation between the monthly air temperature anomalies and the monthly NAO index

(Fig. 4). Significant relationships, i.e., those exceeding 0.75 in the cases of Tmax and Tmean, were found in the layer between the 700 and 200 hPa geopotential heights. For Tmean, the highest correlation (> 0.60) appeared at the 500–200 hPa geopotential level. The hydrostatic balance in a static atmosphere explains the described vertical structure of correlation coefficient obtained in the statistical approach. During positive surface air temperature events, in the warm and thin air column, the geopotential levels are shifted upwards, while in the cold air, adiabatic processes cause subsidence of air masses and lowering the geopotential levels. Atmospheric processes in the middle troposphere influence surface weather conditions; anomalies of geopotential heights are regarded as predictors of air temperature extremes occurrence (Qian et al. 2015, 2016; Chen et al. 2017).

The results of correlation analysis described above allowed the establishment of the geopotential level and the spatial

range within which the circulation types influencing the air temperature are to be determined. The PCA was applied to the standardized z500 mean daily data matrix, which covered the area of the highest positive correlations between the daily air temperature anomalies and z500, namely, the region between 5° and 45° E by 35° and 70° N (Fig. 3). The number of principal components (PCs), i.e., the circulation patterns, to further analysis was established by considering the total amount of variability represented by the first n PCs (Jolliffe 2002; Wilks 2011). The percentage of the total variance of the z500 height represented by each PC is given in Table 1 and the loading patterns of the first six PCs with a total variance exceeding 80% are displayed in Fig. 5. The plotted values at each grid point represent the temporal correlations between the daily standardized z500 at that point and the PC daily index time series. Positive correlation mean higher-than-normal geopotential height in the positive phase of each PC

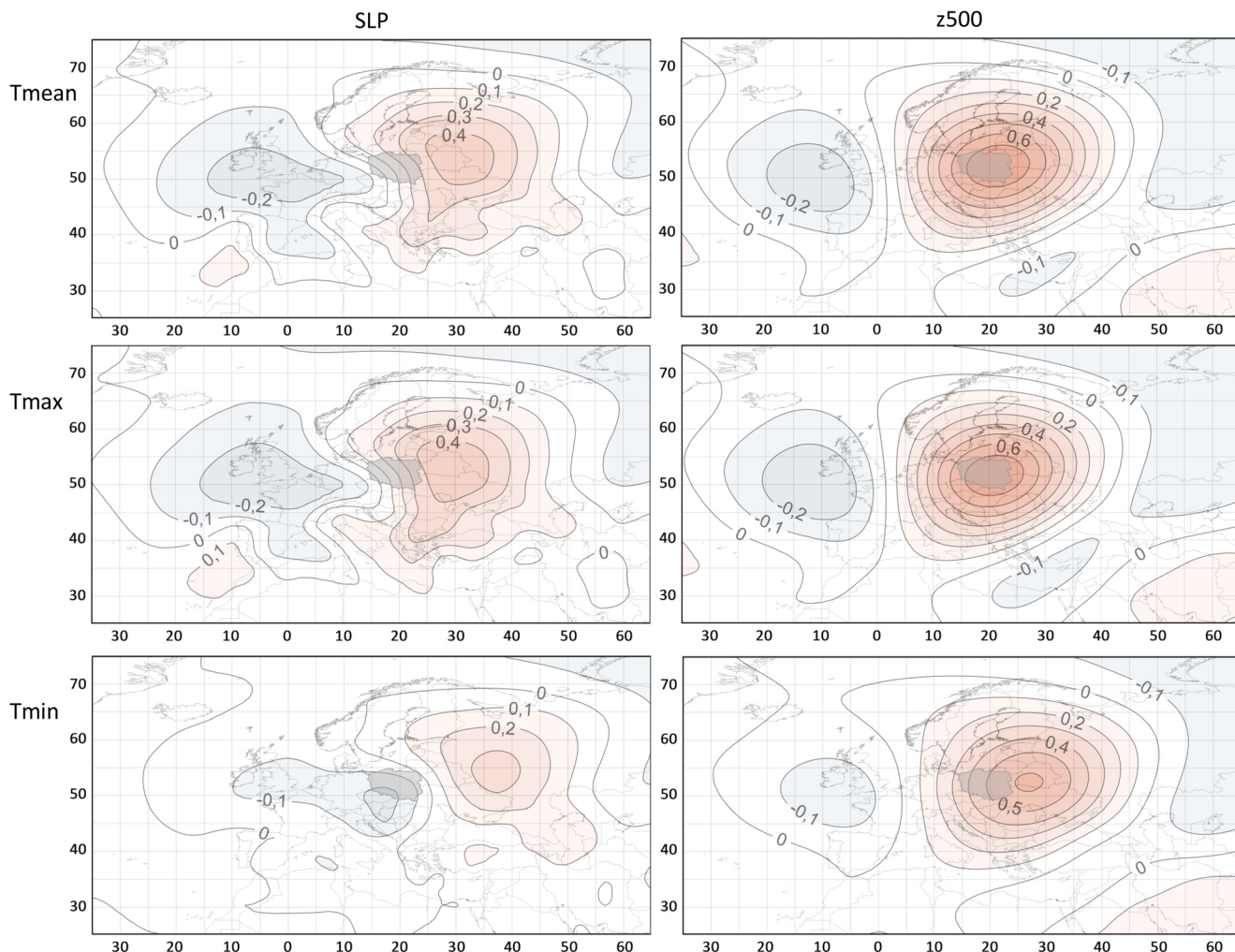


Fig. 3 Correlation between the daily air temperature anomalies (Tmean, Tmax, Tmin) in Poland and the mean daily pressure fields at sea level (SLP, left) and those at a 500-hPa geopotential height (z500, right) in summer (JJA)

(daily indices > 0). The first PC explains 20.6% of the total variability of the z500 within the studied area and reveals a two-dipole pattern. In the positive phase, the centre of lower-than-normal z500 is located over southern Scandinavia and the centre of higher-than-normal z500 is located over eastern

Ukraine. Such a pattern induces western and southwestern inflows of air masses over Poland. The PC2 is almost equally as important as PC1 (20.0% of the total variance). It is characterized by anticyclonic conditions over central Europe in its positive phase. The loading pattern of the PC2 positive phase

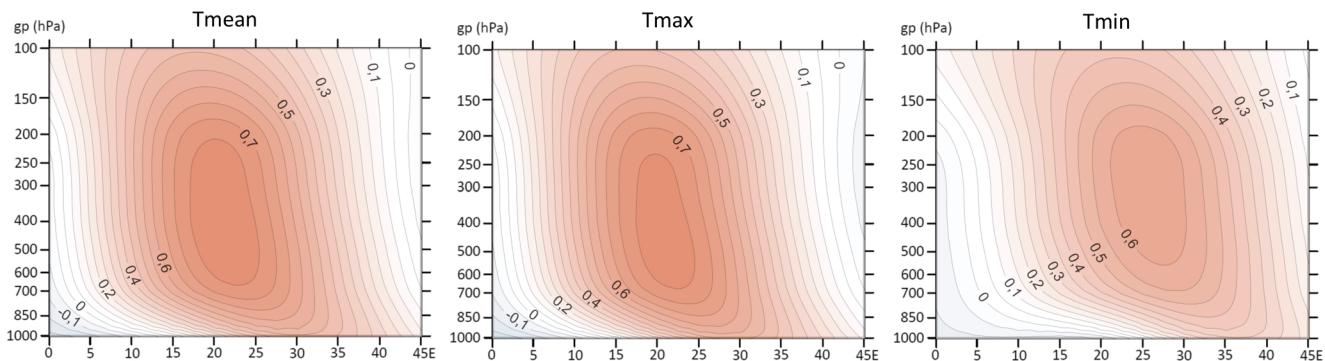


Fig. 4 Correlation coefficients of the daily air temperature anomalies (Tmean, Tmax, Tmin) in summer (JJA) and mean daily geopotential heights along the 52.5° N parallel

Table 1 Results of the principal component analysis, including the percentages of the total variance of the z500 field over Europe represented by the first 12 principal components (PCs)

| | Percentage of total variance | Cumulative percentage of total variance |
|------|------------------------------|---|
| PC1 | 20.61 | 20.61 |
| PC2 | 20.03 | 40.64 |
| PC3 | 17.23 | 57.87 |
| PC4 | 12.10 | 69.97 |
| PC5 | 7.82 | 77.80 |
| PC6 | 4.58 | 82.38 |
| PC7 | 3.77 | 86.15 |
| PC8 | 3.02 | 89.17 |
| PC9 | 1.70 | 90.87 |
| PC10 | 1.55 | 92.42 |
| PC11 | 1.49 | 93.91 |
| PC12 | 1.21 | 95.13 |

shows the area of the shifted z500 (positive correlation coefficient), with a centre right over Poland. The PC3, which explains 17.2% of the total variance, is a double-dipole pattern oriented southwest-northeast. In its positive phase, it triggers southeastern air circulation over Poland. The loading pattern of the next regional circulation model (PC4, 12.1%) shows the four-centre system, with Poland located in the saddle among them. Each of latter circulation patterns show less than 10% of the total variance (Table 1, Fig. 5).

The next step was to recognize the influence of the determined circulation patterns on the daily anomalies of air temperature. To this end, a linear multiple regression was applied to reconstruct the Tmean, Tmax and Tmin daily anomalies for each of the 44 stations. The regression coefficients were estimated by the means of the first 12 PCs (with individual variances higher than 1% and with a total amount of variability exceeding 95%) separately for each of the analysed stations. The best results were obtained for the daily anomalies of the Tmean, for which the Pearson correlation coefficient (r) between the modelled and observed values exceeded 0.75 in the vast area of central and southeastern Poland, while over the rest of the country, it amounted to 0.7 (Fig. 6). A weaker influence of the circulation on the air temperature is observed in the northwestern part of the country along the Baltic Sea ($r < 0.65$). The spatial pattern of the Pearson correlation coefficient computed for Tmax is similar to that for Tmean with slightly lower values of r over central Poland. The weakest correlation was obtained for the daily anomalies of Tmin, for which the r was equal to 0.5–0.6 over most of the country, dropping below 0.4 in the northwest (along the sea shore); values higher than 0.6 appear only in the west (the middle Odra river valley). The weakest correlation computed for the Tmin indicates that the daily minimum temperatures were less

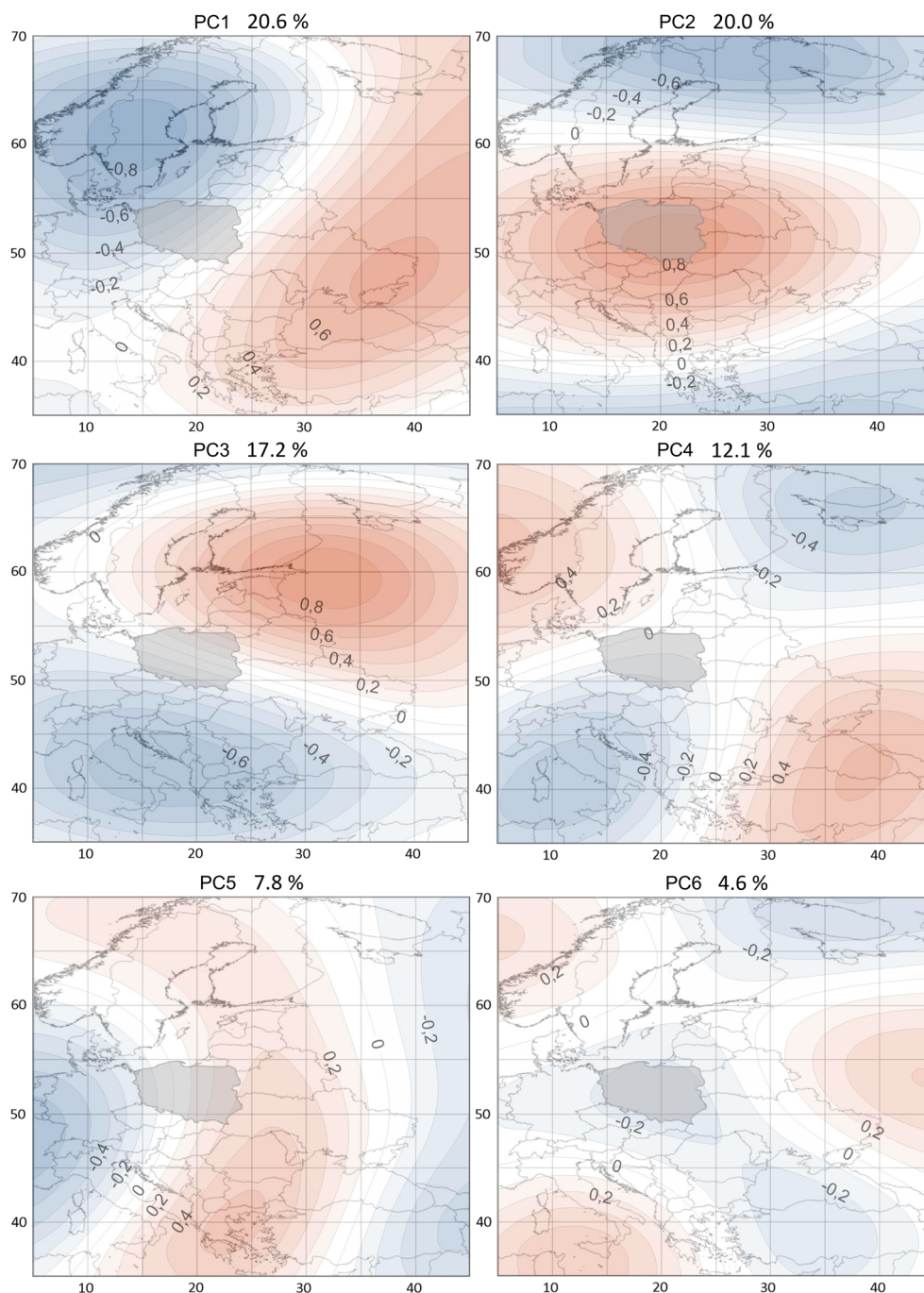
dependent on the circulation patterns and on the direction of air inflows and were probably more associated with local factors. The distribution of the differences between the modelled and observed values of the Tmean, Tmax and Tmin daily anomalies in Fig. 7 show the best fits of the models for Tmean and the worst fits for Tmax. The root mean square error is lowest for Tmean (2.0–2.2 °C for most of the stations) and is highest for Tmax (2.7–2.9 °C for most of the stations).

The next step was to determine how each particular circulation pattern influences the daily anomalies of the air surface temperatures. To this end, the correlation coefficients (r) between the time series of each of the PC daily indices and daily anomalies of Tmean, Tmax and Tmin were computed and plotted (Figs. 8, 9 and 10). For $n = 4600$ (number of daily pairs of values taken to the analysis) very low values of $|r|$ (> 0.04) are statistically significant ($p = 0.05$), however, from climatological point of view the absolute value of correlation coefficient is higher than approximately 0.3 is relevant. The PC1 reveals the negative relationship over the entirety of Poland, with maximum r values exceeding 0.4 in the northwest (Tmean and Tmax, Figs. 8 and 9). This means that, in the positive phase of PC1, the weather in Poland is governed by cyclones located over southern Scandinavia, which bring the maritime Atlantic air masses to central Europe (see Fig. 5 for each PC pattern). The relationship weakens to the southeast, where the influence of over the mentioned cyclones weakens substantially. The opposite conditions are present in the negative phase of PC1, with higher-than-normal pressures over southern Scandinavia and Baltic Sea basin, including northwestern Poland, triggering increases in the air temperatures.

The strongest positive relationship with the air temperature as expressed by a high correlation coefficient (exceeding 0.55) was revealed to be that of PC2. The high-pressure conditions with the anticyclonic centre located over central and southeastern Poland cause positive anomalies of the daily Tmean and Tmax ($r > 0.4$ over most of the country, apart from the northernmost regions). The negative phase of PC2, showing a local low-pressure system over Poland, implies a lowering of the daily mean and extreme air temperatures (Figs. 8, 9 and 10).

The PC3 pattern that characterizes the anticyclonic conditions in the northeast of Poland in its positive phase is positively correlated with the anomalies of Tmean, Tmax and Tmin, but the relationship is strongest only in northeastern Poland, where the southeastern circulation and the anticyclonic conditions in the positive phase of PC3 cause substantial warming, while a cyclone located northeast of Poland in the negative PC3 phase causes substantial cooling (Figs. 8, 9 and 10). The positive phase of the PC5 pattern shows a meridional ridge of higher-than-normal pressures across Europe, encompassing eastern Poland. The PC5 gives a strong signal only in southeastern Poland and is induced by a southern/northern airflow and anticyclonic/cyclonic conditions in its positive/negative phase. Other regional circulation patterns

Fig. 5 Loading patterns of the first six PCs based on standardized daily z500 for Jun–Aug (correlation between the particular PC's index daily time series and the time series of standardized z500 for each grid point)



reveal weaker influences on the daily anomalies of the air surface temperatures (i.e. PC4 and PC6, as shown in Fig. 8).

Finally, the summer indices of each PC were computed in order to recognize the multiannual variability and trends in the intensities of the distinguished regional circulation patterns. Summer indices for every year were computed averages of daily indices in June, July, August, for each PC separately. Only the PC1 pattern revealed a statistically significant ($R^2 > 0.075$ at $p = 0.05$) positive multiannual trend of change (Fig. 11). A positive but not significant trend was recognized

for PC2; the other PCs did not reveal any particular directions of change. In Fig. 11, the 50-year course of the mean summer indices of the two main PCs and the mean summer (JJA) anomalies of the air temperatures in Poland averaged from 44 stations are shown. Extremely warm summers with air temperature anomalies exceeding $1.5\text{ }^{\circ}\text{C}$, such as those 1992, 2002, 2006, 2010 and 2015, were always associated with positive indices of PC2 and negative (or positive but close to 0) indices of PC1. Similar conditions characterized the relatively warm summers of 1982, 1983, 1975 and 1972.

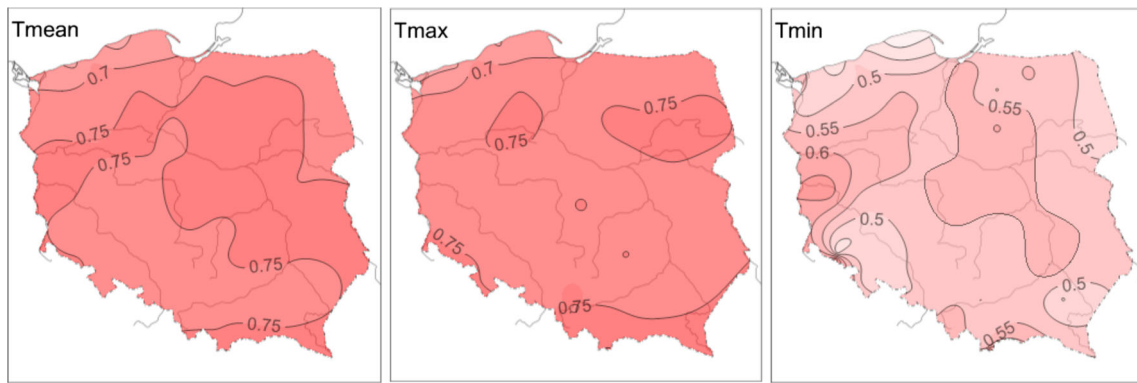


Fig. 6 Correlation between the values of the regression model and the observations for Tmean, T max and Tmin computed for the period Jun–Aug, years 1966–2015

However, relatively cool summers (i.e., 1978, 1980, 1984, 1993) were characterized by prevailing negative PC2 and in most cases, with positive PC1.

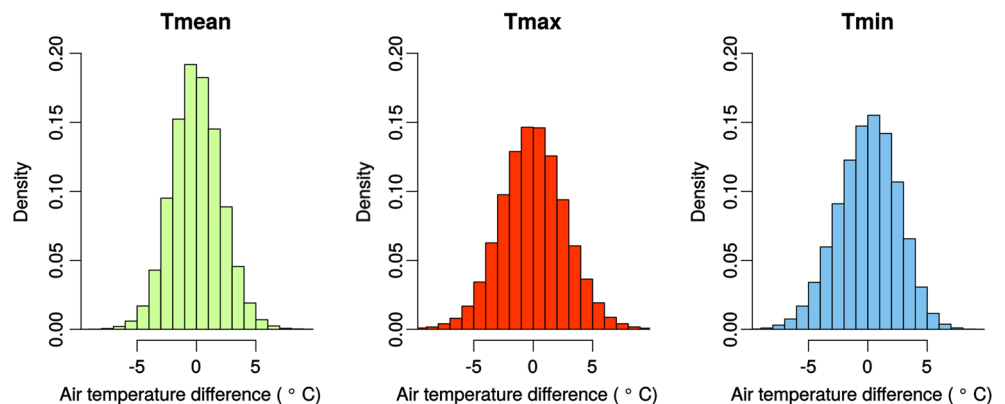
4 Summary, discussion and conclusions

Folland et al. (2009) have postulated that the summer NAO circulation pattern explains the principal variations of the summer climate over some regions of Europe, including the mean temperatures, precipitation, and cloudiness. The positive phase of the summer NAO is associated with warm, dry, and relatively cloud-free conditions over northwest Europe, especially over the United Kingdom and much of Scandinavia, and with the cooler, wetter, and cloudier conditions over southern Europe and the Mediterranean (Folland et al. 2009; Favà et al. 2016). Also in central Europe, some signals of the influence of the NAO on the monthly means of the daily maximum, minimum, and mean surface temperatures in the summer seasons were identified by Pokorná and Huth (2015). These findings were not confirmed in this study as a significant influence of the NAO on the summer surface air temperatures in Poland was not detected, either on a monthly or daily time scale. Having in mind that European climate impacts of the NAO

might be sensitive to how the NAO is defined (Pokorná and Huth 2015), two other than CPC-NAO indices were applied in this study. However, any of them did not reveal significant correlation with summer air temperatures in Poland. Similar results were obtained by Wibig and Głowicki (2002), who proved that the mean monthly minimum and maximum temperatures in Poland are significantly correlated with the NAO index in all seasons but not in the summer. In this case, it was assumed in the preliminary stage of the research that other than the NAO circulation types, presumably those on smaller spatial scales, must govern the variability of the summer surface temperature in Poland.

Beck et al. (2013) acknowledged that the size of the domain in the classification of the circulation types has a strong effect when studying the relationships between circulation and surface climates in moderate climate zones. They postulated that, in general, the best results can be achieved for domain sizes with horizontal dimensions of approximately 1300–1800 km (in west–east direction), thus most frequently covering size ranges of synoptic scale systems. However, the optimal domain sizes tend to be smaller for the summer (as compared to winter) and for continental regions (compared to oceanic regions) (Beck et al. 2015). This is partly explainable by the dimension of extratropical cyclones (the modal values of effective summer cyclone radius 200–800 km, Rudeva and

Fig. 7 Differences between the modelled and observed values of the Tmean, T max and Tmin daily anomalies computed for the period Jun–Aug, years 1966–2015



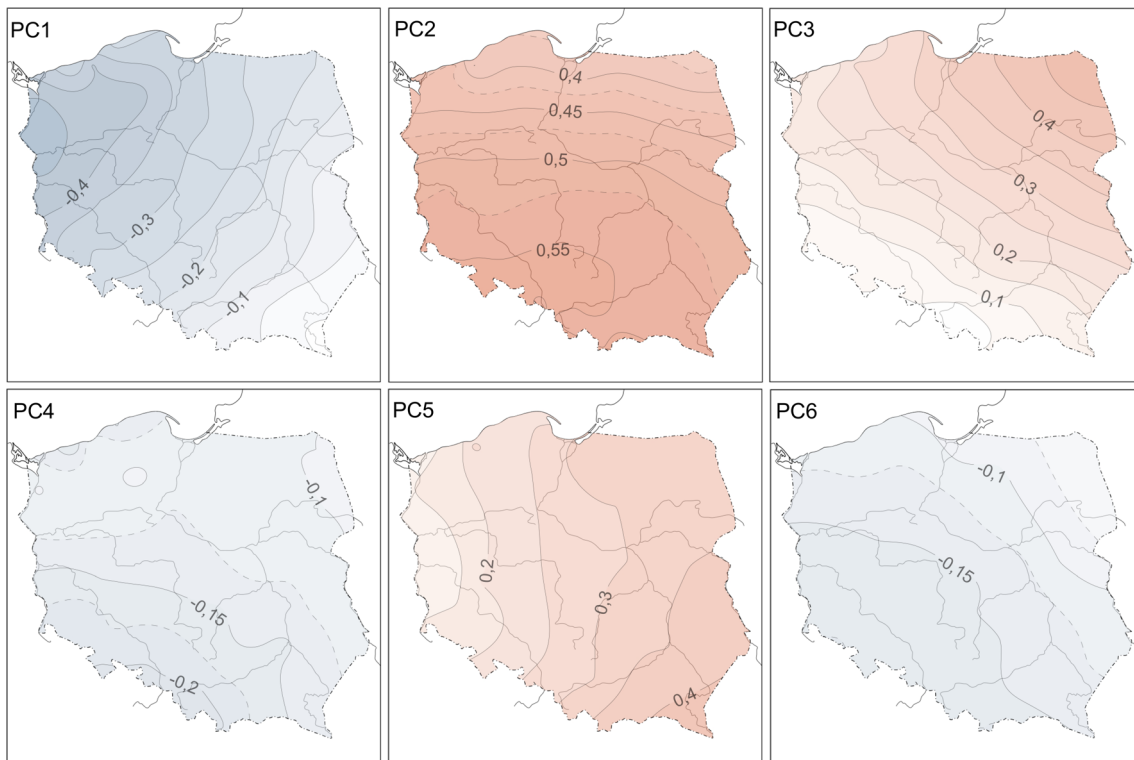


Fig. 8 Correlation between the first six PC daily indices and the daily anomalies of Tmean in summer (JJA)

Fig. 9 Correlation between the selected PC daily indices and the daily anomalies of Tmax in summer (JJA)

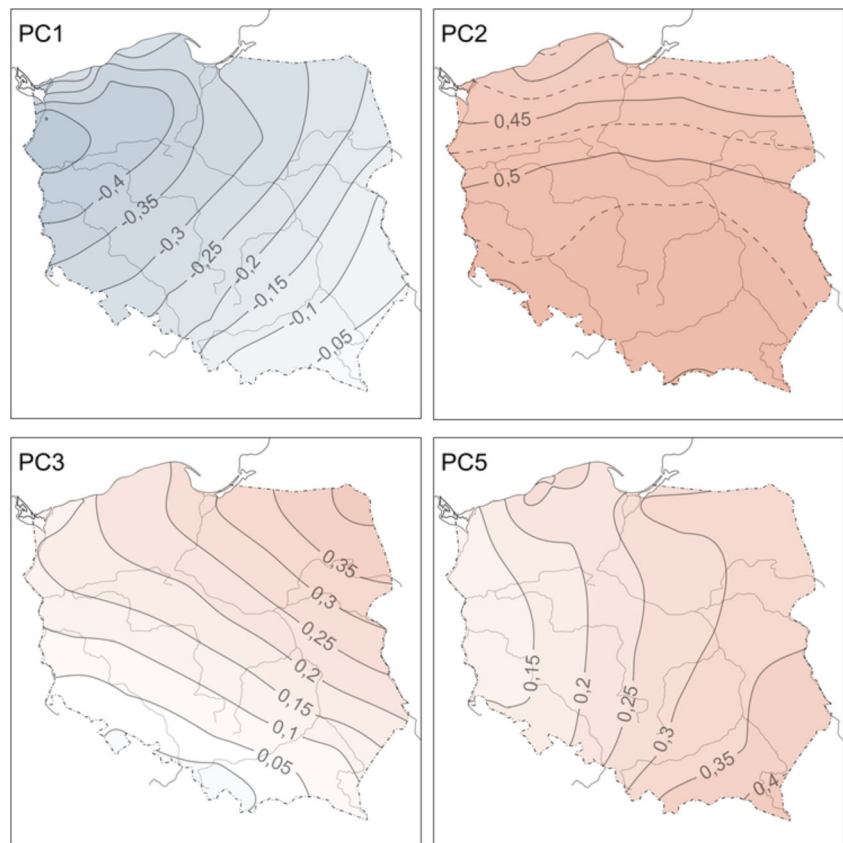
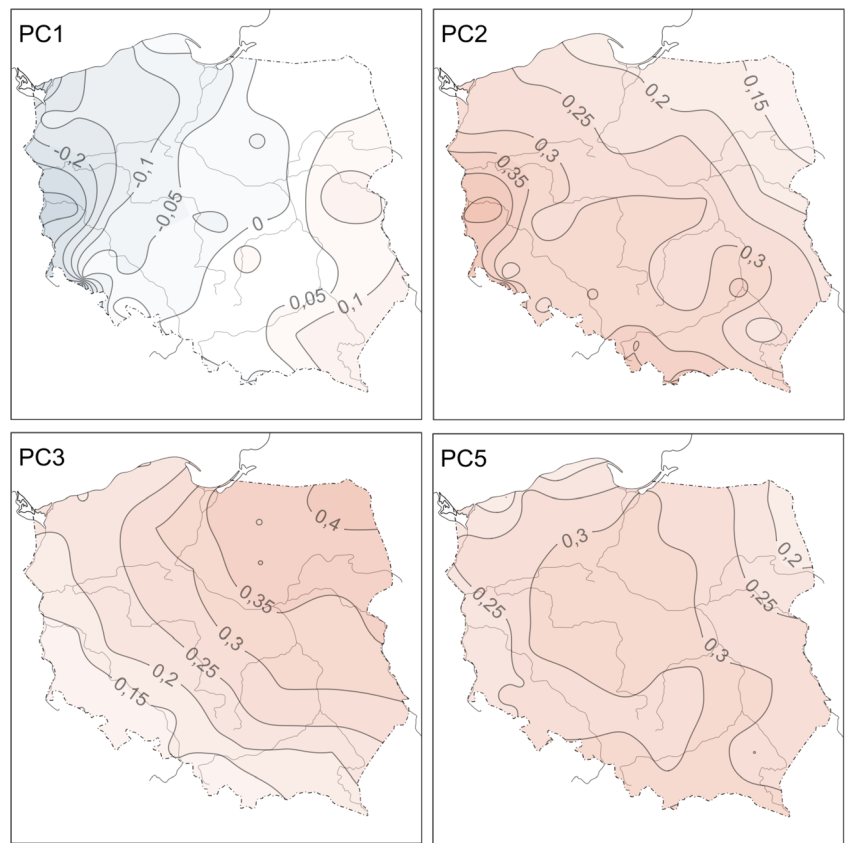


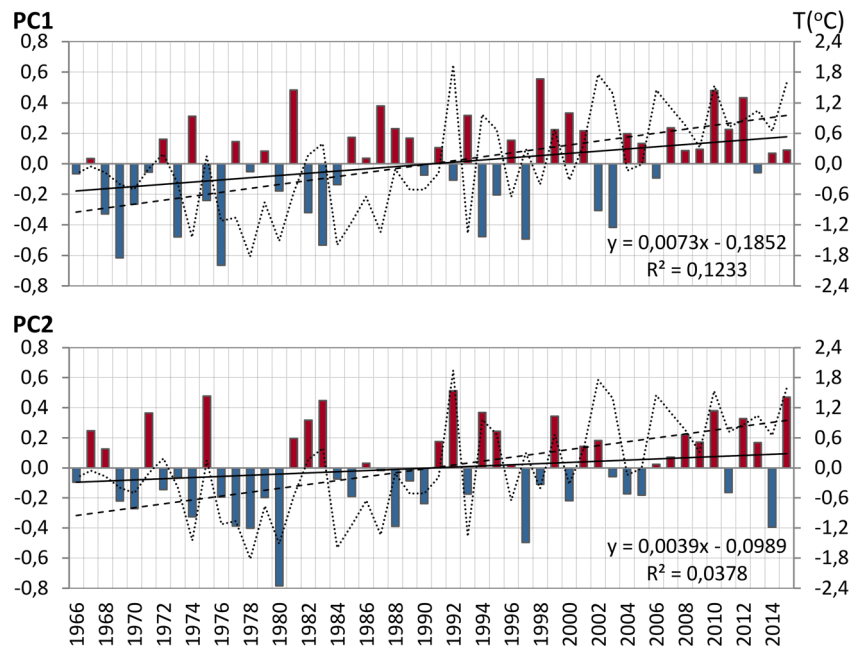
Fig. 10 Correlation between the selected PC daily indices and the daily anomalies of Tmin in summer (JJA)



Gulev 2007), which are highly relevant for surface climate characteristics. In this study, on the basis of the correlation analysis performed at the beginning, the spatial range of the domain for the circulation type classification was established as 40° zonally and 35° meridionally, which presents a

horizontal dimension of approximately 2000 km along 52.5° N. The preliminary analysis also indicated that the middle tropospheric levels are the most highly correlated with surface temperature, which allows the establishment of the z500 level as being appropriate for the purpose of this study.

Fig. 11 Variabilities and trends (with equations and coefficients of determination) of the mean summer (JJA) index of the selected PCs (colour bars, solid line) and the mean summer anomalies of air temperature in Poland (dashed lines)



According to regression models, the established regional circulation patterns explain the variability of daily surface temperature anomalies over Poland in approximately 54% (r equals to 0.73) of the cases of T_{\max} and T_{mean} and in approximately 30% ($r \approx 0.53$) of the cases for T_{\min} . The much weaker relationship between the circulation patterns and minimum temperatures than those for the mean and maximum temperatures in the summer were also obtained by other studies (i.e. Pokorná and Huth 2015; Beck et al. 2015). This indicates that the lowest daily temperatures in the summer seasons are less dependent on circulation patterns and on the direction of air inflows and are probably more associated with local factors and radiative conditions. Miętus et al. (2012) constructed similar regression models for the regional circulations and mean monthly temperatures of 54 Polish stations and have obtained good results for the winter and autumn but much weaker ones for the summer and spring ($r \approx 0.5$).

In general, the results obtained in this study have proved that the regional atmospheric circulation has a strong impact on the surface air temperature in the summer and is therefore a very good potential predictor for the modelling of the thermal conditions on a daily time scale. The weakest relationship between circulation and surface air temperatures was detected in northwestern Poland along the coast of the Baltic Sea ($r < 0.7$ for T_{mean} and T_{\max} , $r < 0.5$ for T_{\min} , statistically significant at $p = 0.05$), where the sea thermal conditions strongly modify the local air circulation and the daily variabilities of the air temperatures.

Numerous studies have recognized anticyclonic circulation patterns as favourable for extreme temperature conditions namely, the heat waves in Europe (e.g. Kyselý 2002, 2007, 2008; Porębska and Zdunek 2013; Tomczyk and Bednorz 2016), which corresponds to the findings of this study. The circulation pattern recognized as PC2, which is distinguished in its positive phase by the high-pressure conditions with an anticyclonic centre located over central and southeastern Poland (Fig. 5), revealed the strongest positive relationship with air temperature variability. Also, PC1 in its negative phase, which is characterized by anticyclonic conditions over southern Scandinavia, increases the air temperature in northwestern Poland. The positive phase of PC3, with a high-pressure system located east of the Baltic Sea, increases the air temperature in northeastern Poland. Despite our expectations, the anticyclonic PC2 pattern did not show a significant positive trend. This would explain the increasing summer air temperatures in Poland and increasing frequencies of heat waves in central Europe. Instead, the only pattern that reveals a significant trend (i.e. increasing the mean summer index) is PC1, which is negatively correlated with the air temperature. This leads to conclusion that the air circulation conditions suppress the summer warming trend in Poland by more frequent occurrences of cyclones over southern Scandinavia and the Baltic Sea, which is indicated by the positive trend of the PC1 index.

Acknowledgements This work was partly supported by the Polish National Science Foundation (grant numbers 2016/21/B/ST10/01440 and 2014/15/N/ST10/00717).

Authors would like to thank the Polish Institute of Meteorology and Water Management for supporting the station data used in this study.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Barnston A, Livezey R (1987) Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon Weather Rev* 115:1083–1126
- Beck C, Jacobeit J, Jones P (2007) Frequency and within-type variations of large-scale circulation types and their effects on low-frequency climate variability in Central Europe since 1780. *Int J Climatol* 27: 473–491
- Beck C, Philipp A, Streicher F (2013) The effect of domain size on the relationship between circulation type classifications and surface climate. *Int J Climatol* 36:2692–2709
- Beck C, Philipp A, Jacobeit J (2015) Interannual drought index variations in Central Europe related to the large-scale atmospheric circulation—application and evaluation of statistical downscaling approaches based on circulation type classifications. *Theor Appl Climatol* 121:713–732
- Bednorz E (2011) Occurrence of winter air temperature extremes in Central Spitsbergen. *Theor Appl Climatol* 106(3–4):547–556
- Beranová R, Huth R (2007) Time variations of the relationships between the North Atlantic oscillation and European winter temperature and precipitation. *Stud Geophys Geod* 51(4):575–590
- Beranová R, Huth R (2008) Time variations of the effects of circulation variability modes on European temperature and precipitation in winter. *Int J Climatol* 28(2):139–158
- Cattell RB (1978) The scientific use of factor analysis in behavioral and life sciences. Plenum Press, New York
- Chen Y, Hu Q, Yang Y, Qian W (2017) Anomaly based analysis of extreme heat waves in eastern China during 1981–2013. *Int J Climatol* 37:509–523
- Esteban P, Jones P, Martín-Vide J, Mases M (2005) Atmospheric circulation patterns related to heavy snowfall days in Andorra, Pyrenees. *Int J Climatol* 25(3):319–329
- Favà V, Curto J, Llasat M (2016) Regional differential behaviour of maximum temperatures in the Iberian Peninsula regarding the Summer NAO in the second half of the twentieth century. *Atmos Res* 182:319–334
- Fleig A, Tallaksen L, Hisdal H, Stahl K, Hannah D (2010) Inter-comparison of weather and circulation type classifications for hydrological drought development. *Phys Chem Earth Parts A/B/C* 35(9–12):507–515
- Folland C, Knight J, Linderholm H, Fereday D, Ineson S, Hurrell J (2009) The Summer North Atlantic oscillation: past, present, and future. *J Climate* 22(5):1082–1103
- Hess P, Brezowsky H (1952) Katalog der Grosswetterlagen Europas. *Berichte des Deutschen Wetterdienstes in d. US-Zone*
- Holton JR (2004) An introduction to dynamic meteorology, Fourth edn. Elsevier Academic Press
- Hurrell JW, Kushnir Y, Ottensen G, Visbeck M. (Eds.) (2003) The North Atlantic Oscillation. *Climatic Significance and Environmental*

- Impact. American Geophysical Union Geophysical Monograph 134: Washington, DC
- Huth R (1993) An example of using obliquely rotated principal components to detect circulation types over Europe. *Meteorol Z* 2:285–293
- Huth R (1996) Properties of the circulation classification scheme based on the rotated principal component analysis. *Meteorol Atmos Phys* 59(3–4):217–233
- Huth R, Beck C, Philipp A, Demuzere M, Ustrnul Z, Cahynova M, Kyselý J, Tveito OE (2008) Classifications of atmospheric circulation patterns: recent advances and applications. *Ann N Y Acad Sci* 1146(Trends and Directions in Climate Research):105–152
- Huth R (2010) Classifications of atmospheric circulation patterns. Elsevier: Amsterdam [u.a.]
- Jolliffe IT (1987) Rotation of principal components: some comments. *J Climatol* 7:507–510
- Jolliffe IT (2002) Principal component analysis, second edition. Springer
- Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds R, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo K, Ropelewski C, Wang J, Jenne R, Joseph D (1996) The NCEP/NCAR 40-year reanalysis project. *B Am Meteorol Soc* 77(3):437–471
- Katsafados P, Papadopoulos A, Varlas G, Papadopoulou E, Mavromatidis E (2014) Seasonal predictability of the 2010 Russian heat wave. *Nat Hazard Earth Sys* 14(6):1531–1542
- Kyselý J (2002) Temporal fluctuations in heat waves at Prague-Klementinum, the Czech Republic, from 1901–97, and their relationships to atmospheric circulation. *Int J Climatol* 22(1):33–50
- Kyselý J (2007) Implications of enhanced persistence of atmospheric circulation for the occurrence and severity of temperature extremes. *Int J Climatol* 27(5):689–695
- Kyselý J (2008) Influence of the persistence of circulation patterns on warm and cold temperature anomalies in Europe: analysis over the 20th century. *Glob Planet Chang* 62(1–2):147–163
- Leckebusch G, Weimer A, Pinto J, Reyers M, Speth P (2008) Extreme wind storms over Europe in present and future climate: a cluster analysis approach. *Meteorol Z* 17(1):67–82
- Li JP, Wang JXL (2003) A new North Atlantic oscillation index and its variability. *Adv Atmos Sci* 20(5):661–676
- Miętus M, Biernacik D, Czernecki B, Filipiak J, Marosz M, Owczarek M, Pilarski M, Wójcik R (2012) Statystyczno-empiryczne projekcje wybranych elementów klimatu Polski na lata 2011–2030. (Statistical and empirical projections of selected climatic elements of the Polish climate for years 2011–2030.) In: (Eds. Wibig J, Jakusik E) Warunki klimatyczne i oceanograficzne w Polsce i na Bałtyku południowym. (Climatic and oceanographic conditions in Poland and southern Baltic.) Institute of Meteorology and Water Management: Warszawa (in Polish)
- NCAR (National Center for Atmospheric Research) Staff (Eds) (2015) The Climate Data Guide: Overview: Climate Indices. Retrieved from <https://climatedataguide.ucar.edu/climate-data/overview-climate-indices>
- NCAR (National Center for Atmospheric Research) Staff (Eds) (2017) The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (PC-based). Retrieved from <https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based>
- Philipp A (2009) Comparison of principal component and cluster analysis for classifying circulation pattern sequences for the European domain. *Theor Appl Climatol* 96(1–2):31–41
- Pokorná L, Huth R (2015) Climate impacts of the NAO are sensitive to how the NAO is defined. *Theor Appl Climatol* 119(3–4):639–652
- Porębska M, Zdunek M (2013) Analysis of extreme temperature events in Central Europe related to high pressure blocking situations in 2001–2011. *Meteorol Z* 22(5):533–540
- Portis DH, Walsh JE, El Hamly M, Lamb PJ (2001) Seasonality of the North Atlantic oscillation. *J Clim* 14:2069–2078
- Qian WH, Yu TT, Du J (2016) A unified approach to trace surface heat and cold events by using height anomaly. *Clim Dyn* 46(5):1647–1664
- Qian WH, Chen Y, Jiang M, Hu Q (2015) An anomaly-based method for identifying signals of spring and autumn low-temperature events in the Yangtze River valley. *China J Appl Meteorol Climatol* 54:1216–1233
- Richman MB (1986) Rotation of principal components. *J Climatol* 6:293–335
- Rencher AC (1995) Methods of multivariate analysis. Wiley, New York
- Rudeva I, Gulev S (2007) Climatology of cyclone size characteristics and their changes during the cyclone life cycle. *Mon Weather Rev* 135(7):2568–2587
- Scherrer S, Croci-Maspoli M, Schwierz C, Appenzeller C (2006) Two-dimensional indices of atmospheric blocking and their statistical relationship with winter climate patterns in the Euro-Atlantic region. *Int J Climatol* 26(2):233–249
- Shabbar A, Huang J, Higuchi K (2001) The relationship between the wintertime North Atlantic oscillation and blocking episodes in the North Atlantic. *Int J Climatol* 21(3):355–369
- Tomczyk A, Bednorz E (2016) Heat waves in Central Europe and their circulation conditions. *Int J Climatol* 36(2):770–782
- Tomczyk A, Półrolniczak M, Bednorz E (2017) Circulation conditions' effect on the occurrence of heat waves in western and southwestern Europe. *Atmosphere* 8(2):31
- Trigo R, Pozo-Vázquez D, Osborn T, Castro-Díez Y, Gámiz-Fortis S, Esteban-Parra M (2004) North Atlantic oscillation influence on precipitation, river flow and water resources in the Iberian peninsula. *Int J Climatol* 24(8):925–944
- Vicente-Serrano S, López-Moreno J (2006) The influence of atmospheric circulation at different spatial scales on winter drought variability through a semi-arid climatic gradient in Northeast Spain. *Int J Climatol* 26(11):1427–1453
- Yarnal B (1993) Synoptic climatology in environmental analysis. Belhaven Press, London
- Wibig J, Głowicki B (2002) Trends of minimum and maximum temperature in Poland. *Clim Res* 20:123–133
- Wilks D (2011) Statistical methods in the atmospheric sciences. Elsevier Academic Press, Amsterdam