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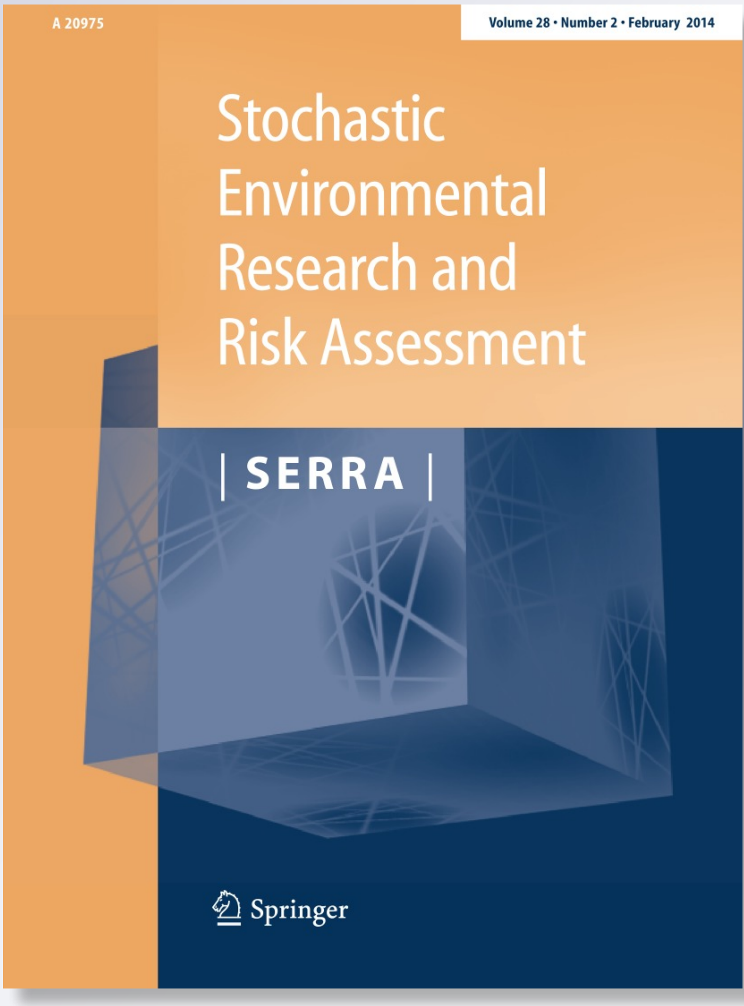

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ORIGINAL PAPER

Joint principal component: wavelet analysis of atmospheric teleconnection: the North Atlantic Oscillation case

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Abstract The impact of the North Atlantic Oscillation (NAO) on synoptic conditions in Ukraine can not be considered as fully defined as the territory of Ukraine is located at the transitional boundary of processes associated with the NAO. As a rule, common methods based on the principal component analysis (PCA) can not reveal the impact of the NAO. Moreover, the analysis of synoptic-scale processes based on the data with the one-day (or lesser) discreteness is affected by noise. In this paper, the wavelet analysis is used jointly with the PCA to determine time intervals when a linkage between the NAO and processes over Ukraine was significant. Such an approach allowed revealing the time intervals during the cold seasons, when simultaneous variations of synoptic conditions in North Atlantic and Eastern Europe occurred at quasi-synoptic time scales. Usually, that process is observed not very often, but simultaneous variations can be in progress during a few weeks. The coherent changes of synoptic conditions do not depend on the strength and phase of the NAO and can be both in-phase and anti-phase. The significant wavelet coherence is probably registered when two intensive synoptic processes different from general synoptic situation are observed.

Keywords Wavelet analysis · Principal component analysis · North Atlantic Oscillation · Synoptic conditions

1 Introduction

In very general view, the North Atlantic Oscillation (NAO) can be considered as the dominant type of winter climate variability in the North Atlantic/European sector from the central North America to the Europe and up to the North Asia. The positive phase of the NAO is described by the stronger subtropical high and the deeper Icelandic low; hereupon the horizontal baric gradient rises and deeper and severe storms move southerly by North Atlantic to the southern Scandinavia. Such a pattern causes warm and wet winter in the Europe. On the contrary, during the negative phases of the NAO the subtropical high is not thus much strong and the Icelandic low is not thus much deep; hereupon the number of cyclones diminishes, they are not much severe and move to the Southern Europe. These cyclones transport wet air to the Mediterranean and cold air to the Northern Europe (e.g. Hurrell and Deser 2009).

If the spatial structure of the NAO is analyzed, one more fact can be revealed (e.g. see review paper of Greatbatch 2000): the impact of the NAO on Ukraine can not be considered as fully defined because the territory of Ukraine is located at the transitional boundary of processes associated with the NAO. For example, in the positive phase of the NAO the cyclones move to the north of Ukraine and do not cause some changes in temperature and precipitation in Ukraine as it occurs in Western Europe. Therefore, the

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general explanation of atmospheric circulation in the North Atlantic/European sector is not enough to define the NAO impact on climatic and, especially, synoptic conditions in Ukraine. Then, there exists necessity to study this impact in detailed way. It must be noted that a few papers only investigate directly the impact NAO and its manifestation in the fields of meteorological variables over Ukraine—common practice is to study the NAO-related atmospheric processes for whole Europe.

Using the observations for 1958–1998, Pinto et al. (2009) analyzed the storm tracks for strong positive (NAO++, NAO index >1.5) and strong negative (NAO−−, NAO index <−1.5) phases of the NAO. They found out that the strong positive and negative phases were observed during 6.3 and 7.3 % days, and the percentages of storms were 8.7 and 4.1 % respectively. For the NAO++, the area with the storm tracks spreads from the east coast of North America to the Scandinavia; for the NAO−− the same area is bounded in the western part of the Atlantic. However in any case, the influence of NAO-related storms on Ukraine is inessential. The results of Pinto et al. (2009) display also that the storm tracks are far from Ukraine, and the storms reach the stage of maximal development over the Atlantic Ocean predominately. Syed et al. (2010) used model data, but their results are similar to the observational results of Pinto et al. (2009).

Another feature of NAO pattern is the correlation between negative phase of NAO and blocking (Stein 2000). However, the NAO causes about 20 % blockings at the East Atlantic and lesser 1 % only in Ukraine (Scherrer et al. 2006; Croci-Maspoli et al. 2007).

So, the variability of processes in North Atlantic atmosphere and ocean at various spatiotemporal scales has significant effect on climatic and synoptic conditions in Europe. One of primary factors of this variability is the NAO, which was studied in many scientific works. However, the NAO impact on variability of atmospheric processes in Ukraine was studied rather insufficiently; which is especially concerned the synoptic scale processes. The luck of knowledge can be conditioned by the following.

First, the NAO-induced changes of hydrometeorological parameters and weather phenomena in Ukraine appear to be not very considerable as its territory is remote relative to the centres of action related to the NAO; consequently the methods based on the correlation and principal component analyses (PCA) can not afford to reveal the impact of the NAO. Second, the analysis of synoptic-scale processes based on the data with the one-day (or lesser) discreteness is affected by noise in initial data.

Thus sufficiently large number of climate-oriented studies does not allow concluding the NAO impact on the synoptic-scale processes in Ukraine. In this connection, it seems to be tempting to develop a method allowing to describe a linkage between processes occurring in North Atlantic (the NAO specifically) and Ukraine from synoptic view. That is what this paper is aimed together with applying the methodology to specific synoptic conditions.

In our opinion, wavelet transform is the best method to make progress to the aim of the paper. Recently, wavelet transforms have become a common tool for analyzing local variations in geophysical time series (see e.g. Grinsted et al. 2004; Khokhlov et al. 2004; Zhang et al. 2010; Pellegrini et al. 2012; Ruiz-Medina and Frías 2012; Maheswaran and Khosa 2012, 2013; Heidary and Javaherian 2013). Wavelet transforms provide useful decompositions of original time series, so that wavelet-transformed data improves the ability of analyzing model by capturing useful information on various resolution levels. The continuous wavelet transform (CWT) is an effective tool for event finding and Morlet wavelet is the most used wavelet in practice, although the generalized Morse wavelets can be used as an alternative to the Morlet wavelet (Olhede and Walden 2002; Lilly and Olhede 2012).

2 Data and methodology

So, the location of Ukraine with respect of the NAO centres of action is such that the study of the NAO impact on variabilities of meteorological parameters in Ukraine by using ordinary methods can not rather reveal some significant influence. It is most probably related to the time-averaging procedure used in correlation and PCA. For example, consider the use of PCA to define the NAO. In this case, the data on geopotential heights in the uniform grid for sufficiently long time period, e.g. a few decades, are used. Then the loading of first principal component (PC) is analyzed to reveal extremes that are assigned with maximal variability of baric field during the time considered. However the NAO-related baric field variability occurs both in the time and in the space. For example, at the end of 20th century the centres of action tended shifting eastward. The same tendency is observed for baric field during single cold period, when the centres of action shift also eastward from the autumn to the spring (e.g. Khokhlov and Romanova 2011). But these changes in the location of centres have no reflection in the loading of 1st PC associated with the NAO pattern. Moreover, when daily data are considered it can be supposed that only certain synoptic processes over Ukraine are associated with variability of NAO-related circulation conditions over North Atlantic. Thus time-averaging procedure used for the correlation coefficient calculation can diminish substantially the impact but, at the same time, de-noise outcomes.

In our opinion, the PCA represents spatial features of variability well enough in the fields of meteorological parameters. However due to a nonstationarity of these fields, which is especially typical for synoptic-scale processes, the PCA can be at fault in the analysis of temporal variability. Therefore, the wavelet analysis (WA) is used jointly with the PCA in this paper to determine and to separate time intervals when a linkage between the NAO and processes over Ukraine was significant. However before stating the procedure for joint use of above methods, let us first consider the data used in this paper and then the PCA and WA one by one.

2.1 Characteristic of synoptic conditions

In spite of the fact that the daily NAO index, as an indicator of synoptic-scale variability in North Atlantic, can be used to investigate the impact of North Atlantic on synoptic conditions in Ukraine, in this paper we apply the Laplacian of sea level pressure (p)

$$\nabla^2 p = \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2}, \tag{2.1}$$

where x and y are the coordinates. It is clear that the Laplacian values can be calculated for any grid point; however, a grid point with maximal variability of baric field during the time period under consideration is reasonable choice. It is not advised also to average over very large areas, e.g. all over Ukraine, as the impact of North Atlantic on separate regions can be different (Loboda et al. 2006).

Note that the Laplacian of geopotential height is a geostrophic "analogue" for the vertical component of vorticity Ω_p. The vorticity greater than $\Omega_p = 1 \times 10^{-5}\ \mathrm{s}^{-1}$ are usually considered as a representative value for the presence of cyclone over the grid point under investigation (Hodges 1994), i.e. the time series of Laplacian values can therewith assist to analyze synoptic conditions over the region under study. However one must be keep in mind that single grid point is only considered not vast territory used to specify synoptic conditions. In other words, the time series of Laplacian values assists to specify some changes of certain synoptic object (or even its parts) over some site, i.e. changes of synoptic conditions over this site not the evolution of synoptic objects. Just in that meaning we use the term "synoptic conditions" throughout this paper.

2.2 Principal Component Analysis

The PCA is the widespread method for the multivariate statistical analysis of various meteorological parameters (e.g. von Storch and Zwiers 1999; Jolliffe 2002). Let us remind that this approach was just used to reveal teleconnection patterns in the whole and the NAO specifically. Moreover, the PCA is also used to determine temporal variability of teleconnection patterns, i.e. to calculate their indices (Wallace and Gutzler 1981; Barnston and Livezey 1987).

The idea of the PCA is as follows. One can have a data set of some meteorological parameter collected at some grid locations (or weather stations) over sufficiently long time period. That is, the data set is of the form $\mathbf{x}(t) = [x_1,\ldots,x_l]$, where each time series x_i ($i = 1,\ldots,l$) has N observations labelled by the index t. The PCA looks for u, a linear combination of the x_i, and an associated vector $\mathbf{a}$, with

$$u(t) = a \cdot x(t), \tag{2.2}$$

so that

$$\left\langle \|\mathbf{x}(t) - \mathbf{a}u(t)\|^2 \right\rangle$$

is minimised, where the angle brackets denote a time mean. Here u, the first PC is the time series, and $\mathbf{a}$, the first eigenvector (also called an EOF or loading), is the first eigenvector of the data covariance matrix and describes a spatially standing oscillation pattern. Together u and $\mathbf{a}$ make up the first PCA mode. From the residual, $\mathbf{x}(t) - \mathbf{a}u(t)$, the second can be similarly extracted and so on for the highest modes. In practice, the common algorithms for the PCA extract all modes simultaneously (Jolliffe 2002).

As an example, apply the PCA to the daily geopotential heights AT-500 hPa using the NCEP/NCAR reanalysis (Kalnay et al. 1996) from 1 December 2003 to 31 March 2004 in grid locations bounded by the 30W and 50E longitudinally as well as 30N and 80N latitudinally with the grid steps 2.5° in the both directions. It is easily computed that the $\mathbf{x}$ contains 663 × 122 values of geopotential heights AT-500 hPa, where 663 is the number of grid points and 122 is the number of days from 1 December 2003 to 31 March 2004. Table 1 shows the percentages of variance explained by the first six PCs of this field—the total variance for these PCs equals 78.11 %, and the first three PCs explains more than 50 %.

Figure 1 shows the spatial distribution of loadings of the first six PCs, and the isolines in these fields can be treated to a certain degree as peculiar "isohypses". Then, the areas with minimum in the centre can be associated with "cyclones", and with maximum—"anticyclones". The first eigenvector (Fig. 1a) defines the NAO but its centres shifted to the north-eastward from the usual location as the negative phase of the NAO was registered during the cold season of 2003–2004. Figure 1b displays the teleconnection pattern "East Atlantic/West Russia" reported by Barnston and

Table 1 Percentages of variance explained by principal components (PC) as a result of PCA from sequential daily 500 hPa geopotential heights in North Atlantic/European sector from 1 December 2003 to 31 March 2004

Principal component	PC1	PC2	PC3	PC4	PC5	PC6
Variance (%)	23.43	18.62	13.93	11.47	2.67	4.99

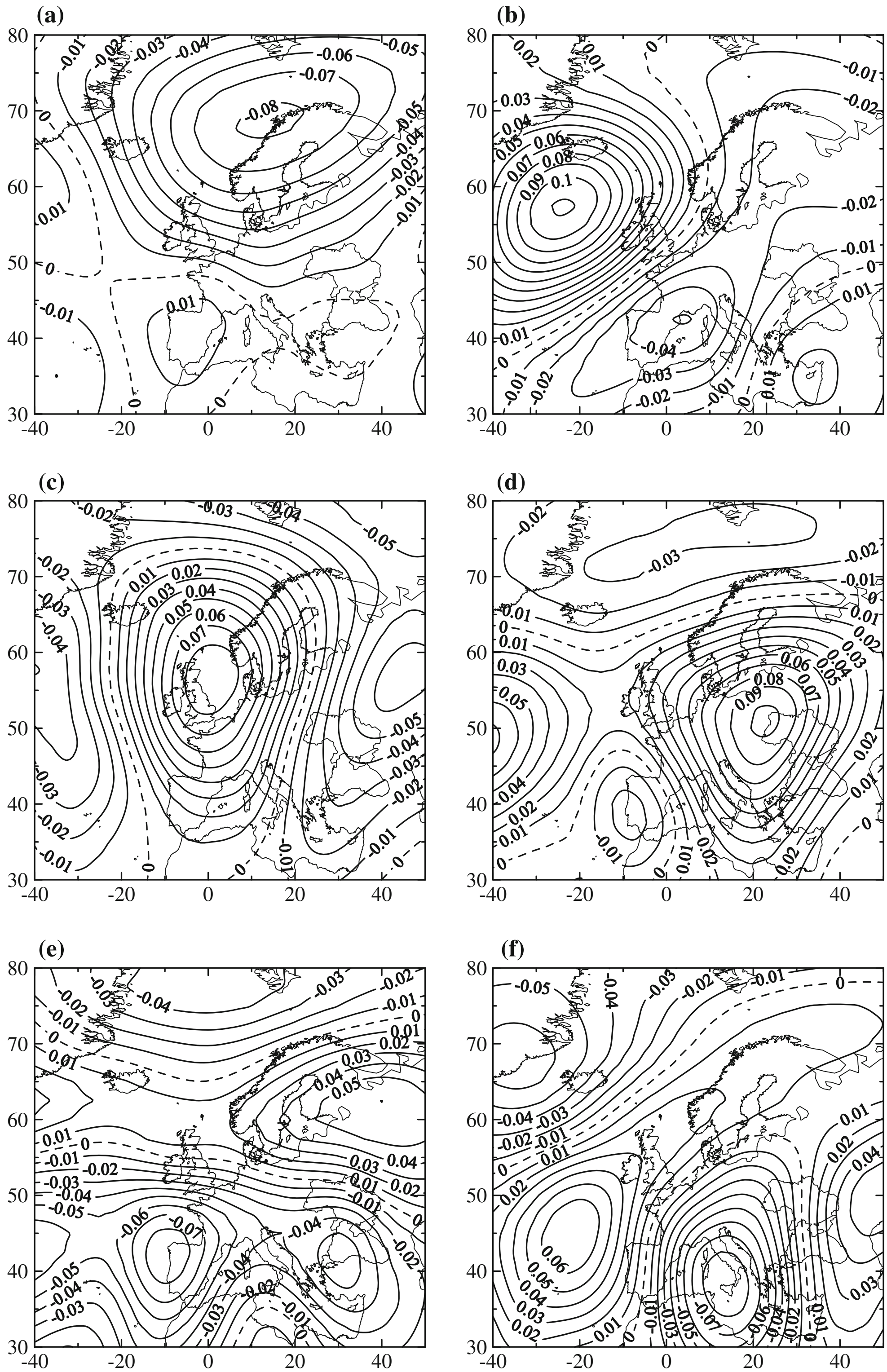

Fig. 1 Spatial distribution of loadings of first six principal components as a result of PCA from sequential daily 500 hPa geopotential heights during the DJFM of 2003–2004

Livezey (1987) as "Eurasia pattern type 2". The rest of plots in Fig. 1 are characterized by smaller-scale processes and can not be associated this certain teleconnection pattern described by Wallace and Gutzler (1981) or Barnston and Livezey (1987). It is usual case as these processes describe transient synoptic and/or lesser scale eddies.

Nevertheless Fig. 1 confirms the conclusion form Sect. 1 about a manifestation of NAO or North Atlantic processes generally in the change of atmospheric circulation pattern in Ukraine—the impact is insignificant. More or less considerable changes are registered in the loadings of third and fourth PCs, which explain about 14 and 11.5 % of variance only (Table 1), whereas the loadings of first and second PCs display insignificant variability of baric field in Ukraine and the synoptic conditions are here described by the "low-gradient baric field".

2.3 Wavelet analysis

Wavelets are fundamental building block functions, analogous to the trigonometric sine and cosine functions. Fourier transform extracts details from the signal frequency, but all information about the location of a particular frequency within the signal is lost. Wavelet transform expands time series into time–frequency space and can therefore find localized intermittent periodicities. Here, we give only brief details on the CWT; Torrence and Compo (1998) and Grinsted et al. (2004) have provided more detail survey.

Consider a time series, x_n, with equal time spacing δt and $n = 0 \ldots N - 1$, where N is the number of values in the time series. Apply a wavelet function, $\psi_0(\eta)$, as a band-pass filter to the time series. This wavelet function is stretched in time by varying its scale (s), so that $\eta = st$, and normalizing it to have unit energy. The CWT of x_n is defined as the convolution of x_n with a scaled and translated version of wavelet function:

$$W_n^X(s) = \sqrt{\frac{\delta t}{s}} \sum_{n'=0}^{N} x_{n'} \psi_0 \frac{(n' - n)\delta t}{s}. \tag{2.3}$$

The Morlet wavelet can be chosen as the wavelet function, since it provides a good balance between time and frequency localization (Grinsted et al. 2004). Because the Morlet wavelet is complex, the wavelet transform $W_n^X(s)$ is also complex. Then, the transform can be divided into the real part, $\Re\{W_n(s)\}$, and imaginary part, $\Im\{W_n(s)\}$, or amplitude, $|W_n(s)|$, and phase, $\tan^{-1}[\Im\{W_n(s)\}/\Re\{W_n(s)\}]$. Finally, we define the wavelet power spectrum as $|W_n(s)|^2$.

The cross-wavelet transform (XWT) of two time series x_n and y_n is defined as $W^{XY} = W^X W^{Y*}$, where the asterisk denotes complex conjugation. Then, the cross-wavelet power is defined as $|W^{XY}|$, and the complex argument $\arg(W^{XY})$ is the local relative phase between x_n and y_n in time–frequency space. Confidence levels for the cross-wavelet power can be also derived (Torrence and Compo 1998).

To illustrate the CWT, we apply this method to the daily NAO indices from 1 December 2003 to 31 March 2004 calculated by using the PCA. As a second time series we use the Laplacian values of geopotential height AT-500 hPa in the grid point with coordinates 70N and 15E. As one can see in Fig. 1a, the maximal variability of baric fields was registered in this grid point; such behaviour can be explained by the presence of northern centre of action assigned with the NAO.

Figure 2 shows the results of CWT for the above time series. In the case of the NAO indices (Fig. 2a), the significant variations with the periods of 8–16 days were observed during whole cold period, and higher-frequency periodicities occurred too. These periods are in good agreement with the outcomes reported by Feldstein (2000) as well as Rivière and Orlanski (2007) related to the variations of the NAO at quasi-synoptic time scales. Some periodicities appear also in the time series of Laplacian values (Fig. 2b), and most striking feature is significant variations with the periods of 8–16 days during the January 2004. One can be therefore supposed that there exists a linkage between the variations of baric field and the NAO indices at quasi-synoptic time scales.

This supposition is confirmed by data in Fig. 3 containing the cross wavelet transform and the wavelet coherence with the relative phase between the two time series. Thus, the significant maximum of cross wavelet power at quasi-synoptic time scales is registered from the middle of December 2003 to the middle of March 2004 (Fig. 3a); the wavelet coherence is also significant in January 2004. It is noteworthy that the detail components for above time period are in anti-phase on the average. If take into account that the NAO was mainly in the negative phase during the cold season of 2003–2004, when a cyclonical centre of action shifted northward, such a result is expected and can be considered as some proof for the efficiency of WA. However, as it was stated above, the CWT can be applied to two separate time series only, i.e. it is difficult to investigate directly the spatial pattern of some atmospheric process.

2.4 The procedure

Finally, to analyze an interaction between synoptic processes over North Atlantic and Ukraine we propose the following procedure:

(i) the PCA are performed for the sea level pressure in the North Atlantic/European sector to determine the PCs (see e.g. Fig. 1);
(ii) the grid points with local extreme values of eigenvectors (first in North Atlantic and second in Ukraine or nearby) describing maximal variability of baric field are found;
(iii) the Laplacian values are calculated in these grid points for each day of time period under study;

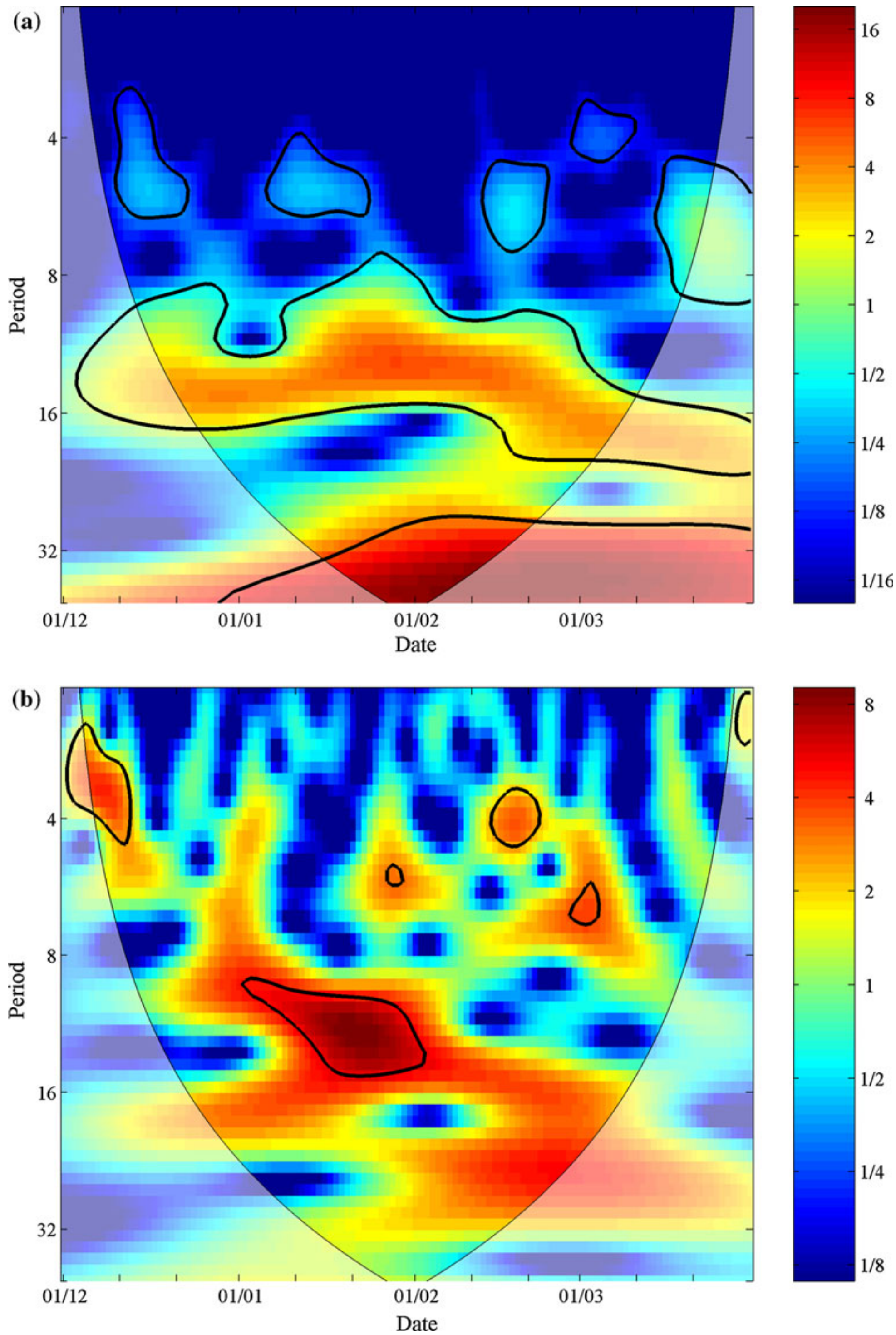

Fig. 2 Continuous wavelet power spectrum of **a** daily NAO indices and **b** Laplacian values of geopotential height AT-500 hPa in the grid point with coordinates 70N and 15E for DJFM of 2003–2004. The *colour scale* represents the wavelet power in arbitrary units. The *thick black contour* designates the 5 % significance level against *red noise* and the cone of influence, where edge effects might distort the picture, is shown as a *lighter shade*

(iv) the cross wavelet transform is performed and wavelet coherence is determined (Fig. 3) for the time series of Laplacian values, and the areas with significant wavelet power and wavelet coherence in the plots are searched to determine time intervals, when the impact of North Atlantic on synoptic conditions in Ukraine occurred at certain time scales.

It must be noted that the PCA of sea level pressure is widely used in meteorological practice whereas the Laplacian values are rather calculated for the analysis of weather conditions.

The joint PC and wavelet analyses were also documented by Pairaud and Auclair (2005), but they used somewhat other approach.

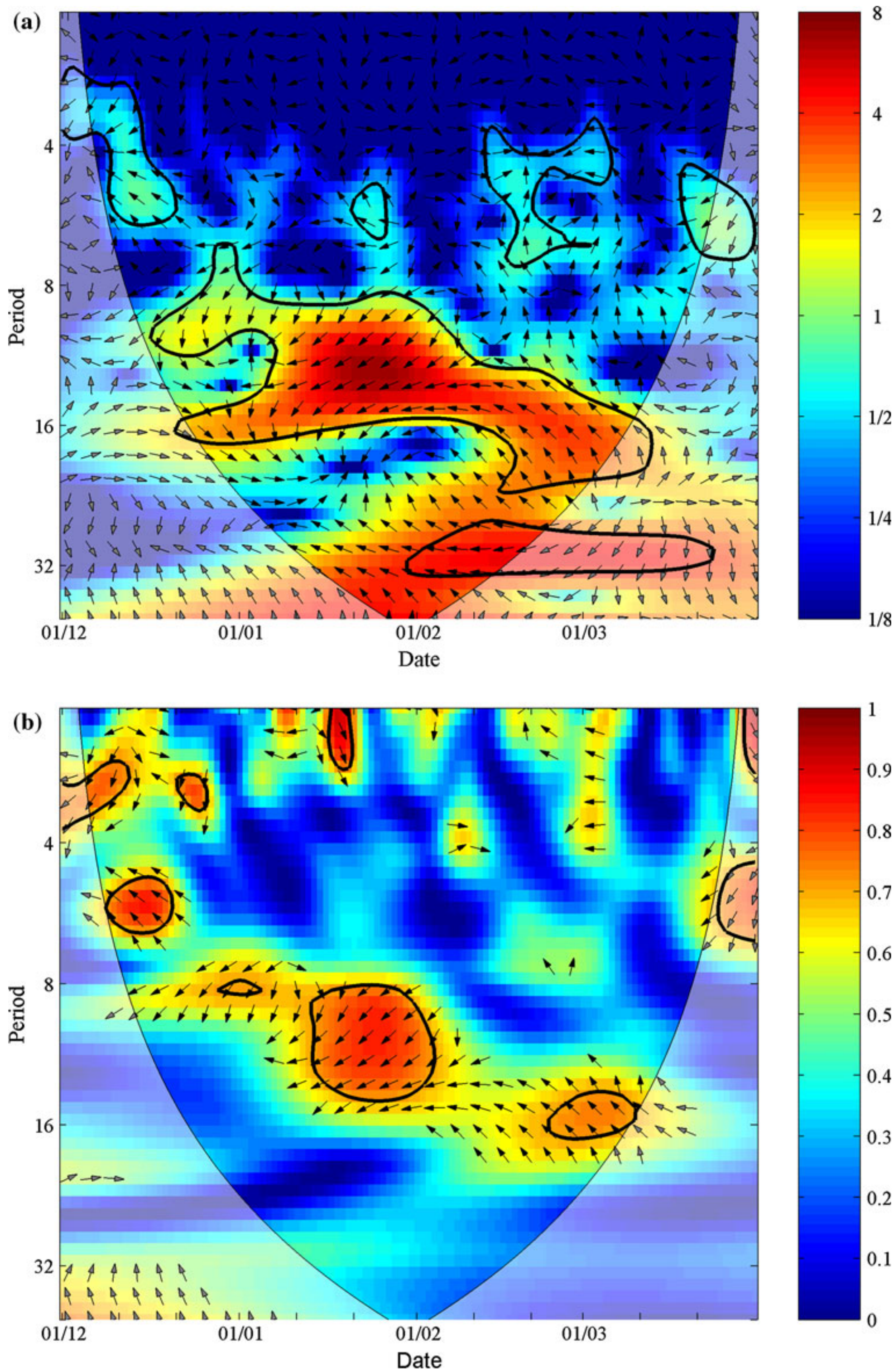

Fig. 3 **a** Cross wavelet transform and **b** wavelet coherence of daily NAO index and Laplacian values of geopotential height AT-500 hPa in the grid point with coordinates 70N and 15E for DJFM of 2003–2004. The *colour scale* represents **a** wavelet power in arbitrary units and **b** wavelet squared coherencies. The 5 % significance level against *red noise* is shown as a *thick contour*. The relative phase relationship is shown as *arrows* with in-phase *pointing right*, anti-phase *pointing left*, and the NAO index leading the Laplacian value by 90° pointing straight down. (Color figure online)

The data on the sea level pressure from NCEP/NCAR Re-Analysis is used in this paper. The spatial domain is bounded by the 30W and 50E longitudinally as well as 30N and 80N latitudinally. The time periods under study are limited by the cold periods for 10 years from 1996–1997 to 2011–2012. The cold periods (from 14 November to 15 March) were chosen as the NAO is more active and has larger spatial extent then the summer pattern (see e.g. Hurrell and Deser 2009).

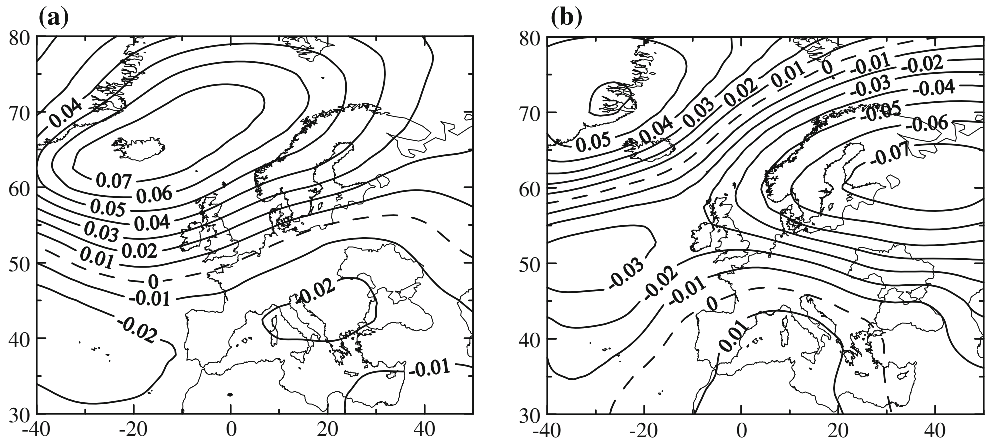

Fig. 4 Spatial distribution of loadings of **a** first and **b** second principal components as a result of PCA from sequential daily sea level pressure from 14 November 2004 to 15 March 2005 in the North Atlantic/European sector

3 Results and discussion

As it was demonstrated in the previous sections, the spatial structure of the NAO seems to be irresponsible directly for some kind of considerable variations in baric field over Ukraine. Moreover there is every likelihood that these variations are influenced by the teleconnection patterns "East Atlantic" or "East Atlantic/West Russia" (see e.g. Barnston and Livezey 1987). As the PCA, that used to reveal these patterns, ensures the orthogonality of decomposed components, the preliminary resume is the pressure variability in the "Azores-Iceland" dipole is not relating to the pressure variability in Ukraine. As a matter of fact, this resume relies rather on the results obtained from climatic view taking into account the initial data. On the other hand, it is a common opinion that the synoptic conditions over Ukraine (and the variability of baric field can be considered as the feature of these conditions) are related to atmospheric processes over North Atlantic. To make sure that this relation exists, the procedure described in Sect. 2.4 will be further applied to the cold period 2004–2005.

3.1 PCA of sea level pressure in North Atlantic and Ukraine

As it was proposed in Sect. 2.4, perform firstly the PCA for sea level pressure from 14 November 2004 to 15 March 2005 in the spatial domain bounded by the 30W and 50E longitudinally as well as 30N and 80N. Figure 4 shows the loadings of the 1st and 2nd PCs; note that these two PCs explain ~60 % of variance totally (46 and 13 % respectively).

If consider the isolines in this figure as peculiar isobars, the plot of 1st PC describes well-known dipole pattern with centres near Iceland and Azores, i.e. the NAO; "pressure ridge" with particular "anticyclone" spreads in the direction of Mediterranean and Ukraine (Fig. 4a). Note that it is can not be concluded what is observed—cyclone or anticyclone—in certain geographical region by the sign of eigenvector as the plot displays rather an oscillation process; it is nevertheless possible to define the strength of oscillation by the magnitude of the eigenvector. In our case, largest variations of pressure, i.e. an alternation of cyclone and anticyclone, are registered over Iceland. The pressure variability over Ukraine is much lesser. In other words, the NAO-related synoptic conditions over Ukraine are described by either weak particular anticyclone or not to deep cyclone over Balkans, and pressure gradients over Ukraine are rather very small.

The plot of 2nd PC (Fig. 4b) looks very much like to the teleconnection pattern "East Atlantic" with the col-like organization of baric field. However, in our case first centre is westward shifted and located over Northwest Russia. The pressure variability over Ukraine is larger in this case as against the 1st PC, but this variability can not be related to the NAO due to the orthogonality of eigenvectors.

The location of centres of action in Fig. 4a is explained by the fact that the NAO is imprescriptible part of circulation conditions in North Atlantic. Therefore, when this region is investigated by using the PCA, the NAO is almost always present in spatial distribution of first eigenvector. Then a single possibility to obtain a plot similar Fig. 4a but without the NAO is to exclude the data over North Atlantic from the analysis, and to perform the PCA over Europe and North Atlantic separately. On the other hand, the teleconnection patterns such as Scandinavia or East Atlantic can be still revealed in spatial distributions of loadings, but this approach allows obtaining over Europe a distribution distinct from above teleconnection patterns. Thus, in this paper we divide the domain under study into two separate sub-domains—first one involves North Atlantic and Western Europe (30N–80N, 40W–20E), second one relates to

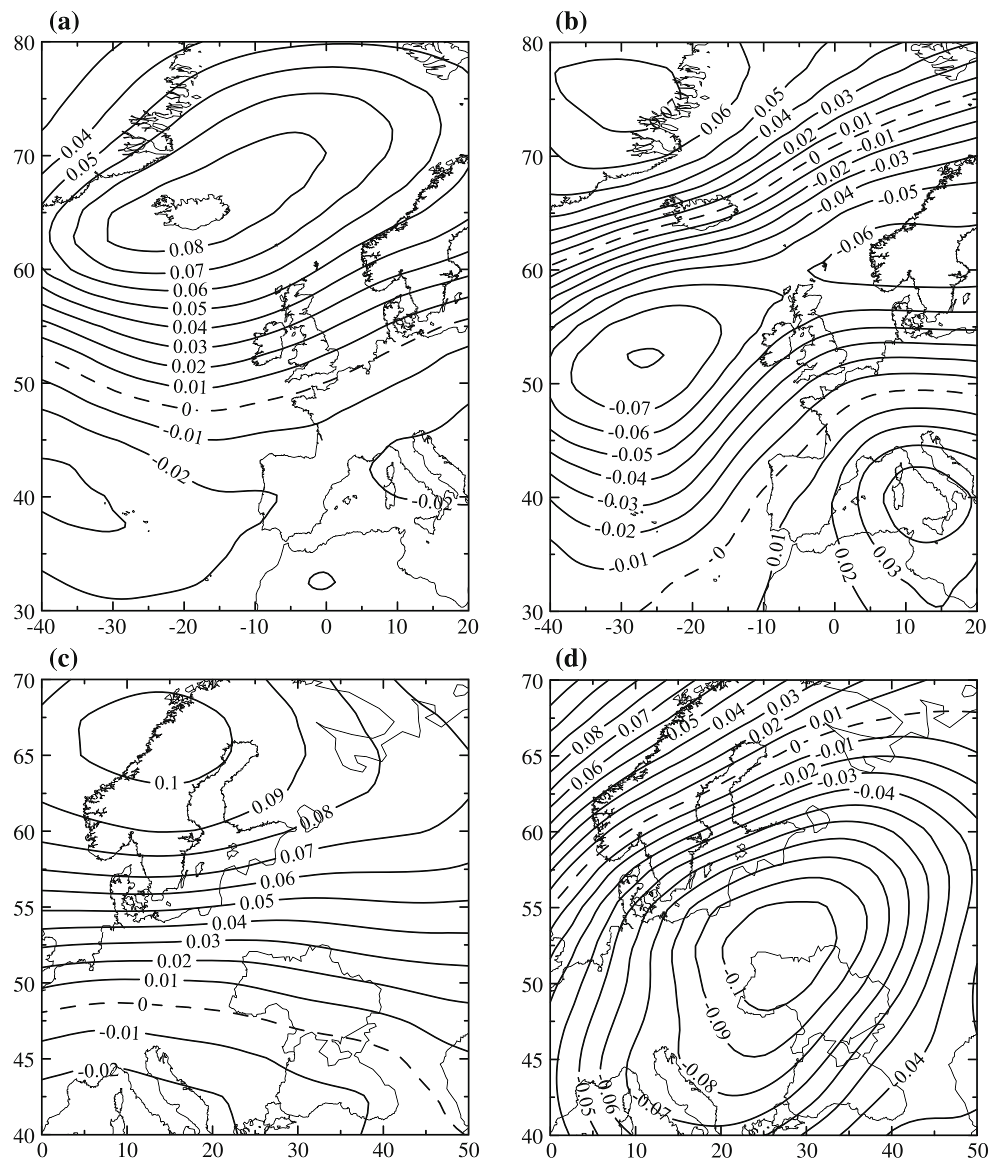

Fig. 5 Spatial distribution of loadings of the first and second principal components as a result of PCA from sequential daily sea level pressure from 14 November 2004 to 15 March 2005 for different regions: **a**, **b** North Atlantic and Western Europe, **c**, **d** Eastern Europe

Eastern Europe (40N–70N, 0–50E)—and apply the PCA to each sub-domain.

Figure 5 shows the spatial distribution of loadings of the first two PCs. In the case of North Atlantic, they explain 52 and 14 % of variance respectively, and in the case of Eastern Europe—49 and 20 % respectively. It is noteworthy that Fig. 5a, b coincides almost completely with Fig. 4a, b: there exist the NAO and East Atlantic pattern though they look like cut off from the east. The exclusion of North Atlantic from the analysis results in the absence of the NAO in the spatial distribution of loading of the first PC—the teleconnection pattern Scandinavia predominates here (Fig. 5c). The loading of second PC (Fig. 5d) is characterized by the extremum over Northwest Ukraine, and the variability of baric field here can be compared by magnitude with the variability of pressure over North Atlantic.

Thus, for the following analysis, we can select the grid points with the extremes of eigenvectors. In North Atlantic, the points have the coordinates 65N, 20W (northern extremum defining the Icelandic Low) and 40N, 37.5W (southern extremum describing the Azores High). The grid point with coordinates 52.5N, 27.5E can be chosen for Ukraine. Just in these grid points we will calculate the Laplacians of sea level pressure for each day of cold period 2004–2005, will apply the WA for two pairs—“Icelandic Low-Ukraine” and “Azores High-Ukraine”—and will concentrate our attention upon the processes with the periods of about 4–8 days, which corresponds to the synoptic time scale.

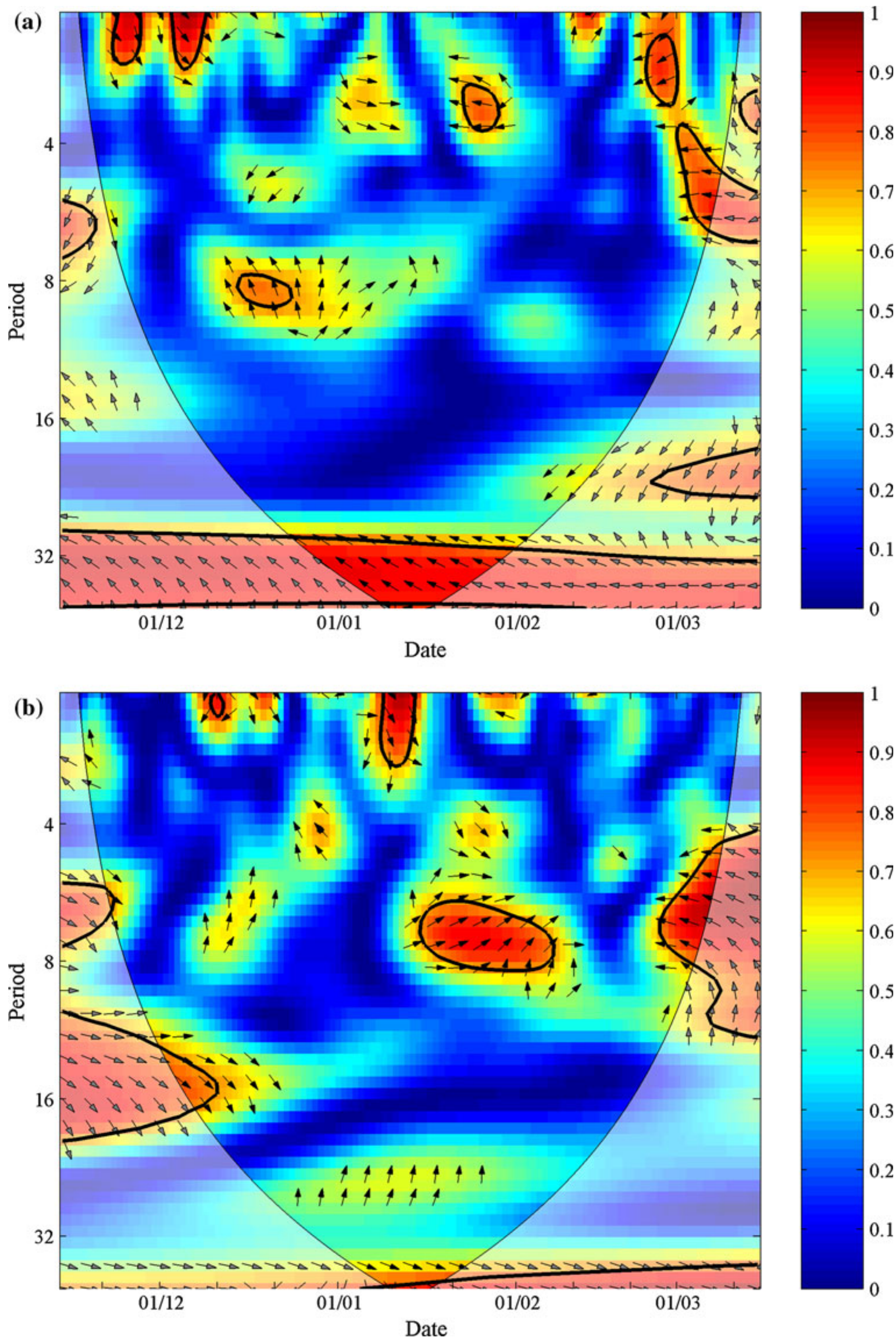

Fig. 6 Wavelet coherencies for Laplacians of sea level pressure for pairs **a** "Icelandic Low-Ukraine" and **b** "Azores High-Ukraine" during cold period 2004–2005. Drawings are as in Fig. 3

3.2 Coherence of sea-level pressure variations in time–frequency domain

Figure 6a displays the three areas in the time–frequency domain with significant wavelet coherencies for variations of sea-level pressure Laplacians at synoptic time scale. First, from 14 to 25 December 2004 the significant wavelet coherency was registered for the periods of ~8 days—changes in synoptic conditions were initially observed near Iceland, and after ~2 day same changes occurred over Ukraine too. Second, from 23 to 29 January 2004 the significant wavelet coherence was registered, and changes of Laplacians with periods less 4 days were in anti-phase (see the supplementary material for the synoptic conditions).

Table 2 Dates and typical periods, when significant wavelet coherence occurred for pressure changes in the pair "Icelandic Low-Ukraine"

Years	Date	Period (days)	Mean phase angle	Time delay (days)	NAO index
1996–1997	13/01–23/01	4.5	65	0.8	0.2
1997–1998	19/12–04/01	5.8	255	4.1	−0.5
	17/01–22/01	4.9	5	0.1	0.2
	16/02–06/03	6.7	85	1.6	−0.4
1998–1999	28/12–13/01	8.4	55	1.3	1.0
1999–2000	21/01–29/01	5.1	105	1.5	1.2
2000–2001	24/11–05/12	7.9	80	1.8	−1.5
	25/02–06/03	7.5	190	4.0	−1.3
2001–2002	18/02–02/03	8.2	270	6.2	0.5
2002–2003	04/02–22/02	8.2	180	4.1	−0.4
2003–2004	13/02–23/02	4.3	50	0.6	−1.6
2004–2005	14/12–25/12	8.0	100	2.2	−1.8
	23/01–29/01	3.7	180	1.9	−0.6
	01/03–08/03	4.9	180	2.5	−0.4
2005–2006	24/12–30/12	7.5	290	6.0	−1.8
2007–2008	24/12–01/01	6.2	267	4.6	−0.8
	26/02–15/03	7.8	93	2.0	−0.1
2008–2009	30/11–14/12	7.8	183	4.0	0.5
	18/01–23/01	6.7	355	6.6	−1.0
2009–2010	20/12–27/12	7.9	4	0.1	0.6
2010–2011	03/01–23/01	5.5	5	0.1	1.1
	23/02–05/03	4.8	265	3.5	0.5
2011–2012	03/12–14/12	5.5	210	3.2	0.8
	02/02–09/02	6.1	340	5.8	−1.2

Third, the wavelet coherence was significant during the March 2005 in the range of periods from 4 to 8 days, but the part of this area was influenced by the cone of influence (see Grinsted et al. 2004) and this result can not be hereupon considered as fully reliable.

Also, during the March 2005 and at approximately same periods the wavelet coherence was significant for the pair "Azores High-Ukraine" (Fig. 6b). As the anti-phase was observed for both cases, one can be supposed that synoptic conditions near Iceland and Azores bore a great resemblance to each other during the March 2005. On the other hand, from 15 January to 7 February 2005 the significant wavelet coherence with periods ~8 days was registered with the quasi-synchronism for the pair "Azores High-Ukraine", i.e. changes of synoptic conditions over Ukraine occurred not long after changes over Azores.

Figure 6 confirms the supposition that the synoptic conditions in North Atlantic can be connected with changes of weather patterns over Ukraine. However it must be taken into account the fact that this connection occurred only during a few days or 2–3 weeks within cold season. Therefore it is naturally that the correlation coefficients calculated by the data for whole cold season are small and insignificant, i.e. they can not define possible linkage between synoptic conditions in North Atlantic and Ukraine. Thus the approach based on the wavelet transform turned out sufficiently effective method to analyze the time series.

Tables 2 and 3 summarize the data on the significant wavelet coherence between the changes of synoptic conditions in North Atlantic and Ukraine for the cold periods for 10 years from 1996–1997 to 2011–2012. The mean phase angle in the tables is calculated by using the method proposed by Grinsted et al. (2004), and the time delays is estimated from the phase angles subject to the period of variations; the NAO index is calculated as a time average by using the PCA. One can be noted first of all, that the dipole intrinsic to the NAO in the pressure variability was not obtained for all the cold periods. Much more frequent pattern has only contained Icelandic Low whereas its counterpart over Azores was absent. The significant wavelet coherence was not always registered at synoptic time scales.

Tables 2 and 3 show that there is no connection between different characteristics. For example, the significant wavelet coherence was obtained for the pair "Icelandic Low-Ukraine" in January 1998 and March 2005 with the period of 4.9 days. However the variations were in-phase in the first case and in anti-phase in the second case. Also,

Table 3 Dates and typical periods, when significant wavelet coherence occurred for pressure changes in the pair "Azores High-Ukraine"

Years	Date	Period (days)	Mean phase angle	Time delay (days)	NAO index
1996–1997	26/12–20/01	5.5	335	5.1	1.0
	02/02–14/02	6.1	20	0.3	−0.4
1997–1998	15/12–22/12	4.0	175	1.9	−0.4
	29/01–04/02	5.1	10	0.1	0.1
1999–2000	26/11–11/12	4.4	190	2.3	2.0
	15/02–28/02	5.5	5	0.1	1.1
2001–2002	15/12–24/12	7.2	230	4.6	1.4
2002–2003	23/11–19/12	4.2	280	3.3	1.5
	20/11–04/12	7.0	330	6.4	1.2
2004–2005	15/01–07/02	7.5	35	0.7	0.3
2010–2011	27/02–11/03	4.8	269	3.6	0.5

the week positive phase of the NAO occurred in 1998 and week negative one in 2005. On the other hand, for the same pair the time lag were equal about 2 days in December 2004 and 6 days in December 2005 though the strong negative phase of the NAO (index = −1.8) and almost identical period of ~8 days were registered for both cases. The single, more or less important conclusion is that the majority of connections (8 from 10) for the pair "Azores High-Ukraine" occurred during the positive phases of the NAO; moreover the NAO index exceeded 1.0 in the 6 from 10 cases. It was however impossible to detect some regularity for the period of variations, mean phase angles, and time lags for this pair.

It is noteworthy that the implementation of WA presupposes the comparison with the background spectrum, which is the red noise here, to determine the significance of results (Sect. 2.3). However, just common changes of synoptic situation in the midlatitudes are usually considered as a manifestation of red noise. In other words, the change of synoptic situation is the process with low noise-to-signal ratio. That the WA may reveal some significant variability, the synoptic processes must be active as, for example, the blocking or the evolution of intensive cyclone. Then the changes of these processes would stand out against a background of common synoptic conditions. Just that very case was observed in current section.

Finally, let us attempt to answer another very important question: do the above regularities associate with the NAO? At first sight, the occurrence of cyclone in Golf of Genoa can not be defined by the atmospheric processes over Iceland. However, most of blocking in North Atlantic relate as a rule to the negative phases of the NAO (Stein 2000). The blocking results in certain pattern of upper-level baric field with south-to-north-oriented ridge reaching central Greenland. At the eastern part of the ridge, the arctic air masses spread to the south even to Mediterranean. This situation can be retraced, for example, in Fig. S1e, where northern part of atmospheric front locates to north of Jan Mayen and southern part reaches Algeria. Just that arctic cold-air surge onto Western Mediterranean, the air temperature in Sardinia decreased from 13 °C on 23 January to 2 °C on 27 January, resulted in the occurrence of intensive cyclone that moved through Ukraine in what follows. Thus the existence of blocking anticyclone assigned with the negative phase of the NAO assisted in the origination of cyclone in Golf of Genoa.

4 Conclusions

First of all, the use of WA allowed revealing the time intervals during the cold seasons, when simultaneous variations of synoptic conditions in North Atlantic and Eastern Europe occurred at periods of 4–8 days. Usually, this process is observed not very often and even for each year, but these variations can be in progress during a few weeks. The coherent variations of synoptic conditions do not depend on the strength and phase of the NAO and can be both in-phase and anti-phase. However most probably the two intensive synoptic processes different from general synoptic situation must be occurred that the significant wavelet coherence is registered. This is conditional on the synoptic processes are usually considered as the red noise, which is used to determine the significance of wavelet coherence. In the previous section, the strong blocking anticyclone in North Atlantic and intensive cyclone in Golf of Genoa were taken for such intensive processes.

We have mentioned in the Introduction that the Morlet wavelet is most used as the wavelet function within the CWT framework and the generalized Morse wavelets are the good alternative. Aguiar-Conraria and Soares (2013) considered advantages and disadvantages for the both wavelets. They noticed that the Morlet wavelet represents the best compromise between time and frequency concentration but is not very versatile—we cannot adjust it to have a better localization in frequency or in time. Lilly and Olhede (2012) asserted that for highly time-localized settings the Morlet wavelet become significantly less concentrated than generalized Morse wavelets. However for the latter, there is no single way to convert scales into frequencies (Aguiar-Conraria and Soares 2013). Most likely, the correct choice of specific wavelet can be defined physically interpreting the results of wavelet transform using some environmental data; in this paper we use synoptic conditions.

In our opinion, one very interesting question is left unanswered. In the above case of two grid points located far one from other, the time delay of $\sim$1.9 days was observed and two detailed components were in anti-phase. It can be supposed that a response of atmospheric processes in Europe on changes of synoptic conditions near to Iceland occurred with smaller time lags closer to North Atlantic. It is also possible that the significant wavelet coherence could be registered in other regions with same periods of variations but different phase angles. In other words, it is interesting to know what effect have the changes of synoptic situation assigned with the NAO on atmospheric processes in Europe? This topic can be clarified by using the PCA and WA (see e.g. Khokhlov and Romanova 2011) and is attractive for further studies.

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