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Using non-decimated wavelet decomposition to analyse time variations of North Atlantic Oscillation, eddy kinetic energy, and Ukrainian precipitation

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Abstract

We employ a non-decimated wavelet decomposition to analyse inter-annual variations of the North Atlantic Oscillations (NAO) indices and relationship of these variations with both the Eddy kinetic energy contents (K_E) in the atmosphere of Northern mid-latitudes and the precipitation in the different regions of Ukraine during July 1960–February 2003. Major advantage of using this tool is to isolate short- and long-term components of fluctuations. Such analysis allows revealing basic periodic behaviours for the NAO indices such as the 4–8-year and the natural change of dominant phase. The main results can be posed as follows. The most essential relationship between the NAO index and K_E content is found for the low frequency variations with the periods of 4–8 and 8–16 years, at that if the NAO phase tends to abrupt changes then the impact of these changes on the K_E content is more significant than for the durational dominance of certain phase. The largest coefficients of correlation for the NAO index and Ukrainian precipitation are stated for the periodicities of 2–4 and 4–8 years; the former is caused by the synoptic-scale activity forced by the NAO while the former is conditioned by the air-mass processes in the warm season.

Keywords: Wavelet analysis; North Atlantic oscillation; Precipitation; Ukraine; Eddy kinetic energy

1. Introduction

The North Atlantic Oscillation is one of the most prominent teleconnection patterns in all seasons and is documented by Barnston and Livezey (1987). The NAO exhibits little variation in its climatological mean structure from month-to-month, and consists of a north–south dipole of pressure anomalies, with one centre located over Greenland and the other centre of opposite sign spanning the central latitudes of the North Atlantic between 35°N and 40°N. The positive phase of the NAO reflects below-normal heights and pressure across the high latitudes of the North Atlantic and above-normal geopotential heights and pressure over the central North Atlantic, the eastern United

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States and Western Europe. The negative phase reflects an opposite pattern of height and pressure anomalies over these regions. Both phases of the NAO are associated with basin-wide changes in the intensity and location of the North Atlantic jet stream and storm track, and in large-scale modulations of the normal patterns of zonal and meridional heat and moisture transport (Hurrell, 1995), which in turn results in changes in temperature and precipitation patterns often extending from eastern North America to western and central Europe. In this paper we show some details of this forcing to cite as an example the spatio-temporal distribution of precipitation in Ukraine. Also, the NAO affects many others processes such as the seasonal variations of atmospheric constituents (Appenzeller et al., 2000; Khokhlov and Glushkov, 2002), the meridional heat transport (Häkkinen, 1999), the Arctic sea ice export (Hilmer and Jung, 2000) etc.

However, all such significant influences of the NAO on Northern Hemisphere climate in general, and precipitation in particular, are affected by local topography and regional circulation, so that the intensity of the NAO's effects vary spatially within the North Atlantic–European region.

This paper represents the time variability of NAO's influence over both the Eddy kinetic energy in the Northern mid-latitudes and the precipitation in the different regions of Ukraine during July 1960–February 2003. The Eddy kinetic energy can be considered as a measure for the activity of synoptic-scale processes which, in turn, are one of main forcings determining the variation of precipitation on the different time scales. To examine such a ternary relationship we use approach based on a wavelet decomposition.

Since the last decades of the past century, many scientists use the new powerful tool based on the wavelet decomposition for analyzing various signals. One can say without exaggeration, wavelets has made revolution in both theory and practice of non-stationary signal processing. At present, the family of analysing function dubbed wavelets is being increasingly used in problems of pattern recognition; in processing and synthesising various signals, speech for instance; in analysis of images of any kind (these may be iris images, X-ray picture of a kidney, satellite images of clouds or a planet surface, an image of mineral, etc.); for study of turbulent fields, for contraction (compression) of large volumes of information, and in many other cases.

Some ideas of the wavelet theory were partially developed a long time ago. For instance, A. Haar published as far back as a 1910 the complete orthonormal system of basis function with the local domain of definition, which are now named as Haar wavelets. However, one can note that probably first mention about wavelets has appeared in the literature on digital processing and analysing of geophysical signals (e.g. Goupillaud et al., 1984; Morlet et al., 1982). From meteorological works on stated subjects, one can be referred the analysis of El Niño dynamics (see, Astaf'eva, 1996; Torrence and Webster, 1999), the analysis of the NAO-El Niño interaction (Jevrejeva et al., 2003; Khokhlov et al., 2004), the wavelet decomposition of low frequency climate variability (e.g. Oh et al., 2003) as well as some aspects of atmospheric turbulence (Meneveau and Lund, 1994; Arneodo et al., 1998).

So, the aim of present paper is to analyse long-term variations of the North Atlantic Oscillation indices and the relationship of these variations with Eddy kinetic energy of Northern mid-latitudes and Ukrainian precipitation.

2. Methodology and data

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. In comparison, the multi-resolution analysis makes wavelets particularly appealing for this study, because they are localized in time and the signals are examined using widely varying levels of focus. For detail about wavelet theory, the monographs of Daubechies (1992), Goswami and Chan (1999) can be recommended. Previously, continuous wavelet transform has been used to capture meteorological (Astaf'eva, 1996; Torrence and Webster, 1999) and solar signals (Fligge et al., 1999; Oh et al., 2003). In this article, we work with non-decimated (discrete) wavelet transform rather than continuous wavelet transform, because from a statistical point of view, they are well adapted (i.e. search for correlations or noise reduction) and offer a very flexible tool for analysis of discrete time series such as the ones under study here. The advantages of non-decimated wavelet transform also include (1) a much better temporal resolution at coarser scales than with ordinary discrete wavelet transform, and (2) it allows us to isolate time series of the major components of meteorological signals in a direct way. Here we provide a brief summary of the non-decimated wavelet transform; Oh et al. (2003) may be consulted for a more in-depth discussion.

2.1. Non-decimated wavelet transform

The dilation and translation of one mother wavelet $\psi(t)$ generates the wavelet $\psi_{j,k}(t)=2^{j/2}\psi(2^j t-k)$, where $j, k\in Z$. The dilation parameter j controls how large the wavelet is, and the translation parameter k controls how the wavelet is shifted along the t-axis. For a suitably chosen mother wavelet $\psi(t)$, the set $\{\psi_{j,k}\}_{j,k}$ provides an orthogonal basis, and the function f which is defined on the whole real line can be expanded as

$$f(t) = \sum_{k=-\infty}^{\infty} c_{0k}\varphi_{0,k}(t) + \sum_{j=1}^{J}\sum_{k=-\infty}^{\infty} d_{jk}\psi_{j,k}(t), \qquad (1)$$

where ϕ_0 is the scaling function or so-called 'father' wavelet, the maximum scale J is determined by the number of data, the coefficients c_{0k} represent the lowest frequency smooth components, and the coefficients d_{jk} deliver information about the behaviour of the function f concentrating on effects of scale around 2^{-j} near time $k\times 2^{-j}$. This wavelet expansion of a function is closely related to the discrete wavelet transform (DWT) of a signal observed at discrete points in time.

In practice, the length of the signal, say n, is finite and, for our study, the data are available monthly, i.e. the function $f(t)$ in Eq. (1) is now a vector $f=(f(t_1),\ldots, f(t_n))$ with $t_i=i/n$ and $i=1,\ldots, n$. With these notations, the DWT of a vector f is simply a matrix product $d=Wf$, where d is an $n\times 1$ vector of discrete wavelet coefficients indexed by 2 integers, d_{jk}, and W is an orthogonal $n\times n$ matrix associated with the wavelet basis. The DWT is quickly computed through an efficient algorithm developed by Mallat (1989). For computational reasons, it is simpler to perform the wavelet transform on time series of dyadic (power of 2) length. In this paper this length is 512 months (from July 1960 to February 2003).

One particular problem with DWT is that, unlike the discrete Fourier transform, it is not translation invariant. This can lead to Gibbs-type phenomena and other artefacts in the reconstruction of a function. The non-decimated wavelet transform (NWT) of the data $(f(t_1),\ldots,f(t_n))$ at equally spaced points $t_i=i/n$ is defined as the set of all DWT's formed from the n possible shifts of the data by amounts i/n; $i=1,\ldots, n$. Thus, unlike the DWT, there are 2^j coefficients on the jth resolution level, there are n equally spaced wavelet coefficients in the NWT: $d_{jk}=n^{-1}\sum_{i=1}^{n} 2^{j/2}\psi[2^j(i/n-k/n)]y_i$, $k=0,\ldots,n-1$, on each resolution level j. This results in $\log_2(n)$ coefficients at each location. As an immediate consequence, the NWT becomes translation invariant. Due to its structure, the NWT implies a finer sampling rate at all levels and thus provides a better exploratory tool for analyzing changes in the scale (frequency) behaviour of the underlying signal in time. These advantages of the NWT over the DWT in time series analysis are demonstrated in Nason et al. (2000).

As in the Fourier domain, it is important to assess the power of a signal at a given resolution. In order to reach this goal, a time-domain model for encapsulating localized scale activity was proposed by Nason et al. (2000). An evolutionary wavelet spectrum (EWS) quantifies the contribution to process variance at the scale j and time k.

From the above paragraphs, it is easy to plot any time series into the wavelet domain. Another way of viewing the result of a NWT is to represent the temporal evolution of the data at a given scale. This type of representation is very useful to compare the temporal variation between different time series at a given scale. To obtain such results, the smooth signal S_0 and the detail signals D_j ($j=1,\ldots,J$) are defined as follows

$$S_0(t) = \sum_{k=-\infty}^{\infty} c_{0k}\varphi_{0,k}(t) \text{ and } S_j(t) = \sum_{k=-\infty}^{\infty} d_{jk}\psi_{j,k}(t). \qquad (2)$$

Sequentially, the temporal multi-resolution decomposition of a signal is derived from

$$D_{j-1}(t) = S_j(t) - S_{j-1}(t).$$

The fine scale features (high frequency oscillations) are captured mainly by the fine scale detail components D_J and D_{J-1}. The coarse scale components S_0, D_1, and D_2 correspond to lower frequency oscillations of the signal. Note that each band is equivalent to a band-pass filter.

Further we use the Daubechies wavelet (db15) as mother wavelet. This wavelet is biorthogonal and supports discrete wavelet transform (Daubechies, 1992).

2.2. Data used

In present study we consider the long-term variations of the monthly NAO index calculated as the difference in the sea-level pressure between Lisbon (Portugal) and Stykkisholmur (Iceland). Motivation for such a choice is grounded by Khokhlov et al. (2004).

The NAO exhibits considerable interseasonal and interannual variability, and prolonged periods (several months) of both positive and negative phases of the pattern are common. Additionally, the wintertime NAO exhibits significant interannual and interdecadal variability (Hurrell, 1995). For example, the negative phase of the NAO dominated the circulation from the mid-1950's through the 1978/79 winter. During this approximately 24-year interval, there were four prominent periods of at least three years each in which the negative phase was dominant and the positive phase was notably absent. In fact, during the entire period the positive phase was observed in the seasonal mean only three times, and it never appeared in two consecutive years. Some details of this behaviour can be found in Fig. 1.

Now, let us dwell on the meteorological signals. As stated above, the Eddy kinetic energy (K_E) is considered as the intensity measure of atmospheric Eddy evolution. It can be calculated by

$$K_E = \frac{\overline{u'2} + \overline{v'2}}{2}, \tag{3}$$

where u and v are the zonal and meridional components of wind, the strokes denote the deviation from the zonal means. The concept of zonal mean value and deviation from it is used in Eq. (3). Integration of K_E over the whole atmosphere at a latitudinal belt gives a typical value of 10^5 and a dimensionality J m^{-2}. Calculations are carried out for the latitudinal belt 30–60°N. The NCEP–NCAR 50-year reanalysis (Kistler et al., 2001) is used as the data for the calculations of K_E content. Fig. 2 shows the variations of K_E content during July 1960–February 2003 and the seasonal variations with 12-month period can be noticed. These variations are explained by the structural reorganization observed in the Northern atmosphere. The magnitude of K_E content is increased in the winter and has minimum in the summer (Khokhlov, 2003).

It is well-known that the precipitation (both frontal and air-mass) variations is forced by the large-scale atmospheric processes and many studies describe this process (see, e.g. Dettinger et al., 1998; Jones, 2000; Genthon and Cosme, 2003; Giannini et al., 2003; Uvo, 2003). On the other hand, the precipitation is one of main factors defining runoff.

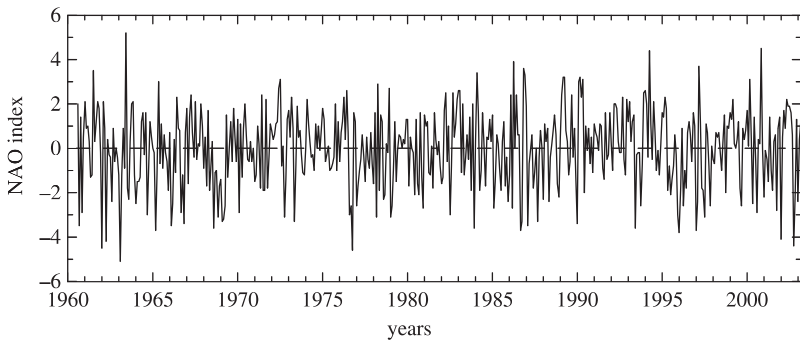

Fig. 1. The original time series of the North Atlantic Oscillation index during July 1960–February 2003.

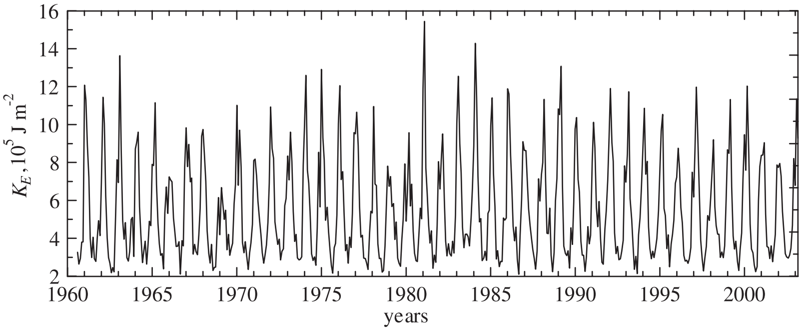

Fig. 2. The original time series of Eddy kinetic energy content (10^5 J m^{-2}) in the Northern mid-latitudes during July 1960–February 2003.

For Ukraine, the cold-season precipitation is the determining factor for annual runoff though the maxima of precipitation are observed in the summer. In other words, the annual runoff for the most of Ukrainian rivers is formed by the precipitation observed on the atmospheric fronts of extra-tropical cyclones. The spatial distribution of precipitation in Ukraine is heterogeneous: the maximum of mean value is observed in the northern and western regions and the minimum is registered for southern Ukraine. Table 1 gives some statistics for the Ukrainian precipitation. One can be noted that both the skewness and the kurtosis for all regions are not equal to zero at that for the eastern and central regions these values are maximal.

Our preliminary analysis showed that the NAO forcing for the precipitation in Eastern Ukraine is practically absent, and in this study we not analyse the precipitation for this region. Fig. 3 shows time series of precipitation for the different regions and two maxima (cold- and warm-season) emerge obviously.

3. Relationship between NAO and Eddy kinetic energy

By using the multi-resolution decomposition, we characterize the major components of the NAO and K_E content. To select the most informative detail component, we consider the correlation coefficient (r) for the signals of NAO indices and K_E content. Table 2 shows that the greatest correlation coefficients between the NAO indices and the K_E contents are registered for the low-frequency spectrum (D_1–D_4). Thus, in further examination we will work with the detail components D_4 and D_3. A consideration of signals with periods larger than 20 years (as for instance periods of D_2 and D_1) not make sense in our case since the duration of whole period under review is a little larger than the 42 years.

Fig. 4a shows the detail component D_4, which is interesting by its period of oscillation (4–8 year) and namely on these durations the maximal anomaly of pressure in the NAO falls (da Costa and de Verdiere, 2002), though one can be noted they used another

Table 1
Statistics of precipitation for the different regions of Ukraine during July 1960–February 2003

Statistics	Region of Ukraine				
	Western	Northern	Central	Eastern	Southern
Mean, (mm)	75.20	75.38	72.26	72.57	71.75
Standard deviation, (mm)	75.55	76.69	75.84	76.28	73.45
Maximum value, (mm)	467.94	472.43	600.45	535.14	422.34
Minimum value, (mm)	0.00	0.00	0.00	0.00	0.00
Skewness	1.68	1.83	1.92	1.93	1.64
Kurtosis	3.24	4.27	5.90	5.21	2.94

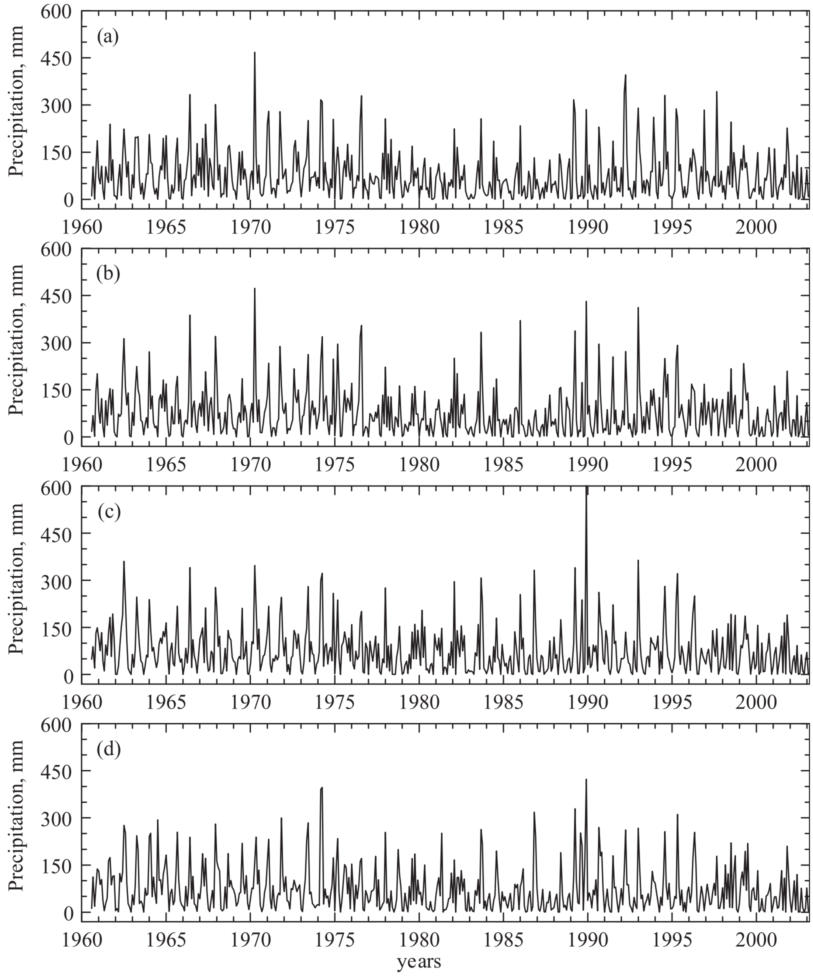

Fig. 3. The original time series of precipitation (mm) in (a) western, (b) northern, (c) central, and (d) southern Ukraine during July 1960–February 2003.

mathematical tool. Also, Fig. 4a confirms the particular advantage of wavelet decomposition namely its flexibility in the adjustment to the local changes of the NAO period, which are wide-ranging. Since wavelets support clear minima and maxima they take into account realistic estimations of cycle-length.

From July 1960 to January 1990 there exists the larger agreement between the NAO indices and the K_E contents. Such a case is presented in Fig. 4a.

Table 2
Periodicities (p, years) for the detail components of the NAO index and correlation coefficients (r) between the detail components of the NAO index and the Northern mid-latitudes K_E content during July 1960–February 2003

	Detail components								
	D_9	D_8	D_7	D_6	D_5	D_4	D_3	D_2	D_1
P	0.25	0.5	1	1–2	2–4	4–8	8–16	>16	>16
r	0.156	0.177	0.216	0.122	0.308	0.533	0.640	0.802	0.860

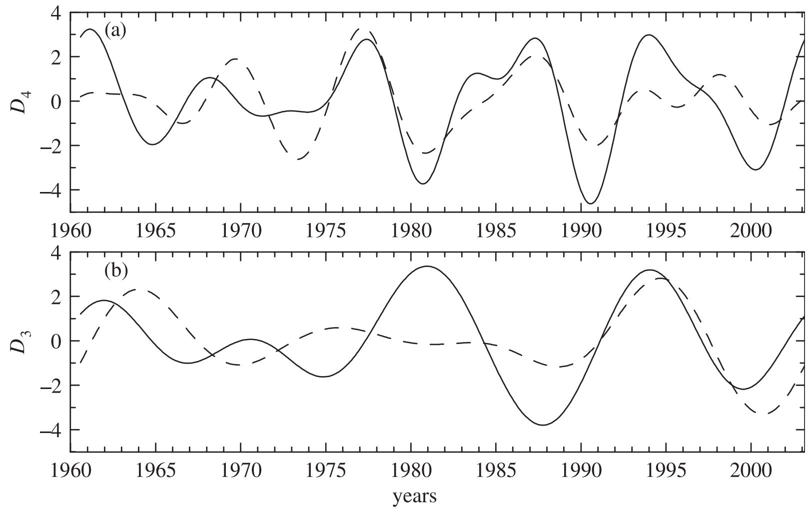

Fig. 4. The detail components (a) D_4 and (b) D_3 for the NAO index (solid) and K_E content in Northern mid-latitudes (dashed) during July 1960–February 2003.

The correlation coefficient for this period amounts to 0.76 for the NAO-K_E, while for period of January 1990–February 2003 this coefficient is -0.05 only. At the same time during the sharper change of NAO indices there exists the same essential variation of Eddy kinetic energy content.

Now we analyse the detail component D_3 (Fig. 4b). First note that this signal characterises a dominance of negative or positive phase of the NAO during long period of time. As it was mentioned above, the negative phase of the NAO dominated the atmospheric circulation from the mid-1950's to the 1978/79 winter. An abrupt transition to recurring positive phases of the NAO then occurred during the 1979/80 winter, with the atmosphere remaining locked into this mode through the 1994/95 winter season. During this 15-year interval, a substantial negative phase of the pattern appeared only twice, in the winters of 1984/85 and 1985/86. However, November 1995–February 1996 was characterised by a return to the strong negative phase of the NAO. Fig. 4b displays all these variations in D_3 for the NAO.

Secondly during the durational negative NAO phase till January 1980 the correlation coefficient NAO-K_E for the D_3 amounts to 0.09. On the other hand, the second half of the considered period is characterised by the correlation coefficient of 0.76. In other words, if the NAO phase tends to the sharp changes then its influence is stronger on the Eddy kinetic energy content both in the tropics and in the mid-latitudes. This can be explained by the baric reconfiguration covering most of the mid-latitudes and tropics when the North Atlantic Oscillation phase is changed. In this case, there exists the significant meridionality of air currents and this implies the K_E contents increasing.

4. Low-frequency NAO forcing of precipitation

Dai et al. (1997) have shown that the first EOF has considerable power at the 11-year timescale, accounts for 12% of the total variance of winter precipitation, and exhibit an alternating pattern in latitude over Europe (high in central Europe and low in northern Europe, the Mediterranean, and northern Africa). The second mode, which accounts for 10% of the variance, has the peak power at the 7-year timescale. During the winters with the high NAO index, the precipitation tends to be above normal in northern Europe, the eastern United States, northern Africa, and the Mediterranean, whereas southern Europe, eastern Canada and western Greenland likely receive below-normal precipitation. Considering the precipitation of Northern Europe, Uvo (2003) has reported that the NAO explains up to 28% of winter precipitation

Table 3
The coefficients of correlation between the detail components of the NAO index and the precipitation in different region of Ukraine during July 1960–February 2003

Region	Detail components of the NAO index								
	D_9	D_8	D_7	D_6	D_5	D_4	D_3	D_2	D_1
Western	−0.050	0.100	0.028	0.202	0.303	0.591	0.102	−0.132	−0.921
Northern	−0.034	0.042	−0.016	0.024	0.556	0.326	0.225	−0.176	−0.984
Central	−0.050	0.065	0.030	−0.024	0.532	0.190	0.386	−0.238	−0.977
Southern	−0.058	0.114	0.067	0.059	0.516	0.178	0.313	−0.340	−0.972

variability, particularly in southern Finland and southwestern Norway. One can be noted that similar estimations for the precipitation in Ukraine were not actually carried out.

To investigate the link between the precipitation and the North Atlantic Oscillation, many researches use the empirical orthogonal function analyses (e.g. Dai et al., 1997; Zveryaev, 2004), the canonical correlation analysis (e.g. Busuioc et al., 2001), the cluster analysis (e.g. Uvo, 2003) or the complex approach used the above mentioned ways. All these methods give a good account of oneself.

In this paper, to evaluate the relationship between the NAO and Ukrainian precipitation, we use procedure described in Section 2.

Table 3 presents the coefficients of correlation for the detail components of the NAO indices and precipitation in different regions of Ukraine. As well as in the case of K_E, the largest coefficients of correlation are registered for low-frequency detail components. However, for the detail component D_4 the conformity is only stated between the NAO index and precipitation in western Ukraine (Fig. 5) whereas for the rest of regions the largest coefficients of correlation are registered for the detail component D_5 with periodicity of 2–4 years (Fig. 6). The lack of significant correlation for the detail component D_3 can be caused by the comparative remoteness of the considered territory from the North Atlantic.

Fig. 5 shows that the detail components D_4 vary quasi-synchronously and the amplitude of variations in the precipitation for western region increases together with the amplitude of the NAO. This finding can be explicated by the enlarged Eddy activity in Northern mid-latitudes (compare Figs. 4 and 5).

The detail components D_5 represent the similar coherency (Fig. 6), but for this periodicity we not find the strong correlation between the NAO index

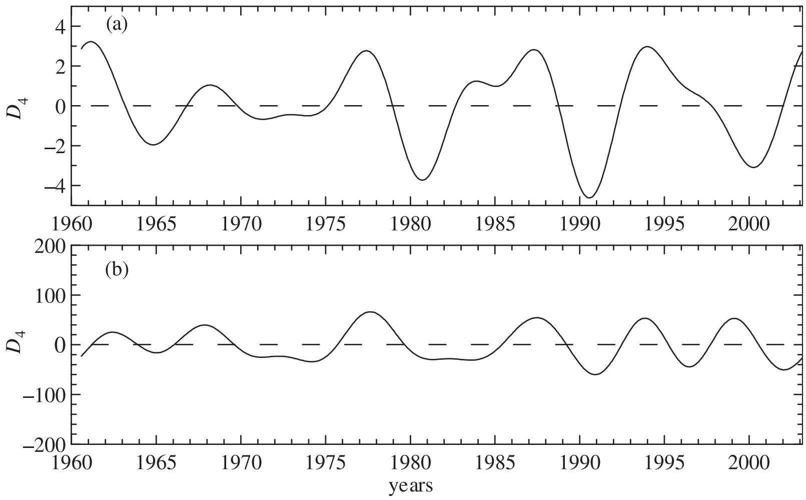

Fig. 5. The detail components D_4 for the (a) NAO index and (b) precipitation in western Ukraine during July 1960–February 2003.

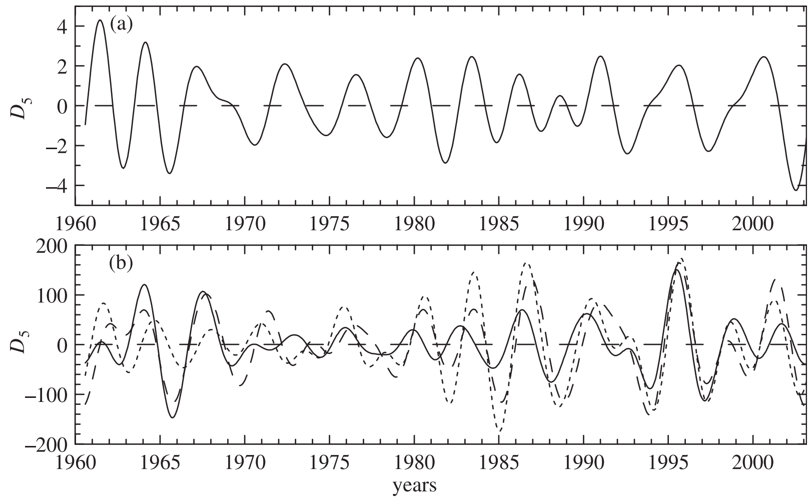

Fig. 6. The detail components D_5 for the (a) NAO index and (b) precipitation in the different regions of Ukraine during July 1960–February 2003: northern (solid), central (dashed), and southern (dotted).

and the K_E content (Table 2). In other words, the precipitation with the periodicity of 2–4 years can not be assigned with the analogous variations in the activity of synoptic-scale processes (we not table here the results for the K_E-precipitation interaction but the coefficient of correlation is too small for this detail component).

To study the above uncertainty we examine the detail components for the cold- and warm-season precipitation separately. It is found that the coefficient correlation for the detail components D_4 of the NAO indices and cold-season precipitation in western Ukraine amounts to 0.81 and exceeds 0.48 for other regions whereas for the warm-season precipitation the maximal coefficient of correlation is registered in central Ukraine (0.44 only). In contrast to this finding, for the case of detail component D_4 the maximal coefficients of correlation is observed for the warm-season precipitation (0.68 at least) while for the cold-season one they decrease significantly. Hence the 4–8 year variations in the Ukrainian precipitation is forced by the synoptic-scale atmospheric processes, which cause the winter frontal precipitation, in turn. On the contrary, the 2–4 year periodicity in the Ukrainian precipitation is conditioned by the air-mass processes observed mainly in the warm season.

Finally, to examine for the influence exerted by the dominance of NAO's prolonged negative phase during 1960–79, we divide whole period into two sub-periods. Let us remind that the negative phase of the NAO dominated the atmospheric circulation from the mid-1950's to the 1978/79 winter whereas since 1980 the alternation of positive and negative phases is observed. As it turned out, during the dominance of NAO's negative phase the coefficients of correlation for the detail components D_5 and D_4 increase up to 0.60 for all regions while during second sub-period these coefficients not exceed 0.35.

5. Conclusions

The advantage of using our decomposition of the NAO index, the Eddy kinetic energy content in Northern mid-latitudes, and the Ukrainian precipitation is to isolate short- and long-term components while retaining the flexibility for variability in the cycle length.

By using the wavelet decomposition based on the non-decimated wavelet transform we reveal some basic periodicities for the North Atlantic Oscillation indices such as the 4–8-year cycle, which is characterised by the maximum of atmospheric pressure anomaly, and the natural change of dominant phase. These fluctuations are analysed together with the Eddy kinetic energy content and the Ukrainian precipitation. Main results of such joint analysis can be briefly stated as follows:

(i) the most essential relationship between the NAO index and the K_E content is registered for the low frequency variations with the periods of 4–8 and 8–16 years;
(ii) if the NAO phase tends to abrupt changes then the impact of these variations on the Eddy kinetic energy content in the mid-latitudes is more significant than for the durational dominance of certain phase;
(iii) the largest coefficients of correlation for the NAO index and Ukrainian precipitation are stated for the periodicities of 2–4 and 4–8 years;
(iv) the 4–8 years variations of precipitation in Ukraine are most likely caused by the synoptic-scale activity forced by the NAO whereas the periodicity of 2–4 years is conditioned by the air-mass processes in the warm season.

Hence we can maintain that method used here allows to identify prominent physical behaviours of large-scale atmospheric dynamics and the spatio-temporal distribution of precipitation over the limited area.

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