Winter Cyclone Regimes Over The North Atlantic

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Abstract

To study regimes of winter cyclones in the North Atlantic, empirical orthogonal function decomposition was applied separately to the frequency, depth and area of cyclones obtained using 6-hourly NCEP/NCAR reanalysis data in 1952–2017 and the developed methodology. The first mode represented the opposite changes of cyclone anomalies in the northern and southern/central North Atlantic. The second mode was characterized by the greatest regional anomalies between its phases over Europe, off its coast and over the Mediterranean. The greatest changes of anomalies for the third modes were in temperate latitudes, both over the ocean and Europe. Linear trends were significant only for the first modes of cyclone parameters. The largest part of variability (74–90% of dispersion) of all cyclone modes corresponded to the periods up to 15 years and was used for spectral analysis, which identified significant spectral peaks: 2.5–3, 4.5, 6 and 8.5 years. These periods coincided with spectral peaks of the main interannual climate signals. Regression analysis allowed to identify the sets of teleconnection patterns responsible jointly for 60–85% of dispersion of the first cyclone modes. The North Atlantic Oscillation and Arctic Oscillation were the main patterns for the first modes of the cyclone parameters. For the second and third frequency modes, the East Atlantic (EA) pattern and a combination of the East Atlantic/West Russia (EA/WR) and Scandinavia patterns played the major role, respectively. As for the third depth and area modes, the association with the EA and EA/WR patterns was shown, respectively.

Introduction

The North Atlantic, along with the North Pacific, is one of the two distinct regions of high cyclonic activities over the Northern Hemisphere, with a secondary center over the Mediterranean (Ulbrich et al. 2009). It is important to study the regimes of North Atlantic cyclones due to the following reasons. Cyclone activity (implying anticyclone activity in antiphase) is a form of general atmospheric circulation in the middle latitudes. Impact of the North Atlantic cyclones is especially prominent in the Atlantic-European region in the cold season when there is an intensification of synoptic activity due to hemispheric temperature gradients. Cyclones are the part of the feedback mechanisms by which large-scale anomalies of global climate signals (ocean and atmosphere interaction) impact regions distant from the North Atlantic, as well as the Black Sea-Mediterranean region (Voskresenskaya and Polonskii 1995; Spanos et al. 2003; Bartholy et al. 2009; Maslova et al. 2010; Nojarov 2013; Krichak et al. 2014). Cyclones lead to meteorological, hydrological and geomorphological anomalies (Lionello et al. 2006; Dayan et al. 2015), resulting in losses of economic, socio-cultural values and human lives. Thus, cyclone regimes determine regional climatic regimes and environmental anomalies.

Currently, for the parameters of cyclones (storm tracks, frequency), an association was shown with the phases of such teleconnection patterns as the North Atlantic Oscillation, Arctic Oscillation and others (Serreze et al. 1997; Pinto et al. 2009; Hofstätter and Blöschl 2019). Teleconnection patterns or climate signals (oscillations / processes) are global processes of interaction in the ocean–atmosphere system, which is the main part of the climate system (Monin 1986). Initially, the indices of these oscillations were calculated as a sea level pressure difference at observation stations associated with the main

atmospheric action centers or energy-active zones of the ocean (Ropelewski and Jones 1987; Trenberth and Hurrell 1999; Hurrell and Deser 2009). Alternatively, they were identified as principal components of geopotential height and sea surface temperature (SST) decomposition (Barnston and Livezey 1987; Enfield and Mestas-Nuñez 1999; Fraedrich et al. 1993). In this regard, depending on the identification method, the same climate signals have different temporal variability and spatial centers of anomalies. For example, for the North Atlantic Oscillation (NAO, the main North Atlantic pattern), two different indices were used in this study, based on station data (Hurrell 1995) and data (results) of the principal component analysis according to Climate Prediction Center (NOAA Center for Weather and Climate Prediction).

Another example is the East Atlantic Oscillation (EA), which is often called a southeastward shifted NAO mode (Moore and Renfrew 2012). Nevertheless, it is orthogonal to the NAO and is the second prominent mode over the North Atlantic (<https://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml>). It differs from the NAO by its connection with subtropical processes (by a position and intensity of the pressure ridge). By analogy with the NAO, the EA structure consisted of a dipole in the north and south of the North Atlantic, covering latitudinal bands from east to west. According to Wallace and Gutzler (1981), the EA spatial structure at 500hPa consisted of three centers of action: to the southwest of the Canary Islands, to the west of the British Isles and near the Black Sea. According to Barnston and Livezey (1987), the EA spatial structure at 700hPa consisted of two centers: to the west of the British Isles and in the south of the Mediterranean Sea. According to Nesterov (2009), Comas-Bru and McDermott (2014), the EA had a single center to the south of Iceland. The EA pattern used in this study was similar to that shown in the Barnston and Livezey (1987) study, but was distinctly different from the EA pattern originally defined by Wallace and Gutzler (1981). Despite different approaches, the main component of the EA manifestations in the European climate (as well as for the other signals) was considered to be the shift of cyclone trajectories or storm tracks (Mikhailova and Yurovsky 2017).

Besides the NAO and EA, according to Climate Prediction Center, the most prominent teleconnection patterns were the following (<https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml>):

- East Atlantic / West Russia pattern
- Scandinavia (SCAND) pattern
- Polar / Eurasia (POL/EUR) pattern
- West Pacific (WP) pattern
- East Pacific-North Pacific (EP-NP) pattern
- Pacific / North American (PNA) pattern
- Tropical / Northern Hemisphere (TNH) pattern
- Pacific Transition (PT) pattern.

These patterns were identified using rotated principle component analysis technique (Barnston and Livezey 1987) applied to standardized 500 hPa geopotential height anomalies.

Below there are those climate patterns which were identified using complex empirical orthogonal function analysis applied to ocean data (SST anomaly) by Enfield and Mestas-Nuñez (1999):

- El Niño–Southern Oscillation (ENSO)
- Pacific interdecadal variability
- Pacific multidecadal variability
- Atlantic multidecadal variability or Atlantic Multidecadal Oscillation (AMO) after Kerr (2005).

As an example of manifestations of these patterns in the North Atlantic, it was shown in (Xie et al. 2005) that leading three empirical orthogonal function (EOF) principal components of hurricane trajectories in the North Atlantic were associated with AMO-like pattern, while the first and third hurricane modes were also associated with ENSO and vertical wind speed shear in the tropical Atlantic, and the second mode was related to NAO and EA pattern. The relationship between five teleconnection patterns (NAO, AO, EA/WR, SCAND and ENSO) and the frequency of occurrence of days with extreme precipitation in the Euro-Mediterranean region was shown in (Krichak et al. 2014). A link between drought events in Europe and NAO was shown in (Tsanis and Tapoglou 2019).

Association of cyclone parameters with teleconnection patterns was usually shown as average values during different phases of oscillations, using a so called composite analysis. The EOF method was used mainly for identification global teleconnection patterns (Barnston and Livezey 1987; Enfield and Mestas-Nuñez 1999), as well as regimes of regional climate anomalies (Fraedrich et al. 1993; Popova 2007; Mikhailova and Yurovsky 2017). As for storm tracks, Lau (1988) applied EOF analysis to the 19-year dispersion of geopotential height to identify regimes of winter storm tracks over the North Atlantic and North Pacific. In this study, EOF analysis was applied to study winter cyclone regimes in the North Atlantic and their temporal variability.

This research was based on the logic of the previous studies (Bardin 2000; Bardin et al. 2015). Bardin (2000) applied EOF method to study regimes of the frequency of January North Atlantic cyclones for the 38-year period (1951–1988), however, there were no assessment of association with the indices of teleconnection patterns in that paper. Later Bardin et al. (2015) applied composite analysis to compare regimes of the Northern Hemisphere cyclones for the positive and negative phases of the main teleconnection patterns. In this study, winter North Atlantic cyclone regimes were identified for the 66-year period (1950–2017) and studied using correlation-regression analysis to show separate and joint contribution on the main teleconnection patterns.

The aim of this paper was to study spatio-temporal variability of the principal components of the frequency, depth and area of winter North Atlantic cyclones and their association with the indices of the

main teleconnection patterns.

This paper addressed mainly three questions: (1) What are the objective regimes of winter cyclone variability in the North Atlantic? (2) What are the estimates of temporal variability of these main regimes? (3) What teleconnection patterns are associated with these regimes?

The advantages of this study are that the modes of cyclones were identified using objective EOF analysis of three parameters (frequency, depth and area), and that the joint contribution of the main teleconnection patterns was shown.

The paper includes the following sections: 2 Data and Methods, 3 Results, 4 Discussion and 5 Conclusions. Results were grouped in the following subsections: 3.1 Composite maps of cyclone anomalies for the leading EOF modes; 3.2 Variability of time series of the principal components; 3.3 Spectral analysis of the high-frequency variability; 3.4 Correlation analyses with teleconnection indices. Description of the methods was also grouped accordingly.

Data And Methods

Northern Hemisphere cyclones and their parameters were identified using 6-hourly NCEP/NCAR reanalysis data sets (Kalnay et al. 1996) on 1000 hPa geopotential height for the period 1952–2017. Cyclone identification methodology (Bardin 1995) was based on allocation of a low pressure system delimited by the first closed isobar contour. The methodology was tested for example in the international project IMILAST (Neu et al. 2013).

For the empirical orthogonal function (EOF) analysis, the cyclone parameters (frequency, depth and area) were averaged for the winter season (December, January, February) in the North Atlantic region within the boundaries: 27.5° N–72.5°N, 90°W–15°E on a 7.5°×15° regular grid. Using the standard EOF decomposition, the principal components or modes / regimes of cyclone anomalies were identified for each analyzed parameter.

2.1 Composition of maps of cyclone anomalies

For the three leading cyclone modes, the composition of the frequency / depth / area anomalies for the strong and weak cases of each mode was obtained similar to Bardin (2000) and Trigo et al. (2000). Cyclone anomalies (normalized to standard deviation, σ) were averaged over 10 years for the highest positive and 10 years for the lowest negative principal component coefficients and then subtracted to show differences between them (composition for the highest positive years minus composition for the lowest negative years).

Composite maps were obtained for the winter averaged (December–February) cyclone parameters (frequency, depth and area) over the Atlantic–European region within the boundaries: 30°N–75°N, 90°W–90°E on a 5°×10° regular grid.

2.2 Analysis of variability of cyclone regimes

Variability of the time series (1952–2017) was analyzed for the three leading principal components of the EOF modes frequency, depth and area of winter cyclones in the North Atlantic. For the initial time series, linear trends were estimated. Then the series were filtered with a 15–16-year threshold of to obtain higher-frequency and lower-frequency parts of variability. This threshold is about a fourth of the 66-year time series (1952–2017) and it was chosen to exclude periods which significance cannot be identified (for a given row length) using spectral analysis.

2.3 Spectral analysis

A spectral (Fourier) analysis was carried out to identify the typical periods of variability for the different regimes of the North Atlantic cyclones. We used the method of averaging periodograms with the Parzen window (Parzen 1962). The window width was taken equal to 20 and the number of frequency points was 100. Time series of principal components of the EOF modes were preprocessed: detrended and filtered saving higher-frequency variability with periods up to 15 years.

2.4 Correlation analysis

Synchronous linear Pearson's correlation analyses was done for the winter season between the time series of the three leading EOF modes of the winter North Atlantic cyclones and indices of the following teleconnection patterns retrieved from

(<https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml>):

- the North Atlantic Oscillation (NAO);
- the East Atlantic Oscillation (EA);
- the East Atlantic / West Russia (EA/WR) pattern;
- the Scandinavia pattern (SCAND);
- the Polar / Eurasia pattern (POL/EUR);
- the Tropical / Northern Hemisphere (TNH) pattern;
- the Pacific / North America (PNA) pattern;
- the West Pacific oscillation (WP).

Indices of the following teleconnection patterns were retrieved from the other National Oceanic and Atmospheric Administration (NOAA) sites:

- The Arctic Oscillation (AO) retrieved from (https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao_index.html)

- The Atlantic Multidecadal Oscillation (AMO) retrieved from (<https://psl.noaa.gov/data/timeseries/AMO/>)
- The Southern Oscillation (SO) (<https://www.cpc.ncep.noaa.gov/data/indices/soi>).

Additionally, we involved the North Atlantic Oscillation index (Hurrell 1995) based on standard pressure observations (NAO-H) retrieved from (<https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based>).

The significance of the correlation coefficients was identified using the Student's *t*-test:

$$t = |r| \cdot \frac{\sqrt{n-2}}{\sqrt{1-r^2}},$$

where *t* is Student's criterion, *r* is correlation coefficient, *n* is row length.

Regression analysis was used to show joint contribution of the teleconnection indices to the variability of cyclone modes.

Results

Table 1 shows the percentage contribution of the ten leading EOF modes to the dispersion of the winter cyclone parameters. As for the depth of cyclones, the total contribution of the ten leading EOF modes was about 60%. As for the frequency and area of cyclones, it was about 65%. The contribution of the first mode reached 14%, 10.8%, 14.8% for the frequency, depth and area of cyclones, respectively. The contribution of the leading three modes reached 33.4% for the frequency of cyclones, 26.5% for the depth and 31.8% for the area of cyclones.

These values for the three leading modes were considered reliable because they corresponded with an accuracy of 1% to those obtained by Bardin (2000), who used similar methods and data, but shorter time series (1951–1988) only for January, and complied with accuracy of 1–5% to those obtained by Lau (1988), who identified winter storm tracks in the North Atlantic by a root-mean-square deviation of a geopotential height field. This study focused on the three leading modes because they reliably represented the winter cyclone regimes in the North Atlantic.

Table 1
Contribution of the ten leading EOF
modes to the dispersion of cyclone
parameters, %

Mode	Frequency	Depth	Area
1	14,0	10,8	14,8
2	10,5	8,3	8,9
3	8,9	7,4	8,1
4	6,1	6,1	7,1
5	5,3	5,4	5,8
6	4,9	4,9	4,8
7	4,2	4,4	4,6
8	3,8	4,4	4,4
9	3,5	3,9	3,7
10	2,9	3,7	3,4
Σ	64,2	59,2	65,7

3.1 Composite maps of cyclone anomalies for the leading EOF modes

To describe how cyclone anomalies differ for the prevailing regimes, the composite maps of cyclone parameters were obtained for the strong and weak years (extrema) of each mode and subtracted one from another (Fig. 1–9). On the one hand, these composite maps corresponded to the regimes/modes of cyclones over the North Atlantic. On the other hand, regional anomalies were interpreted as manifestations of different cyclone regimes/modes.

The spatial distribution of the three leading EOF modes of the *frequency* of winter cyclones in the North Atlantic (Fig. 1, 2, 3) resembled the structure of the modes of January cyclone frequency (Bardin 2000). In one phase of the first leading mode (conventionally negative), the maximum frequency of cyclones over the North Atlantic was to the east of Newfoundland (Fig. 1a) and, in the other phase (conventionally positive), it was to the west of Iceland. Regional frequency maxima were over the Mediterranean Sea and at the mouth of the Baffin Bay in both phases (Fig. 1a,b), and at the mouth of the Hudson Bay in positive phase (Fig. 1b). The largest differences between these two phases (in standardized anomalies) (Fig. 1c) were located over the North Atlantic in a strong system ($> 1.5-2\sigma$) centered to the west of Iceland accompanied by a little weaker (1.5σ) but larger system of the opposite sign between $40^{\circ}-50^{\circ}\text{N}$ with a center over East Atlantic. However, the first mode of winter storm tracks (Lau 1988) was characterized by

a different dipole structure with centers in the central and eastern parts of the ocean. Nevertheless, that structure also showed the north–south shift of cyclones from their climatological position (Lau 1988).

The spatial structures of the second (Fig. 2) and third (Fig. 3) frequency modes over the ocean resembled that of the first mode but with lesser gradients and systems generally shifted to the south (anomalies of the difference $> 1\sigma$).

In the both phases of the second frequency mode, the maximum frequency over the North Atlantic was to the southeast of Iceland (Fig. 2a,b). The highest frequency centers were regional: over the Mediterranean Sea in the negative phase (Fig. 2a) and at the mouth of the Baffin Bay in the positive phase (Fig. 2b). The largest anomalies of the difference between the phases (Fig. 2c) were centered over the Mediterranean Sea, in the south of Italy. As for the North Atlantic, there was a stronger system of anomalies centered to the south of Iceland accompanied by a weaker system of the opposite sign with a center located southwest of the Azores (Fig. 2a). Thus, in the temperate latitudes of the North Atlantic, there was one strong system in the second frequency mode. From this point of view, the described structure resembled a monopole structure of the second mode of January cyclones (Bardin 2000) and winter storm tracks (Lau 1988). According to Lau (1988) such a structure was close to the climatological position of the main trajectories of cyclones and identified an increase or decrease in frequency without changing the spatial position of the trajectories.

In the third frequency mode, maximum frequency centers were located similarly in the both phases: over the North Atlantic to the southwest of Iceland, and regionally at the mouth of the Baffin Bay and over the Mediterranean Sea, but these centers were stronger in the positive phase (Fig. 3b). In this regard, as for the anomalies of the difference between the phases, over the North Atlantic, there was a stronger system centered to the southeast of the Azores (reaching 1.5σ) and accompanied by a weaker system (more than 1σ) with a center of the opposite sign located to the southwest of Iceland. In contrast to this dipole structure of the third frequency mode of winter cyclones in this study, a structure of the third mode of winter storm tracks by Lau (1988) was characterized by multiple centers of alternating polarity, resembling the wave modulation of vortex activity with a change in amplitude above and below normal in certain parts of the ocean. Similar structures were obtained in this study for the second and third depth and area modes (Figs. 4a and 7a).

Our results can be interpreted to mean that mentioned systems for the three leading frequency modes were associated with the semi-permanent centers of atmospheric pressure: the Icelandic Low and Azores High. Pressure seesaw between these centers forms the North Atlantic Oscillation (NAO) (Hurrell and Deser 2009). Thus, we expected these leading three frequency modes to be associated with the NAO index. Nevertheless, there were some features for the different modes. Centers of anomalies for the first frequency mode were characterized by increased gradients and were located farther north than those for the second and third mode. This means that the spatial pattern for the first mode was more like the NAO and for the second and third modes was more like the EA or EA/WR.

The stronger one of the opposite systems over the North Atlantic was the northern one (near Iceland) for the first and third modes and the southern one (near the Azores) for the second mode. This could mean that larger manifestations and, possibly, influence came from the Icelandic Low and subpolar latitudes in the first and third modes and from the Azores High and subtropical latitudes in the second mode.

Another common feature of the second and third frequency modes was increased anomalies over the Mediterranean, near Italy. It evidenced that the largest regional manifestations over the Mediterranean region were not for the first frequency mode of the North Atlantic cyclones, but for the second and third modes. The region of maximum values was also found over the Mediterranean Sea for the third frequency mode of January cyclones (Bardin 2000).

Figures 4, 5, 6 show spatial distributions of the three leading EOF modes of the *depth* of winter North Atlantic cyclones. In the first depth mode, maximum depth center was between Iceland and the British Isles in the negative phase (Fig. 4a) and to the southeast of Greenland in the positive phase (Fig. 4b). As for the anomalies of the difference between the phases (Fig. 4c), there were two opposite systems: one to the east of Iceland ($> 1\sigma$) and another ($> 1-1.5\sigma$) to the west of the Bay of Biscay. In the second depth mode, center of the maximum values was near southern Iceland in the negative phase (Fig. 5a), over the Labrador Sea and to the northwest of Ireland in the positive phase (Fig. 5b). The anomalies of the difference between the phases had two maxima ($> 1.5\sigma$): over Germany and near southwestern Ireland (Fig. 5c). In the third depth mode, centers of the maximum values were diagonally located spreading from the north of Newfoundland to Iceland in the negative phase (Fig. 6a) and more zonally oriented spreading from the Labrador Sea to the northwest of Ireland in the positive phase (Fig. 6b). The centers of the maximum anomalies of the difference between the phases ($> 1.5\sigma$) were: in the middle of the ocean between the Labrador Sea and the British Isles; near the northeast of the British Isles (Fig. 6c).

In contrast to the dipole structure of anomalies over the North Atlantic for the first depth mode (Fig. 4c), the centers of anomalies for the second (Fig. 5c) and third (Fig. 6c) depth modes were more regional and localized, respectively. But the common features for the three depth modes were that, in the negative phase, maximum depth centers were diagonally spread from Newfoundland to Iceland (Fig. 4a, 5a, 6a), and, in the positive phase, the depth values were greater and more zonally spread from the south of the Labrador Sea towards the north of the British Isles (Fig. 4b, 5b, 6b). In this regard, all three depth modes resemble a scheme of north to south shift of storm tracks over the North Atlantic (typical for the NAO and EA).

Besides, one distinctive feature of the second mode was from the first and third modes that the centers of its anomalies of the same sign did not occupy the entire latitudinal band over the North Atlantic, but divided the region meridionally: negative anomalies were in the northwest and southwest and positive anomalies were over the eastern coast, near the British Isles (Fig. 5c). A dipole north to south structure for the second depth mode was observed only over the northeastern part of the North Atlantic: negative anomalies were over Iceland and Norwegian Sea and positive anomalies were near southwestern Ireland and Germany, resembling the structure of the NAO localized only in the northeast of the North Atlantic.

Figures 7, 8, 9 show spatial distributions of the three leading EOF modes of the *area* of winter North Atlantic cyclones. In the negative phase of the first area mode (Fig. 7a), maximum values were located over the Greenland and in a couple of weaker regional centers: over the Labrador Peninsula, over the north of the North Sea and over Poland. In the positive phase (Fig. 7b), centers of maximum area were located more or less latitudinally from the Labrador Peninsula eastward, bending to the south of Ireland. Anomalies of the difference between the phases (Fig. 7c) formed two opposite systems in the southwestern and northeastern parts of the North Atlantic: one strong system ($> 2\sigma$) off the European coast, to the southwest of Ireland and a weaker opposite system (about 0.5σ) extending from Iceland to Norway. In the second area mode, center of maximum values was over the North Sea and spread westward to the Labrador Sea in the negative phase (Fig. 8a); and was over the Labrador Peninsula, Newfoundland and to the south of Greenland in the positive phase (Fig. 8b). Anomalies of the difference between the phases (Fig. 8c) were focused in regional maxima ($> 1\sigma$): over Greenland, the North Sea and southeastern Black Sea. In the negative phase of the third area mode (Fig. 9a), there were neighboring centers of maximum values over the North Atlantic: at the coast of Labrador Peninsula and to the west of the British Isles, and a regional center over Poland. In the positive phase (Fig. 9b), centers of the maximum area were weaker than in the negative phase and located over the north of the North Sea and over the Labrador Peninsula spreading eastward to the south of Iceland. The maximum anomalies of the difference between the phases ($> 0.75-1\sigma$) (Fig. 9c) were centered over the North Atlantic to the west of the British Isles and to the southwest of the Azores, and were centered regionally over the coast of the Labrador Peninsula and over Poland.

The results for the spatial distribution of the three leading EOF modes of the depth and area of winter North Atlantic cyclones can be interpreted as follows. The structure of the first depth and area modes was very similar. If we assume that the centers of these modes were associated with the centers of action of the atmosphere, then the latter approached each other and were characterized by increased gradients. It was likely that the Icelandic minimum was shifted towards the North Sea and Norwegian Sea, and the Azores maximum was shifted northeast towards the coast of Europe.

Common feature of the second and third depth and area modes was that their systems, despite strong gradients, were not extensive and did not occupy the entire latitudinal belt over the North Atlantic as a rule, but were localized regionally. Common positions of the regional systems of anomalies were the eastern North Atlantic, to the west of the British Isles, the North Sea, Europe, Greenland, Labrador Peninsula. The strongest systems of the second depth and area modes (Figs. 5c, 8c) were double-centered near the western coast of Europe, onshore and offshore.

The strongest system of the third depth mode geographically corresponds to the northern branch of the North Atlantic Current reaching the Northern Sea and could be associated with the temperature anomalies of the current. The location of the systems of the third area mode could indicate their association both with the centers of atmospheric action over the ocean centered in the east and the subtropics of the North Atlantic (likely the EA), and with the center of action over the Western Mediterranean (likely the

Mediterranean Oscillation after Conte et al. (1989), Maheras et al. (1999), Dunkeloh and Jakobeit (2003) or Western Mediterranean Oscillation after Martin-Vide and Lopez-Bustins 2006).

3.2 Variability of time series of the principal components

Figure 10–12 show the time series (1952–2017) of the principal components of winter cyclones in the North Atlantic, linear trends and low-frequency filtered row with periods over 16 years (see Data and Methods section). All time series were characterized by a substantial part of interannual variability and the by quasiperiodic multidecadal variability and linear tendencies. According to Table 2, linear trends were significant (on the 90–99% level) only for the first frequency (upward), depth (downward) and area (downward) modes. Their contribution to the total dispersion exceeded 40%, 7% and 14% for the frequency, depth and area principal components of the first modes, respectively. Contribution of the high-frequency filtered rows to the dispersion of the initial series generally exceeded 80%. Only for the first depth and area principal components, it was 75% and 74%, respectively. It means that the first depth and area modes were characterized by the highest contribution of the low-frequency variability, reaching 25 and 26%, respectively. As for the frequency modes, contribution of the low-frequency filtered row was a little higher for the second (16,8%) than that for the first (16%) principal component.

Table 2 Characteristics of linear trends of the leading three principal components of the EOF modes of winter North Atlantic cyclones (PC-1, PC-2, PC-3) and coefficients of determination (contribution to the dispersion of the nonfiltered series) of the high-frequency (≤ 15 years) and low-frequency (≥ 16 years) filtered rows: $k(\text{lin})$ – linear trend coefficient; p -value – level of significance, %; $R^2(\text{lin})$ – linear trend determination coefficient, %; $R^2(\text{low})$ – coefficient of determination of the low-frequency filtered row, %; $R^2(\text{high})$ – coefficient of determination of the high-frequency filtered row, %

Principal component	k(lin)	p-value	R ² (lin)	R ² (low)	R ² (high)
<i>Frequency (F)</i>					
F-PC1	+0,0009	89,92	41,5	16,0	84,0
F-PC2	+0,0002	41,71	0,47	16,8	83,2
F-PC3	+0,0003	48,26	0,66	11,6	88,4
<i>Depth (D)</i>					
D-PC1	-0,9458	97,08	7,21	25,0	75,0
D-PC2	-0,5231	81,38	2,71	18,5	81,5
D-PC3	+0,4345	73,65	1,95	13,7	86,3
<i>Area (A)</i>					
A-PC1	-0,0389	99,81	14,03	26,0	74,0
A-PC2	-0,0002	1,86	0,00	14,4	85,6
A-PC3	+0,0099	69,48	1,64	10,2	89,8

3.3 Spectral analysis of the high-frequency variability

The periods of interannual variability of the regimes of the North Atlantic winter cyclones were identified using spectral analysis (see Data and Methods section). Figure 13 show the averaged periodograms of the high-frequency filtered principal components of the leading three EOF modes (PC1, PC2, PC3) of the frequency, depth and area of cyclones (F, D и A, respectively). Significant spectral peaks were identified at the following periods according to Table 3.

Table 3
Periods (years) of significant spectral peaks of the high-frequency filtered principal components of the leading three EOF modes (PC1, PC2, PC3)

	Frequency	Depth	Area
PC1	8,3; 3,1	8; 4,3	8,6; 4,5; 2,6
PC2	5,9; 2,5	8; 4,3; 2,5	6,7; 2,7
PC3	4,8	5,7; 3,4	7,1; 3,5; 2,3

For the cyclone frequency modes (Fig. 13a), the most energy was concentrated at the first mode peaks of 8.3 and 3.1 years. Less energy was at the third mode peak of 4.8 years, then at the second mode peaks of 2.5 years and 5.9 years.

As for the cyclone depth modes (Fig. 13b), the highest energy peak was for the second mode at a period of 2.5 years. For the first and third depth modes, the highest peaks were at the periods of 8 and 5.7 years, respectively. In addition, for all depth modes, peaks at 3.5–4.5 years were identified, but they had more energy for the first and third modes.

For the area of cyclones (Fig. 13c), two groups of close peaks were identified: one at the periods 2.3–2.7 years with the highest energy peak of the second area mode and another group at the periods about 7–8 years with the highest peak of the first mode (8.6 years). In addition, a peak at 4.5 years was also identified for the first area mode.

Close spectral periods were typical for the teleconnection patterns. Gamiz-Fortis et al. (2002) showed that the main spectral peaks of the winter North Atlantic Oscillation were for the periods of 2.4; 4.8; 7.7 years. Seip and Gron (2019) identified that the El Nino–Southern Oscillation major spectral peaks were 3–4 and 7–8 years.

3.4 Correlation analyses with teleconnection indices

Further, we addressed the question what physical mechanisms could be associated with the main modes of the winter North Atlantic cyclones from the point of view their correlation with teleconnection patterns. Table 4 shows linear correlation coefficients (r) between the EOF principal components and winter-averaged teleconnection indices. We used coefficient of determination r^2 to estimate the proportion of explained dispersion.

The first frequency mode was characterized by a strong positive correlation with the indices of the North Atlantic and Arctic Oscillations ($r = 0.78–0.87$ at 99.9% confidence level) with the strongest association with the NAO-H index based on station data (Hurrell 1995) and proportion of explained dispersion, r^2 , reaching 75.7%. Correlation coefficients between the first frequency mode of winter cyclones and monthly indices were significant for the December–March NAO indices and November–February AO indices (not shown). In addition, there was a negative correlation between the first frequency mode and the Scandinavia Oscillation ($r^2 = 11\%$, 99% level) and a positive correlation with the East Atlantic/West Russia Oscillation ($r^2 = 4\%$, 90% level). According to the results of multiple linear regression, the combined effect of the NAO-H, AO, EA/WR and SCAND indices on the first frequency mode was estimated by the coefficient of regression $R = 0.92$ and coefficients of determination: $R^2 = 84.4\%$, normalized $R^2 = 83\%$.

The second frequency mode was characterized by a positive correlation with the East Atlantic Oscillation ($r^2 = 41\%$, 99.9% level) and with the Arctic Oscillation ($r^2 = 6\%$, 90% level), and by a negative correlation with the Tropical Oscillation of the Northern Hemisphere ($r^2 = 9\%$, 95% level). Combined effect of these AO, EA and TNH indices was estimated by the coefficient of regression $R = 0.69$ and coefficients of determination: $R^2 = 47.5\%$, normalized $R^2 = 45\%$.

For the third frequency mode, there were significant at the 99.9% level negative correlation with the East Atlantic/ West Russia oscillation index ($r^2 = 22\%$,) and positive correlation with the Scandinavia pattern

index ($r^2 = 17.6\%$). Besides, correlations, significant at 95% confidence level, were positive with the NAO-H index ($r^2 = 9\%$) and the East Atlantic Oscillation index ($r^2 = 8\%$), and negative with the Polar-Eurasia Oscillation index ($r^2 = 6\%$). Combined effect of these indices (NAO-H, EA, EA/WR, POL/EUR and SCAND) was estimated by the coefficient of regression $R = 0.73$ and coefficients of determination: $R^2 = 53\%$, normalized $R^2 = 49\%$.

The first depth and area modes were characterized by similar significant correlation coefficients and sets of associated teleconnection indices. At the 99.9% level, there were negative correlation coefficients with the North Atlantic Oscillation indices and the Arctic Oscillation index ($r = -0.69 - -0.78$). The contribution to dispersion of these modes was maximal for the NAO indices ($r^2 = 58-61\%$). For the Arctic Oscillation index, it reached 48% for the first depth mode and 55% for the first area mode. Correlation coefficients with monthly NAO and AO indices were significant from November to March for the first depth mode and from November to February for the first area mode (not shown). Additionally, the first depth and area modes were positively correlated with the Scandinavia Oscillation index ($r^2 = 8\%$, 95% level for the depth; $r^2 = 5\%$, 90% level for the area) and negatively correlated with the Tropical Oscillation index ($r^2 = 4\%$, 90% level for the depth, $r^2 = 15\%$, 99% level for the area). According to the results of multiple linear regression, the combined effect of these NAO, AO, SCAND, TNH indices on the first depth / area modes was estimated by the coefficient of regression $R = 0.79 / 0.81$ and coefficients of determination: $R^2 = 62\% / 65\%$, normalized $R^2 = 60\% / 63\%$.

The third depth mode was characterized by a significant positive correlation with the East Atlantic Oscillation ($r^2 = 16.8\%$, at 99.9% level) and the Tropical Oscillation ($r^2 = 8.4\%$, at 95% level). Combined effect of these indices (EA, TNH) was estimated by the coefficient of regression $R = 0.48$ and coefficients of determination: $R^2 = 22.6\%$, normalized R^2 about 20%. As for the third area mode, there was a significant (95% level) positive correlation with the East Atlantic / West Russia pattern index ($r = 0.26$, normalized $R^2 = 6\%$).

For the second depth and area modes, no significant correlations were found for the chosen winter teleconnection indices.

Table 4 Correlation coefficients for the winter season between principal components of the leading three modes (PC1, PC2, PC3) of cyclone frequency, depth and area (F, D and A, respectively) and indices of the main teleconnection patterns: the North Atlantic Oscillation (NAO), the North Atlantic Oscillation after Hurrell (1995) (NAO-H), Arctic Oscillation (AO), the East Atlantic / West Russia pattern (EA/WR), the Scandinavia pattern (SCAND), the East Atlantic Pattern (EA), the Polar / Eurasia pattern (POL/EUR), the Tropical / Northern Hemisphere pattern (TNH). Significant coefficients are highlighted in color*. R_{mult} – coefficient of multiple regression; R^2 – coefficient of determination, which shows the proportion of explained dispersion associated with the teleconnection indices with colored coefficients; R^2_{norm} – normalized R^2

	f-pc1	d-pc1	a-pc1	f-pc2	d-pc2	a-pc2	f-pc3	d-pc3	a-pc3
NAO	0.78	-0.78	-0.76	0.16	-0.03	-0.17	0.18	0.12	-0.09
NAO-H	0.87	-0.76	-0.78	0.13	-0.03	-0.16	0.30	0.08	-0.12
AO	0.82	-0.69	-0.74	0.24	-0.06	-0.14	-0.12	0.10	0.04
EA/WR	0.21	-0.17	-0.19	0.00	-0.10	0.02	-0.47	0.01	0.26
SCAND	-0.33	0.29	0.23	-0.06	0.11	-0.06	0.42	0.11	-0.06
EA	-0.14	0.08	-0.11	0.64	-0.17	-0.02	0.28	0.41	-0.09
POL/EUR	0.09	0.12	0.10	-0.18	-0.02	-0.01	-0.25	-0.04	0.20
TNH	0.20	-0.21	-0.39	0.30	-0.07	-0.08	0.13	0.29	-0.18
R_{mult}	0.92	0.79	0.81	0.69			0.73	0.48	0.27
R^2	84.4	62.4	65.4	47.5			53	22.6	7.5
R^2_{norm}	83.1	59.9	63.1	44.9			49.3	20	6

*

90%	95%	99%	99,9%
90%	95%	99%	99,9%

Then, we decided to check how the second depth and area modes were correlated with the surface temperature and pressure over the North Atlantic region (Figs. 14, 15). The second depth mode negatively correlated with the sea surface temperature (SST) in the North Atlantic with the strongest correlation (<-0.3) near the Azores Isles (Fig. 14a). Significant correlation between the second depth mode and sea level pressure was over the Western Mediterranean region (Fig. 14b). The second area mode negatively correlated with surface temperature and sea level pressure (SLP) off the eastern shores of North America (Fig. 15).

So, the results of the correlation analysis showed that the second depth mode was associated with the SST in the typical location of the Azores High center of action. As for the second area mode, it was associated with SST and SLP in the Gulf Stream region and off the eastern shores of North America.

Additionally, a correlation analysis was carried out with monthly Atlantic Multidecadal Oscillation index and seasonal North Pacific and Southern Oscillation indices. It showed significant (90% level) negative correlation between the second depth mode and January–February AMO index ($r^2 = 4.8\%–5.7\%$). Also there were significant negative correlation coefficients between:

– the third depth mode and the autumn Pacific / North America index ($r^2 = 7.8\%$, 95% level);

- the first frequency mode and the spring Southern Oscillation index ($r^2 = 4.4\%$, 90% level);
- the second frequency mode and the autumn Pacific / North America index ($r^2 = 4.4\%$, 90% level);
- the third frequency mode and summer Southern Oscillation ($r^2 = 4.8\%$, 90% level);
- the third area mode and autumn West Pacific Oscillation index ($r^2 = 5.3\%$, at 90% level).

Discussion

Our results showed that the NAO (to a greater extent) and AO (to a lesser extent) were the determining predictors for the first modes of the frequency, depth and area of winter cyclones. In addition to a strong correlation, this was evidenced by the location of major systems of the EOF spatial distribution, which corresponded to the Icelandic Low and Azores High, as well as by the periods of spectral peaks and regions of manifestations.

This conclusion is supported by the results by Lau (1988) who showed that atmospheric circulation associated with the modes of storm tracks resembled the spatial structure of the NAO. Also there is a general consistency with the previous results by Bardin et al. (2015) which showed changes in the mean long-term frequency, depth and area fields of winter cyclones in different NAO phases.

The involvement of other teleconnection patterns, besides the NAO and AO, made it possible to increase the explained dispersion to more than 80% for the first frequency mode (involving SCAND and EA / WR) and to more than 60% for the first depth and area modes (involving SCAND and TNH). Lau (1988) showed that, for the first mode of winter storm tracks, there was a negative association with the East Atlantic pattern after Wallace and Gutzler (1981), which differed from the EA index in this study.

For the second frequency mode and third depth mode, the East Atlantic Oscillation was the main defining pattern. As for the second frequency mode of January cyclones, the association with EA phases could be traced from the papers by Bardin (2000), Bardin et al. (2015). In contrast, Lau (1988) showed the association of the second mode of winter storm tracks with the West Atlantic and Eurasia patterns after Wallace and Gutzler (1981). Moreover, the West Atlantic mode manifested in a change in the density of storm tracks in the western North Atlantic, and the East Atlantic mode led to a north–south shift of storm tracks in the eastern North Atlantic (Lau 1988).

Combination of the EA and TNH increased the explained dispersion up to 50% for the second frequency mode and up to 25% for the third depth mode. The largest regional manifestations for the second frequency mode of winter cyclones were over the central Mediterranean in contrast to manifestations shown by Bardin (2000) over the eastern North Atlantic for the second frequency mode of January cyclones. For the cyclone third depth mode, the largest manifestations were in the middle part of the North Atlantic Current and over the North Sea.

The absence of significant correlations for the second depth and area modes with the analyzed teleconnection indices could be explained by the locality and multipolarity of their main spatial systems (Fig. 5a, 8a). The main North Atlantic teleconnection patterns, such as the NAO, AO and EA are characterized by the north-south dipole of anomalies covering the North Atlantic in a latitudinal band from east to west. As for the second depth and area modes, their spatial structures included both the north-south and west-east dipoles. It should be mentioned that these second depth and area modes were characterized by a pronounced interannual variability of 2.5–2.7 years, which was characterized by the highest energy in comparison with the spectral peaks of all other depth and area modes. This could indicate that some processes were imposing this interannual variability. First, we noticed that combination of the centers of action of the West Atlantic and East Atlantic patterns defined by Wallace and Gutzler (1981) could resemble a multipolar structure of the second depth and area modes. We checked their correlation but did not obtain significant coefficients. Then, we checked synchronous correlation (for winter) with many other climate patterns and the strongest correlation was between the second depth mode and AMO index ($r = -0.24$), Atlantic tripole after Deser and Michael (1997) ($r = -0.22$), Caribbean index after Penland and Matrosova (1998) ($r = -0.22$), Mediterranean Oscillation after Conte et al. (1989), Maheras et al. (1999), Dunkeloh and Jakobeit (2003) ($r = -0.24$); and between the second area mode and Mediterranean Oscillation ($r = +0.23$). Finally, we decided to obtain spatial correlations with surface temperature and pressure to identify centers of action associated with time series of the second depth and area modes (Figs. 14, 15). And such centers were SST center in the region of the Azores Isles for the second depth mode and SLP and SST centers off the coast of North America for the second area mode.

For the third frequency and third area modes, the East Atlantic / West Russia pattern could be considered as the main predictor, but with different connection magnitude and sign. More than 50% of the dispersion of the third frequency mode was explained by the combination of the EA/WR with SCAND, NAO-H, EA and POL/EUR. The third area mode was associated with the only EA/WR, which explains 6,7% of its dispersion.

This result for the third frequency mode is supported by the following results. A spatial structure of the third frequency mode of January cyclones (Bardin 2000) resembled the mean long-term frequency field of winter cyclones for the phases of the East Atlantic / West Russia pattern and Scandinavia pattern (Bardin et al. 2015). Lau (1988) showed association of the third mode of winter storm tracks with the East Atlantic patterns after Wallace and Gutzler (1981).

Conclusions

Cyclone regimes in the North Atlantic region in winter, their variability and relationship with the main teleconnection patterns were analyzed using 6-hourly NCEP / NCAR reanalysis data in 1952–2017. The results of this study improved understanding of the objective regimes of winter cyclone anomalies in the North Atlantic, their temporal and spatial variability and association with the main teleconnection patterns.

Contribution of the three leading principal components to the dispersion of winter cyclones in the North Atlantic was 33.4% for the frequency, 26.5% for the depth and 31.8% for the area. The spatial structure and sign of the frequency, depth and area differences were similar for the same EOF modes, especially regarding the depth and area differences. However, regional features occurred due to contour configuration and the shift of the centers of the largest differences.

Centers of the first modes of winter cyclones were confined to the typical or shifted location of the centers of action of the North Atlantic atmosphere: the Azores High and Icelandic Low. Centers of the second depth and area modes were multiple and local, which could explain the poor association with teleconnection patterns. The spatial structure of the second frequency mode showed maximal differences over the Mediterranean.

Linear trends were significant only for the first modes of cyclone parameters. The positive linear trend determined the largest part of the dispersion (40%) for the first frequency mode. Negative linear trends of the first depth and area modes determined less than 8% and 15% of their dispersion, respectively.

Filtration of the EOF principal components into high-frequency (up to 15 years) and low-frequency (over 16 years) parts of variability showed the following. The highest contribution of the low-frequency variability was for the first depth and area modes and explained about a fourth of their dispersion. The predominant part of variability (74–90% of the dispersion) of the modes of all cyclone parameters corresponded to the periods up to 15 years and was used for spectral analysis, which identified significant spectral periods: 2.5–3, 4.5, 6 and 8.5 years. Interannual teleconnection patterns, such as the North Atlantic and Southern Oscillations, were characterized by the spectral peaks on similar periods (Gamiz-Fortis et al. 2002; Seip and Gron 2019).

Regression analysis allowed to identify sets of teleconnection patterns responsible jointly for 60–85% of the dispersion of the first modes of cyclone parameters. Such teleconnection patterns as the NAO and AO can be considered the main patterns for the first modes of the cyclone parameters. For the second and third frequency modes, the EA and combination of EA/WR and SCAND patterns played the major role, respectively. As for the third depth and area modes, the association with the EA and EA/WR patterns was shown, respectively.

Our study promotes knowledge of the periods and patterns of cyclone regimes in the North Atlantic region in winter and generally contributes to understanding the mechanisms of global and regional climate variability. The results could help improve the predictability of cyclone activity on a seasonal basis (for winter), as well as on the interannual and decadal scale.

Declarations

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Conflicts of interest/Competing interests

The authors declare no conflict of interest.

Availability of data and material

Time series of the three leading EOF modes are included as electronic supplementary material. Other associated data will be made available on reasonable request.

Code availability

Not applicable.

Authors' contributions

All authors contributed to the study conception and design. Conceptualization was carried out by Veronika N. Maslova and Elena N. Voskresenskaya. Material preparation, data collection and analysis were performed by Veronika N. Maslova, Mikhail Yu. Bardin and Alexander V. Yurovsky. The first draft of the manuscript was written by Veronika N. Maslova. Review and editing was done by Elena N. Voskresenskaya. All authors read and approved the final manuscript.

Conceptualization: Veronika N. Maslova and Elena N. Voskresenskaya; Methodology: Mikhail Yu. Bardin and Veronika N. Maslova; Formal analysis and investigation: Veronika N. Maslova and Alexander V. Yurovsky; Writing - original draft preparation: Veronika N. Maslova; Writing - review and editing: Elena N. Voskresenskaya; Funding acquisition: Elena N. Voskresenskaya; Resources: Elena N. Voskresenskaya and Mikhail Yu. Bardin.

Ethics approval

Not applicable.

Consent to participate

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Consent for publication

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Figures

Figure 1

Spatial patterns for the first frequency mode: (a) 10-year composite for the negative phase; (b) 10-year composite for the positive phase; (c) anomalies (differences between b and a). Contour interval for (a) and (b) is 0.01.

Figure 2

Spatial patterns for the second frequency mode: (a) 10-year composite for the negative phase; (b) 10-year composite for the positive phase; (c) anomalies (differences between b and a). Contour interval for (a) and (b) is 0.01.

Figure 3

Spatial patterns for the third frequency mode: (a) 10-year composite for the negative phase; (b) 10-year composite for the positive phase; (c) anomalies (differences between b and a). Contour interval for (a) and (b) is 0.01.

Figure 4

Spatial patterns for the first depth mode: (a) 10-year composite for the negative phase; (b) 10-year composite for the positive phase; (c) anomalies (differences between b and a). Contour interval for (a) and (b) is 20 gpm.

Figure 5

Spatial patterns for the second depth mode: (a) 10-year composite for the negative phase; (b) 10-year composite for the positive phase; (c) anomalies (differences between b and a). Contour interval for (a) and (b) is 20 gpm.

Figure 6

Spatial patterns for the third depth mode: (a) 10-year composite for the negative phase; (b) 10-year composite for the positive phase; (c) anomalies (differences between b and a). Contour interval for (a) and (b) is 20 gpm.

Figure 7

Spatial patterns for the first area mode: (a) 10-year composite for the negative phase; (b) 10-year composite for the positive phase; (c) anomalies (differences between b and a). Contour interval for (a) and (b) is 0.25.

Figure 8

Spatial patterns for the second area mode: (a) 10-year composite for the negative phase; (b) 10-year composite for the positive phase; (c) anomalies (differences between b and a). Contour interval for (a) and (b) is 0.5.

Figure 9

Spatial patterns for the third area mode: (a) 10-year composite for the negative phase; (b) 10-year composite for the positive phase; (c) anomalies (differences between b and a). Contour interval for (a) and (b) is 0.5.

Figure 10

The time series of the principal components of the leading three frequency (dimensionless value) EOF modes: (a) the first mode (F-PC1), (b) the second EOF mode (F-PC2), (c) the third EOF mode (F-PC3). A dashed line is a linear trend, a curve is a low-frequency filtered variability with periods over 16 years.

Figure 11

The time series of the principal components of the leading three depth (gpm) EOF modes: (a) the first mode (D-PC1), (b) the second EOF mode (D-PC2), (c) the third EOF mode (D-PC3). A dashed line is a linear trend, a curve is a low-frequency filtered variability with periods over 16 years.

Figure 12

The time series of the principal components of the leading three area (106 sq. km⁻¹) EOF modes: (a) the first mode (A-PC1), (b) the second EOF mode (A-PC2), (c) the third EOF mode (A-PC3). A dashed line is a linear trend, a curve is a low-frequency filtered variability with periods over 16 years.

a

b

c

Figure 13

Averaged periodograms of the high-frequency filtered (≤ 15 years) principal components of the leading three modes (PC1, PC2, PC3) of the winter North Atlantic cyclones: (a) frequency (F); (b) depth (D); (c) area (A).

a

b

Figure 14

Correlation maps between the second depth mode and (a) surface temperature, (b) sea level pressure. Coefficients significant at 80% level exceed 0.2.

Figure 15

Correlation maps between the second area mode and (a) surface temperature, (b) sea level pressure. Coefficients significant at 80% level exceed 0.2.

Supplementary Files

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