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ORIGINAL PAPER

Atlantic Oscillation indices in meridional distribution

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Abstract

The goal of this study was to define new oscillation indices of the Atlantic Ocean covering latitudes of both hemispheres, for the period from 1900 until 2014. Indices described sea level atmospheric pressure (SLP) oscillations between neighbouring cells of global atmospheric circulation (northern and southern Hadley, Ferrel and polar cells) and were calculated using two methods: conventional (based on SLP values in selected stations) and extreme values method (counted using maximum or minimum SLP from adequate areas). Twelve time series of new Atlantic Oscillation indices have been obtained—six conventional and six extreme, which have been presented in continuous form and through selection data by seasons: December–February (DJF), and June–August (JJA). The indices' time series showed similarities in shared maxima and minima moments and long-lasting increasing tendency of five extreme and three conventional indices. There were strong correlations between oscillation indices describing variability in Hadley cells on both hemispheres (conventional 0.593–0.907, extreme 0.088–0.908). A strong correlation occurred between Southern Atlantic and Antarctic South Atlantic Extreme indices (0.668 to 0.979). Overall, stronger connections were found between extreme indices than the conventional ones, and most regularities were found in the Southern Hemisphere oscillations and wintertime indices (DJF for Northern and JJA for Southern Hemisphere). Power spectrum analysis showed major impact of 6- and 12-month periods, as well as less distinct significance of approximately 5.5-year-long interval and its multiples.

1 Introduction

In idealised Earth thermal circulation model to maintain stable conditions, it is necessary to retain radiative equilibrium in which energy absorbed by atmosphere, hydrosphere and lithosphere is counterbalanced by the energy radiated by them. Since solar energy influx on the globe differs significantly depending on latitudes, hemisphere, earth's surface type and time, the imbalance of heat distribution is moderated through air mass movements in the atmosphere and water currents in the world's ocean (Vallis 2006).

Global atmosphere circulation from the equator to the poles can be described through a simplified system of northern and southern circulation cells: Hadley, Ferrel and polar (Fig. 1). In the tropics, air heated up near the earth surface rises to the upper layers of the troposphere and is moved in the direction of poles and the subtropical region cools down. A portion of this air mass drops to the sea level and trade winds drive circulation back to the equator, closing up the Hadley cell. A share of descending air from the upper troposphere is transported further in the polar directions, where it is deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere, creating westerly winds. Mainly due to impact of low pressure areas, in the temperate regions, air is lifted to the upper troposphere and moved in the direction of the equator, creating the Ferrel cell. Part of the air from the upper stream of Ferrel cell is distorted and becomes part of the polar cell in which it is transported further to the poles and cooled down. Eventually, it drops to the surface and is carried back to lower latitudes (Fig. 1).

Variability of air mass circulation in troposphere and adjoined upper level of hydrosphere may be observed through oscillation indices that indicate energy exchange interactions through air pressure systems and oceanic vortices. Phases of oscillation indices (positive, neutral or negative) correspond to specific weather occurrences.

Currently, fluctuations in oscillation indices' time series are analysed in different scales and localisations. These research were pioneered by Sir Gilbert Walker who in the 1930s defined North Atlantic Oscillation (NAO), a bipolar variability of sea level pressure (SLP) between two constant pressure

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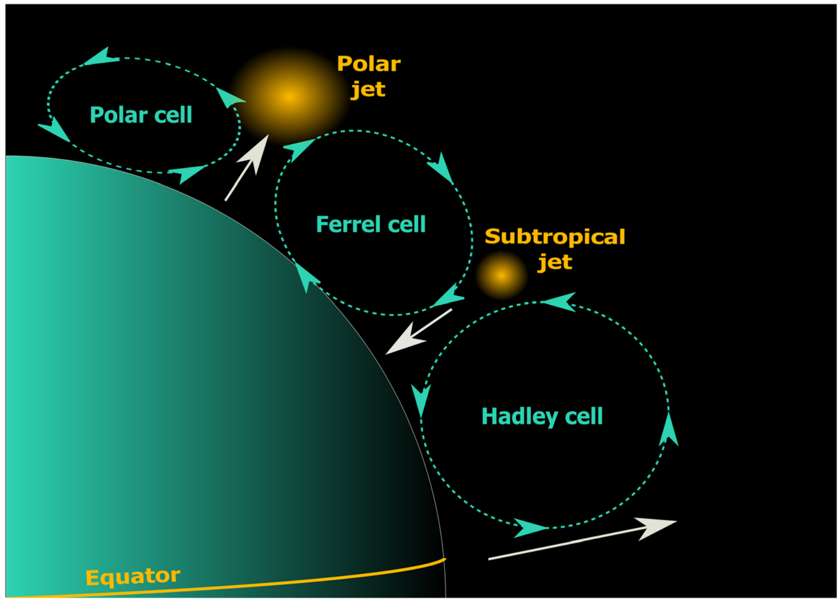


Fig. 1 Global air circulation

centres: Islandic Low and Azores High (Walker and Bliss 1932). High NAO index values are a sign of relatively large pressure differences between two centres that induce westerly winds carrying wet air masses over Europe and consequently pushing cold arctic air to North America. Low NAO index means weakening of this mechanism causing continental weather in northern Europe.

Since the first half of the twentieth century, studies on the North Atlantic Oscillation (NAO) have been based on two-point time series of atmospheric pressure fluctuations in the area of the subtropical Azores High and the Icelandic Low. The research method focused on pairing different measuring stations and extending the observation series (Rogers 1984, Hurrell 1995, Jones et al. 1997, Osborn 2006, Cornes et al. 2013). Thanks to increase in available data and more sophisticated methodology, NAO index time series have been extended, firstly to 1823 (Jones et al. 1997), then to 1692 (Cornes et al. 2013), up to 1500 (Luterbacher et al. 2001), and with a larger degree of uncertainty for the whole duration of Holocene (Rimbu et al. 2003).

Two-point indicators have the advantage of a wide range of historical data availability, but they do not reflect dynamic changes in pressure action centres, so the currently accepted notion is that spatially defined indices (most often based on Empirical Orthogonal Functions (EOF)) provide a more precise description of NAO fluctuation (Jones et al. 1997; Li and Wang 2003). Other approaches to overcome this obstacle include the NAOI index introduced by Li and Wang (2003) using normalised averaged zonally SLP or Borström methodology (2012) determining NAO index with the highest from the Azores High and lowest from the Icelandic Low region SLP values. The advantage of this last solution was used in the submitted work. Nevertheless, the station-based indices were not abandoned, since the correlation coefficient between them and EOF indices was proven to be 0.92 (Hurrell et al. 2003).

In the last four decades of the twentieth century, a significant warming in extratropical areas in the Northern Hemisphere, including Europe, has been observed, coinciding with an unprecedented upward trend in the course of the NAO index (Hurrell 1995; Osborn 2006). Naturally, this increase in the NAO indicator has been linked to the global warming of the area, so it has strongly increased interest in its studies since the 1990s.

Since then, NAO has been considered a factor in the number of occurring anomalies, among others, of surface air temperature (SAT) (Hurrell and Van Loon 1997; Folland et al. 2008; Osborn 2011; Deser et al. 2017), SST (Hurrell 1995; Hurrell and Van Loon 1997; Czaja and Frankignoul 2001), precipitation (Hurrell 1995; Hurrell and Van Loon 1997; Jones et al. 1997; Hurrell et al. 2003; Folland et al. 2008; Deser et al. 2017), wind tracks and magnitude (Hurrell 1995, Hurrell and Van Loon 1997, Osborn 2006, Delworth et al. 2016), cloudiness (Folland et al. 2008), sea ice melting (Hurrell and Deser 2010; Delworth et al. 2016), ocean mixing (Hurrell and Deser 2010, Delworth et al. 2016) and even ecology and economy (Hurrell et al. 2003) of Europe and North America. Despite these efforts, the mechanisms controlling NAO fluctuations are not yet fully understood (Hurrell et al. 2003; Hurrell and Deser 2010) with a multitude of factors being considered, including increasingly anthropogenic impact (Hurrell 1995; Osborn 2006; Folland et al. 2008; Dong et al. 2011; Deser et al. 2017). Oscillation of NAO showed either quasi-variability in periods of 2 to 3 years (Hurrell et al. 2003) and more or less a decade (Hurrell et al. 2003, Li and Wang 2003, Luterbacher et al. 2001).

There is a consensus that North Atlantic Oscillation is a most important pattern influencing weather variability in this region (Osborn 2006; Wanner et al. 2001), but it has been suspected to be a regional emanation for a more complex oscillation in the Atmosphere-Ocean system, so it was analysed in comparison with other known oscillations (definitions in Table 1). With ENSO (Rogers 1984), NAO shared impact over western Atlantic, but had no noticeable communal variability. In other studies, North Atlantic Oscillation has been considered to be a subpart of Arctic Oscillation (Hurrell et al. 2003; Osborn 2006; Dong et al. 2011) especially since 1970s the relation between their indices has risen (Dong et al. 2011).

In the southern part of the Atlantic, Morioka et al. (2011) identified a new mechanism for the growth and decay of SST anomalies in the Southern Atlantic Subtropical Dipol (SASD) between the northeast and the southwest of the South Atlantic, showing growing dipole when the subtropical High South Atlantic migrates south and becomes stronger in late spring. It then causes a positive anomaly of the latent heat stream and reduces the thickness of the mixing layer in early summer. Also, in the southern part of the Atlantic, an oscillation in dominant Southern Atlantic Subtropical High (SASH) was used for the climatic description (Sun et al. 2017). The main study results revealed that SASH achieves the largest available surface ranges and pressure extremes during the solstice months (in June and December). In June, during the winter in the Southern Hemisphere, the SASH is the weakest, closest to the equator and located on the west side of the South Atlantic basin. In December, during the austral summer, it moves farthest towards the South Pole and reaches maximum pressure. This mode occurs in sync with La Niña phase in the Southern Oscillation (ENSO) as well as the positive phase of Southern Annular Mode (SAM) (Sun et al. 2017).

Through analysis in atmosphere fluctuation over other oceans, a multitude of different oscillations and teleconnections have been described, from which the most considered are summed up in Table 1. Continued advancement of the field flourished in using different then SLP variables to describe its lability such as sea surface temperature (SST), mass air movement tendencies and shifts in geopotential height.

It is apparent from Table 1 and referred literature that there is a disproportion between the number of defined oscillation indices on both hemispheres. NAO AMO, PNA and PDO describe only the Northern Hemisphere's dynamics; ENSO, MJO and IOD refer to oscillations in the vicinity of the equator, and only the Antarctic Oscillation represents variations on the southern half of the globe. South Atlantic Subtropical Dipole that describes SST between north-eastern and western parts of the South Atlantic is a fluctuation driven by ocean mixed layer thickness, not directly explained by atmospheric circulation over the ocean. South Subtropical High location and magnitude analysed by Sun et al. (2017) needs further investigation for it to be represented as a numerical descriptor. The lack of precisely defined oscillation indices of southern Atlantic is particularly contrasting with the well-examined northern part of this ocean.

This is important since in spite of the simplified scheme from Fig. 1 atmospheric circulation in the Southern Hemisphere is not identical to that of the Northern, mainly due to an asymmetric distribution of solar energy, uneven thermohaline circulation and disproportion in quantity of land and water between the two.

The overview from Table 1 also shows diversity of the parameters used for calculation of particular indices as well as different methodologies used, which disallows direct comparison of their values, phases and coherence coefficients.

Therefore, there is a demand for oceanic oscillation indices on varied latitudes, calculated using the same variables. Identical methodology and data source promise comparability of homogenous results.

In response to above stipulations, the goal of this study was to calculate oscillation indices on latitudes covering both hemispheres of the Atlantic, consistent in both methodology and data source. The indices were calculated using two earlier formulas: first using standard methods introduced by Walker and Bliss (1932) and simplified by Rogers (1984) and formulated by Hurrell (1995), and the second using the highest SLP values from high pressure centres and lowest SLP values from low pressure centres from selected areas (Boström 2012).

The data source and its validation was also described. In the results section, new indices' time series are presented: their basic statistic, analysis of their long-lasting trends, extreme moments and power spectra. Then, the relations between particular oscillation indices were shown through correlation and coherence investigation. In the final part of the article, the discussion with previous works and conclusions from the whole analysis were summed up and further goals outlined.

2 Materials and methods

In this study, the fluctuations in oscillation indices on Atlantic Ocean were examined throughout 115 years, calculated with a formula (Hurrell 1995):

$$\text{Index} = \frac{\text{SLP}_{\text{high}} - \text{SLP}_{\text{high}115}}{\sigma(\text{SLP}_{\text{high}115})} - \frac{\text{SLP}_{\text{low}} - \text{SLP}_{\text{low}115}}{\sigma(\text{SLP}_{\text{low}115})} \quad (1)$$

Where,

SLP_{high}Sea level pressure on the high pressure station

$SLP_{high115}$Mean sea level pressure on the high pressure station in the 115-year period

SLP_{low}Sea level pressure on the low pressure station

Table 1 Overview of most important ocean oscillation indices

		Name	Authors	Calculation method	Phases	Phase shifts
Southern Hemisphere	Global impact	Antarctic Oscillation index (AAO) or Southern Annular Mode (SAM)	Rogers and Van Loon 1982	EOF from SLP or 500 mb geopotential shifts from the area from South Pole to 20° S latitude	Positive: Strengthening of polar jet stream disallowing flow of polar air to the north Negative: Weakening of polar jet stream, allowing polar and temperate air mixing	From couple of weeks to couple of years
Northern Hemisphere		Arctic Oscillation (AO) index or Northern Annular Mode (NAM)	Thompson and Wallace 1998	EOF from SLP or 500 mb geopotential shifts from the area from North Pole to 20° N latitude	Positive: Strengthening of polar jet stream disallowing flow of polar air to the south Negative: Weakening of polar jet stream, allowing polar and temperate air mixing	From couple of weeks to couple of years
	Atlantic Ocean	North Atlantic Oscillation (NAO) index	Walker and Bliss 1932	Traditionally difference between mean SLP from two stations: one in Azores High, second in Icelandic Low	Positive: Relatively large SLP difference between stations, wet air in Northern Europe carried by strengthened westerlies, cold Arctic air in Northern America Negative: Small SLP difference between stations, dry, continental weather in Europe and north-eastern America	On average 2–3 years
		Atlantic Multidecadal Oscillation (AMO) index	Schlesinger and Ramankutty 1994	EOF from 10-year SST anomalies from the Atlantic north of the equator	Positive: Acceleration of thermohaline circulation, warming in North America and Europe Negative: Deceleration of thermohaline circulation, colder weather in North America and Europe	65–70 years
	Pacific Ocean	Pacific Decadal Oscillation (PDO) index	Mantua et al. 1997	EOF from SST anomalies on the Pacific north from 20° N latitude	Positive: Western Pacific coast is cooling down, eastern Pacific coast is warming up Negative: Western Pacific coast is warming up, eastern Pacific coast is cooling down	15–70 years
		Pacific North American (PNA) Pattern	Wallace and Gutzler 1981	EOF from SLP anomalies on 500-mb height between four pressure centres over North America	Positive: High pressure in Hawaii and central Canada, lower than average in south of Aleutian Islands and Mexican Bay, high temperatures in Canada and east of USA, relatively low in southern USA *Negative*: lower pressure in Hawaii and central Canada, higher than	Couple of months–couple of years

Table 1 (continued)

		Name	Authors	Calculation method	Phases	Phase shifts
					average in south of Aleutian Islands and Mexican Bay, low temperatures in Canada and extraordinarily high temperatures and draught in southern USA	
Low latitudes in the vicinity of the equator		El Niño Southern Oscillation (ENSO) index or Southern Oscillation index (SOI)	Walker and Bliss 1932	Initially SLP differences between stations in pressures centres: low—Darwin, high—Tahiti; nowadays numerous methods based on SST, sea levels, different stations and EOFs of varied areas. All are proxies for fluctuation in zonal Walker circulation between Indonesian Low and South Pacific High	Neutral: Most often, stable pressures system with high centre on the east, and low on the west of Pacific Positive: so-called La Niña—acceleration of Walker circulation, cooling down of Pacific waters and in Americas, warming up in Australia and Asia Negative: So-called El Niño—weakening of Walker circulation, warming in the Pacific and Americas, cooling down and draught in Australia and Asia	Negative and positive phases irregular from 2 to 7 years lasting 6–18 months
	Indian Ocean	Madden-Julian Oscillation (MJO) index	Madden and Julian 1971	Movement of deep convection centres from west to east in the northern part of the Indian Ocean, Indonesia and West Pacific, described by EOF of Outgoing Longwave Radiation (OLR) and wind speed induced in convection areas	Positive: Wet phase, intense precipitation in area over which convection area passes from east to west Negative: Dry phase in between convection occurrences	Relatively dependable 30–90-day cycles
		Indian Ocean Dipole (IOD)	Saji et al. (1999)	Differences between observed temperatures between eastern and western coasts of Indian Oceans	Positive: Above average temperatures in the west of Indian Ocean, colder in the east, wet air mass transported over Africa, and cold dry weather in Australia and Indonesia Negative: Below average temperatures in the west of Indian Ocean, warmer in the east, wet and warm in Australia and Indonesia, colder and dryer air over Africa	Every 3–4 years one of the phases, in between neutral phase

Sourced from: Ambaum et al. 2001, Barnston and Livezey 1987, Lin et al. 2015, Madden and Julian 1971, Mantua et al. 1997, Mantua and Hare 2002, Marshall 2003, Rogers and Van Loon 1982, Sae-Rim and Kwang-Yul 2015, Saji et al. 1999, Schlesinger and Ramankutty 1994, Thompson and Wallace 1998, Walker and Bliss 1932, Wallace and Gutzler 1981, Wanner et al. 2001

SLP_{low115}Mean sea level pressure on the low pressure station in the 115-year period

σStandard deviation

These indices were named conventional and were calculated using SLP values from chosen stations located in the areas of constant pressure centres (alternating lows and highs) in the Atlantic (Fig. 2, Table 2). Therefore, this index shows differences between the standardised air pressure values between stations representing anticyclone and cyclone regions. The localisation of pressure centres overlaps the climatic zones along the meridian. The nomenclature of the indices was rooted in naming introduced by Walker and Bliss (1932).

Taking into account the dynamic variability of pressure centres, Boström (2012) proposed an extended formula (2) using the highest values of SLP in the high pressure centres and minimal SLP values from low pressure centres from general areas of constant highs and lows:

$$\text{Index} = \frac{\max\left(\text{SLP}_{\text{high\_centre}}\right) - \max\left(\text{SLP}_{\text{high\_centre\_115}}\right)}{\sigma\left(\max\left(\text{SLP}_{\text{high\_centre\_115}}\right)\right)} - \frac{\min\left(\text{SLP}_{\text{low\_centre}}\right) - \min\left(\text{SLP}_{\text{low\_centre\_115}}\right)}{\text{std}\left(\min\left(\text{SLP}_{\text{low\_centre\_115}}\right)\right)} \quad (2)$$

Where,

$max(SLP_{high_centre})$Maximum SLP in the strongest high centres of high-pressure zone

$max(SLP_{high_centre_115})$Mean maximum SLP in the strongest high centre of high-pressure zone in a 115-year period

$min(SLP_{low_centre})$Minimum SLP in the deepest low centre of low-pressure zone

$min(SLP_{low_centre_115})$Mean minimum SLP in the deepest low centres of low-pressure zone in a 115-year period

σStandard deviation

These extreme indices, calculated with formula (2), were named identically as their conventional counterparts but with a word "Extreme" in the end of them, e.g. NAOE—North Atlantic Oscillation Extreme. Extreme SLP values were gathered from Atlantic areas divided in accordance with the climatic zones, in the meridional belt between 70° W and 20° E (Fig. 2, Table 2).

Since in previous works wintertime NAO indices were proved to be superior fluctuation describers (Hurrell 1995, Jones et al. 1997, Li and Wang 2003, Hurrell et al. 2003, Osborn 2006), three types of each time series have been presented: continuous oscillations, boreal wintertime/austral summertime indices (mean values from December to February (DJF)) and boreal summertime/austral wintertime indices (mean values from June to August (JJA)). Summertime oscillations are also valuable according to results presented by Hurrell et al. (2003) and Folland et al. (2008).

For index calculation, the SLP values were downloaded from the Twentieth Century Reanalysis (V2c) provided by National Oceanic and Atmospheric Administration (NOAA) and Cooperative Institute for Research in Environmental

Fig. 2 Localisation of large-scale pressure centre areas used for calculating extreme indices and measurement stations used for conventional oscillation indices

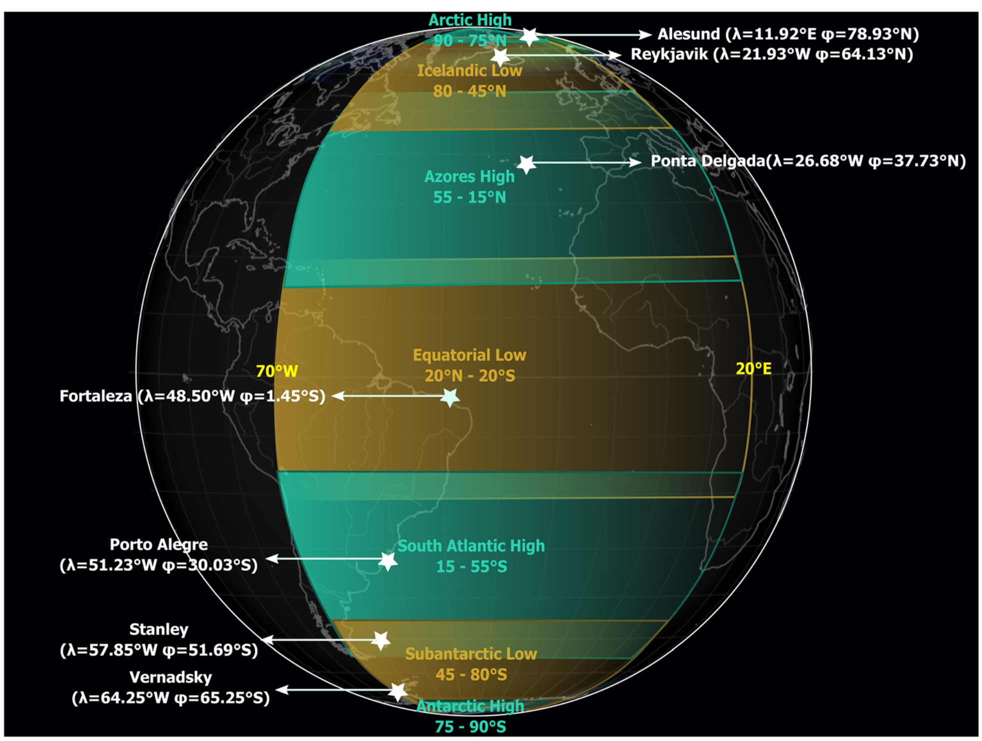


Table 2 Conventional and Extreme Atlantic Oscillation Indices (*C* conventional, *E* extreme)

Oscillation Index	Method	Abbreviation	High pressure station or area between 70° W and 20° E	Low pressure station or area 70° W and 20° E
Arctic North Atlantic Oscillation	C	ANAO	Ålesund	Reykjavik
	E	ANAOE	Zone: 90–75° N	Zone: 80–45° N
North Atlantic Oscillation	C	NAO	Ponta Delgada	Reykjavik
	E	NAOE	Zone: 55–15° N	Zone: 80–45° N
North Atlantic Tropic Oscillation	C	NATO	Ponta Delgada	Fortaleza
	E	NATOE	Zone 55–15° N	Zone: 20° N–20° S
South Atlantic Tropic Oscillation	C	SATO	Porto Alegre	Fortaleza
	E	SATOE	Zone: 15–55°S	Zone: 20° N–20° S
South Atlantic Oscillation	C	SAO	Porto Alegre	Stanley (Falklands)
	E	SAOE	Zone: 15–55° S	Zone: 45–80° S
Antarctic South Atlantic Oscillation	C	ASAO	Stanley (Falklands)	Vernadsky
	E	ASAOE	Zone: 45–80° S	Zone: 90–75° S

Sciences (CIRES) (NOAA 2018). Mean daily SLP values were taken from 1 January 1900 to 31 December 2014.

Reanalysed data were validated through observational SLP values from the *World Monthly Surface Station Climatology* report available on National Centre for Atmospheric Research/University Corporation for Atmospheric Research (NCAR/UCAR) website (National Climatic Data Center/NESDIS/NOAA/U.S. Department of Commerce et al. 1981). The longest times series of observed data were acquired from the measurement stations in Reykjavik, Ponta Delgada, Porto Alegre and Stanley, Falklands. Values from the reanalysis—modelled data—were investigated through quantitative analysis by comparison with observational datasets. Data validation was done by calculating dependency ratio, root mean square error (RMSE) and correlation coefficients (all of the values were statistically significant, tested by *T* test, with $\alpha = 0.05$) between observational and modelled data (Table 3).

Additionally, new North Atlantic Oscillation Indices were compared with officially available NAO time series from the NOAA's Climate Prediction Centre website (NOAA 2005) for further confirmation of the selected methodology (Fig. 3). All of NAO indices show parallelism, convergent amplitude and similar fluctuation trends. The correlation coefficients between mean yearly NAO index from NOAA (calculated using EOF method) and new conventional and extreme NAO series were respectively 0.814 and 0.846, in boreal wintertime 0.930 and 0.835, and in boreal summertime 0.510 and 0.681. These results are in agreement with outcomes presented by Hurrell et al. (2003), confirming validity of Northern Hemisphere wintertime stationary indices by their 0.92 correlation with EOF results. Disparities between time series of NOAA NAO and new NAO indices seen on Fig. 3 are most noticeable in the years before 1970, so when available data for analysis was reduced. Also, NOAA time series has been normalised with standard deviation of each month which is observable since the orange plot is less wavering than others. Other discrepancies may be attributed to less compatible results depending on season between stationary and EOF indices, since NAO's impact on weather variability in this region during summer was shown to be less significant (Hurrell et al. 2003, Li and Wang 2003).

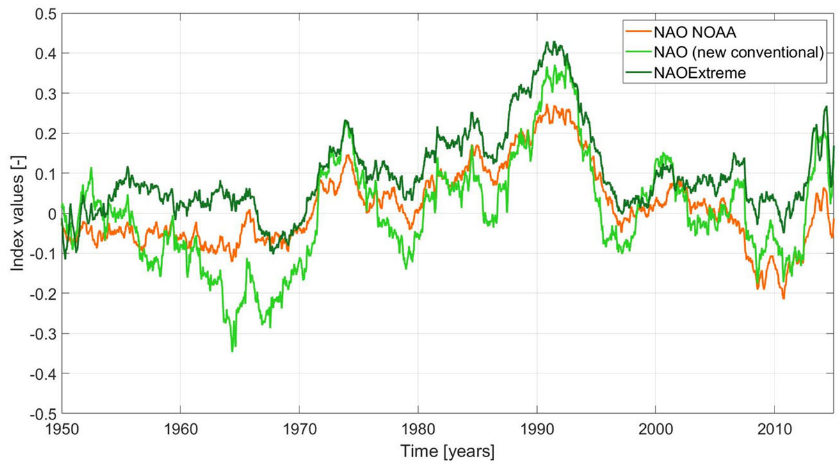
Conducted validation has proven satisfactory and confirmed using chosen methodology for calculating new Atlantic Oscillation Indices.

Basic statistics were calculated for mean monthly values of new oscillation indices: mean and extreme values, standard deviation and 95% confidence interval.

Table 3 Statistical validation of the modelled data from reanalysis used for calculating Atlantic Oscillation indices

Station	Dependency ratio (hPa)	RMSE (mb)	Correlation coefficient R	Number of data N	Time extent of observed data available
Reykjavik	0.487	4.648	0.983	1136	May 1920–December 2014
Ponta Delgada	0.170	0.355	0.990	1380	January 1900–December 2014
Porto Alegre	1.799	0.760	0.927	648	January 1961–December 2014
Stanley	2.966	4.122	0.868	716	July 1922–February 1982

Fig. 3 Fluctuations of NAO index from NOAA compared with new NAO indices: conventional and extreme in years 1950–2014



Analysis of series characteristics was performed through comparison of their overall fluctuations, extreme moments and amplitudes as well as their individual and collective periodicity using fast Fourier transform (FFT) (Mathworks 2017). In reference to results from Li and Wang (2003) showing that decadal variations of Atlantic index are stronger using data from all months, power spectrum analysis was performed on continuous datasets, not seasonal ones. Due to intense variability of new indices' series, they were monthly averaged, and later normalised with moving means of different lengths: 1, 3, 5, 11 and 25 years long.

In FFT analysis, the longest period investigated was 19.2 years which accounts to one-sixth of the total time of 115 years, although it is recommended that the longest cycle should be repeated ten times within the analysed time. This means that periods longer than 11.5 years may not be evaluated to a satisfactory degree (MathWorks 2017).

To investigate relations between new indices in particular climatic zones, Pearson correlation (Łomnicki 2003) and coherence (Kowalik 1968) coefficients were calculated for monthly averaged sequences values as well as for all moving-mean normalised series.

3 Results

3.1 Basic statistics

In the indices' time series, long-lasting trends were noticeable with differing amplitudes indicating range of fluctuations. Annual mean values of all indices were close to 0; the largest deviations from it were in extreme index series, maximally 0.0056 in NAOE index. Also, standard deviation values were larger in the extreme index series with maximum value of 1.082 for NAOE. Predictably, with two exceptions, both minimal and maximal values were more extreme for the extreme indices. Confidence intervals were narrower for conventional indices with exception of North Atlantic Tropical indices, and ranged from 0.025 for ANAO to 0.057 for both NAOE and SAOE (Table 4).

3.2 New Atlantic Oscillation index fluctuations

On Fig. 4, new Atlantic Oscillation indices' variability from 1900 until 2014 was presented. Figure 4 was divided into six rows of plots each representing, in meridional order, the time series of overlapping conventional and extreme indices in three columns showing separately their annual, December–February and June–August fluctuations. Shown plots are mean yearly index values normalised with 3-year moving mean. Additionally, in Table 5, general characteristics of overall fluctuations are presented: their approximate amplitude, range and most noticeably extreme positive and negative moments. Table 5 also shows which global atmospheric circulation cells are represented by particular indices, although it is important to remember this is only a vastly simplified concept.

Oscillation amplitudes were generally smaller in the conventional indices than in extreme ones apart from the North Atlantic Tropic Oscillation. Wintertime values for both hemispheres (DJF for the north and JJA for the south) showed more similarities to annual oscillations and higher values. A regularity is shown that annual oscillations in general fluctuating around 0 are a composite of positive wintertime and negative summertime values. In boreal summertime (JJA), ANAO/ANAOE and NAO/NAOE variability plots were flattened in comparison with their wintertime and annual counterpart and lacked common maxima. In the south, ASAO/ASAOE and SAO/SAOE variability is also reduced and has fewer shared characteristics of the annual fluctuations; however, this tendency is fainter than that in the north.

Table 4 Basic statistics for monthly mean values of Atlantic Oscillation indices in years 1900–2014

Index	Mean value	Standard deviation	Minimum	Maximum	Confidence interval ($\alpha = 0.05$)
ANAO	− 0.0004	0.472	− 1.696	2.035	0.025
ANAOE	0.0047	0.961	− 2.365	3.073	0.051
NAO	− 0.0003	0.904	− 3.270	2.693	0.048
NAOE	0.0056	1.082	− 2.148	3.117	0.057
NATO	0.0024	0.900	− 2.472	2.701	0.046
NATOE	0.0020	0.762	− 2.185	2.514	0.040
SATO	0.0001	0.547	− 1.775	1.730	0.029
SATOE	− 0.0036	0.835	− 2.358	3.199	0.044
SAO	− 0.0026	0.583	− 1.788	1.857	0.031
SAOE	− 0.0032	1.079	− 2.756	3.526	0.057
ASAO	− 0.0004	0.567	− 2.230	1.882	0.030
ASAOE	− 0.0005	0.887	− 2.310	2.488	0.047

Index oscillation showed similarities: most noticeable in tropical zone (NATO and NATOE with SATO and SATOE indices) (Fig. 4) with positive extreme values around year 1905 and 1950 and negative extremes around year 1920 and 1960 and amplitude around 1. Also tropical plots represent the closest relation between conventional and extreme method results. This could indicate symmetry between dynamics in northern and southern Hadley cells.

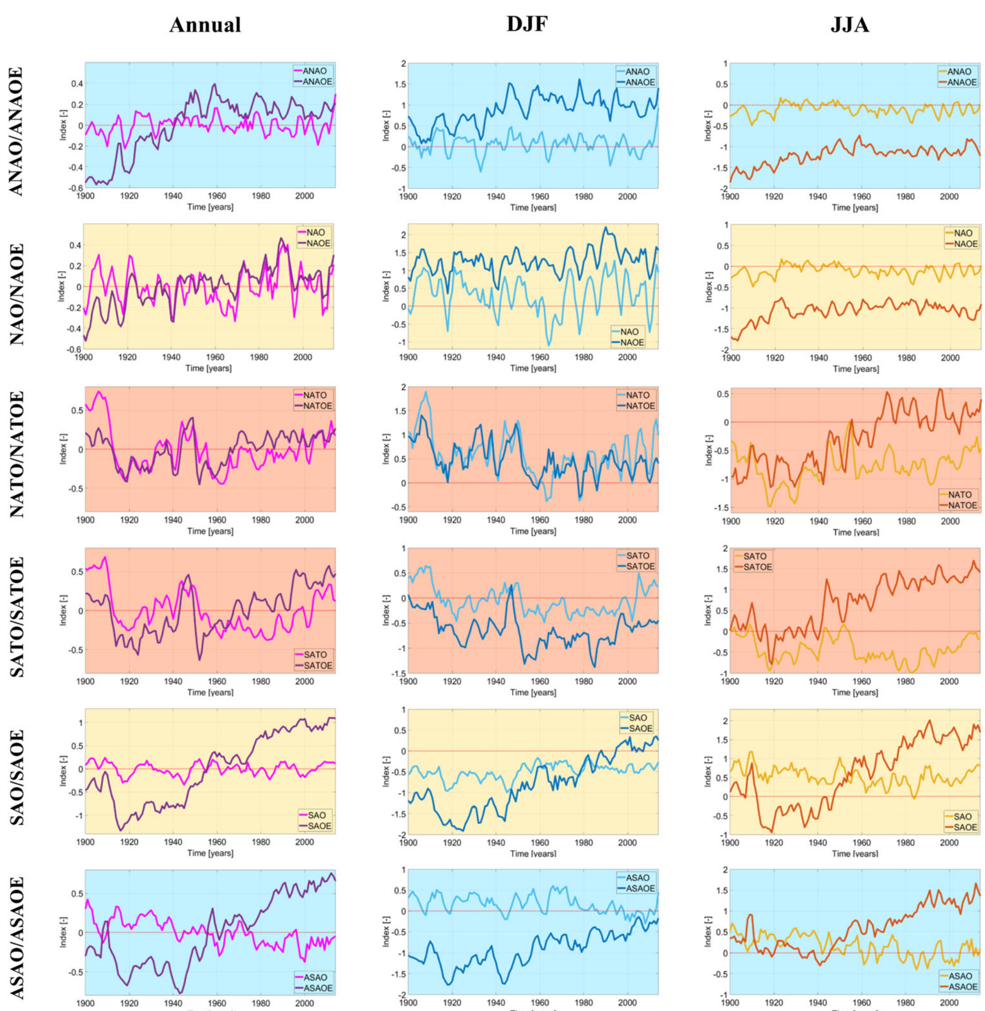


Fig. 4 Fluctuation of new Atlantic Oscillation indices in all latitudes: blue background, polar cell; yellow background, Ferrell cell; orange background, Hadley cell; annually, DJF December-February, JJA June-August

Table 5 New Atlantic Oscillation index fluctuation characteristics (*C* conventional index, *E* extreme index)

Oscillation	Corresponding global circulation cells	Index (C/E)	Approximate oscillation amplitude	Approximate oscillation range	Approximate positive and negative extremes
Arctic North Atlantic Oscillation (ANAO)	Northern polar cell	ANAO (C)	0.2	− 0.1 to 0.1	− ~ 1920
		ANAOE (E)	0.8	− 0.5 to 0.3	− ~ 1920
					+ ~ 1960
North Atlantic Oscillation (NAO)	Northern Ferrel cell	NAO (C)	0.4	− 0.2 to 0.2	− ~ 1920, 1940, 1965, 2000, 2010
					+ ~ 1905,1995
		NAOE (E)	0.7	− 0.4 to 0.3	− ~ 1900, 1920, 1940, 1965, 2010
					+ ~ 1995
North Atlantic Tropical Oscillation (NATO)	Northern Hadley cell	NATO (C)	1.0	− 0.4 to 0.6	− ~ 1920, 1940, 1960
					+ ~ 1905, 1950
		NATOE (E)	0.5	− 0.3 to 0.2	− ~ 1920, 1940, 1960, 1980
					+ ~ 1905, 1950
South Atlantic Tropical Oscillation (SATO)	Southern Hadley cell	SATO (C)	1.0	− 0.4 to 0.6	− ~ 1920, 1960, 1980
					+ ~ 1905, 1950
		SATOE (E)	1.0	− 0.4 to 0.6	− ~ 1920, 1955
					+ ~ 1905, 1950
South Atlantic Oscillation (SAO)	Southern Ferrel cell	SAO (C)	0.4	− 0.2 to 0.2	− ~ 1920, 1940
					+ ~ 1910, 1950, 1995
		SAOE (E)	2.2	− 1.1 to 1.1 (not seen on Fig. 4)	− ~ 1920, 1940
					+ ~ 1910, 1960, 1995
Antarctic South Atlantic Oscillation (ASAO)	Southern polar cell	ASAO (C)	0.5	− 0.2 to 0.3	–
		ASAOE (E)	1.4	− 0.6 to 0.8	− ~ 1920, 1940
					+ ~ 1910, 1960, 1995

'Further from the equator indices' plots seem to be less parallel but repeated extremes still occur: negative in 1920 for ANAO, ANAOE, NAO, NAOE, NATO, NATOE, SATO, SATOE, SAO, SAOE and ASAOE; in 1940 for NAO, NAOE, NATO, NATOE, SAO, SAOE and ASAOE; in 1955–1965 for NAO, NAOE, NATO NATOE, SATO and SATOE; positive in 1910 for SAO, SAOE and ASAOE; in 1995 for NAO, NAOE, SAO, SAOE and ASAOE, often more vividly announced in the winter season (DJF for the Northern Hemisphere, JJA for the Southern Hemisphere).

A less obvious close association exists between fluctuations of SAO, SAOE and ASAOE, in which annual plots all have similar extreme points and are overall parallel despite SAOE values ranging in a wider spectrum. This is mimicked in both JJA and DJF plots, with JJA showing more similarities to annual changes.

In general, in many indices' time series exists a long-running increasing tendency, apparent in plots of the following: ANAOE, NAOE, SATOE, SAOE and ASAOE, so all but NATOE extreme indices. This could signify a meaningful discrepancy between two used methods—either extreme formula due to a wider range of analysed data is more responsive to an important, secular trend or it is somehow defective.

It is also worth noting that more parallel variabilities of indices are represented in the Southern Hemisphere which may suggest that Atmosphere-Ocean circulation in the southern Atlantic is more systematic.

3.3 Periodicity in time series of new Atlantic Oscillation indices

Investigating periodicity in annual new Atlantic Oscillation indices' time series was performed using the FFT method. In power spectrum plots of all sequences, by far, the largest extremes were assigned to 6- and 12-month periods (Table 6). This indicates that most meaningful variability of SLP values on the Atlantic took place in annual and semi-annual cycles. In 70% of cases, yearly maxima overweighed 6-month periods by at least one order of magnitude, and its impact was most significant in extreme oscillation indices (Table 6).

Apart from annual and semi-annual extremes in indices' periodograms, other maxima occurred, however with a dozen

Table 6 Atlantic Oscillation indices' power spectrum most meaningful maxima in years 1900–2014 (extremely high values in bold)

Period	ANAO	ANAOE	NAO	NAOE	NATO	NATOE	SATO	SATOE	SAO	SAOE	ASAO	ASAOE
6 months	0.29	20.83	24.37	8.26	28.11	14.48	53.15	4.95	2.34	20.61	27.73	39.52
12 months	4.77	**449.42**	20.03	**579.20**	197.56	69.17	20.29	**219.04**	106.28	**221.96**	18.77	**274.03**

times lesser impact (Table 7). Most frequent was the 5.5-year period in power spectra of NATO, NATOE, SATO, SATOE and ASAOE; 10.5-year period in ANAOE, SATOE, SAOE and ASAOE; as well as 16.4-year period in SAO, NAO, ANAOE and SATOE periodograms. With convenient approximation, 10.5 and 16.4 are multiplicities of 5.5, which would further validate this cycle's significance in long-term Atlantic Oscillations. It is relevant that the most repeated periodicity maxima are attributed to extreme oscillation indices, predominantly in the Southern Hemisphere, which could be another display of greater regularity in these sequences.

3.4 Relationships between new Atlantic Oscillation indices

Connections between newly calculated oscillation indices were examined through correlation and coherence analyses on its monthly average values, as well as its moving-mean normalised sequences.

In Tables 8 and 9, Pearson's correlation coefficients for yearly mean values are presented for conventional and extreme indices, respectively, annually and separately for DJF and JJA months. Most significant relations were further investigated using power spectrum comparison and coherence analysis.

Table 7 Atlantic Oscillation indices' power spectrum maxima in 1900–2014 excluding extremes in 6- and 12-month cycles (5.5-year cycle and its multiplicities in bold)

	Index	Power spectrum maxima (years)				
Conventional indices	ANAO	4.8	5.2	12.8		
	NAO	4.6	5.8	7.7	9.6	**16.4**
	NATO	**5.5**	12.8			
	SATO	**5.5**	6.1	8.8		
	SAO	7.7	9.6	19.2		
	ASAO	11.5	12.8	19.2		
Extreme indices	ANAOE	4.1	8.8	**10.5**	**16.4**	
	NAOE	2.7	7.7	9.6		
	NATOE	**5.5**	12.8			
	SATOE	**5.5**	9.6	**10.5**	12.8	**16.4**
	SAOE	3,2	6.4	**10.5**	**16.4**	
	ASAOE	**5.5**	6.8	**10.5**	14.4	19.2

Overall, stronger correlations were found between extreme indices over conventional ones, in the Southern Hemisphere rather than in the north, and in wintertime (DJF for the north, JJA for the south) (Tables 8 and 9). This is represented in Table 9 in boreal summertime/austral wintertime (JJA) section, where high correlation coefficients connect NAOE-NATOE, NATOE-SATOE, NATOE-SAOE, NATOE-ASAOE, SATOE-SAOE, SATOE-SAOE, SATOE-ASAOE and SAOE-ASAOE.

Tropical indices NATO–SATO and NATOE–SATOE describe interconnection between northern and southern Hadley cells and their relations were further examined on different levels of data normalisation. Calculated correlation values of annual fluctuations ranged from 0.593 to 0.907 for conventional indices and from 0.088 to 0.908 for extreme indices, with high correlations also in DJF and JJA period analyses with

Table 8 Correlation coefficients between yearly mean conventional Atlantic Oscillation indices (values in italic: insignificant statistically ($p = 0.05$); bold values: very strong and strong correlation > 0.5), divided into annual, December–January and June–August time schemes

Annual	ANAO	NAO	NATO	SATO	SAO	ASAO
ANAO	1	0.209	*−0.086*	*−0.113*	*−0.025*	*0.033*
NAO	0.209	1	0.406	*−0.073*	*−0.006*	*−0.009*
NATO	*−0.086*	0.406	1	**0.774**	*0.142*	*0.065*
SATO	*−0.113*	*−0.073*	**0.774**	1	0.313	*0.101*
SAO	*−0.025*	*−0.006*	*0.142*	0.313	1	*0.160*
ASAO	*0.033*	*−0.009*	*0.065*	*0.101*	*0.160*	1
	Boreal wintertime/austral summertime (DJF)					
ANAO	1	*0.054*	*−0.134*	*−0.061*	*0.051*	*0.118*
NAO	*0.054*	1	**0.736**	*0.269*	*0.006*	−0.219
NATO	*−0.134*	**0.736**	1	**0.632**	*−0.152*	−0.200
SATO	*−0.061*	*0.269*	**0.632**	1	*−0.039*	*−0.115*
SAO	*0.051*	*0.006*	*−0.152*	*−0.039*	1	0.189
ASAO	*0.118*	−0.219	−0.200	*−0.115*	0.189	1
	Boreal summertime/austral wintertime (JJA)					
ANAO	1	0.370	*−0.083*	*−0.047*	*−0.051*	*0.022*
NAO	0.370	1	0.206	*−0.096*	*−0.153*	*−0.088*
NATO	*−0.083*	0.206	1	**0.610**	*−0.037*	*−0.033*
SATO	*−0.047*	*−0.096*	**0.610**	1	**0.522**	*0.102*
SAO	*−0.051*	*−0.153*	*−0.037*	**0.522**	1	*0.177*
ASAO	*0.022*	*−0.088*	*−0.033*	*0.102*	*0.177*	1

Table 9 Correlation coefficients between yearly mean extreme Atlantic Oscillation indices (values in italic: insignificant statistically ($p = 0.05$); bold values: very strong and strong correlation > 0.5), divided into annual, December–January and June–August time schemes

Annual	ANAOE	NAOE	NATOE	SATOE	SAOE	ASAOE
ANAOE	1	0.392	*− 0.009*	0.215	**0.547**	0.434
NAOE	0.392	1	0.387	*0.098*	0.421	0.392
NATOE	*− 0.009*	0.387	1	**0.720**	0.390	0.423
SATOE	0.215	*0.098*	**0.720**	1	**0.642**	**0.587**
SAOE	**0.547**	0.421	0.390	**0.642**	1	**0.926**
ASAOE	0.434	0.392	0.423	**0.587**	**0.926**	1
Boreal wintertime/austral summertime (DJF)						
ANAOE	1	− 0.208	**− 0.541**	*− 0.107*	0.347	0.296
NAOE	− 0.208	1	**0.530**	*− 0.186*	0.249	*0.170*
NATOE	**− 0.541**	**0.530**	1	0.384	*− 0.220*	*− 0.139*
SATOE	*− 0.107*	*− 0.186*	0.384	1	*0.042*	*− 0.088*
SAOE	0.347	0.249	*− 0.220*	*0.042*	1	**0.728**
ASAOE	0.296	*0.170*	*− 0.139*	*− 0.088*	**0.728**	1
Boreal summertime/austral wintertime (JJA)						
ANAOE	1	*0.153*	0.287	0.430	0.360	0.279
NAOE	*0.153*	1	**0.510**	0.216	*0.149*	*0.141*
NATOE	0.287	**0.510**	1	**0.847**	**0.653**	**0.637**
SATOE	0.430	0.216	**0.847**	1	**0.827**	**0.698**
SAOE	0.360	*0.149*	**0.653**	**0.827**	1	**0.841**
ASAOE	0.279	*0.141*	**0.637**	**0.698**	**0.841**	1

exception of boreal wintertime in extreme indices (Table 9). Their power spectra both had maxima in 0.5-, 1- and 5.5-year periods (Figs. 5 and 6). Coherence above significance level of 0.4 (red line on right side of Fig. 5) between NATO and SATO occurred over ten times, occasionally drawing near 1 which indicates correlation of the signals and similarities in its determination. Between NATOE and SATOE, significant coherence happened more rarely and was weaker than per conventional indices (right side of Fig. 6).

For indices describing corresponding Ferrel and polar cells on both hemispheres (NAO-SAO, NAOE-SAOE, ANAO-ASAO, ANAOE-ASAOE), correlation coefficients for differently smoothened data series, annually and separately for DJF and JJA periods, did not show significant relations.

Very strong correlations, from 0.668 to 0.978, were noted between extreme indices of South Atlantic Oscillation (SAOE) and Antarctic South Atlantic Oscillation ASAOE, for both analysed seasons and continuous data. This is a proof of strong connection between circulation in austral Ferrel and polar cells. Their power spectra had shared maxima in 0.5-, 1-, 5.5- and 10.5-year periods. Coherence above 0.4 level occurred over ten times, occasionally getting close to a value of 1 suggesting deterministic connection of signals (Fig. 7).

4 Possible data errors and uncertainties

Firstly, possible uncertainties may occur through data acquisition process. Reanalysed values are always only modelled approximations and especially in secluded areas and in distant past, where there was no sufficient amount of observational data for validating the model, its values may be untrue. Therefore, results from the beginning of the twentieth century and from polar regions should be treated with special caution. This particularly concerns ASAO index series, since, due to lack of stations further south, the southernmost measurement point used for calculating conventional index, Vernadsky Antarctic station, is located in the general area of Subantarctic Low not Antarctic High (Fig. 2).

Chosen index calculation methods may also cause data errors; partly because of imperfection of available formulas, two solutions were used in this study. Conventional method is limited in its undynamic data source localisation, whereas extreme formula has not been well tested and validated in the scientific community. Visible in the results section are discrepancies between extreme and conventional indices, such

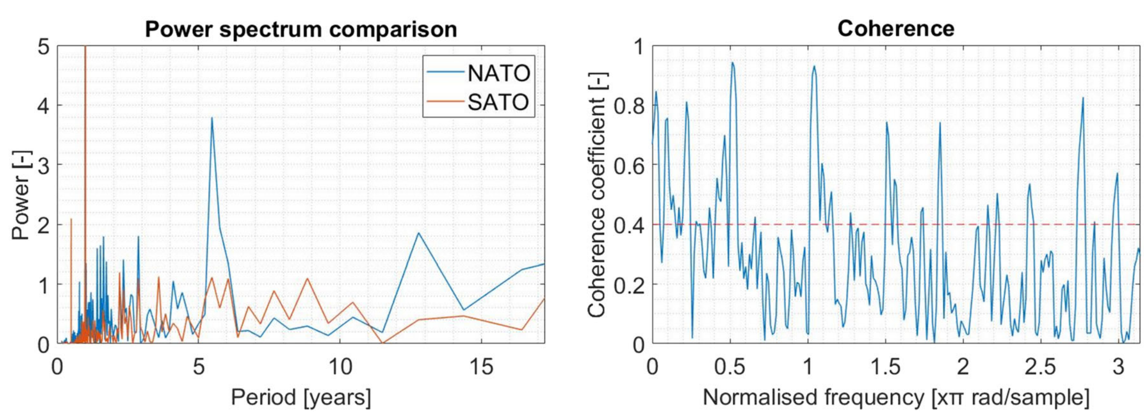


Fig. 5 Power spectra and coherence comparison between NATO and SATO indices in years 1900–2014

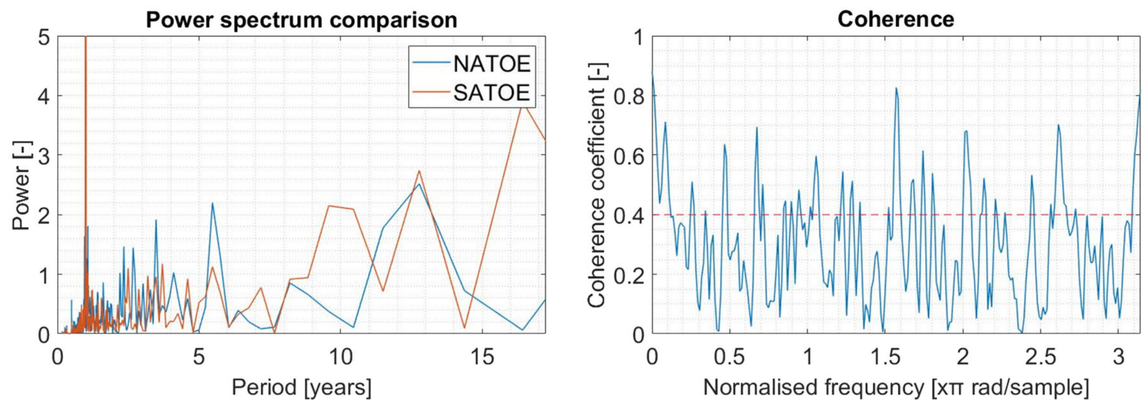


Fig. 6 Power spectra and coherence comparison between NATOE and SATOE indices in years 1900–2014

as general increasing tendency in extreme sequences not noticeable in conventional plots, which may indicate inferiority of one of the methods.

Data smoothing applied for sake of plot readability could have hidden valuable information.

Additionally, sequence analysis tools are also imperfect. Since only 115 years of validated data was available, FFT power spectrum examination can appropriately check only periods shorter than 11.5 years; however, it is possible that a longer cycle could be especially significant.

Correlation and coherence coefficients cannot detect all forms of relations between data series.

5 What the newly obtained results reveal: discussion

The correlation coefficients of NAO, NAOE, NAO_{DJF} and $NAOE_{DJF}$ indices with NAO_{NOAA} index were 0.814 and 0.846 for annual indices and 0.930 and 0.835 for winter ones; therefore, we concluded that the obtained time series represent real processes in the Atlantic Ocean climate system (Figs. 2 and 4). This positive validation confirms the correctness of chosen methodology of determining extreme and conventional indices.

The variability of new indices' oscillation showed some resemblance to previously reported data. Rogers (1984), Hurrell (1995), Hurrell and Van Loon (1997) and Li and Wang (2003) reported NAO index values decreasing from around the 1920s until the 1960s to the 1970s. This trend is distinguishable in new Atlantic index time series (Fig. 4), although a more general downward tendency from the beginning to more or less the middle of twentieth century is shown on NATO, NATOE, SATO, SATOE, SAOE and ASAOE plots. A long upward trend from the 1960s to the 1980s in NAO was reported (Hurrell 1995, and Hurrell and Van Loon 1997, Jones et al. 1997, Li and Wang 2003), which is also true for variability of new: NAO, NAOE, NATO, NATOE, SATO and SATOE, SAOE and ASAOE (Fig. 4). Increasing NAO trend in the second half of twentieth century was interrupted in the winter of 1995 (Jones et al. 1997) and particularly low values of NAO have since been recorded in the winter of 2009/2010 (Osborn 2011), but a more general increase is alleged in the near future (Folland et al. 2008) due to its possible relation to rising greenhouse gases present in the Earth's atmosphere (Dong et al.

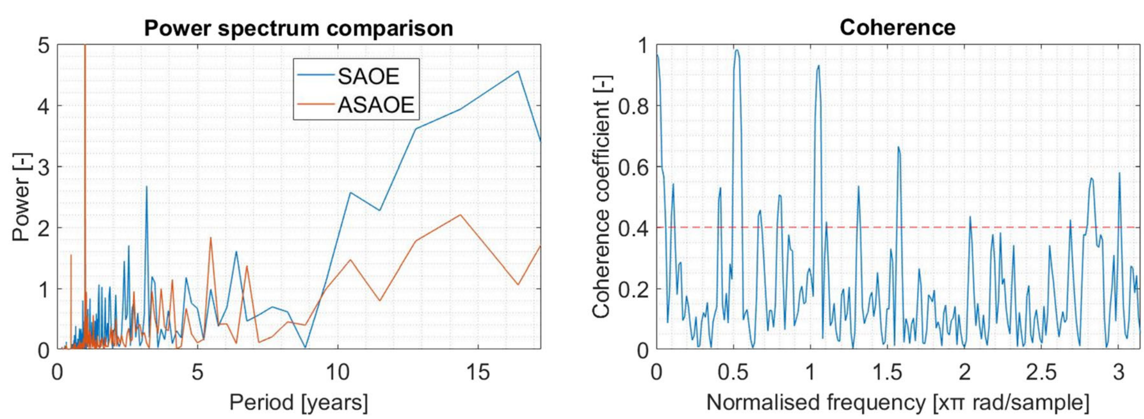


Fig. 7 Power spectra and coherence comparison between SAOE and ASAOE indices in years 1900–2014

2011). This presumption may be confirmed by escalating values of a majority of new Atlantic Oscillation indices (Fig. 4).

A power spectrum analysis has proved strong significance of 6-month and yearly periods for all new indices' fluctuations, as well as showed repeated importance of 5.5-year-long period multiples:

- 5.5-year maximum for NATO, NATOE, SATO, SATOE and ASAOE
- 10.5-year maximum for ANAOE, SATOE, SAOE and ASAOE
- 16.4-year maximum for ANAOE, NAO, NATOE and SAOE

The interannual and decadal variabilities in atmospheric oscillations have been identified for NAO: Hurrell and Van Loon (1997) and Hurrell et al. (2003) (2–4-, and 6–10-year periods), also recognised by Luterbacher et al. (2001), and is believed to describe South Atlantic Subtropical High position and magnitude (Sun et al. 2017). Some of the new Atlantic Oscillation indices share close to decadal variability with period of 10.5 years, possibly connected to previously shown decadal regularities in the results of Hurrell (1995) and Hurrell and Van Loon (1997). Rogers (1984) found that covariance between winter NAO and ENSO indices has been strongest in periods between 5 and 6 years in accordance with the 5.5-year cycle in a majority of new indices but the nature of this parallel is unknown. The 25–30-year cyclicity of SST thermal anomalies was identified in the western subtropical Southern Ocean (Wainer and Venegas 2002). The obtained 5.5-year cycles and their multiples of 10.5 and 16.4 years of conventional and extreme indices of the Southern Hemisphere in the Atlantic sector refer to this two decades. Therefore, the undertaken works have the character of "kinematic descriptions of features" of one of the main components of the South Atlantic oscillations through time series of SATO, SATOE, SAO, SAOE, ASAO and ASAOE.

The determined correlations between the new oscillation indices showed a significant and high correlation in tropical and the combination of tropical and temperate zones in winter seasons. The relationship between NATO and SATO conventional indices is clearly shaped at 0.774 correlation. The connections between the NAO_{DJF} and $NATO_{DJF}$ showed a correlation of 0.736 and between SAO_{JJA} and $SATO_{JJA}$ of 0.522 (Tab. 8). This means that tropical zones, located almost symmetrically on both sides of the equator, appear to be strongly associated with Hadley cells; however, indices of moderate adjacent zones (Ferrel cells) correlate only during winter periods of atmospheric activity.

The high correlations between the ASAOE and SAOE indices suggest regularities in fluctuations of the atmosphere in the southern polar cell. During the winter in the Southern Hemisphere, the Subtropical South Atlantic High is displaced towards the pole in the La Niña years with coinciding positive phase of the Southern Annual Mode (SAM/AAO) (Sun et al. 2017). This shows that during the austral winter the atmosphere variability in the Southern Hemisphere is interconnected not only in directly neighbouring zones but possibly in the entire Southern Hemisphere. Further analysis into new Atlantic Oscillation indices could bring more information about these consistencies.

High correlations were confirmed by significant coherence in adjacent zones.

New conventional and extreme indices have been calculated for the area of the whole ocean and cautiously may be treated as proxies for oscillations in particular cells of global atmospheric circulation (northern and southern Hadley, Ferrel and polar cells).

6 Conclusions

Twelve new Atlantic Oscillation indices were established: (conventional) ANAO, NAO, NATO, SATO SAO, ASAO; (extreme) ANAOE, NAOE, NATOE, SATOE, SAOE and ASAOE. New indices' fluctuations had coherent tendencies, which in some respect are in accordance with NAO fluctuations recognised in previous studies, with the most apparent and common upward trend from the middle of the twentieth century.

An overall close proximity between NATO-SATO, NATOE-SATOE and SAOE-ASAOE has been detected, giving evidence for close relations between fluctuations in two Hadley cells, and southern polar and Hadley cells. This is linked to a general conclusion that more apparent regularities exist in southern indices suggesting uniform fluctuations in the austral part of the Atlantic.

More positive index values, and accentuated general tendencies shown in annual variations, are attributed to wintertime index variations, DJF for northern and JJA for Southern Hemisphere. This is a confirmation of previous works suggesting superiority of wintertime-based NAO index (Hurrell 1995, Jones et al. 1997, Li and Wang 2003, Hurrell et al. 2003, Osborn 2006); however, it is the first time this regularity has been shown for oscillation across all latitudes.

FFT power spectrum analysis showed predominant impact of 0.5- and 1-year periods on all indices' variability, confirming results of Li and Wang (2003). Moreover, maxima around 5.5-year period and its multiplicities occurred, suggesting significance of this cycle for Atlantic Oscillation.

Correlation analysis showed stronger relations between extreme indices than conventional ones possibly indicating the superiority of this method. Strong correlations adjoining all Southern Hemisphere and extreme JJA indices imply localisation and approach that provide data with most recognised regularities.

Strong correlation and promising coherence between tropical indices NATO-SATO and NATOE-SATOE suggested symmetry in dynamics of Hadley cells on both hemispheres and a very strong correlation was visible between extreme indices of SAOE and ASAOE, describing southern Ferrel and polar cells, proving their cohesion.

In further studies, Empirical Orthogonal Function methodology should be applied to examine Atlantic Oscillation variability from even more dynamic perspective. Weather phenomena connected to specific phases of NAO have been thoroughly examined, and the same scrutiny is necessary to understand significance of new Atlantic Oscillation indices, especially in the southern part of the ocean. Moreover, past search for oscillations is mainly focused on the troposphere and its interaction with oceans. Increased interest in this approach and focus on the North Atlantic resulted in some forgetfulness of the direction initiated by Rossby and Willett (1948), who proposed a deterministic approach taking into account covariation in the troposphere and the stratosphere. With these in mind, further investigation may bring desirable information about Earth's climate system and possibilities of its real forecasting.

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