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REGIME SHIFTS IN ARCTIC OSCILLATION (AO) VARIABILITY 1951–2009

Abstract: Arctic Oscillation (AO) reflects the dominating mode of SLP (or 1000hPa) variability in hemispheric scale and seems to bear an effect on the weather and, in longer time scales, on climate. The aim of the research was to identify the possible regime shifts in the multiannual course of AO index which in turn might be utilised in the identification and quantification of the regional/local meteorological field response. The data (AO monthly and daily index values) were acquired from the NOAA Climate Prediction Centre. The AO index is constructed by projecting monthly/daily anomalies of 1000hPa heights poleward of 20°N onto the loading pattern of the AO – 1st (leading) EOF of the 1000hPa height field for the same spatial domain. The temporal scope of analysis was 1951–2009. The analysis comprised the regime shift identification techniques that track the shifts in the mean values and in the magnitude of fluctuations as well as the usage of the classical linear trend identification in the annual and seasonal scale. The regime shift recognition was followed by the compositing method that allowed the analysis of spatial anomalies in SLP field in Euro-Atlantic region that reflect the response of the regional airflow to identified circulation regimes.

Key words: Arctic, Arctic Oscillation, regime shifts

Introduction

Climate system is a non-linear dynamical system and as such is prone to rapid shifts (regime shifts – RSs) which might be described as reorganisation from one relatively stable state to another (Rodionov, Overland 2005). The idea of early regimes detection seems to be crucial in ecosystem (incl. climatological) research and further ability of adaptation of societies to changing condition. The examples of such RSs were provided by Mantua (1997) who recognized them in Pacific Decadal Oscillation (PDO) which then resulted in significant shifts in salmon yields. Also, as the lifespan of regimes is much longer than the transition itself (Rodionov, Overland 2005) timely detection of changes provides an opportunity of now-casting and makes possible adaptation necessity less strenuous for the population and economies.

The variability of the atmospheric circulation is one of the major factors governing the climate changeability in mid-latitudes. Its variability was vastly investigated with the usage of relatively simplistic yet informative circulation indices such as Rossby Index (Rossby 1941), or NAO. Degirmendžić et al. (2000) presented a review of the circulation epochs classification for the 20th century. They also proposed their own with the usage of zonal circulation index. Kożuchowski (1993) also investigated the variability of the hemispheric zonal index since 1899.

In the last decades of 20th century the method of empirical orthogonal functions was used to decipher the spatial and temporal variability of atmospheric circulation and concept of annular modes emerged from the analysis of the hemispheric pressure/geopotential height fields (Thompson, Wallace 2000). In the northern hemisphere Arctic Oscillation was identified as a leading mode of circulation variability that owes its existence to the internal atmospheric dynamics in middle latitudes. It should be also stressed that so called annular modes are essentially hemispheric scale patterns of climate variability. The variability of atmospheric circulation in such spatial scale (mirrored by AO) has also direct effect on air flow system in smaller scales thus might be an agent of climatic conditions shifts that follow rapid change in the index course itself.

This paper presents an attempt to identify the regime shifts in AO multiannual course for relatively long period: 1950–2009. Not only average values were analysed [those were analysed in earlier publications] but daily AO index was used to calculate annual and seasonal AO characteristics (percentiles) that allowed the recognition of the shifts in the range of AO variability which is restricted when only averages are taken into account. The RSs analysis is accompanied by the trend coefficient analysis for selected periods: 1950–2009 & 1989–2009 together with 20-years moving trend coefficients values for the whole period. The final element of the analysis comprised the composite analysis of the SLP anomalies in the Euro-Atlantic region during the identified regimes that might reflect the response of the local/regional air flow to hemispheric forcing thus modifying the weather characteristics and in the long run possibly the climate.

Data and Methods

Daily values of AO index were acquired from the servers of NOAA CPC (Climate Prediction Center) and they were constructed by projecting the daily (00Z) 1000hPa height anomalies poleward of 20°N onto the loading pattern of the AO. NCEP/NCAR Reanalysis (Kalnay et al. 1996) was used as a source of monthly mean SLP values (downloaded from NOAA Physical Science Division). The time scope of the analysis comprised the years 1950–2009 and the spatial extent of the investigation of the SLP field response to the distinctive AO regime forcing covered Euro-Atlantic region (40°W-40°E, 35°N-75°N).

The main aim of the investigation was the recognition of the regimes in the AO course. The detection of regime shifts encounters multiple problems even though there are statistical tools used solely for this purpose. Rodionov (2005) provides a vast review of such methods that generally might be divided into either detection of change in the average values or in second order statistics (e.g. variance). Most important problems comprise the detection of multiple shifts, accounting for trend in the data, the quality of testing near the end of the data series and also the autoregressive processes that might pose a serious impediment to the proper identification of the regime shift (Rodionov 2004). All this implies the impossibility of now-casting (in short temporal scale) which in the view of rapid changes of circulation characteristics might have an enormous impact on the economies and societies. Rodionov (2004) proposed a STAR (Sequential T-test Analysis of Regime Shifts) algorithm and provided freely available tools (http://www.beringclimate.noaa.gov/). The testing procedure comprises the comparison of the successive values with the average of present regime. If the value exceeds calculated (with aid of the t-test) range this time step is considered a beginning of a new regime and thus the probable RS is identified. The new regime persistence is subsequently tested with the successive values using the RSI (Regime Shift Index measure). If the RS is confirmed, new average is calculated for the second regime which becomes a reference for the search of the next regime. The STAR algorithm, its merits and usage was described in detail by Rodionov (2006). The full algorithm description is also placed at the end of the paper (see Annex).

In the course of analysis multiple test were performed for different initial significance levels of RSs. Finally, the identified RS are almost all statistically significant at 0.05 level (with the exception of the 1995–2008 spring regime which is significant at 0.08 level). The recognition of AO regimes was followed by the trend analysis. Its output was tested for significance with the F-Snedecor test (Wilks 2008). Next step was the analysis of the SLP response to the reign of the distinctive AO regimes and it was based on compositing analysis (Wilks 2008). The results were presented as anomalies (in hPa) from the averages for reference period 1971–2000.

Results

The STARS algorithm was used to provide an insight into the RSs in AO multiannual variability. Average annual AO values exhibit five distinctive regimes (Fig. 1). First regime comprises the period 1950–1970 (21 years). It was characterised by the lowest average value of AO (-0.34) during the whole analysed period. First RS (1970/1971) was only recorded in average AO values and its 10th percentile. Second regime lasting from 1971 until 1988 (18 years) is characterised by the AO near zero and inter-annual variability of the index shows vacillations between positive and negative polarisation of AO without significant long-term swerve towards any of its polarities. Late 1980-ties (1988/1989) exhibit major shift (+0.63) into positive AO values and it is apparent not only in the average values but also other analysed characteristics. The end of this regime seems to be as rapid as its onset. Year 1996 marks definite return to average AO values near zero and relative limitation of the range of its variability. STARS method identified year 2009 as a probable beginning of the new regime which could be indicated by the relatively strong shift in average AO values into negative polarity of the index. The course of other statistics seems to confirm this thesis as one can see significant drop in the values of lower percentiles meaning the increase of AO range of variability thus indicating the end of the AO stability era which was characteristic for the previous regime.

Seasonal variability of AO (Fig. 2) provides an insight into characteristics of AO (averages, 10th and 90th percentile). Winter (DJF) exhibits 5 regimes with significantly indicated shifts in AO polarity. Only the last regime (1994–2009) does not seem to favour any of the polarities and shows rapid

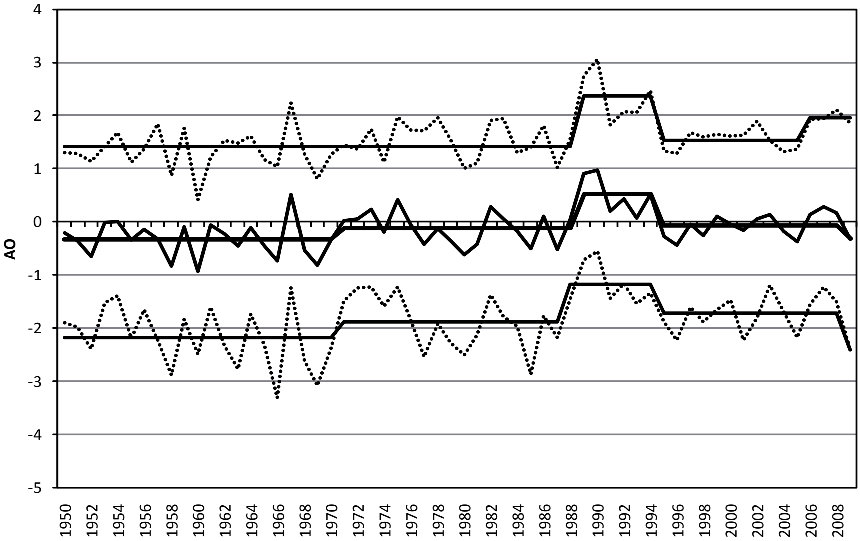


Fig. 1. Course of annual statistical characteristics of AO together with identified regimes (solid bold lines) 1950–2009. Dotted lines – percentiles 10th & 90th

changes of AO characteristics in year-to-year scale. First part of the analysed period (1950–1970) is characterised by negative AO polarity in winter. Early 70-ties (1971–1976) recorded visible shift into positive AO values. Above mentioned RSs are also reflected by other statistical properties (percentiles 10th & 90th). Generally, it might be stated that winter is a season with the highest AO variability. Spring months (MAM) represent relative stability in AO course. What seems to be evident is the shift towards positive AO values in the period 1989–1994. Also, year 2009 suggests the possible RS. The overall variability in spring is slightly lower than in winter. Summer is the season with the lowest AO variability range (the overall averages' variability ranges is between +1 and -1) and identified regime shifts are not very substantial though statistically significant at level 0.05. The change in the averages between the shifts is +0.23 (1st RS) and -0.36 (2nd RS). There is a long period without the regime shift extending from 1950 until 1988. More visible is the shift in the 90th percentile which occurred in 1994 thus marking increased overall variability range of AO. The beginning of the 21st century was marked by the RS towards the negative polarity of AO which

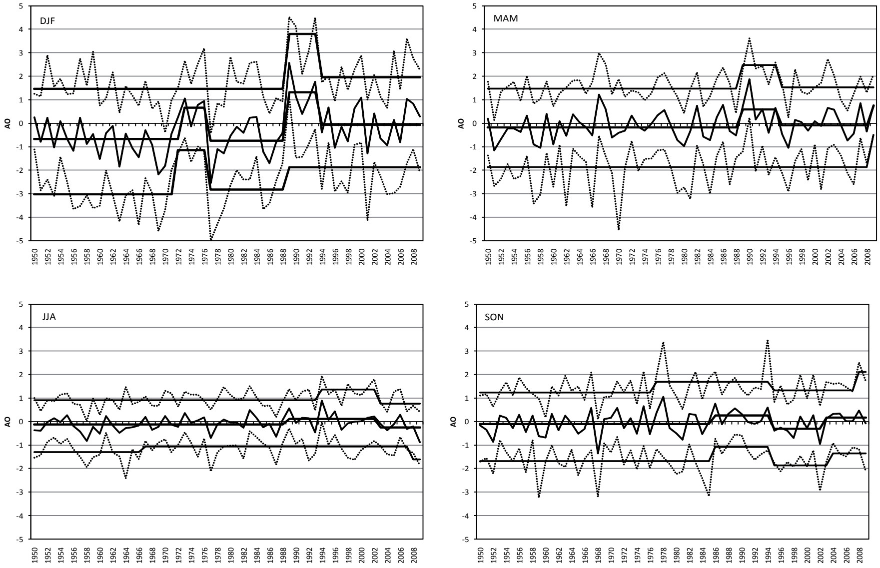


Fig. 2. Course of seasonal statistical characteristics of AO together with identified regimes (solid bold lines) 1950–2009. Dotted lines – percentiles 10th & 90th, solid line – average. DJF – winter, MAM – spring, JJA – summer, SON – autumn

was then further amplified by the negative RS in 10th percentile. This was not accompanied by the RS in average values but year 2009 apparently exhibits the continuation of the downward trend. Autumn is characterised by higher seasonal AO variability than in summer. The identified RSs are also more pronounced. Similarly to the summer situation the average AO course does not exhibit RS until 1985. However there is a substantial RS in 90th percentile towards positive AO values that occurred in 1976. This, together with no changes in regimes for average and 10th percentile suggests the reign of extended variability range in the AO values. The 1976 shift in 90th percentile is followed by average and 10th percentile values only in 1985 thus restricting the AO range. This regime ended in 1994 when RS towards negative AO polarity occurred. Next RS in average AO values was identified in 2003. This was also followed by the RS in 10th percentile. Year 2007 experienced a significant shift in 90th percentile again marking the increase of overall AO variability.

Table 1. Trend coefficient (per 10y) of the AO averages and its statistical properties for chosen periods

Season	Average	Percentiles				
		10th	25th	50th	75th	90th
Jan-Dec 1950–2009	0.08	0.09	0.06	0.06	0.07	0.10
Jan-Dec 1989–2009	-0.31	-0.38	-0.31	-0.25	-0.26	-0.33
DJF 1950–2009	0.17	0.19	0.18	0.17	0.15	0.16
DJF 1989–2009	-0.61	-0.84	-0.79	-0.47	-0.52	-0.64
MAM 1950–2009	0.08	0.13	0.09	0.08	0.07	0.06
MAM 1989–2009	-0.23	-0.02	-0.12	-0.23	-0.33	-0.52
JJA 1950–2009	0.03	0.02	0.03	0.02	0.03	0.05
JJA 1989–2009	-0.30	-0.30	-0.37	-0.31	-0.31	-0.27
SON 1950–2009	0.04	0.02	0.03	0.03	0.06	0.08
SON 1989–2009	-0.02	-0.24	0.00	0.05	0.06	0.07

Above analysis indicates very strong shift towards positive AO polarity for almost all seasons and majority of the statistical properties during early 1990-ties. Table 1 presents a comparison of AO index trend coefficients for the whole period of analysis together with the period comprising last 21 years of analysis (1989–2009). Period 1950–2009 is somehow coherent with many views expressed in literature commenting on the increasing intensity of the polar vortex and its regional emanations (e.g. NAO). Results, especially those comprising last decade of the 20th century were primarily the outcome of the very intense increase in the polar vortex intensity in the early 90ties. On the other hand such views might be confronted by the last 20 years of analysis when not only did we experience the change in the direction of the AO index evolution but also substantial strengthening of its pace. The only season which does not exhibit such behaviour is autumn. Figures 3 & 4 present the variability in the values of 20-years moving trend coefficients of AO for annual and seasonal averages. One can see substantial fluctuations in the course of trend coefficients. In an annual scale the beginning of the period of analysis was characterised by slightly negative trend coefficients. Period 1954–1973 commenced an era of positive trend coef-

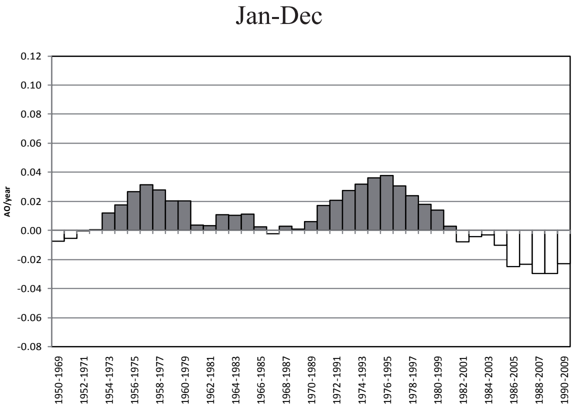

Jan-Dec

Fig. 3. 20-years moving trend coefficients (change/year) of AO index annual averages 1950–2009

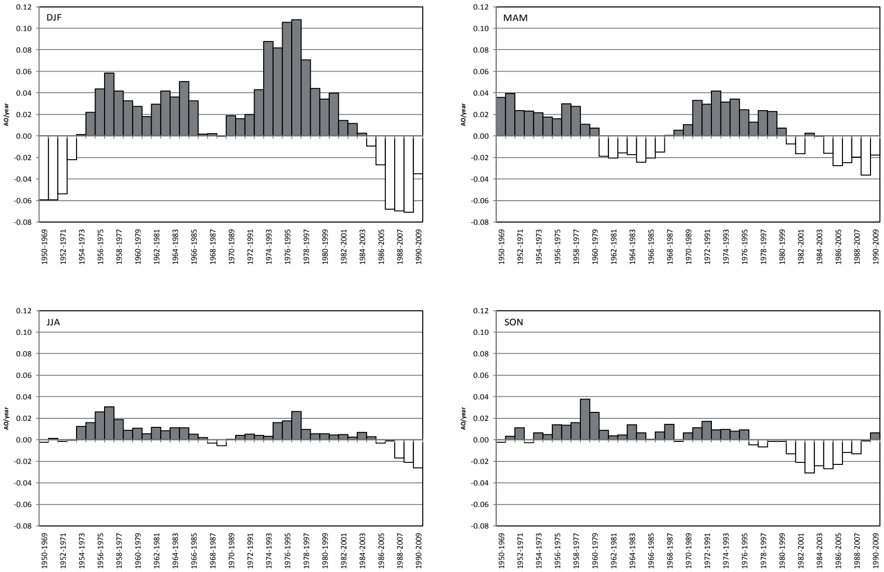
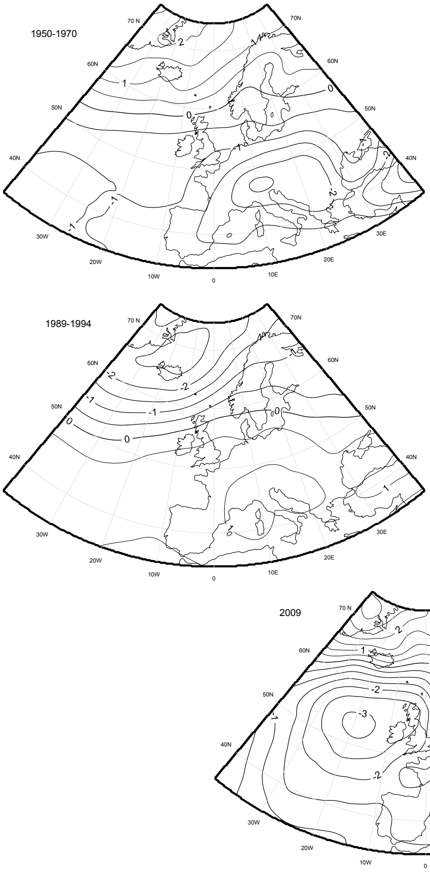


Fig. 4. 20-years moving trend coefficients (change/year) of AO index seasonal averages 1950–2009

ficients with the highest values for periods 1957–1976 & 1977–1996 with the relative weakening in the period 1966–1991. Starting from 1982–2001 AO experienced negative trend which reached the highest intensity during the last five 20-years periods of the analysis. The course of AO trend coefficients in winter complements the annual picture however the scale of the variability is much greater with more pronounced fluctuations. Spring is characterised by lower range of variability quite comparable with the range of annual values. In contrast to annual and winter course of trend coefficients the period of substantially negative values is clearly indicated beginning in 1961–1980 and lasting to 1967–1986 period. Also during this season the values change into negative commencing in period 1980–1999 and lasting until 1990–2009. Summer is a season of the lowest variability in AO trend coefficients. There is also a prevalence of slightly positive values with a strong shift towards negative ones starting in 1986–2005. Autumn can be divided into two sub-periods of contrasting AO development characteristics. From the beginning of the analysis period until 1976–1995 there is a dominance of positive trend coefficients and from this point onwards the negative values prevail. Last 20-year period shows the return of positive trend.

SLP anomalies for identified circulation regimes (Fig. 5) seem to be connected with the AO variability. First period (1950–1970) of AO weakening shows a substantial decrease in zonal flow intensity. This is a result of a pressure gradient decrease over North Atlantic – positive anomalies north of Iceland exceeding +2hPa and negative ones over the usual location of Azores High. This situation has relatively significant spatial extent and one might say that the whole analyzed area is divided in zonal belts of positive/negative anomalies. Two regimes (1971–1980 & 1993–2008) are characterised by weak variability of SLP anomalies field and this coincides with the fact that during those periods of time average AO values were close to zero. What strikes is a regime of substantial increase of zonal flow intensity over North Atlantic (1989–1994) which concurs with positive AO polarity. Characteristic feature is a strong drop in SLP values north of Iceland (anomalies below -3hPa) together with positive anomalies occupying southern part of the research area. Year 2009 is identified as a probable onset of a new regime with very strong negative anomalies west of Ireland together with positive ones north of Iceland. This major feature, however, is restricted to the oceanic foreground of the continent and its continuation over Europe is much weaker.


1950-1970

1971-1988

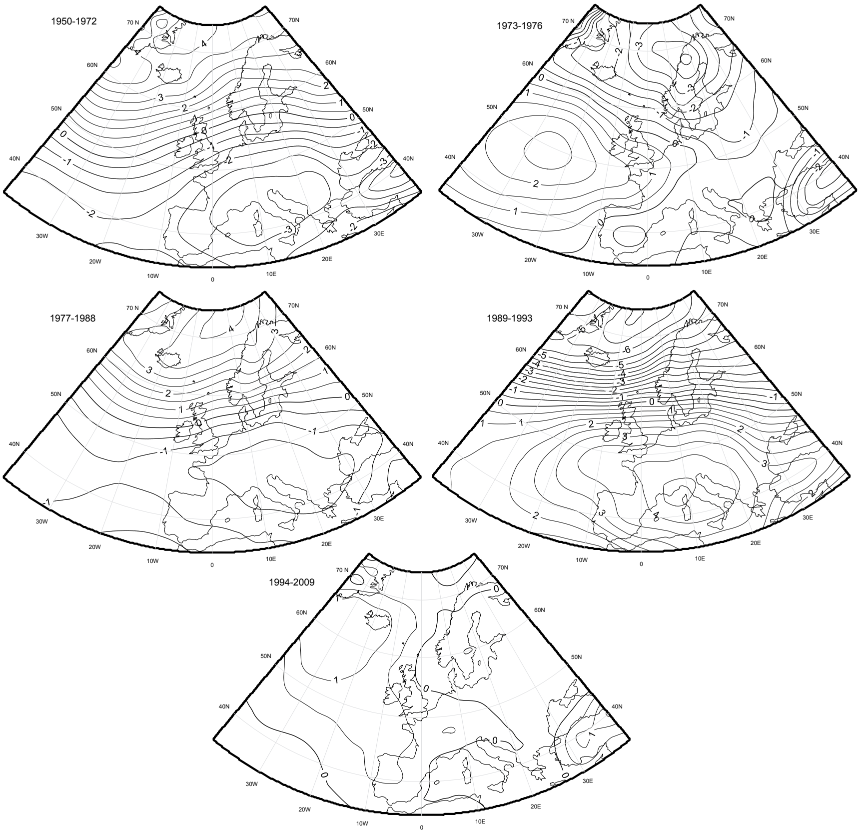
1989-1994

1995-2008

2009

Fig. 5. Annual SLP anomalies (hPa) during identified circulation regimes (reference period: 1971–2009)

Winter anomalies show substantial variability in the SLP field for identified circulation regimes. Periods 1950–1972 and 1977–1988 indicate strong weakening of the zonal flow which is exhibited by significant positive anomalies in the northern part of the area of research with the anomalies over +4hPa. Simultaneously, corresponding areas of Azores High in the southern part of the research area experience negative anomalies below -4hPa. The resulting weakening of pressure difference in the south-north axis by more than 8hPa clearly presents itself. Such situation extends in a zonal form over



1950-1972

1973-1976

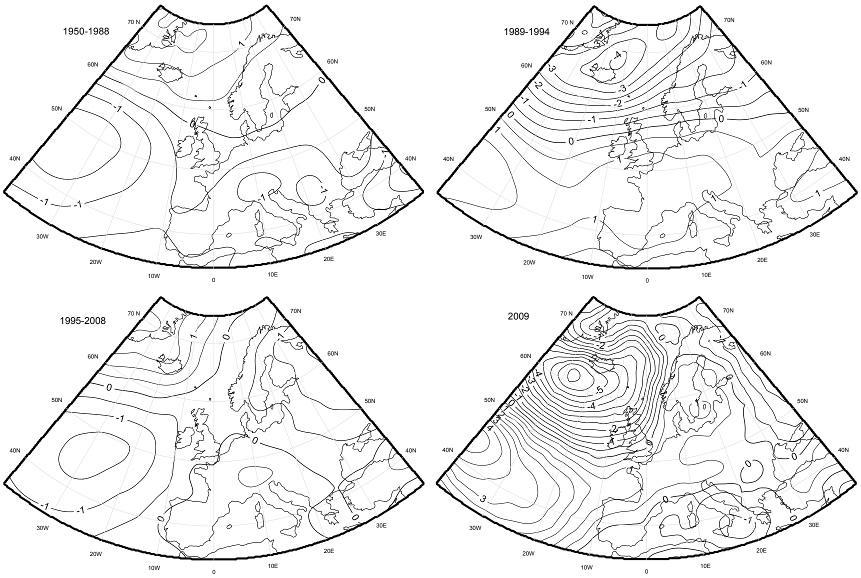
1977-1988

1989-1993

1994-2009

Fig. 6. Winter SLP anomalies (hPa) during identified circulation regimes (reference period: 1971–2009)

all of the research area. What might also be stressed is that during the first period of negative AO dominance the anomalies amplitude was substantially greater meaning stronger influence on airflow over the region. Period 1973–1976 exhibited very strong increase in AO values and this is connected with the presence of two areas of positive/negative anomalies. Positive anomalies can be connected spatially with the strengthening of Azores High while the negative ones occupy lower pressure area extending from Iceland towards east with the highest value of anomalies (below -4hPa) over


1950-1988

1989-1994

1995-2008

2009

Fig. 7. Spring SLP anomalies (hPa) during identified circulation regimes (reference period: 1971–2009)

the northern part of Scandinavian Peninsula and adjacent basin of Norway Sea. This suggests the intensification of the flow from NW over the central Europe. While in the case of previous period of the strengthening of the AO positive polarity the pattern of SLP anomalies was spatially confined, in the case of 1989–1993 they are extending over the entire research area. Also, the anomalies north of Iceland fall below -6hPa while those over Mediterranean exceed +5hPa which gives a total of over 11hPa SLP difference. Last of the analysed periods showed slight decrease in SLP over area west and south-west of Iceland which slightly exceeds -1hPa.

Spring variability of AO index allowed the identification of four regimes. First one (1950–1988) comprising 39 years was connected with weak decrease of SLP difference over North Atlantic with the total anomaly amplitude at 4hPa. Next short regime (5 years) of positive AO polarity was indicated by a strengthening of the SLP gradient over North Atlantic. The highest negative anomaly (lower than -4hPa) was located over Iceland and extended north-east. Regime comprising years 1995–2008 resulted in a drop

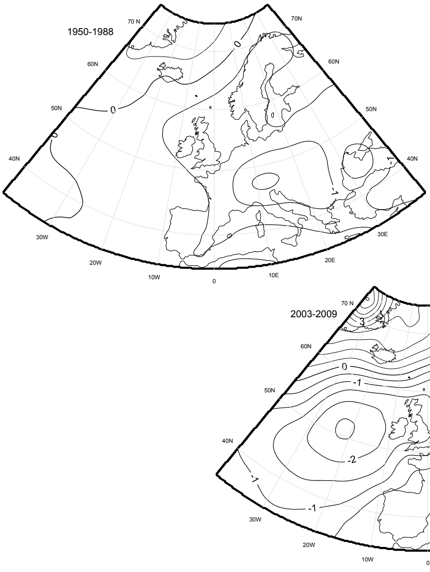


Fig. 8. Summer SLP anomalies (hPa) during identified circulation regimes (reference period: 1971–2009)

of SLP in the south-western and eastern part of the research area. Mediterranean and larger part of continental Europe exhibit slight increase of SLP. Final identified spring regime comprised only one year (2009) – thus, it should be considered no more than a probable change and this RS must be confirmed by the subsequent years. It shows significant intensification of zonal flow over North Atlantic with total anomalies amplitude exceeding 12hPa. The area is however restricted to the Atlantic Ocean and is only vaguely indicated over the continental Europe.

Summer is a season of the weakest AO variability and the RS identification procedure recognised 3 regimes. First two: 1950–1988 & 1989–2002 are characterised by only slight SLP anomalies and their amplitude exceeds 4hPa, however over the most of the research area the anomaly is negative with the highest values over Alps. Also, the second of the identified regimes does not show pronounced SLP anomalies. Only the last one (2003–2009) which is characterised by relative drop in AO values exhibits the weakening of the normal SLP gradient over North Atlantic with the area of negative

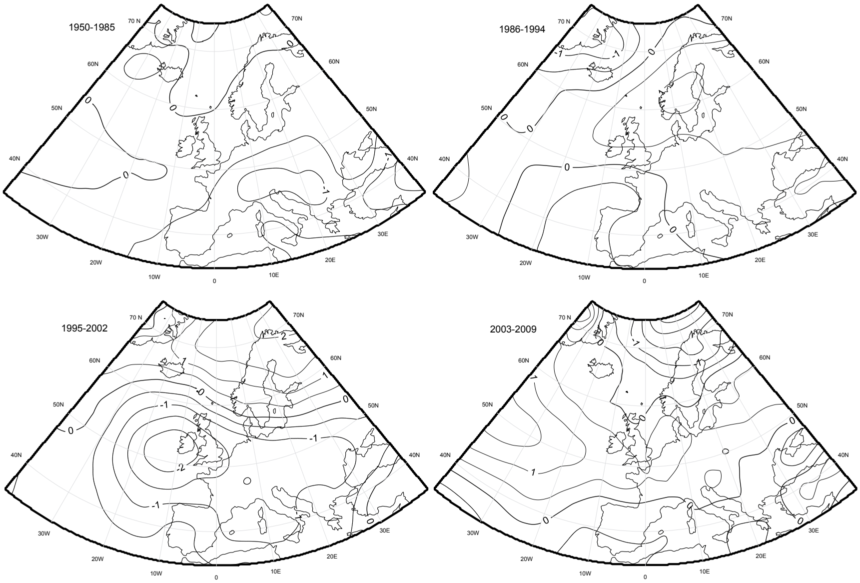


Fig. 9. Autumn SLP anomalies (hPa) during identified circulation regimes (reference period: 1971–2009)

anomalies extending from the centre west of Ireland. Generally, most of the area is covered by the anomalies of negative sign. The area of positive anomalies extends north of Iceland.

With four identified AO regimes in autumn (Fig. 9) the SLP anomalies do not exhibit substantial variability. First regime comprising 36 years with AO values near 0 does not reveal much spatial variability in the SLP anomalies. Second regime (1986–1994) with a shift of AO into the positive polarity shows the increase of SLP over continental and northern Europe. Negative values of SLP anomalies extend north/north-west of Iceland, Next regime (1995–2002) shows the weakening of zonal flow with negative anomalies over southern part of the area of research. Latest regime (2003–2009) with positive anomalies extending from west (highest values) to east. Northern areas exhibit negative anomalies thus intensification of zonal flow is apparent especially in the north.

Conclusions

Introductory research showed that sequential testing for regime shifts seems can be a useful tool in analysing the regime shifts of Arctic Oscillation. It is flexible and provides vast range of additional information characterising the identified regimes. The RSs in early 1970-ties, late 1980-ties and mid 1990-ties are most prominent (occur in annual scale and multiple seasons). 1970/1971 RS also appears in many publications as significant shift in circulation characteristics (e.g. Degirmendžić et al. 2000). RSs in JJA and SON are less evident mainly due to the restricted AO variability in those seasons. The RSs indicate the shifts between 3 major "positions" of AO. First "positive" with highly marked shifts towards the positive AO values are more pronounced in winter and for annual averages. Those tend to be relatively short – 1973–1976 and 1989–1994 in winter, and 1989–1994 for annual averages. Second type (neutral) with AO averages close to zero and accompanying substantial year-to-year changes in its values. Those are evident for summer (1950–1988), autumn (1950–1986), winter and spring (1995–2008) and also for annual averages (1995–2008, 1971–1988). Last type is the shift towards the negative values and those were typical for the early stages of the analysis period – 1950–1970 (annual averages), 1950–1972 & 1977–1988 (in winter) and relatively weakly indicated period 1995–2002 in autumn. Recognised trends of AO confirm the positive long-term tendencies (1950–2009) however last 21 years witnessed a rapid turn in the direction of air flow system development in hemispheric scale. This change appears evidently in annual as well as seasonal scale (DJF, MAM & JJA).

The RSs in AO play an important role in shaping a regional air flow – depicted as SLP anomalies – thus changing the general advection direction and resulting climate characteristics in a regional scale. Increased range of AO variability in the second part of the first decade of 21st century and the identification of a new RS in the year 2009 might reflect more pronounced changes that await the behavior and the further development of the characteristics of the hemispheric and regional flow patterns.

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Annex

STAR algorithm description

1) Set the cut-off lenght *l* for the regimes to be determined (similar to cut-off point in low pass filtering)

2) Determine the difference *diff* between mean value of subsequent regimes that would be statistically significant (t- stands for critical t distribution value at given significance level)

$$diff = t\sqrt{2\sigma_l^2 / l}$$

3) Calculate the mean of the initial *l* values as an estimate of the regime R1 and the levels in the subsequent year *j* that would qualify as a RS to R2

$$x_{aveR1} \pm diff$$

4) For each values starting with year *i=l+1* check whether it is beyond the range established in step 3). If not, there is no RS. Include the new value to R1 and proceed to the next value . If the value exceeds the threshold it is considered a possible starting point *j* of the new regime R2
5) After the possible shift point is established each new value of x_i where *i>j* is used to confirm or reject the null hypothesis of a regime shift at year *j*. If the anomaly x_i-x_{aveR2} is of the same sign as the one at the time of a regime shift it would increase the confidence or *vice versa*. This change in the confidence of a regime shift at *i=j* is reflected by the value of RSI – Regime Shift Index which represent a cumulative sum of the standardised anomalies

$$RSI_{i,j} = \sum_{i=j}^{j+m} \frac{x_i^*}{l\sigma_l}, m = 0,1,...,l-1.$$

$x_i^*=x_i-x_{aveR2}$ *if the shif is up or* $x_i^*=x_{aveR2}-x_i$ if it is down

If at any time from *i=j+1* to *i=j+l-1* RSI turns negative the test for RS at *j* failed.

6) Assign zero to RSI include x_j to R1 recalculate x_{aveR1} and keep testing the values of x_i starting from *j=j+1* for their exceedence of threshold as in step 4
7) The positive values of RSI means that the RS at *j* is significant. Calulate the x_{aveR2} and this becomes the base one for new RS search. The search starts from year *i=j+1*.