Arab J Geosci (2016) 9: 102
DOI 10.1007/s12517-015-2086-y

ORIGINAL PAPER

A re-interpretation of impact of the Icelandic Low and Azores High on winter precipitation over Iberian Peninsula

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Received: 23 June 2014 / Accepted: 10 September 2015 / Published online: 22 February 2016

Abstract Several studies show that North Atlantic Oscillation (NAO) has dominant influence on the variability of climate over Iberian Peninsula. The traditional definition of the NAO index is a very simple representation of the atmospheric state of negative correlation between the Azores High and the Icelandic Low. The NAO index does not take into account the geographically extensive nature of the high and the low pressure systems and their movements. Fluctuations in both the characteristic shapes and positions of the Azores High and the Icelandic Low influence atmospheric circulation over the north Atlantic region. We study interannual variations of winter rainfall over Iberia, taking into account variations in the Azores High and the Icelandic Low pressure systems. Analysis presented in this paper shows that the north–south migrations of the Azores High exert the greatest impact on winter precipitation over Iberian Peninsula. Using NCEP/NCAR reanalysis data, this approach allows us to understand the changes in atmospheric circulation through which latitudinal shifts of the Azores High influence regional precipitation over Iberia.

Keywords Azores High · Icelandic Low · Winter rainfall

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Introduction

The North Atlantic Oscillation (NAO) has been recognized for more than 60 years as one of the major patterns of atmospheric variability in the Northern Hemisphere (Walker 1924; Walker and Bliss 1932; Trigo et al. 2002; Rogers 1984; Barnston and Livezey 1987; Hurrell 1995; Hurrell and van Loon 1997). The NAO index is defined by measurement of the pressure difference between the Icelandic Low and Azores High at two fixed locations: Lisbon, Portugal and Stykkisholmur, Iceland (Hurrell 1995). When sea-level pressure is below normal over the Icelandic region and above normal over Azores, the NAO is said to be in its high index. At these time, the jet stream and storm tracks tend to be displaced pole ward of their normal positions, temperatures tend to be unseasonably mild over Eurasia and most the USA, and northern Europe experiences heavier than normal rainfall while the Mediterranean bask in sunshine (Wallace and Hobbs 2005). In contrast, episodes of abnormally high pressure over the Arctic (i.e., low NAO index) tend to be marked by relatively frequent occurrence of cold air outbreaks over Eurasia and the USA.

Recently, a number of studies have shown the relevance of the NAO to the winter surface climate of the Northern Hemisphere in general and over the Atlantic/European sector in particular (Hurrell 1995; Qian et al. 2000; Rogers 1997). However, the present work aims to present an improvement over the traditional NAO definition by taking account of the extended nature of the Azores High and the Icelandic Low and apply it to analyze the interannual variability of winter precipitation over the Iberian Peninsula. The Azores High, the Icelandic Low, and other such semi-permanent pressure systems were called the "centers of action". It is better to analyze the impacts of fluctuations of the pressures and locations of these centers of action, which vary considerably over spatial and temporal scales; we calculate objective indices for the pressure, latitude, and longitude locations for both centers, using gridded sea level pressure data from National Center for Environment Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis.

Data

We use monthly precipitation data obtained from Climate Research Unit, University of East Anglia: http://www.cru.uea.ac.uk/cru/data/hrg/cru_ts_2.10 for the period from 1951 to 2012 for our study for calculating the seasonal average precipitation. Monthly averaged gridded sea level pressure (MSLP) data from NCEP reanalysis on 2.5°×2.5° grid (Kalnay et al. 1996) for 1948–2012 was also used for calculating objective COA indices for the monthly averaged pressure, latitude, and longitude of the Icelandic Low and the Azores High as described by (Bakalian et al. 2007). NAO, Arctic Oscillation (AO), and Southern Oscillation Indices (SOI) monthly indices are available at the Climate Data Center, National Center for Environmental Prediction. The NCEP reanalysis was also used for constructing composite maps to understand meteorological changes that accompany different extreme conditions of the Atlantic Ocean.

Method

We can characterize the large-scale fluctuation in atmospheric pressure over North Atlantic Ocean using NAO index. As mentioned earlier, the NAO index is defined by measurement of the pressure difference between the Icelandic Low and Azores High at two fixed locations: Lisbon, Portugal and Stykkisholmur, Iceland. However, it is known that these two pressure systems have extended structures that migrate considerably and motions are not entirely coupled. As such, a better estimate of influence of atmospheric pressure fluctuations on the climate variability over Europe can be attained through a more quantitative assessment of the fluctuation in the pressure and locations of the Centers of Action (COA). The large-scale semi permanent pressure centers known as "centers of action" were introduced by Rossby (1939). Each COA exhibits a characteristic seasonal cycle. During winter, the Icelandic Low, the Aleutian Low, the Azores High, and the Siberian High are most pronounced. In summer, the low-pressure centers weaken, and the Hawaiian High and the Azores High dominate. Additionally, in the summer, the South Asia Low, related to the Indian monsoon, forms as a center of low pressure. In addition to a weakening and strengthening of the pressure centers, there is also displacement; for example, in summer the Hawaiian High and the Azores High move to the east compared to the winter season. The position and the strength of the COA are captured by three indices representing its longitude, latitude, and pressure. Recently, this approach has successfully been used to explain the role of the movement and intensity of individual atmospheric COAs on such varied biogeochemical systems as copepod abundance (Piontkovski and Hameed 2002), the variation in the location of the Gulf Stream (Hameed and Piontkovski 2004), the variability of the transport of African dust (Riemer et al. 2006), impact of Indian Ocean High pressure on precipitation over Western Australia (Hameed et al. 2011), and influence of Azores High Pressure on Middle Eastern Rainfall (Iqbal et al. 2013). Compared to the traditional NAO approach (Hurrell 1995), the COA are decoupled, and their meridional and zonal movements are considered independently as are the variations in the intensity of the pressure. The approach is well described by Piontkovski and Hameed, Hameed and Piontkovski, and Riemer et al., but it is briefly summarized as follows.

The pressure index I_p is defined as an area-weighted pressure departure from a threshold value over the domain (I, J):

$$I_{p,\Delta t} = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\left(P_{ij,\Delta t}-P_t\right)\cos\varphi_{ij}(-1)^M\delta_{ij,\Delta t}}{\sum_{i=1}^{I}\sum_{j=1}^{J}\cos\varphi_{ij}\delta_{ij,\Delta t}}$$

Where $P_{ij,\Delta t}$ is the SLP value at grid point (i, j) average over a time interval Δt, in this case monthly SLP values are taken from NCAR, P_t is the threshold SLP value (P_t= 1014 mb for Azores High and Icelandic Low), ϕ_{ij} is the latitude of the grid point (i, j), M=0 for the Azores High, and M= 1 for the Icelandic Low. δ=1 if $(-1)^M(P_{ij,\Delta t}-P_t)>0$ and δ=0 if $(-1)^M(P_{ij,\Delta t}-P_t)<0$, this ensures that the pressure difference is due to an Azores High or Icelandic Low system. The intensity is thus a measure of the anomaly of the atmospheric mass over the section (I,J).

Similarly, the latitudinal index is defined as:

$$I_{\varphi,\Delta t} = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\left(P_{ij,\Delta t}-P_t\right)\varphi_{ij}\cos\varphi_{ij}(-1)^M\delta_{ij,\Delta t}}{\sum_{i=1}^{I}\sum_{j=1}^{J}\left(P_{ij,\Delta t}-P_t\right)\cos\varphi_{ij}(-1)^M\delta_{ij,\Delta t}}$$

and the longitudinal index $I_{\lambda,\Delta t}$.

We first calculate seasonal average of winter precipitation for the months from December to March over Europe at each grid point. We next compute correlation between winter precipitation at each grid point over Europe and NAO. The purpose is to identify regions where a significant amount of variation can be possibly explained by further study.

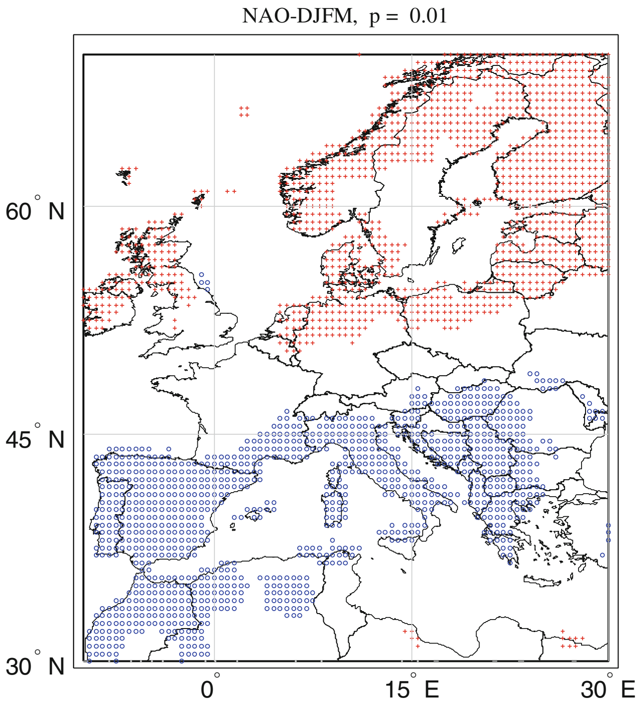

Fig. 1 Correlation between NAO and winter precipitation over Europe

Next, we identify the indices with large contributions that could be significant. Correlations are calculated among the COA indices using data from 1952 to 2002. The last 10 years data from 2003 to 2012 are used for model validation. Only mutually independent indices are considered for further investigation. Thus, significant independent COA indices are identified for the construction of a linear regression model of identified region.

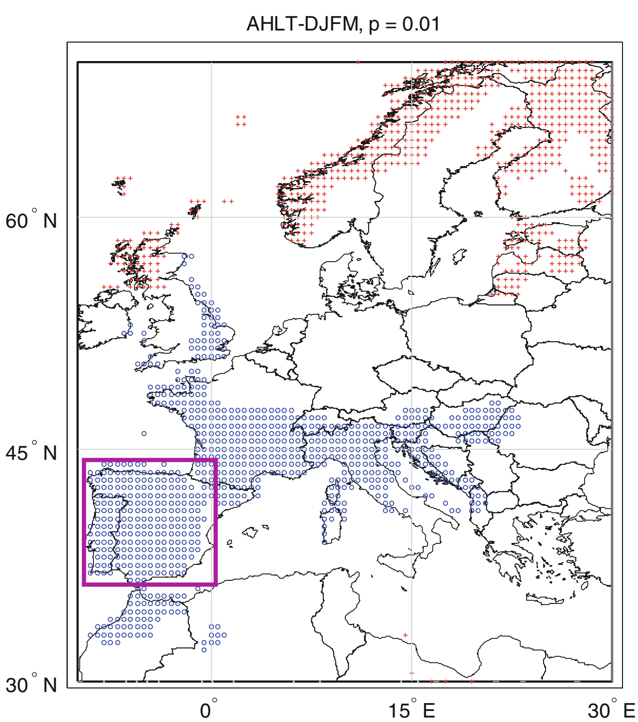

Fig. 2 Correlation between Azores High latitude and winter precipitation over Europe

Table 1 Correlation coefficients of winter precipitation of Iberian using DJFM average of Icelandic Low and Azores High variables

Number	Variables	Correlation coefficients
1	NAO index	−0.74
2	AO	−0.65
2	AHPS	−0.66
3	ILPS	0.50
4	AHLT	−0.80
5	ILLT	−0.72
6	AHLN	−0.69
7	ILLN	−0.16

Results

With p=0.01, we have plotted correlation map in Fig. 1 for examining the impact of NAO on wintertime (DJFM) precipitation for the period from 1952 to 2002. It shows that winter precipitation over a large region of Northern Europe is strongly correlated. But there are some regions in Northern Europe where winter precipitation is not significantly correlated with p=0.01. For instance, winter precipitation over Central Europe (Germany, Poland, etc.) is not significantly influence by NAO. However, Fig. 2 shows that winter precipitation over Iberian Peninsula (8°W −1°W, 37°N −44°N) is significantly correlated with Azores High Low Latitude. While as Fig. 1 shows, winter precipitation over the Iberian Peninsula is also influenced by NAO. Therefore, we will use partial correlation analysis for examining whether NAO index or COA variables have dominant influence on winter precipitation over the Iberian Peninsula because this region is located near Azores High. We investigate the impact of COA indices on other regions of Europe in our forthcoming articles.

Table 2 Partial correlation matrix for winter precipitation of Iberia with respect to NAO index, AO, Icelandic Low pressure, Icelandic latitude, Azores High pressure, Azores High latitude, and Azores High longitude

Number	Variables	Partial correlation coefficients
1	NAO index and rain	−0.11
2	AO index and rain	−0.17
3	AHLT and rain	−0.51
4	AHLN and rain	−0.34
5	AHPS and rain	−0.17
6	ILPS and rain	−0.13
7	ILLT and rain	0.11

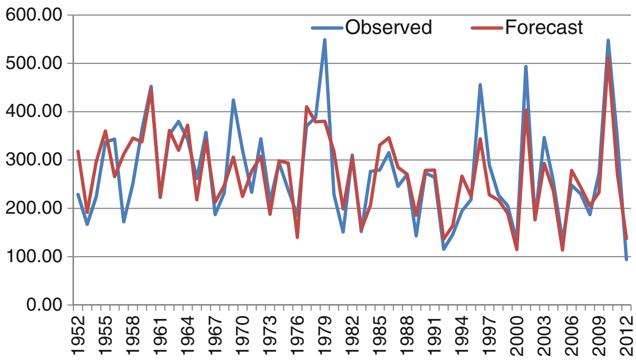

Fig. 3 A comparison of the winter precipitation of Iberian Peninsula and our modeled values based on linear regression model for the years 1952–2002. The independent variable in our regression model is December, January, February, and March (DJFM) averaged Azores High pressure latitude (AHLT). The variance in the winter precipitation explained by our regression model is R^2=0.64

Then, we next compute Pearson's correlations between nine indices of COA (Icelandic Low latitude, Icelandic Low longitude, Icelandic Low pressure, Azores High pressure, Azores High latitude, Azores High longitude, AO, and NOA with the mean of winter precipitation over Iberia Peninsula separately for the period from 1952 to 2002). From the correlation coefficients, we find that NAO, Icelandic Low pressure, Icelandic latitude, Azores High pressure, Azores latitude, Azores longitude, Siberian high latitude, and AO are all potentially important variables influencing rainfall over Iberia (see Table 1).

However, these independent variables are mutually dependent. Thus to isolate the effect of each index, we compute the partial correlation coefficients for NAO index, Icelandic Low pressure, Icelandic latitude, Azores High pressure, Azores High latitude, Azores High longitude, and winter precipitation. Partial correlation is a procedure that allows us to estimate what the correlation between two of the variables would be, hypothetically, if they were not each correlated with the third variable. Alternatively, we can say that partial correlation allows us to determine what the correlation between two of the variables would be if the third variable was held constant. The partial correlation of x and y, with the effects of z removed, or held constant, is given by the formula

$$r_{xy-z} = \frac{r_{xy} - r_{xz} r_{yz}}{\sqrt{\left(1 - r_{xz}^2\right)\left(1 - r_{yz}^2\right)}}$$

There is precedent for using a partial correlation analysis to select among mutually correlated variables in regional climate studies. Partial Correlation have been used to evaluate the signal of the Indian Monsoon on Eurasian seasonal snowfall without the influence of ENSO. More recently, partial correlation was used similarly in a paper on mineral dust, tropical cyclone activity, and ENSO As shown in Table 2, Azores latitude and winter rainfall are correlated 95 % confidence level, when these Azores latitude and winter rainfall are held fixed for other combinations of COA indices, NOA, and winter rainfall, the contributions drop non-significant level. Thus, the partial correlation is $r=-0.54$, which shows that the position of Azores latitude has a direct and significant effect on the winter rainfall over Iberia. Similarly, the partial correlation between Azores longitude and the rainfall is −0.32, keeping other variables as fixed.

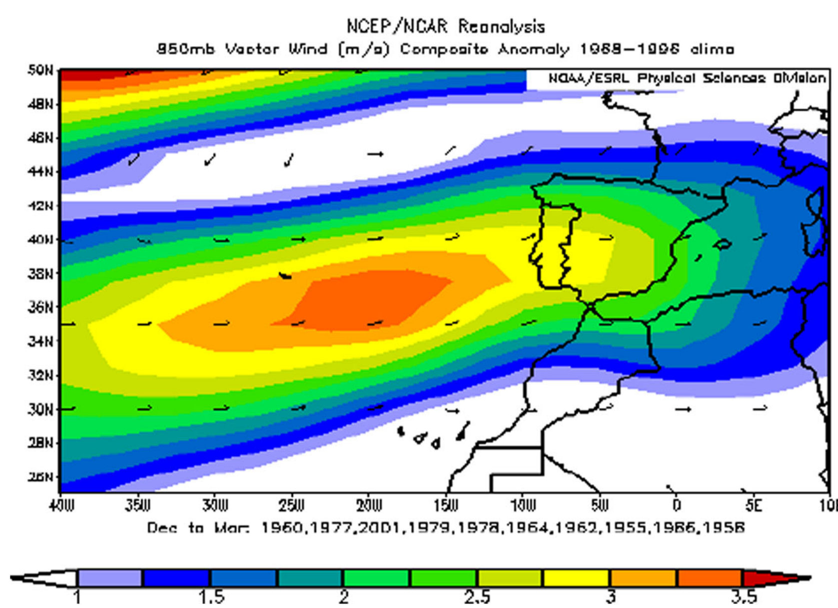

Fig. 4 Eight hundred fifty millibars vector wind anomaly when Azores High to the south shows that there is anomalous westerly flow towards Iberian Peninsula

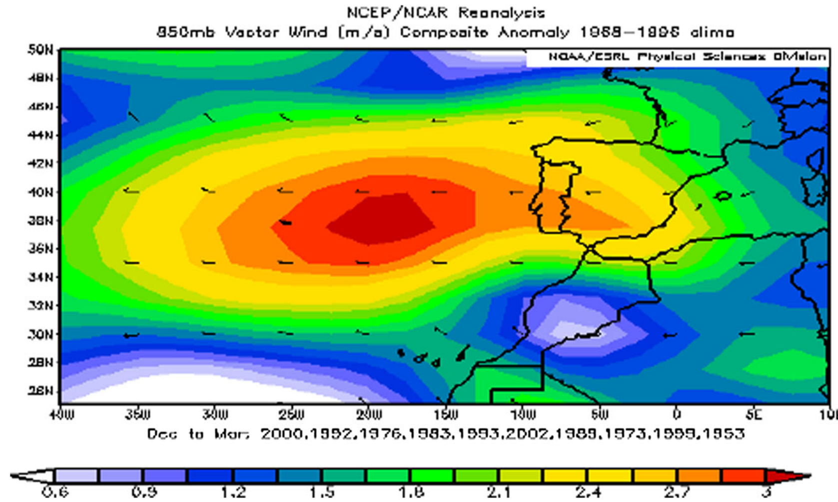

Fig. 5 Eight hundred fifty millibars vector wind anomaly when Azores High to the north shows that there is anomalous easterly flow towards Iberian Peninsula

Linear regression model

As correlation between Azores High latitude and winter rainfall over Iberia is high. Moreover, on the basis of partial correlation, we then construct a linear model for AZ latitude (AHLT) and the rainfall over Iberian Peninsula (IWR):

$$\mathrm{IWR} = 1859.661 - 49.973\ (\mathrm{AHLT})$$

R^2 for the region is 0.64, a significant enhancement over the NAO value of R^2=0.54. The above regression model is constructed using data of AHLT and IWR for the period 1952 to 2002. Data for period from 2003 to 2012 are used for model validation. The regression with Azores High latitude also captures the major patterns of wintertime observed precipitation variations from 1952 to 2012 over Iberia (Fig. 3). By separating the NAO index into COA components, we have been able to isolate the main variable related to the rainfall and thus improve our regression model by 10 % over the fit to the NAO data alone.

Mechanisms for the relationships between COA and the rainfall variability over Iberia

We first construct different composites with the phase of Azores High latitude for the relationships between COA and the rainfall variability. Figure 4 shows composite mean of 850 mb vector wind for 10 years when Azores High was located to extreme south (more rain over Iberia). There is anomalous westerly flow from Atlantic Ocean to Iberian Peninsula, invading over Germany. Figure 5 shows composite mean of 850 mb vector wind for 10 years when Azores High was located to extreme north (dry over Iberia). There is anomalous easterly flow from Iberian Peninsula to Atlantic Ocean.

The vector wind composites for the years of extreme south minus extreme north at 850 mb are shown in Fig. 6. It shows anomalous cyclonic flow over Northern Atlantic and NW Europe. Seasonal mean cyclonic anomalies represent greater frequency of synoptic scale storm in the region. Similarly, Fig. 7 shows the difference in surface pressure between summers in which AH is southward and northward. Anomalous

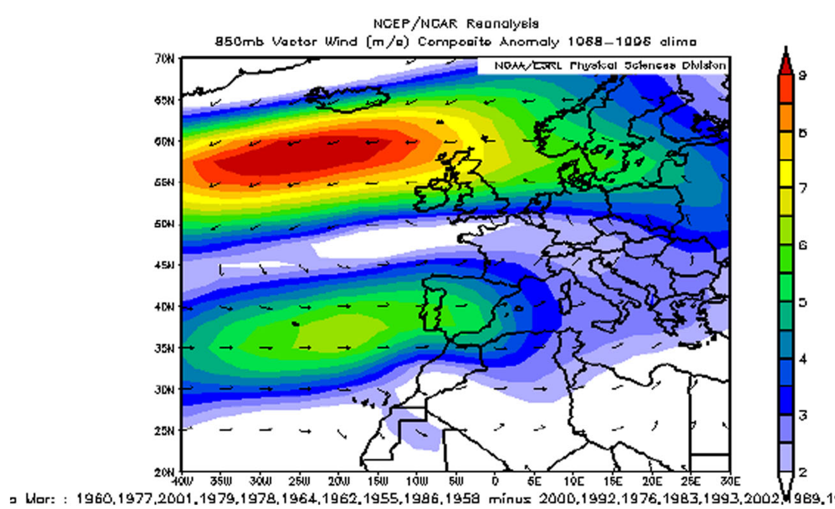

Fig. 6 Eight hundred fifty millibars vector wind composites when Azores High to the extreme south minus extreme north shows cyclonic flow over Northern Atlantic and NW Europe.

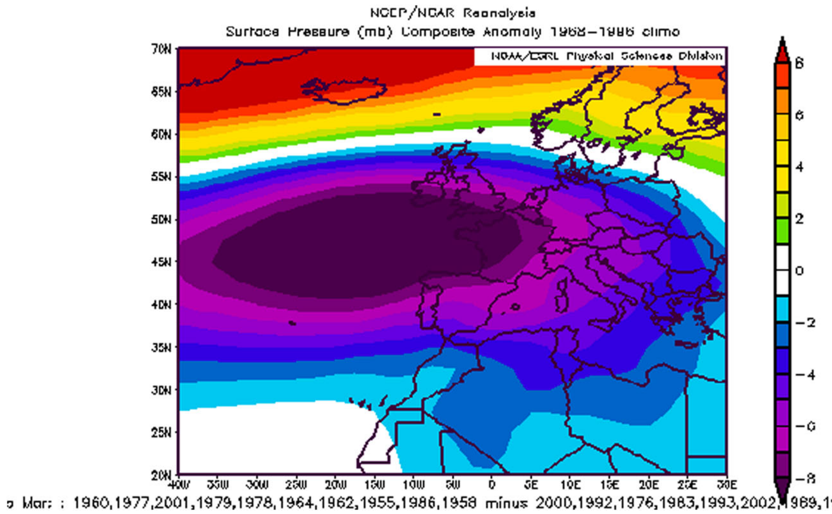

Fig. 7 Difference in surface pressure between summers in which AH is southward and northward. Anomalous low pressure band extends over Iberian Peninsula

low pressure band extends over Iberian Peninsula ward and northward. Anomalous low pressure band extends over Iberian Peninsula

Conclusions and discussion

The North Atlantic Oscillation has in recent literature been considered the dominant modulator of regional variability in Europe. The results presented in this work show that when the Azores High is low there is flux of moist and warm air from the Atlantic and from the Arabian Sea into the Iberian Peninsula. Moreover, the Iberian rainfall depends not only changes in the intensity of pressure but also changes in the positions of the Azores High. When Azores High was located to extreme south, there is anomalous westerly flow from Atlantic Ocean to Iberian Peninsula, invading over Germany. While when Azores High was located to extreme north (dry over Iberia), there is anomalous easterly flow from Iberian Peninsula to Atlantic Ocean.

There has been a discussion in the literature on whether the NAO or the AO represent the best paradigm for representing atmospheric variability in the north Atlantic region (Ambaum et al. 2001; Wallace 2000). Wallace (2000) has suggested criteria for choosing between the two by considering their impact on regional climate: "If its impacts prove to be largely attributable to (1) anomalous temperature advection involving the strong thermal contrasts between the North Atlantic and the upstream and downstream continents, (2) changes in the latitude or intensity of the North Atlantic storm track and its downstream extension into Europe, (3) anomalies in the stationary wave configuration by diabatic heating and/or storm track dynamics over the North Atlantic, or (4) changes in the frequency of blocking in the North Atlantic sector, it would argue in favor of the NAO paradigm. On the other hand, if the impacts can be shown to be more pervasive and extensive than can be accounted for processes operating in or remotely forced from the Atlantic sector, it would argue in favor of annular mode paradigm." In the results presented in this paper, we see that the correlation of winter precipitation in the Iberia Peninsula with the AO is smaller than with the NAO. When the constituent centers of action of the NAO, i.e., Azores High and the Icelandic Low, are considered separately, we can explain a much greater fraction of the variance of Iberian precipitation by zonal and meridinal movements of Azores High, and the four criteria mentioned by Wallace (2000) are satisfied. Therefore, the COA indices are best suited for the study of regional climate variability because their interannual displacements are not represented in either NAO or AO. Thus, the COA paradigm is more useful than either the NAO or the AO because it does not represent fixed spatial patterns.

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