INTERANNUAL VARIABILITY OF THE LOCATION OF THE MAIN ATLANTIC PRESSURE SYSTEMS AND THE NAO INDEX

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ABSTRACT

The North Atlantic Oscillation (NAO) is a major feature of the Northern Hemisphere climate system. The unprecedented trends it exhibited after the early 60’s led some authors to propose human induced climate forcing as a possible cause.

The various NAO indices are not able to distinguish the variability associated to the magnitude strengthening/weakening of the action centers and the variability associated with the movement of these centers. Using the NCEP/NCAR reanalysis for the years 1958 till 1998 the positions of the Iceland low-pressure and of the Azores high-pressure systems were tracked down. With the geographic position of these two action centers and the corresponding pressure values, an
ensemble of six predictors was formed and used in a multiple linear regression model accounting for the variance of the traditional NAO index. It was found that this model explains 89% of the NAO index variance; the main contributions to the variance are the pressure difference between the action centers and the latitude of the action centers. These three variables are all in phase and present a positive trend in the period under study, which leads to the high positive trend that has been observed in the NAO index over recent decades.

1. INTRODUCTION

The North Atlantic Oscillation (NAO) is one of the major features of the Northern Hemisphere climate system. It was first acknowledged by Walker (1924), who found that the difference in sea level pressure between the Azores and Iceland could be used to predict climate variables in different parts of Western Europe, proposing to use that difference as a climate index. However, a systematic study of the NAO index only took place in the last quarter of the 20th century. As stated by Hurrell et al. (2003) NAO is one of the most prominent and recurrent patterns of atmospheric circulation variability. It dictates climate variability from the eastern coast of the United States to Siberia and from Arctic to the subtropical Atlantic.

The strong impact of NAO on weather and climate justifies an increasing interest in knowing the limits of its predictability, on an interanual and seasonal basis. Unfortunately, NAO appears to be a noisy mid-latitude phenomenon and even the best possible linear predictions are not able to explain more than about 10% of the total variance (Stephenson et al. 2000). Nevertheless, the possibility that some fraction of NAO variance is predictable has motivated a recent increase in the NAO predictability studies. Recently, ensembles of long range weather prediction models are being tested to forecast the NAO index for the next season, apparently with some success (DEMETER project "Development of a European Multimodel Ensemble system for seasonal to inTERannual prediction"). The slow variations and inertia of the Atlantic Ocean are also being explored to try to predict the atmospheric circulation. This method requires the existence of an ocean impact on the overlying atmosphere. Some scientific evidence for such a link from Atlantic sea-surface temperatures (SSTs) to the winter NAO was presented in Rodwell et al (1999).

Understanding the long term behavior of NAO is also an important issue in climate change studies. NAO is a North Atlantic phenomenon, affecting Western Europe and North America, where much of the climate change political debate is focused. In the past decades NAO has experienced an anomalous persistent positive trend (Hurrell 1995). While this trend can be considered one of the signs of anomalous climate behavior in the second half of the 20th century, accompanying an increase in world mean surface temperature, it may be responsible for the very
weak signs of global warming observed in North America (Hansen et al. 1999) up to 2000. This has been an important argument, scientific but also political in what concerns the USA debate, against the credibility of climate change detection. Also, the apparent large cooling impact of the last decades NAO phase in North America has been used to dismiss much of the observed mean temperature trends, as largely due to natural variability.

So, it is rather important to understand the NAO signal. Unlike the trends in temperature, which could in principle climb steadily with appropriate global forcing, the NAO index is constrained by atmospheric mass conservation and so it is bound to oscillate around some mean value, whether its variation is internally generated or anthropogenically forced. For that reason, it is not surprising that the persistent positive trend beginning in the early 1960s seems to have stopped in the early 1990s (Tomé and Miranda 2004). Hansen et al (1999) predicted that the end of the cool NAO phase will soon lead to significant warming over North America. We will soon see if that is true.

The NAO index value from Hurrell (1995) is presented in Figure 1 together with the 10 year moving average (stronger line) and the stepwise linear fit by Tomé and Miranda (2004).

Figure 1 NAO and 10 years average from Hurrell 1995. The continuous line segments are partial trends from Tomé and Miranda 2004.
The NAO index was originally defined as the difference in pressure between Ponta Delgada (in the Azores, Portugal) and Reykjavic (Iceland). Later studies used Lisbon instead of Ponta Delgada (Hurrell 1995) or Gibraltar (Jones et al 1997). Although the main reason for changing the south point was the ability to build a longer time series, it was also pointed out that it led to an increase of the negative correlation with the North point. Inspired by the search of a more negatively correlated point, Portis et al. (2001) defined a mobile NAO index (NAOm) using different North and South points for each calendar month. The pair of points was selected as those with the most negatively correlated values. Another usual way of defining the NAO index is through the principal component (PC) time series corresponding to a pressure field principal component pattern (Rogers 1990). A more complete discussion about the several NAO index can be found in Osborn et al. (1999) and Hurrell et al. (2003).

Given the movement of the NAO centers of action through the annual cycle, it is commonly argued that station-based indices, because they are fixed in space, can only adequately capture NAO variability for parts of the year. This is usually pointed out as a disadvantage of station-based indices, fixed in space, when confronted with the PC based index. Yet, if one looks closer to the PC index definition one could easily arrive to the same conclusion. The first PC of the normalized sea level pressure (SLP) in the area (20º-70ºN; 90ºW-40ºE) is connected to a fixed spatial configuration. The PCA (principal component analysis) methodology is able to account for the full variability of the sea level pressure but they are distributed among the various significant components and not concentrated in the first one, usually taken as NAO index.

None of the mentioned NAO indices are able to distinguish the variability associated to the magnitude strengthening/weakening of the action centers and the variability associated with their movement. However, one must acknowledge that the PCA methodology consecutively applied to different time intervals could, through the analysis of the corresponding spatial configuration, give an idea of possible displacements of the NAO centers. Nevertheless that cannot be done in a year-to-year basis and at most could be done on a decade-to-decade basis (Ulbrich and Christoph, 1999). In fact, driven by the fact that the NAO index changed the correlation with the ice flux from the Fraim Strait from 0.1 in the period 1958-1977 to 0.7 in the period 1978-1997, Hilmer and Jung (2000) evaluated the NAO index for this two distinct periods, using a PCA methodology, and were able to detect an eastward displacement of the low action center in the second period.

In this work we analyze, in a year-to-year basis and for the Winter season (December, January and February – DJF), the position and intensity of the two action centers connected to NAO (the Azores anticyclone and the Iceland depression) and try to associate, trough a multiple regression model, the variability
of the NAO index with the position and the intensity of the formerly mentioned pressure centers. We try to understand if the positive trend that NAO has experienced in the latter decades of the 20th century was due only to an increase of the intensity of the action centers, strengthening of the Azores Anticyclone and/or deepening of the Iceland low, or also to changes in the position of those large scale pressure systems.

2. METHODOLOGY AND DATA

This work was performed with the NCEP/NCAR reanalysis data for the 41-year period spanning 1958 to 1998, coming from the annual CD-ROM distribution. The sea level pressure was obtained from the 1000hPa and 500hPa geopotential height fields, by extrapolation. In the NCEP/NCAR reanalysis, the atmospheric data are available on a coarse 2.5º latitude by 2.5º longitude grid. Using spherical harmonics the grid was downscaled to a finer one, 0.5º latitude by 0.5º longitude, to allow for a better resolution in the location of the action centers.

From all the local SLP minima found in the area 65ºW-15ºE, 40ºN-75ºN the lowest one was taken as the low pressure center, and from all the local maxima found in the 65ºW-15ºE, 40ºN-75ºN area the biggest one was considered the high pressure center. Six variables were obtained that completely defined the position and magnitude of the two pressure centers: (1) the pressure difference between the high pressure center and the low pressure center ($\Delta p$), (2) the pressure value of the high pressure center ($p_H$), (3) and (4) the longitude ($\lambda_H$) and latitude ($\varphi_H$) of the high pressure center and finally (5) and (6) the longitude ($\lambda_L$) and latitude ($\varphi_L$) of the low pressure center. All these variables were normalized to avoid biases in the multiple regression model due to different magnitudes and units.

The six variables were used as predictors of the traditional NAO index ($Y$), the normalized SLP difference between Azores and Iceland, on a multiple regression model, based on the linear combination

$$Y = c_1\Delta p + c_2 p_H + c_3 \lambda_H + c_4 \varphi_H + c_5 \lambda_L + c_6 \varphi_L = \sum_k c_k X_k$$

(1)

There was no need to consider a constant term because the dependent variable and the predictors were normalized. The $c_k$ are regression coefficients, representing the amount the dependent variable $Y$ changes when the corresponding independent factor increases one standard deviation, the others held constant. The ratio of these coefficients is the ratio of the estimated predictive importance of the
independent factors $X_k$.

Associated with this type of model are the coefficients of multiple determination, $R^2$, that represent the fraction of the variance in the dependent variable explained collectively, individually or jointly, by the independent factors. $R^2$ can have values in the interval [0,1] and high values or $R^2$ can be used as a condition to accept a linear model described by equation (1).

Figure 2  The 41 years and the decadal average positions of the low (L) and high (H) pressure centers.

It is important to keep in mind that each of this $c_k$ coefficients reflects the individual contribution of each independent variable. Joint contributions add to the variance explained by the model but are not attributed to any particular independent variable. Therefore, the value of the $c_k$ may underestimate the importance of a variable that makes strong joint contributions to explaining the dependent variable but which does not make a strong individual contribution. Thus, when reporting these values it is also reported, as usual in this type of models, the correlation of the independent variable with the dependent variable.
3. RESULTS

In Figure 2, the 41 geographic positions of the pressure centers for the winter season (DJF) are shown. The letter L identifies the low-pressure center and the letter H the high-pressure center. The average position of the pressure centers for the ten year periods: 1958-1967, 1968-1977, 1978-1987 and 1988-1998, are also shown, identified by the numbers 1, 2, 3 and 4, respectively.

From Figure 1 it is easy to conclude that the low pressure center was more frequently southwest of Iceland and the high pressure center southeast of the Azores, and that in the four decades under study the low pressure center presented a more consistent movement, northeastwards towards Iceland, while the High pressure center moved in a more random way.

The observed eastward movement of the low-pressure center was previously acknowledged by Hilmer and Jung (2000). It is also worth mention that Ulbrich and Christoph (1999) have obtained similar eastward movement of the low pressure center in scenarios of a climate model, but they were, however, unable to detect the same movement in the control run of the model. That result made them speculate about a possible relation between the effect of greenhouse gases increase and the movement of the NAO centers. Indeed, the movement they obtained for the scenario is already observed in the NCEP/NCAR reanalysis.

The regression coefficients of the predictors in equation 1 and also the correlation between the predictors and the dependent function $Y$ are presented in Table 1, for the DJF period. The computed $R^2$ is equal to 0.89 which means that the model of equation (1), with the coefficients of Table 1, is able to account for 89% of the variance of the NAO index.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Regr. Coef. ($c_k$)</th>
<th>Correlation with $Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta p$</td>
<td>0.73</td>
<td>0.88</td>
</tr>
<tr>
<td>$P_H$</td>
<td>0.014</td>
<td>0.81</td>
</tr>
<tr>
<td>$\lambda_H$</td>
<td>0.046</td>
<td>0.14</td>
</tr>
<tr>
<td>$\varphi_H$</td>
<td>0.15</td>
<td>0.53</td>
</tr>
<tr>
<td>$\lambda_L$</td>
<td>-0.064</td>
<td>0.47</td>
</tr>
<tr>
<td>$\varphi_L$</td>
<td>0.30</td>
<td>0.60</td>
</tr>
</tbody>
</table>

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From Table 1 we can conclude that the predictor $\Delta p$, the normalized difference of pressure between the high-pressure center and the low-pressure center, is the more relevant predictor, followed by the latitude of the low pressure center, $\varphi_L$, and the latitude of the high pressure center, $\varphi_H$. As stated earlier, the regression coefficients may underestimate the importance of a variable, as is the case of predictor $p_H$ (pressure value at the high-pressure center) that contributes very little to the variance in this model, but is strongly correlated with $Y$. This fact is due to the high correlation between the predictors.

Taken individually, the variance explained by predictor $\Delta p$ is 77%, by $p_H$ 67%, by $\lambda_H$ 2%, by $\varphi_H$ 28%, by $\lambda_L$ 23% and by $\varphi_L$ 36%. Only $\Delta p$ has a significant $R^2$ increment of 13%. All the others five predictors have an $R^2$ increment lower than 1%.

Looking at the movement of the pressure centers displayed in Figure 1 it is easier to understand the signals of the regression coefficient in Table 1. Higher values of predictors $\lambda_L$ and $\varphi_L$ imply a low-pressure center near Iceland because the mean position of the low-pressure center is Southwest of Iceland. Higher values of $\varphi_H$ imply the high pressure center near the Azores because the mean latitudinal position of the high pressure center is south of the Azores. The same happens with lower values of $\lambda_H$ because the mean longitude of the high pressure center is located East of the Azores.

The time evolution, the 5 years moving averages and the linear trend for the six chosen predictors are given in Figure 3. All predictors but $\lambda_H$, the longitude of the high-pressure center, show a tendency towards higher values in time. The longitude of the high pressure center presents a slight negative tendency. This predictor together with $\lambda_L$, longitude of the low pressure center, are according to Table 1 the only ones contributing for a decrease of the NAO index but, because to the small tendency of $\lambda_H$ and to the small values of the $c_k$ coefficients for these two predictors given in Table 1, the decrease they imply are strongly compensated by an increase of the NAO due to the other four predictors with special relevance for the pressure difference between the two action centers and its latitudes. So, the evolution of the North-South position of the pressure centers together with the pressure difference between them, all three predictors presenting relatively positive high trends and significant positive regression coefficients explain the significant trend, towards high index values, that NAO has exhibited in recent decades (Hurrell 1995, Ostermeier et al 2003, Tomé and Miranda 2004).
From Figure 3 one can see that the pressure difference, $\Delta p$, presents a trend of 0.42/decade, the high pressure value, $p_H$, a trend of also the 0.42/decade, the evaluated trend of the low pressure value is negative and equal to −0.38/decade (not shown in Figure 3, because it was not chosen as predictor). So the observed pressure difference is due not only to a strengthening of the Azores Anticyclone but also to the deepening of the Iceland Low. The evolution rate of the low pressure cannot be inferred from the evolution rate of the pressure difference and high-pressure value because one is dealing with normalized variables and the low-pressure center has a larger range of pressure anomalies values. The three traditional station based NAO index, from the gridpoint values of NCEP reanalysis data by spherical harmonics interpolation of the SLP in the geographical position of the stations are given in Figure 4.

The NAO index used in the equation (1) was the normalized SLP difference between Ponta Delgada and Stykkisholmur, lower panel of Figure 4, after the analysis of Table 1 and Figure 3, we are able to conclude that the observed increase of the NAO index (Figure 4) was due not only to an increase of the sea level pressure difference between the high level pressure center and the low

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**Figure 3** The temporal evolution of the six predictors of equation 1.
pressure center but also to a more frequent placement of the action centers at latitudes that imply an increase of the traditional NAO index.

![Figure 4](image_url) The temporal evolution of the three station based NAO index.

Many of the recent impact studies of NAO may be attempted using this six predictors or several combination of some of them. It would be interesting to know if for the climate variability of Southern Europe the variables of the high-pressure center are enough to explain the observed variability, or if they are better correlated with the more global “teleconnection” feature associated with NAO index. An European spatial distribution of the most important of this six predictors in explaining the observed climatic variability will be very useful; specially to know where the zonal index (pressure difference) is more relevant.
4. RELEVANCE OF NAO TO PORTUGUESE CLIMATE

The NAO index has been the focus of much interest in Portugal due to the observed correlation between NAO and precipitation in mainland Portugal. The connection has been more clear in what concerns the precipitation in late winter, during the month of March, which experienced a continuous decrease in the period 1970-2000, as the NAO increased (Zhang et al 1997, Miranda et al 2002), down to 50% of the 1941-1970 climate normal. This is a remarkable evolution. Because many simulated climate change scenarios predict a reduction of the winter rainy season in southern Europe, the evolution of March precipitation easily interpreted as a preview of what is to come.

![Figure 5](image)

**Figure 5** The normalized (December through Mars) NAO index and Lisbon Precipitation.

That Lisbon precipitation strongly correlates with the NAO index was already a known fact (e.g., Hurrell, 1995) but the link between Lisbon Precipitation and NAO is also present in the slow evolution of both time series. The low frequency pattern of the accumulated December through Mars Lisbon precipitation
almost mirrors de decadal tendency of the NAO index, highlighted by the partial trend fitting of Tomé and Miranda (2004), both presented in Figure 5.

5. **FINAL REMARKS**

During the last decade a large number of studies were able to associate the variability of the NAO index with many regional and hemispheric features that strongly influence not only human activities, with social and economic impacts (e.g. water availability, energy production systems, agricultural changes), but also several ecological processes of great interest to the biological research community. The strong impact of NAO justifies a need to understand the physical mechanisms responsible for its variability. In this work we were able to conclude that the observed increase of NAO in the latter four decades of the 20th century was due not only to an increase of the sea level pressure difference between the Azores anticyclone and the Iceland Low, but also to a systematic change in its the position.

The NAO decomposition presented in this work does not make it easier to forecast its variability, because the forecast of the NAO center position and its values shares the same difficulties of forecasting the NAO itself.

The long seeking answer to question if the NAO variability is influenced by anthropogenic climate change associated to the greenhouse gas emission remains unknown. Ulbrich and Christoph (1999), using results from a specific coupled Atmosphere-Ocean general circulation model (ECHAM4/OPYC3), have reported a shift into easterly position of the northern NAO center near 2020 when the anthropogenic forcing surpass 3W/m². A similar systematic northeast movement of the Low pressure center in North Atlantic in the latter four decades of the 20th was found in this work, confirming an easterly shift, previously found by Hilmer and Jung (2000), with a different methodology.

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