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The impact of the North Atlantic Oscillation on hydroelectric power generation in the Iberian Peninsula

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1. INTRODUCTION

Over the last few decades the annual consumption of energy in Iberia has never ceased to increase. However, the production of energy has been hampered by technical and environmental constraints. Since the middle of the 20th Century, Portugal and Spain have invested a considerable amount of resources and money to build large dams with hydroelectric production capacities (Melo and Gomes, 1992). More recently, the investment in so called "green energy" has been mainly directed towards the construction of wind farms. However, at the present time, the bulk of this renewable electricity production in both Portugal and Spain still comes from hydroelectric power generated in large dams situated in major river basins. In Portugal the hydroelectric production represents (on an average year of precipitation) one third of the total Portuguese electricity production but its absolute value can vary by a factor of almost three between wet (16 TWh) and a dry (6 TWh) years (Collares Perreira, 1998). Similarly the Spanish hydroelectric production accounts, on average, for 20% of total Spanish production, however the actual production presents a wide range of values, varying between wet (40 TWh) and dry (20 TWh) years (REE, 2002).

The western Mediterranean area is characterized by large values of inter-annual variability of precipitation (Esteban-Parra et al, 1998; Trigo and DaCamara, 2000). As a consequence river flow is also characterized by large disparities between wet and dry years especially in southern Iberia.

Recently, it has been shown that the North Atlantic Oscilation is the single most important[1] atmospheric circulation mode to control Iberian precipitation (Rodriguez-Puebla et al., 1998; Trigo et al., 2002). Here we intend to show that such influence is extensive to the flow regime and hydroelectrical production capabilities of important Iberian rivers.

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2. DATA AND METHODOLOGY

1. NCEP/NCAR reanalyses for 1958-1997 (Kalnay et al., 1996). Daily values of sea leval pressure, precipitation rate, and 2m u and v wind components were extracted for the area 80°N - 30°N; 60°W - 70°E.
2. Monthly values of precipitation between 1901 and 1995 from the high resolution (0.5º lat .by 0.5º long.) data set developed by CRU (New et al., 1999).
3. Monthly values of river flow for three large Iberian rivers, namely Douro, Tejo and Guadiana.
4. Monthly values of Potential electricity production for the entire Spanish hydroelectrical system. (REE, 2002)

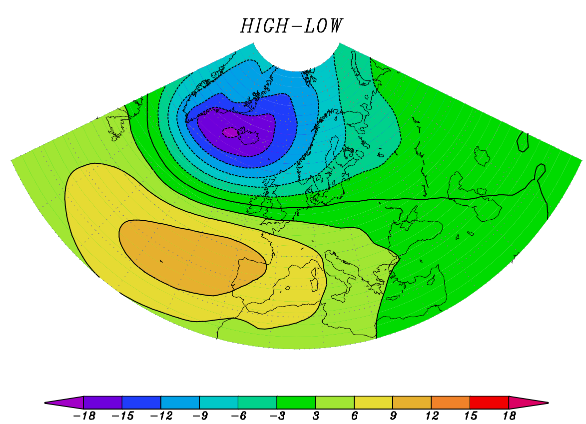

Figure 1 - Difference in SLP (hPa) between winter months (DJFM) with an NAO index > 1.0 and with an NAO index < -1.0 from 1958 to 1997.

Composites of all analysed NCEP/NCAR fields between December and March from, 1958 to 1997, were derived following the procedure developed by Hurrell

(1995). However, unlike Hurrell, composites of high (low) NAO index were produced using a monthly (not seasonal) criterion. The spatial signature of the NAO is represented by the difference in SLP between composites of winter months with an NAO index > 1.0 and with an NAO index < -1.0 from 1958 to 1997 (Fig. 1). This shows the expected dipole between the Iceland and the Azores regions.

3. NAO IMPACT ON PRECIPITATION

The precipitation regime in Iberia has a highly irregular behaviour in both the spatial and temporal dimensions, namely in the amount and distribution of rainfall (Esteban-Parra et al., 1998; Serrano et al., 1999; Trigo and DaCamara, 2000). Most of winter and spring precipitation can be explained in terms of a relatively small number of large-scale modes at the monthly scale, especially over the western sector of Iberia (Rodriguez-Puebla et al., 1998; Trigo and Palutikof, 2001). In particular, several authors have investigated the prominence of the North Atlantic Oscillation to model the winter precipitation regime over the Iberian peninsula (Rodó et al., 1997; Rodriguez-Puebla et al., 1998; Corte-Real et al., 1998; Gonzalez-Rouco et al., 2000; Trigo and Palutikof, 2001).

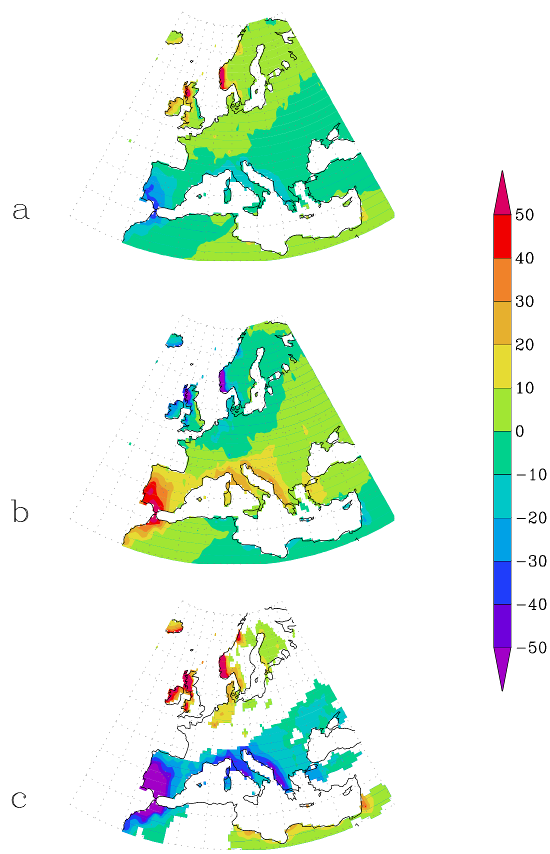

Figure 2. Precipitation anomaly fields (mm/month) for winter months with (a) high NAO index > 1.0, (b) low NAO index < -1.0 and, and, c) their difference (represented only if significant at the 5% level).

The impact of NAO mode on the entire European continent and for the 1901-1995 period can be seen in Fig.2. Winter months characterized by high and low NAO index are shown in Figs. 2a and 2b, respectively. It is immediately striking the magnitude of these anomaly fields over western Iberia. The differences between high and low NAO composites observed precipitation are represented in Fig. 2c, whenever those differences are significant at the 5% level. While the northern Europe region presents scattered patches of significant differences (over the UK, Scandinavia and Germany) the southern Europe sector reveals a more consistent significant region stretching from Western Iberia to the Black sea. In particular, the entire Iberian peninsula presents significant differences between composites. Similar patterns are obtained if the shorter period 1958-1995 is used.

The use of NCEP/NCAR reanalyses allows the extension of the previous study into oceanic areas such as the Atlantic. Furtehrmore such an analysis can be used as a tool to validate the reanalysis precipitation variability associated with NAO.

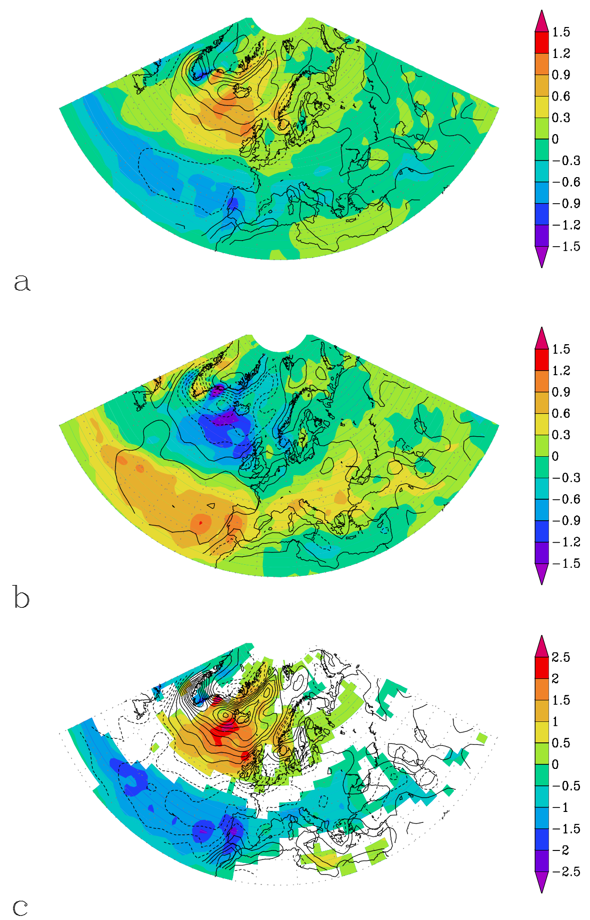

Figure 3 - Precipitation rate anomaly fields (mm/day) for winter months with (a) high NAO index > 1.0, (b) low NAO index < -1.0 and, and, c) their difference (represented only if significant at the 5% level). Positive (solid) and negative (dashed) isolines of the 10m vorticity anomaly field, with intervals in s^{-1}, for (a) high, and (b) low NAO composites are also represented.

With this purpose, precipitation rate (PR) anomaly fields for winter months characterized by high and low NAO index values were computed and are shown in Figs. 3a and 3b, respectively.

Both figures present quasi-zonal bands of opposite anomaly signs. Differences between high and low NAO composites of PR are shown in Fig. 3c, whenever those differences are significant at the 5% level. Anomaly values of PR are concentrated in the northern latitudes and extend from southern Greenland to northern Russia with a maxima near Iceland and Scotland. At lower latitudes, a strong negative band of PR spans from the eastern USA coast, across the Atlantic into Iberia presenting a weaker elongation across the Mediterranean until the Middle East. Overall, there is a remarkable geographical coincidence over Europe between areas of significant differences identified in Figs. 2 and 3.

Condensation of the precipitable water content typically requires uplift provided by a range of mechanisms, particularly low level convergence associated with cyclonic circulation (i.e. positive vorticity). In fact, the vorticity field (computed from the 10m wind field monthly composites) indicates that much of the PR response to high (Fig. 3a) and low (Fig. 3b) NAO index values is associated with anomalous values of the vorticity field. The maximum value of positive (negative) vorticity, represented by solid (dashed) lines, is consistently located a few degrees north of regions with higher (lower) than average PR values. This northward shift of the vorticity maxima is compatible with the typical configuration of a mid-latitude synoptic disturbance, with low-pressure centre positioned poleward of the fronts that induce precipitation through strong vertical motions. In summary, precipitation rate anomalies (Fig. 3) can be mainly attributed to the vorticity of the mean composite circulation (Trigo et al., 2002).

4. NAO IMPACT ON RIVER FLOW

Only recently it has been recognized that the strong control exerted by NAO on precipitation over the Mediterranean basin could be directly reflected on the seasonal streamflow of rivers across the region. In fact, recent works have proved that this is the case for the Middle East rivers Tigris and Euphrates (Cullen and deMenocal, 2000) and the large central European river Danube (Stanev and Peneva, 2002; Rîmbu et al., 2002). Here we intend to show that such influence on river flow regimes is extensive to the Iberian rivers, and that the magnitude of such influence is even larger for Iberian rivers than it is the case with the Danube, Tigris or Euphrates.

The three main international Iberian rivers are represented in Fig. 4. River flow data from both Douro (at Pocinho) and Tejo (at Fratel) spans between 1922 and 1997. The impact on the hydrological cycle (from Oct. to Sep.) of years characterized by winters with large positive and negative NAO index anomalies is shown in Figs. 5a and 6a for Douro and Tejo rivers, respectively. For river Douro these differences are significant (at the 5% significance level) only between January and April while for river Tejo they are consistently significant between January and September. This reflects the fact that river Tejo basin is located in central Iberia, a region more affected by the impact of the NAO in the precipitaion field (Fig. 2c).

Figure 4 −Location of the three main international rivers in Iberia. The river courses are highlighted in blue and each border basin is delimeted by a different colour. Small black dots show the location of river flow gauges used in Tejo and Douro.

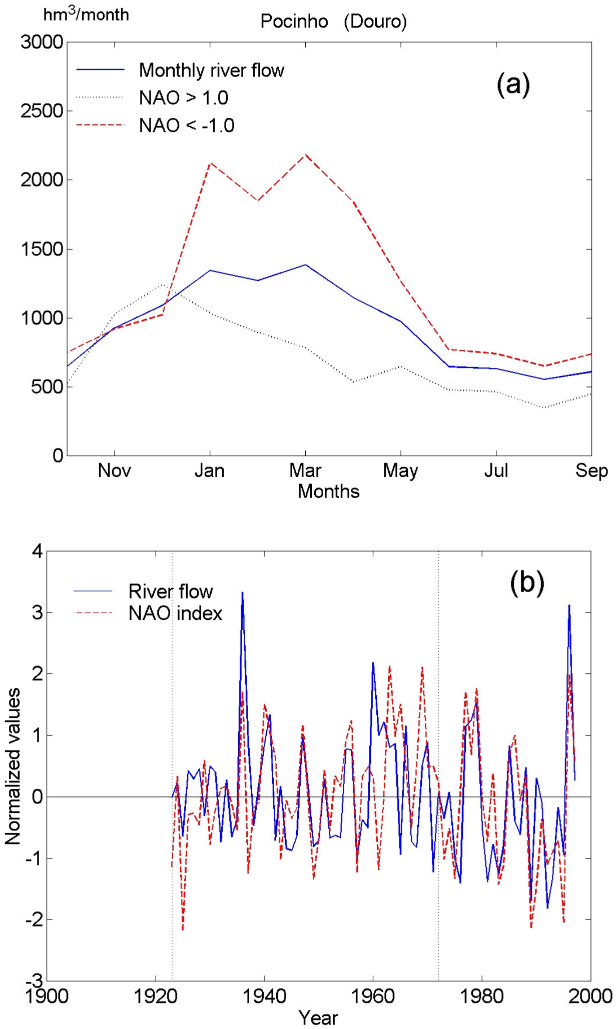

Figure 5 – (a) Monthly river flow of river Douro at Pocinho for winters with high NAO index (dotted curve), for winters with low NAO index (dashed curve) and for the average winter (solid line), (b) Interannual variability of the mean winter (JFM) river flow (solid curve), for river Douro at Pocinho, and the lagged winter (DJF) NAO index, multiplied by –1 to facilatate analysis (dashed curve); both curves have been normalised and so are dimensionless**.**

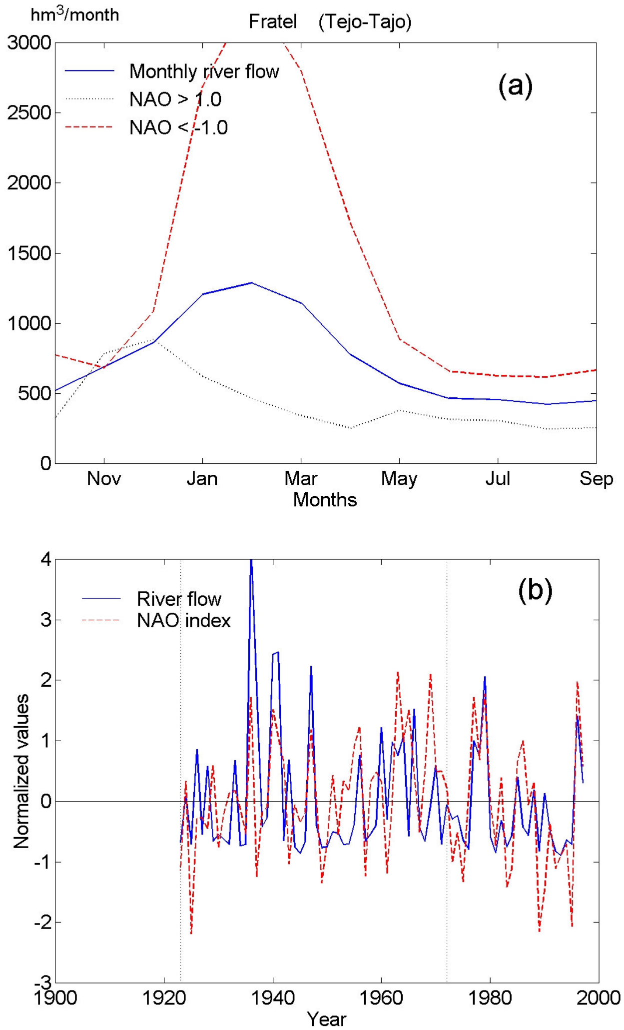

Figure 6 – The same as in fig. 5 but for river Tejo at Fratel**.**

We have computed the correlation coefficients between winter river flow (DJFM) and contemporaneous winter NAO index. We have also computed the lagged correlation between the NAO index for DJF and the river flow for JFM. Furthermore, we have computed correlation coefficients for shorter periods, namely between 1922 and 1971 and between 1972 and 1997. Results are summarized in Table 1. Two important conclusions can be drawn from this table:

1) The magnitude of all lagged correlation coefficients is consistently higher than the corresponding non-lagged ones. This fact is particularly relevant because it increases the potential for using this empirical relationships in effective forecasting tools.

2) There is a major increment in the magnitude of correlation coefficient values between the first sub-period and the second sub-period. This is particularly impressive for the Douro river where it increases between -0.28 and -0.62. Figs. 5b and 6b show the inter-annual variability of river Douro (5b) and Tejo (6b) against the lagged winter NAO index (multiplied by –1 to facilitate analyis).

It is worth noticing that previous studies have detected an increase in the magnitude of the correlation coefficient between the NAO index and precipitation over central Iberia (Rodó et al., 1997). However, we believe that part of this increment might be related with the enormous increase in water storage volume associated with the construction of major dams in the 1950s and 1960s.

Table 1 – Contemporaneous (lag 0) and lagged (lag 1) correlation coefficients between winter NAO index and river flow in Pocinho (douro) and Fratel (Tejo). Significance level greater than 90% and 95% are highlighted using, respectively, * and **.

Douro	Lag 0	Lag 1
1922-97	-0.45**	-0.55**
1922-71	-0.28*	-0.37*
1972-97	-0.62**	-0.76**
Tejo	Lag 0	Lag 1
1922-97	-0.48**	-0.52**
1922-71	-0.42**	-0.42**
1972-97	-0.60**	-0.77**

5. NAO IMPACT ON HYDOELECTRICITY

A similar analysis was developed to assess the real impact of NAO on the production of hydroelectric power. Total Spanish hydroelectric production over the period 1972-2000 has been analyzed. These data were analyzed on a monthly basis, with a monthly anomaly series being constructed after subtracting the mean for the entire 1972-2000 period. Finally, seasonal values were calculated by averaging the corresponding monthly values, *i.e.* DJF for winter, MAM for spring, JJA for summer and SON for autumn.

Table 2 shows the contemporaneous correlations between seasonal hydroelectric production and the seasonal NAO index. A very high (-0.72) and statistically significant (at 95% confidence level) negative correlation is found for winter. In accordance with results obtained in previous sections, the negative sign makes sense, since a negative NAO index leads to positive precipitation anomalies in the western and southwestern parts of the Iberian Peninsula. A lower values (-0.35) but still significant (at 90% confidence level) is attained for the spring season. No significant values are found for summer and autumn. Thus, the influence of the NAO on hydroelectric seems to be confined to the two wettest and, consequentially, most important seasons of the year, the winter and spring.

Table 2. Contemporaneous correlations between seasonal hydroelectric production and the NAO index. Significance level greater than 90% and 95% are highlighted using, respectively, * and **.

Winter	-0.72**
Spring	-0.35*
Summer	0.08
Autumn	-0.18

Composite values of winter hydroelectric production associated with low, normal and high NAO index have been computed and compared each other. Results are shown in Table 3. High NAO winters (NAO index > 0.7) are characterized by a negative composite average anomaly of –1113 GWh. On the contrary, the composite for low NAO winters (NAO index < -0.7) presentes an average positive anomaly of 2196 GWh. Both composite values are statistically significantly different (at the 95% level) when compared with the composite for the remaining winters, (-0.7 < NAO index <0.7). Since the mean winter hydroelectric production for the period 1972-2000 is 3700 GWh, this implicates that, during high NAO index winters, an average decreasing in hydroelectric production of 30% can be expected, while during low NAO winters, an average increasing of up to 60%, compared to normal production, can be anticipated.

Table 3. Composite winter anomaly hydroelectric production (GWh) associated with high, low and normal NAO index values. Statistical significance of the difference between the composite series have been computed using a t-test. Significance level greater than 95% are highlighted using *.

	Winter
NAO > 0.7	-1113*
-0.7 < NAO < 0.7	714
NAO < -0.7	2196*

The important influence of the NAO on the winter hydroelectric production makes the study of the forecasting of this production based on relatively simple statistical methods, an exercise worth to be carried out. We have conducted a preliminary analysis of this type based solely on the NAO index itself.

Firstly, we have computed the lagged (by one season) correlation between the NAO index and the hydroelectric production. Results are summarised in Table 4. The most promising results are found for the spring and summer season, the hydroelectric production during spring (summer) has a correlation of –0.49 (-0.47) with the NAO index from the previous winter (spring). The result makes sense, since the accumulation of water in large dams during winter (spring) contributes to the hydroelectric output during the following season.

Table 4. Lagged (by one season) correlations between seasonal hydroelectric production and the NAO index. Significance level greater than 90% and 95% are highlighted using, respectively, * and **.

Winter	0.04
Spring	-0.49**
Summer	0.47**
Autumn	-0.01

Secondly, we have carried out an analysis using an ARMA model developed to forecast the winter NAO index on an interannual basis. The model characteristics are fully explained in Gámiz-Fortis et al., (2002). This model gives a forecast of the next winter NAO index based on the current and past winter NAO index values. Given the high and negative contemporaneous correlation between winter NAO index and hydroelectric production, we have compared the sign (phase) of the forecast of the NAO index and the sign of actual winter hydroelectric production anomaly. Over the period 1972-2000, and using the one-year-ahead ARMA estimation of the NAO index phase, we found that sign of the one-year-ahead forecast winter NAO index and the sign of the hydroelectric production have opposite values in 44.8% of the winters. That is, the sign of the hydroelectric anomaly production is properly forecasted in 44.8% of the cases. This promising result, obtained for one-year-ahead forecast, encourages us to use in further analysis seasonal and monthly forecast of the NAO index to forecast the hydroelectric production.

6. SUMMARY

We have made an effort to evaluate the magnitude and spatial extent on the impact of the NAO mode on the precipitation field throughout Europe in general, and over Iberia, in particular. We have confirmed that the NAO mode of variability is the single most important large-scale feature to constrain seasonal winter precipitation and, additionally, river flow regime in two important Iberian river basins. This control exerted by NAO on the river flow regime has important economical consequences especially regarding the yearly production of hydroelectricity in both Spain and Portugal.

Increasing demands of water supply from the domestic and agricultural sectors are augmenting pressure for a firm control on river flow for the three largest international Iberian rivers, namely, the Douro (north), the Tejo (centre) and the Guadiana (south). Furthermore, recent studies have shown that over the last two decades the Northern centre of the NAO dipole (the Icelandic low) has moved closer to Scandinavia with major consequences to the level of association between climate variables and NAO (Lu and Greatbatch, 2002). Thus, the possibility of a future large shift in the location or intensity of one (or both) NAO centres could represent in itself an enormous challenge to be tackled by water resources management in general and hydroelectric production companies in particular. In this sense, we believe that an important effort should be given to the development of forecasting models, based in both statistical and dynamical methodologies. Such models could be used as seasonal forecasting tools or to assess changes in river flow regime under climate change scenarios.

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