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NORTH ATLANTIC OSCILLATION INFLUENCE ON PRECIPITATION, RIVER FLOW AND WATER RESOURCES IN THE IBERIAN PENINSULA

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ABSTRACT

The Iberian Peninsula precipitation and river flow regimes are characterized by large values of inter-annual variability, with large disparities between wet and dry years, especially in southern Iberia. This situation is a major problem for water resources management in general, and for the production of hydroelectricity in particular. Hydroelectric production represents, in an average year of precipitation, 20% of the total Spanish electricity production (and 35% for Portuguese production). Its absolute value, however, can vary by a factor of three between wet and dry years. We have assessed the impact of the North Atlantic oscillation (NAO) on winter precipitation and river flow regimes for the three main international Iberian river basins, namely the Douro (north), the Tejo (centre) and the Guadiana (south). Results show that the large inter-annual variability in the flows of these three rivers is largely modulated by the NAO phenomenon. Throughout most of the 20th century, the January-to-March river flow is better correlated with the December to February (DJF) NAO index than is the simultaneous (DJF) river flow. Correlation values for the period 1973–98 are highly significant (−0.76 for Douro, −0.77 for Tejo and −0.79 for Guadiana), being consistently of higher magnitude than those obtained over previous decades. This impact of the NAO on winter river flow was quantified in terms of total Spanish potential hydroelectricity production. The important control exerted by the NAO and the recent positive trend in the NAO index contribute to a significant decrease in the available flow. This reduction represents an important hazard for the two Iberian economies because of its negative impact on water-dependent resources, such as intensive agriculture and hydroelectric power production. Copyright © 2004 Royal Meteorological Society.

KEY WORDS: NAO; precipitation; river flow; hydroelectricity; Spain; Portugal

1. INTRODUCTION

Over the last few decades the annual consumption of energy in both developed and developing countries has never ceased to increase. However, the production of energy has been hampered by technical and environmental constraints. Following the international directives agreed under the Kyoto Protocol and the European Environmental Agency, ambitious goals for the production of energy from renewable sources have been established (CEC, 2000). With an optimistic view, the European Union aims to double the overall production of electricity from renewable energy sources to 22% by 2010 (Santos *et al.*, 2002). Both Iberian countries (Portugal and Spain) import large quantities of oil, coal and gas in order to fulfil their increasing demands for electrical energy. The full exploration of the two most important sources of renewable energy production, namely hydro and wind, not only constitute a considerable scientific and engineering challenge,

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but also an imperative political goal. Since the middle of the 20th century, Portugal and Spain have invested considerable resources in the building of large dams with hydroelectric production capabilities (Melo and Gomes, 1992). Although more recent investment has been directed mainly towards the construction of wind farms (CEC, 2000), the bulk of renewable electricity production in both Iberian countries still comes from hydroelectric power generated in large dams situated in major river basins located in the northern and central regions of the peninsula (Santos *et al*., 2002).

Increasing demands on the 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 (or Duero) in the north, the Tejo (Tajo or Tagus) in the centre and the Guadiana in the south. In the latest report released by the International Panel on Climate Change, it is stated that the entire Mediterranean region (including the southern Iberian sector) is already experiencing broadly consistent decreases in precipitation and stream flow (Houghton *et al*., 2001). In fact, there is already a discernible trend towards desertification in southern Iberia, with water flows and arable land becoming scarcer and thinner (Balabanis *et al*., 1999). It is not surprising, therefore, that besides large dams with hydroelectric production capabilities, many dams and associated hydraulic works have been constructed in southern Iberia to divert water (mainly for agricultural, tourism and domestic uses) to offset the water stress problem partially. However, recent climate-change scenarios developed for the European continent and for the 21st century (Parry, 2000) point explicitly to: '... a general increase in the risk of summer droughts in Europe, particularly in the south' with possible '... widening uncertainty in the reliability of water supplies in many areas of Europe'.

The western Mediterranean area is characterized by large inter-annual variability of precipitation (Barry and Chorley, 1998). As a consequence, river flow is also characterized by large disparities between wet and dry years (Daveau, 1988), especially in southern Iberia. This situation presents a major problem for water resources management in general, and production of hydroelectricity in particular. In a year with average precipitation, Portuguese hydroelectric production contributes 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 dry (6 TWh) years (Collares Pereira, 1998). Similarly, the Spanish hydroelectric production accounts for 20% of total production in an average year, but varies between 40 TWh and 20 TWh in wet and dry years respectively (REE, 2002).

It is a well-known fact that the amount and distribution of precipitation in Iberia is highly irregular in both the spatial and temporal dimensions (Esteban-Parra *et al*., 1998; Serrano *et al*., 1999; Trigo and DaCamara, 2000). However, it should be stressed that most of the precipitation during the wet winter season can be explained in terms of a relatively small number of large-scale atmospheric modes at the monthly time scale (Rodríguez-Puebla *et al*., 1998; Trigo and Palutikof, 2001). In particular, several workers have investigated the prominence of the North Atlantic oscillation (NAO) as a predictor of winter precipitation over western Iberia (Zorita *et al*., 1992; Corte-Real *et al*., 1995, 1998; Rodó *et al*., 1997; Rodríguez-Puebla *et al*., 1998; González-Rouco *et al*., 2000; Trigo and Palutikof, 2001). This precipitation variability drives large inter-annual variations in the river flow regime of all Iberian rivers, especially those located in the southern, drier areas. Thus, the possibility of establishing a strong relationship between river flow and the relatively simple large-scale atmospheric circulation modes is very attractive.

It has been recognized that the strong control exerted by the NAO on precipitation over the Mediterranean basin could be directly reflected in the seasonal flow of rivers across the region. Recent studies have proved that this is the case for Middle Eastern rivers, including the Tigris, Euphrates and Jordan (Cullen and deMenocal, 2000; Cullen *et al*., 2002), and the large central European river, the Danube (Stanev and Peneva, 2002; Rîmbu *et al*., 2002). All these studies have shown that river flow tends to be lower (higher) when the NAO index is in its positive (negative) phase. Here, we will show that this influence on river flow regimes extends to Iberian rivers, and that the magnitude of the NAO influence is even larger for Iberian rivers than it is for either the Danube or Middle Eastern rivers. It is becoming clear that this capacity of the NAO index to constrain winter and spring flow in these Iberian rivers represents not only an enormous challenge, but also a potential opportunity to water resources management and hydroelectric power production companies.

Unfortunately, this well-established association between the NAO circulation mode and the surface climate of the European continent has recently been shown to be non-stationary, i.e. the strength of the correlation between the NAO index and local (or regional) climate variables has changed over time (Rodó *et al*., 1997;

Goodess and Jones, 2002). Here, we intend to analyse the temporal evolution of the changing relationship between the NAO index and the river basin precipitation and river flow throughout most of the 20th century.

Thus, the main objectives of the analysis presented here are as follows:

1. To quantify the influence of the NAO on the wet-season precipitation and river flow for three large Iberian river basins and to evaluate the extent of such influence in terms of hydroelectric power production.
2. To investigate the consequences of non-stationary relationships between the NAO index and the precipitation and river flow regimes of the Iberian Peninsula.

Furthermore, by making use of different precipitation data sets, we intend to assess the ability of the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay *et al*., 1996) to capture correctly the spatial structure of significant impacts of the NAO on the precipitation fields of Europe, particularly over southern Europe.

In Section 2 we describe the data sets used in this work; then in Section 3 we present the main characteristics of the NAO mode and hydrological basins and flow regime for the three rivers considered. Section 4 explores different precipitation data sets to compute and compare areas where the impact of the NAO on the Atlantic/European sector is significant. An analysis on the stationarity of the NAO impacts on the Iberian precipitation regime is also given. The impact of the NAO mode on the river flow regime and hydroelectric production is described in Section 5. Finally, some conclusions and a discussion are given in Section 6.

2. DATA SETS

The following data sets are utilized:

1. Quasi-observed large-scale data from the NCEP–NCAR reanalysis for 1958–97 were used. These reanalysis data were derived through a consistent assimilation and forecast model procedure that incorporated most available weather and satellite information (Kalnay *et al*., 1996). Six-hourly values of precipitation rate and 10 m height u and v wind components were extracted for the NCEP 2.5° latitude by 2.5° longitude grid, for the area 80–30 °N, 60 °W–70 °E. Daily values were computed by averaging the six-hourly values.
2. Monthly values of precipitation between 1958 and 1995 for the entire European continent and part of northern Africa were obtained from the high-resolution (0.5° latitude by 0.5° longitude) data set developed by New *et al*. (1999, 2000) at the Climatic Research Unit (CRU). This data set uses a dense network of observations, particularly over Europe.
3. Monthly values of precipitation between 1922 and 1997 were used for 17 stations located within the three river basins considered (Figure 1). This data set has been checked for several different quality criteria in previous studies (e.g. Esteban-Parra *et al*., 1998). Although the number of stations per river basin with sufficiently long, quality-controlled, records is smaller than desired, they are still capable of representing the precipitation that falls in the Spanish sector of each river basin.
4. Monthly river flow data were provided by the Portuguese Institute of Water (INAG) for the River Guadiana, and data for the Rivers Tejo and Douro were obtained from the Portuguese National Electrical Supply Company (REN). The locations of the river gauges within the Portuguese sections of the rivers are depicted in Figure 2, and the main characteristics of the flow measured at these gauges are given in Table I.
5. Monthly values of potential hydroelectric production for the entire Spanish hydroelectric system between 1920 and 2000 (REE, 2002) were used. The potential hydroelectric production is the maximum quantity of electrical power that theoretically could be obtained based on the hydraulic contributions registered during a certain period of time.
6. The NAO index defined by Jones *et al*. (1997) was used. This formulation of the NAO index uses Gibraltar as the southern station. The rationale for using this particular index of the NAO and its main characteristics is widely discussed in Osborn *et al*. (1999) and Pozo-Vázquez *et al*., 2001).

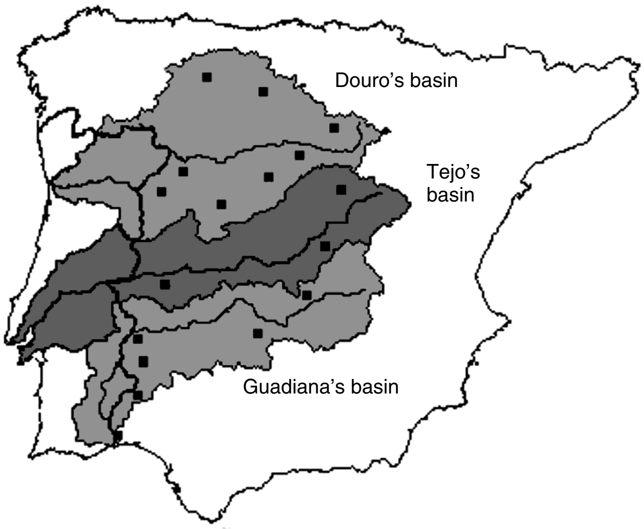

Figure 1. Location of the three main international rivers in Iberia and their catchment boundaries. Small black dots show the locations of the precipitation stations used (Spanish section only) in each river basin

3. MAIN CHARACTERISTICS OF NAO AND IBERIAN RIVER BASINS

3.1. The North Atlantic oscillation

The NAO has been recognized for more than 70 years as one of the major patterns of atmospheric variability in the Northern Hemisphere (Walker, 1924). However, it has only become the subject of wider interest in recent years (e.g. van Loon and Rogers, 1978; Rogers, 1984; Barnston and Livezey, 1987; Hurrell, 1995; Hurrell and van Loon, 1997). Several 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, 1996; Pozo-Vázquez *et al*., 2001).

In a previous study (Trigo *et al*., 2002) the NCEP–NCAR reanalysis was used to characterize the climate influence of the NAO mode in the Atlantic–European region. Trigo *et al*. (2002) were able to relate anomaly fields of many different climate variables with physical mechanisms associated with the anomalous mean atmospheric circulation and anomalous eddy activity. The NAO is strongly related to the strength of the westerly winds, for example, and this is responsible for anomalous heat advection (and hence temperature) over the Eurasian continent (Hurrell, 1995; Thompson and Wallace, 1998; Osborn *et al*., 1999; Slonosky and Yiou, 2001). This strong association between anomaly mean flow associated with the NAO and corresponding anomalous temperature fields is related to two contemporaneous wintertime trends over the last three decades: a trend towards the positive phase of the NAO and a trend towards warmer northern Eurasian land temperatures (Wallace *et al*., 1995; Hurrell, 1996; Hurrell and van Loon, 1997).

Several studies have also established links between the NAO and precipitation in western Europe and the Mediterranean basin (Hurrell 1995; Qian *et al*., 2000; Trigo *et al*., 2002). This control exerted by the NAO on the precipitation field is related to corresponding changes in the associated activity of North Atlantic storm tracks (Serreze *et al*., 1997; Osborn *et al*., 1999; Ulbrich *et al*., 1999; Goodess and Jones, 2002; Trigo *et al*., 2002). In fact, several studies have been looking at the increasing capacity of general circulation models (GCMs) to reproduce the spatial pattern of the NAO accurately (Saravanan, 1998), as well as much of its influence on the climate and storm track paths over the North Atlantic region (Osborn *et al*., 1999; Ulbrich and Cristoph, 1999). The role played by North Atlantic sea-surface temperature (SST) anomalies in establishing an NAO pattern has also been demonstrated through the use of an ensemble of runs with an uncoupled GCM (Rodwell *et al*., 1999; Mehta *et al*., 2000), and through the use of statistical techniques (Rodwell and Folland, 2002).

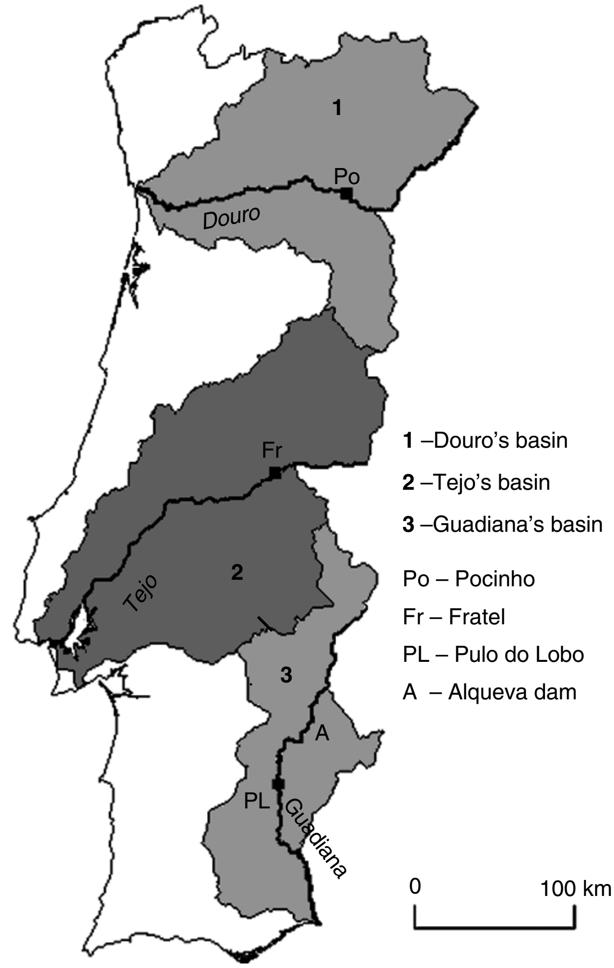

Figure 2. Location of the Portuguese section of the three river basins under consideration. Small black dots show the locations of river flow gauges used in each basin

Table I. Main characteristics of the three river basins considered. The average and standard deviation (SD) values corresponding to annual river flow were obtained using the full available period. Storage volumes for Portugal and Spain were obtained from the recently released Portuguese National Plan for Water (INAG, 2001)

River (gauging station)	Basin area (10^3 km^2)		Period	Annual river flow (10^3 hm^3)		Storage (10^3 hm^3)	
	Total	Upstream gauging station		Average	SD	Total	Spain
Douro (Pocinho)	98.4	83.0	1922–98	11.36	4.02	8.7	7.7
Tejo (Fratel)	80.1	59.0	1922–98	8.96	6.17	13.9	11.1
Guadiana (Pulo do Lobo)	66.9	60.9	1947–98	4.53	4.11	9.7	9.2[a]

[a] Does not include the recently built large dam of Alqueva with 4200 hm^3 volume in the Guadiana river.

3.2. Iberian river basins

Portugal shares with Spain five river basins, but the basins of the Douro, Tejo and Guadiana rivers constitute the three largest in area. River flow data from both Douro (at Pocinho) and Tejo (at Fratel) span between 1922 and 1998, and the data for the Guadiana river (at Pulo do Lobo) is restricted to the shorter period between 1947 and 1998. Under natural conditions, i.e. without artificial water transfers, about 70% of the total outlet flow of these three rivers has its origin in Spain (INAG, 2001). This is a natural consequence of Iberian geography, where almost 80% of the combined basin area of these three transnational rivers is located in Spain (Figure 1).

Similar to other Mediterranean regions, the river flow regime in the Iberian Peninsula is influenced by the highly seasonal precipitation regime. Figure 3 presents the seasonal variability of the mean monthly flow for the Douro (a), Tejo (b) and Guadiana (c) rivers. It is no surprise that winter- and spring-time river flows account for the majority of runoff, this being followed by a relatively long and dry summer period (Daveau, 1988; INAG, 2001). However, there is a distinct difference in flow characteristics between northern and southern basins, with Guadiana having a larger inter-quartile range than the Tejo and much larger than the Douro (notice the different ranges of the logarithmic scales). The Douro presents the highest average values of annual and monthly flow (not shown), and extreme maximum values for the wet winter season can be observed for the Tejo and Guadiana.

4. SPATIAL EXTENT OF THE NAO IMPACT ON THE PRECIPITATION FIELD

4.1. Over Europe

Trigo *et al.* (2002) have recently characterized extensively the climatic impact of the NAO mode over Europe using different variables from the NCEP–NCAR reanalysis. However, the analysis undertaken by Trigo *et al.* (2002) did not highlight the areas where the NAO influence was statistically significant, and it was limited by the use of only reanalysis data sets. Here, we extend the work of Trigo *et al.* (2002) by also computing the statistical significance and by comparing results obtained using the high-resolution, observation-based CRU data set ($0.5^\circ \times 0.5^\circ$) with those obtained with the reanalysis data set. An obvious by-product of this methodology is the possibility of evaluating the ability of the NCEP–NCAR reanalysis to reproduce the areas with significant climatic impacts of the NAO over Europe. Reanalysis precipitation has previously been shown to present *some* skill in comparison with observations (e.g. Widmann and Bretherton, 2000; Stendel and Arpe, 1997). Stendel and Arpe (1997) show that the NCEP scheme presents a dry (wet) bias during the winter (summer) season over central Europe, thus affecting the region under study. The ability of the NCEP reanalysis to reproduce daily variations of precipitation over Europe was studied further by Reid *et al.* (2001), who found that, for both England and Italy, the reanalysis presents better skill in the winter and poorer skill in the summer. The impact of model inadequacies on our results may, therefore, be low, because all the analyses performed herein are done only for winter, and are also based on the use of anomaly composites (mean field removed), thus diminishing the impact of mean bias.

Following the procedure used by Trigo *et al.* (2002), composites representing high (low) NAO index conditions were produced using a monthly (not seasonal) criterion. Thus, composites were obtained by averaging on a monthly basis, taking only those months where the NAO index is higher than $+1$ (high NAO composite) or those where the NAO index is lower than -1 (low NAO composite). The number of months with high NAO index (64) is slightly greater than those characterized by a low NAO index (43). The remaining months (53) are characterized by 'near-normal' values of the NAO index. Anomaly composites are obtained after removing the seasonal average. To facilitate the comparison of results obtained with the NCEP–NCAR reanalysis and the high-resolution CRU data sets, we present all results in millimetres per day.

The impact of the NAO mode on the entire European continent and for the 1958–95 period was computed first with the high-resolution CRU data set and can be seen in Figure 4. Winter months characterized by high and low NAO index are shown in Figure 4(a) and (b) respectively, and the magnitude of the anomaly field over western Iberia is immediately striking. The differences between high and low NAO composites

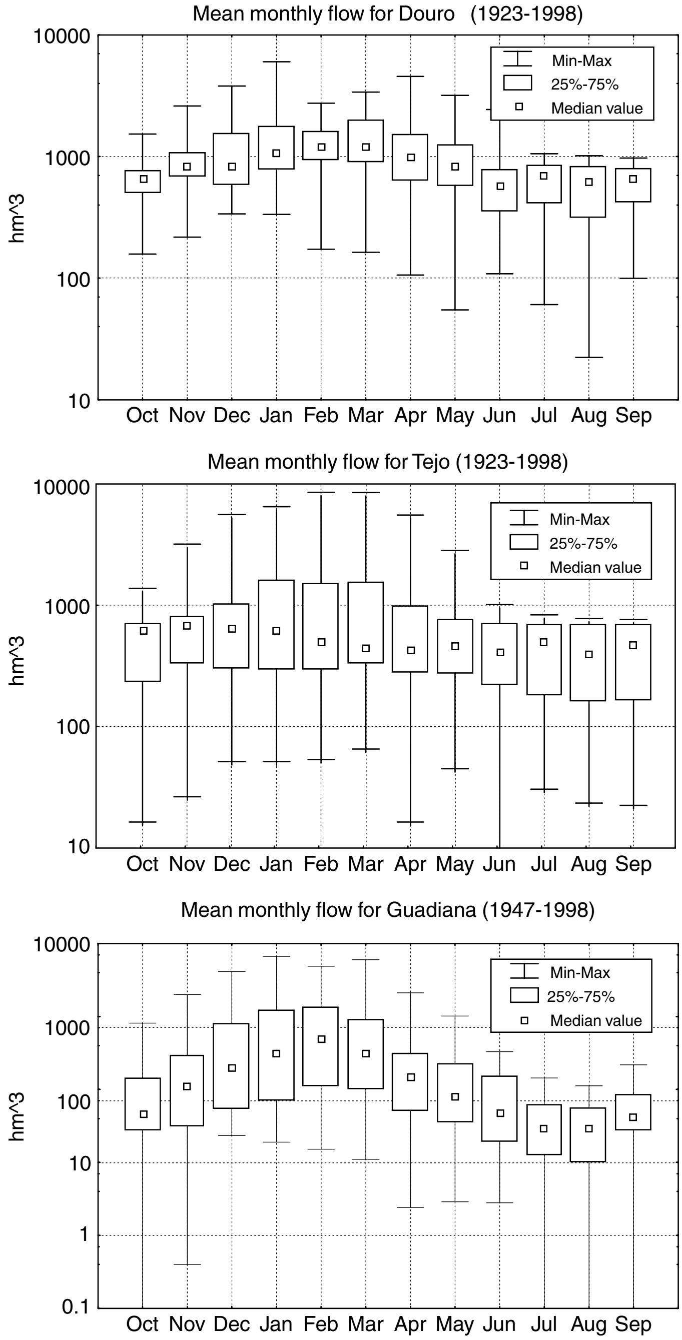

Figure 3. Box plots showing the annual cycle of the variability of average monthly river flow for (a) Douro, (b) Tejo and (c) Guadiana. The small squares (□) represent the median value for each month, the lower (upper) box limits represent the first (third) quartile and the lower (upper) whisker represents the minimum (maximum) monthly precipitation. Notice the use of a log scale in all three cases and also the different lower bound limit for Guadiana

observed precipitation are shown in Figure 4(c), but only if those differences are significant at the 1% level (statistical significance of composites was computed with a two-tailed t-test for the null hypothesis of equal means). Naturally, no precipitation information is available over the oceans, as this data set is

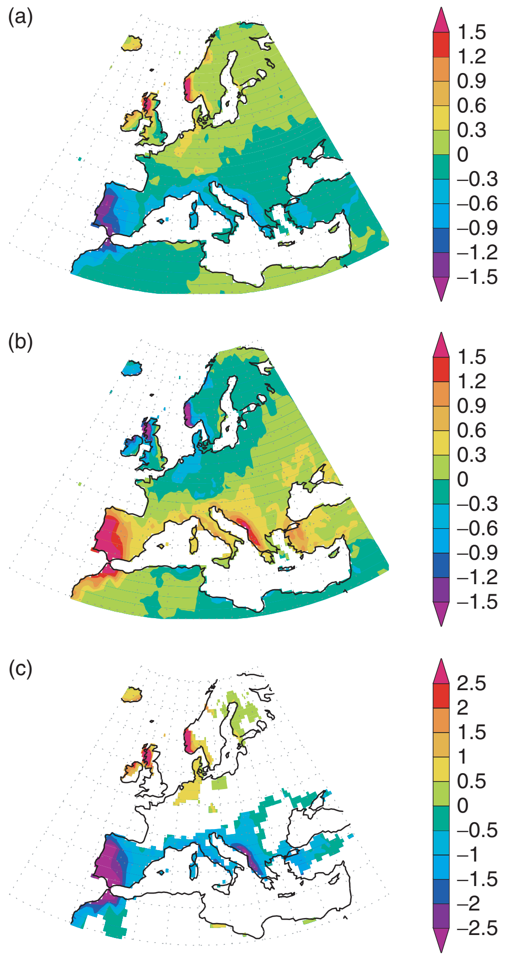

Figure 4. Precipitation anomaly fields (mm/day) from the CRU data set for winter months with (a) high NAO index >1.0, (b) low NAO index <−1.0 and (c) their difference (represented only if significant at the 1% level)

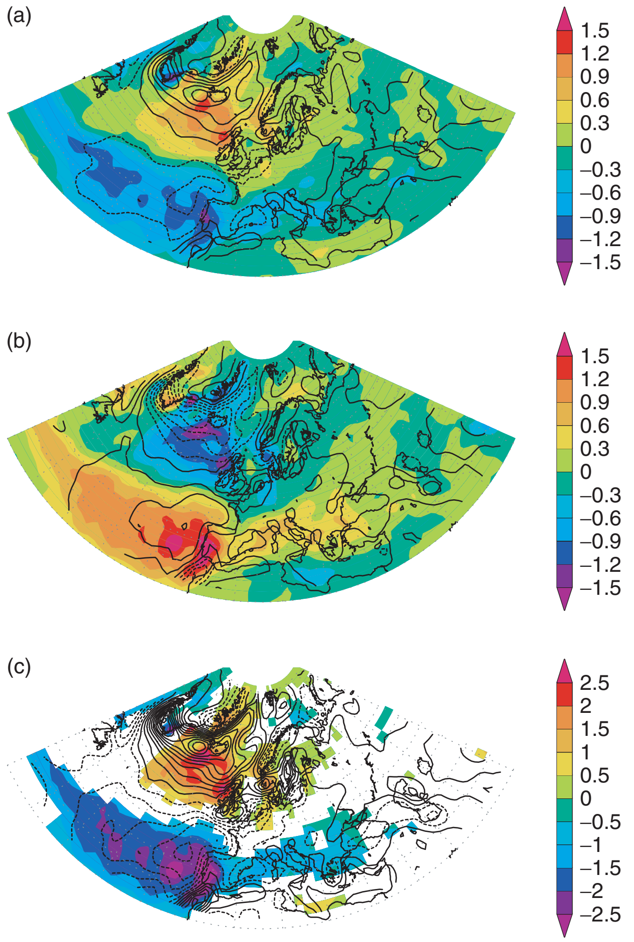

Figure 5. Precipitation rate anomaly fields (mm/day) from the NCEP–NCAR reanalysis for winter months with (a) high NAO index >1.0, (b) low NAO index <−1.0 and (c) their difference (represented only if significant at the 1% level). Positive (solid) and negative (dashed) isolines of the 10 m vorticity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

constructed with precipitation values observed with rain gauges. Over northern Europe there are relatively small, scattered patches of significant positive differences (mainly over the UK, Scandinavia and the Benelux countries), whereas southern Europe shows widespread, statistically significant negative differences in a region stretching from western Iberia to the Black Sea. In particular, the entire Iberian Peninsula exhibits significant differences between composites.

The impact of the NAO over oceanic and continental areas is identified with the use of NCEP–NCAR reanalysis. Precipitation rate (PR) anomaly fields for winter months characterized by high and low NAO index values were computed and are shown in Figure 5(a) and (b) respectively. Both figures present quasi-zonal bands of opposite anomaly signs. Differences between high and low NAO composites of PR are shown in Figure 5(c), wherever those differences are statistically significant at the 1% level. Positive PR differences are concentrated in the northern latitudes and extend from southern Greenland to Finland, with maximum values south of Iceland and west of Scotland. At lower latitudes, a strong band of negative PR differences spans from west of the Azores to the Black Sea region, with the greatest differences located between the Azores archipelago and western Iberia, and over Portugal. Overall, there is a promising geographical correspondence over Europe between areas of significant difference identified in Figures 4(c) and 5(c). Furthermore, the magnitude of these significant differences over southern Europe is very similar in both figures, including the maximum located over western Iberia (less than −2.5 mm/day). The most striking discrepancies between them are over northern Morocco (significant in the CRU data, but not according to the NCEP–NCAR reanalysis) and over the Balkan Mountains (notably stronger NAO signal in the CRU data).

An important advantage of reanalysis is the availability of so many different variables (at various levels within the atmosphere) that can be used to relate surface climate anomalies to dynamical variables. In particular, the vorticity field (computed from the 10 m wind field monthly composites) indicates that much of the PR response to high (Figure 5(a)) and low (Figure 5(b)) NAO index values is associated with anomalous values of the vorticity field. The maximum value of positive (negative) vorticity anomaly, 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 a low-pressure centre positioned poleward of the fronts that induces precipitation through strong vertical motions. In summary, PR anomalies (Figure 5) can be mainly attributed to the vorticity of the mean composite circulation (Trigo *et al.*, 2002).

4.2. Over Iberia

The Iberian Peninsula precipitation regime is characterized by high variability in both the spatial and temporal domains (Esteban-Parra *et al.*, 1998; Trigo and Palutikof, 2001). The distribution of orography and the Atlantic origin of many synoptic disturbances contribute to enormous spatial variations in the amounts of observed precipitation (Serrano *et al.*, 1999; Trigo and DaCamara, 2000). In fact, annual precipitation values over Iberia range from 300 mm/year in the coastal semi-desert southeast regions (Romero *et al.*, 1998) to more than 2500 mm/year in the mountains located in the northwestern provinces of Minho (Portugal) and Galicia (Spain). Most of the precipitation falls between October and May and is produced by synoptic-scale baroclinic perturbations that originate in the Atlantic sector and move eastwards (Serrano *et al.*, 1999). In fact, during winter the large-scale circulation is mainly driven by the position and intensity of the Icelandic low, and western Iberia is affected by westerly winds that carry moist air and produce rainfall events mainly in northern Portugal. This precipitation is intensified by the passage of cold fronts associated with families of transient depressions. This mechanism is particularly efficient when the Icelandic low is very deep and shifted southwards. However, during winter, most of the Iberian Peninsula may also be affected by northward extensions of the Azores anticyclone. This steers a warm and dry airflow into Portugal of tropical maritime origin, but modified to become polar continental (Trigo and DaCamara, 2000).

Recent studies have looked at the magnitude of correlation between the NAO and Iberian precipitation (e.g. Hurrell 1995; Rodó *et al.*, 1997; Rodríguez-Puebla *et al.*, 1998), including the problem of stationarity (e.g. Rodó *et al.*, 1997; Goodess and Jones, 2002). Here, we extend those studies by performing an extensive analysis of the relationship between the NAO index and the precipitation that falls within each individual river basin.

First, we have selected the stations located in the Spanish section of the three study basins (Figure 1). Second, we computed the correlation coefficient between the NAO index and the average precipitation within each basin for each individual month from October through to April. Furthermore, to study the temporal evolution of the NAO–precipitation relationship, we computed the correlation coefficients for three sub-periods of roughly 25 years each, i.e. between 1923 and 1947, between 1948 and 1972 and between 1973 and 1998. The results are presented in Table II, and our main conclusions are as follows:

1. Over the whole period, 1923–98, the highest correlation values are found for winter months (December through to March); all of them are statistically significant at the 95% level. Generally, correlation values increase from north to south, thus being higher for the Guadiana than for the Tejo and Douro.
2. For the rest of the months analysed, only the Guadiana basin (and just for October and November) shows some consistent significant (at the 90% level) correlation values over the entire period (1923–98). Stronger

Table II. Monthly correlation coefficient values between NAO index and river basin average precipitation over Douro, Tejo and Guadiana

	Period	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Douro	1923–47	−0.22	0.01	−0.40**	−0.42**	−0.15	−0.32*	0.11
	1948–72	−0.46**	−0.10	−0.22	−0.39**	−0.37*	−0.40**	−0.55**
	1973–98	−0.27	−0.23	−0.66**	−0.37*	−0.53**	−0.41**	−0.08
	1923–98	−0.30	−0.13	−0.46**	−0.38**	−0.41**	−0.40**	−0.20
Tejo	1923–47	−0.27	−0.10	−0.46**	−0.46**	−0.24*	−0.40**	0.10
	1948–72	−0.47**	−0.10	−0.33*	−0.41**	−0.47**	−0.51**	−0.50**
	1973–98	−0.21	−0.30*	−0.77**	−0.52**	−0.61**	−0.40**	0.10
	1923–98	−0.32	−0.23	−0.47**	−0.43**	−0.47**	−0.48**	−0.16
Guadiana	1923–47	−0.40**	−0.32*	−0.44**	−0.46**	−0.50*	−0.43**	−0.02
	1948–72	−0.40**	−0.15	−0.40**	−0.44**	−0.55**	−0.50**	−0.52**
	1973–98	−0.12	−0.50**	−0.83**	−0.62**	−0.63**	−0.36*	−0.08
	1923–98	−0.33*	−0.33*	−0.53**	−0.51**	−0.57**	−0.45**	−0.17

* Significance level >90%.
** Significance level >95%.

correlations (95% level) occur in April and October, for all three river basins, during the middle period (between 1947 and 1972).

3. Regarding the temporal evolution of the strength of the correlation, a range of differing results are obtained when we analyse on a monthly basis or when we look at each individual basin. A common feature, however, is that for December through to February (DJF) and for all the basins, the most recent sub-period considered (1973–98) has the highest correlation values. In fact, the highest absolute correlation value in Table II is for the Guadiana basin in December ($r = -0.83$), during this recent sub-period.

Overall, these results are in agreement with those obtained previously (e.g. Rodo *et al.*, 1997; Rodríguez-Puebla *et al.*, 1998; Serrano *et al.*, 1999; Goodess and Jones, 2002). Rodó *et al.* (1997) have studied the change in correlation over the longer period 1910–94, but, by splitting into only two sub-periods (1910–52 and 1953–94), the intensification of the NAO–precipitation relationship with time was partially offset. Recently, Goodess and Jones (2002) analysed the time evolution of the NAO–precipitation relationship over the Iberian Peninsula during the period 1958–97. Their results are in better agreement with those obtained here, with an intensification of this relationship in central and northern Spain during the period 1978–97 in comparison with the previous period, 1958–77.

5. NAO IMPACTS ON IBERIAN WATER RESOURCES

5.1. River flow

The study of river flow regimes in the Iberian region using the calendar year (January to December) may result in misleading results, since the high winter precipitation would be split between two different years. Thus, we have adopted the October-to-September definition of the hydrological year: the average river flow for the year 1961, say, is the sum of monthly flow from October 1960 until September 1961.

It is natural to expect that the strong impact of the NAO on precipitation over the central and western sectors of Iberia should extend to the flow of rivers located within these sectors. River flow reflects precipitation integrated both spatially (over the catchment) and temporally; therefore, a seasonal (rather than monthly) time scale is considered here, taking the DJF average of the NAO index. Taking into account that the original NAO index is not normalized, we decided to normalize the entire winter NAO index so it has zero mean and unit variance. We define the seasonal high NAO composite (low NAO composite) to be constituted by all winters with NAO higher than 0.5 (lower than −0.5). Between 1923 and 1998 (76 winters), the number of winter seasons with high NAO index (24) is equal to the number characterized by a low NAO index (24). The remaining winters (28) are characterized by 'near-normal' values of the NAO index.

The impact on the hydrological cycle (from October to September) of years characterized by winters with large positive and negative NAO index anomalies is shown in Figures 6(a), 7(a) and 8(a) for the Douro, Tejo and Guadiana rivers respectively. In all three cases there is a clear difference of mean river flow in winter and spring months between the high and low NAO composites. For the River Douro these differences are significant (at the 5% significance level) only between January and April, whereas for the Rivers Tejo and Guadiana they are consistently significant between January and September.

Correlation coefficients between winter river flow (DJF) and contemporaneous winter NAO index (lag zero) were computed, using the entire period of data available for each river. We have also computed the 1-month lagged correlation between the NAO index for DJF and the river flow for January to March (JFM). Following the approach presented in Section 4, correlation coefficients for three sub-periods 1923–47, 1948–72 and 1973–98 were also computed for the Rivers Tejo and Douro. For the shorter Guadiana time series we have only computed the correlation coefficient for the two most recent sub-periods. The results are summarized in Table III. The inter-annual variability of winter (JFM) river flow against the winter NAO index leading by one month (DJF, multiplied by −1 to facilitate visual comparison) can be observed in Figures 6(b), 7(b)

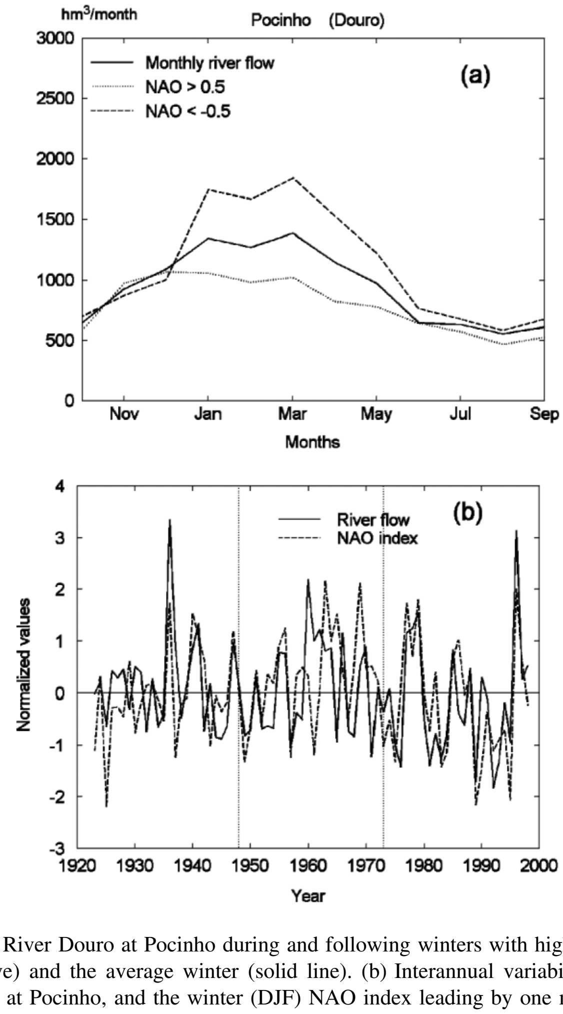

Figure 6. (a) Monthly river flow of River Douro at Pocinho during and following winters with high NAO index (dotted curve), winters with low NAO index (dashed curve) and the average winter (solid line). (b) Interannual variability of the mean winter (JFM) river flow (solid curve), for River Douro at Pocinho, and the winter (DJF) NAO index leading by one month (multiplied by −1 to facilitate analysis, dashed curve); both curves have been normalized, and so are dimensionless

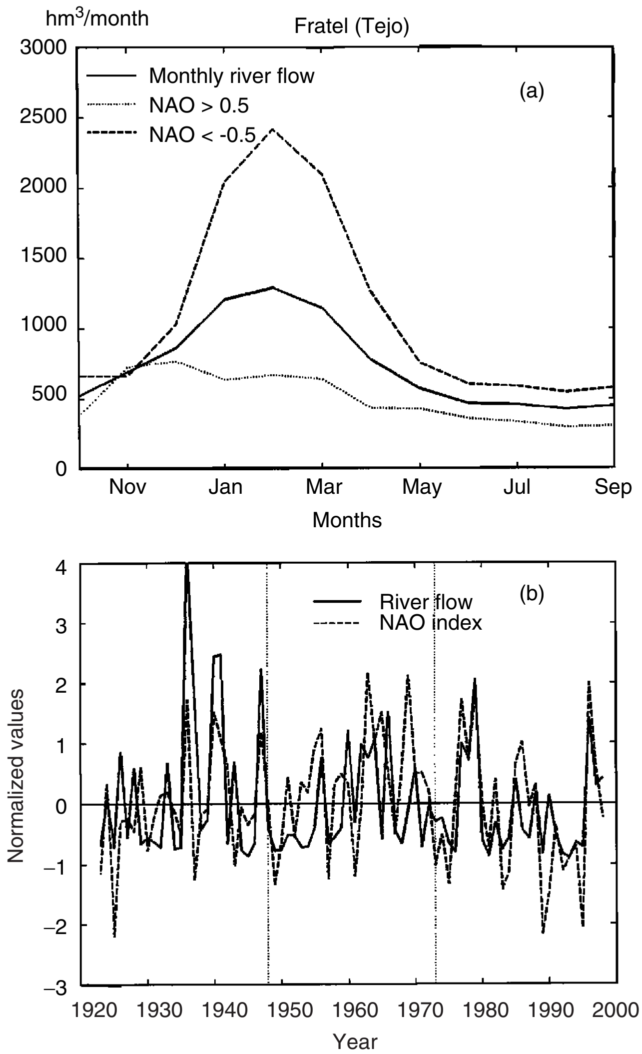

Figure 7. As Figure 6, but for River Tejo at Fratel

and 8(b) for the Douro, Tejo and Guadiana rivers respectively. Sub-periods are delimited by a vertical dotted line while both curves (river flow and NAO index) were normalized and represented between 1920 and 2000 to facilitate comparisons between all three rivers. The simultaneous analysis of these figures and Table III suggests the following conclusions:

1. The magnitudes of all 1-month lagged correlation coefficients are consistently higher than the corresponding non-lagged ones. In particular, over the full period (1923–98), correlation coefficient values for all three rivers increase when the NAO index leads river flow by 1 month. This is relevant because it highlights the potential use of these relationships for forecasting.
2. For both the Douro and Tejo rivers there is a decrease in the magnitude of correlation coefficient values between the first and second sub-periods followed by a major increase between the second and third sub-periods. The change in coherence between the time series is obvious in Figures 6(b), 7(b) and 8(b). The 1-month lagged correlation values for the most recent sub-period (1973–98) are the strongest overall: −0.76 for Douro, −0.77 for Tejo and −0.79 for Guadiana.

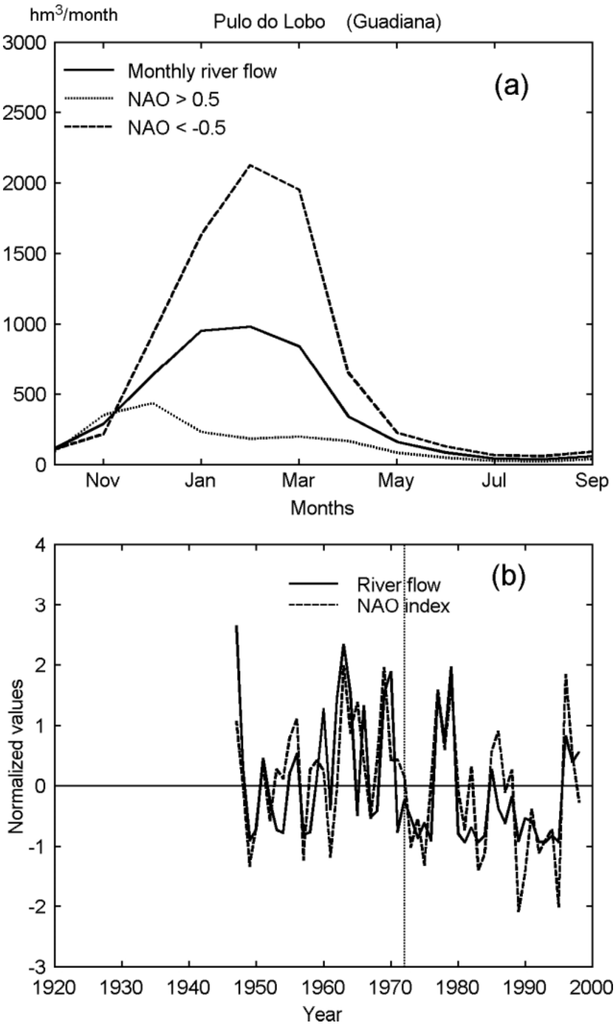

Figure 8. As Figure 6, but for River Guadiana at Pulo do Lobo

3. Despite these consistently high values of anti-correlation, it is evident that the river flow of both the Guadiana and Tejo did not reduce to the low levels expected from the high NAO index values in the 1980s and 1990s.

Comparison with similar studies of other river basins is hampered by the use of different periods, seasonal aggregations, etc. Nevertheless, it should be emphasized that neither the Rivers Tigris, Euphrates (Cullen and deMenocal, 2000) and Danube (Rîmbu *et al.*, 2002), nor rivers in England and Wales (Wedgbrow *et al.*, 2002) demonstrate such strong correlations with the NAO index as found here for the Iberian rivers. In fact, we have no knowledge of any European river presenting a seasonal correlation coefficient value higher than 0.75 with any large-scale climate index, such as NAO, El Niño–southern oscillation, etc.

The smaller amplitude of Tejo and Guadiana river flow variability since the 1980s could reflect the large increase in storage volume capacities provided by large Spanish dams built in the middle and upper sections of both rivers (Daveau, 1988). In particular, large-scale agricultural facilities have been developed in the Spanish province of Extremadura, including two water irrigation canals that divert significant amounts of water from the River Guadiana (Daveau, 1995).

Table III. Seasonal simultaneous (lead 0) and 1-month leading (lead 1) correlation coefficients between winter NAO index and river flow in Pocinho (Douro), Fratel (Tejo) and Pulo do Lobo (Guadiana)

	Lead 0 NAO (DJF), flow (DJF)	NAO lead 1 NAO (DJF), flow (JFM)
Douro		
1923–47	−0.27*	−0.48**
1948–72	−0.10	−0.29*
1973–98	−0.58**	−0.76**
1923–98	−0.35*	−0.55**
Tejo		
1923–47	−0.54**	−0.56**
1948–72	−0.25*	−0.37*
1973–98	−0.61**	−0.77**
1923–98	−0.45**	−0.52**
Guadiana		
1948–72	−0.45**	−0.60**
1973–98	−0.67**	−0.79**
1948–98	−0.57**	−0.69**

* Significance level >90%.
** Significance level >95%.

5.2. Hydroelectricity production

A similar analysis was applied to assess the impact of the NAO on the production of hydroelectric power. Owing to the unavailability of hydroelectric production data for Portugal, we restricted our study to Spain. The total potential hydroelectric production (PHP) of the entire Spanish hydroelectric production system is available on a monthly basis (REE, 2002) and has been analysed over the period 1923–98. The Douro and Tejo rivers are the most important basins as far as hydroelectric production is concerned, accounting for roughly 50% of the average total Spanish hydroelectric production (REE, 2002). The large storage capacity provided by dams in the Guadiana basin is mostly for agricultural purposes (Daveau, 1995) and this basin accounts for only 5% of the country's average hydroelectric production. The remaining 45% of hydroelectric production is mainly provided by dams from smaller river basins located in the northern provinces of Spain, a wetter region characterized by much lower values of inter-annual variability. The precipitation regime in this mountainous region of Iberia is less associated with a single large-scale mode of atmospheric circulation (Rodó *et al*., 1997; Rodríguez-Puebla *et al*., 1998).

Simultaneous and 1-month lagged correlation values between monthly NAO index and the monthly PHP, from November through to May, were obtained for the entire 1923–98 period, and for the previously analysed sub-periods, 1923–47, 1948–72 and 1973–98 (Table IV). The negative correlation found for the vast majority of cases is in agreement with results from previous sections, since a positive NAO index implies less precipitation for most of the Iberian Peninsula. Over the entire period, significant negative contemporaneous correlations are obtained for December to March, whereas lagged values are significant for all months from November to May, except December; the most notable correlation is −0.52 between March PHP and the February NAO index.

As with precipitation (Table II) and river flow (Table III), the correlations between NAO and PHP are strongest during the latest period, 1972–98. The maximum contemporaneous correlation over this period is obtained for the month of February (−0.57). Correlations with NAO leading river flow by 1 month are all stronger, with the highest over the period 1972–98 being for PHP in January (−0.66) and March (−0.64).

Correlation coefficients were also computed using seasonal values, between the JFM and DJF PHP averages and the winter (DJF) NAO index (Table V). The lagged correlation (i.e. DJF NAO with JFM PHP) found for

Table IV. Monthly simultaneous (lead 0) and 1-month leading (lead 1) correlation coefficients between the NAO index and total Spanish PHP

Period	NAO lead 0	NAO lead 1	NAO lead 0	NAO lead 1	NAO lead 0	NAO lead 1	NAO lead 0	NAO lead 1
	1923–98		1923–47		1948–72		1973–98	
Jan	−0.42**	−0.38**	−0.34*	−0.26	−0.52**	−0.40**	−0.44**	−0.66**
Feb	−0.41**	−0.37**	−0.17	−0.40**	−0.40**	−0.33*	−0.57**	−0.36*
Mar	−0.39**	−0.52**	−0.43**	−0.34*	−0.27	−0.48**	−0.09	−0.64**
Apr	−0.10	−0.29**	0.25	−0.23	−0.44**	0.00	−0.20	−0.39**
May	−0.03	−0.23**	−0.11	0.11	0.27	−0.43**	−0.04	−0.51**
Nov	0.07	−0.23**	0.25	−0.23	0.24	−0.22	0.25	−0.19
Dec	−0.33**	−0.08	−0.24	0.24	−0.16	−0.17	−0.50**	0.00

* Significance level >90%.
** Significance level >95%.

Table V. Simultaneous (lead 0) and 1-month leading (lead 1) correlation coefficients between winter NAO index and Spanish PHP index

Period	Lead 0 NAO (DJF), PHP (DJF)	Lead 1 NAO (DJF), PHP (JFM)
1923–47	−0.29	−0.36**
1948–72	−0.36*	−0.62**
1973–98	−0.69**	−0.78**
1923–98	−0.51**	−0.63**

* Significance level >90%.
** Significance level >95%.

the entire 1923–98 period is strongly negative (−0.63) and is statistically significant with 99% confidence. As expected from previous results, the magnitude of this correlation increases for the last sub-period (1973–98), where it reaches −0.78. The contemporaneous correlation shows a similar behaviour to the lagged correlation, but with less negative amplitude. The temporal JFM PHP anomaly and the winter (DJF) NAO index time series (Figure 9) show exceptional coherence since the mid 1970s; since then, the NAO has controlled most of the Spanish river flow inter-annual variability, and consequently the PHP index.

For completion of our analysis, composite values of monthly PHP associated with low (<−0.5) and high (>0.5) NAO index have been computed and compared with each other (Figure 10). This analysis was carried out on a monthly basis, but the NAO index used to define the composites is the winter (DJF) average and was normalized for the entire period. Positive NAO winters are characterized by lower PHP, particularly from December through to March, whereas negative NAO winters are associated with greatly enhanced PHP from December through to April. For these months, the increase during a negative NAO index is greater than the decrease associated with a positive NAO index. During January and February, negative NAO months provide an increase in PHP of roughly 80% with respect to the mean production, whereas positive NAO months are associated with a 40% reduction.

Totalling our PHP composites over the period JFM shows that positive NAO winters (NAO index >0.5) are characterized by a composite PHP average of 925 GWh below the mean of 4049 GWh, whereas the composite for low NAO index winters (<−0.5) is 1254 GWh above this mean. Both composite values are significantly different (with 95% confidence) than the composite average of the remaining winters (−0.5 < NAO index < 0.5). During high NAO index winters, therefore, an average decrease in JFM PHP of 25% can be expected, whereas during low NAO index winters an average increase of 30% can be anticipated.

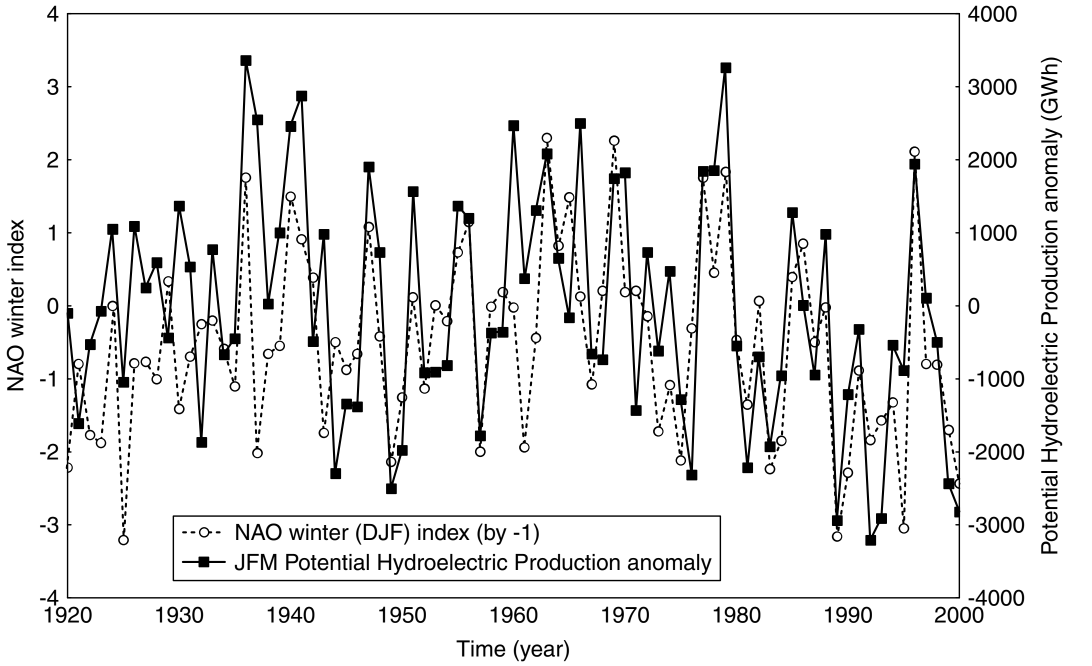

Figure 9. Inter-annual variability of the mean winter (JFM) Spanish PHP anomaly (solid curve) and the winter (DJF) NAO index leading by 1 month, multiplied by -1 to facilitate analysis (dashed curve)

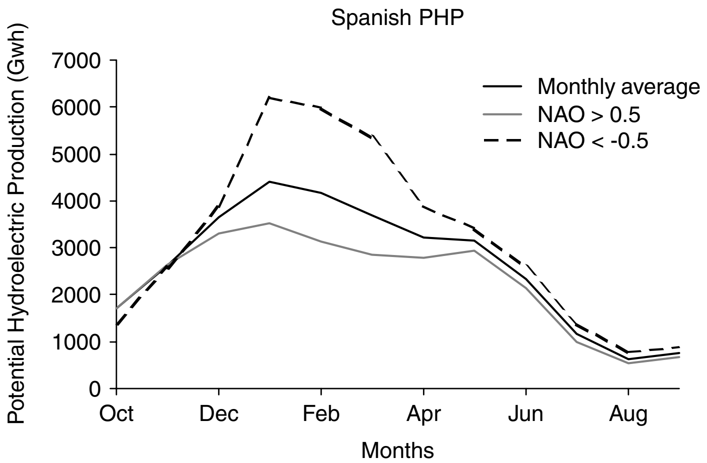

Figure 10. Composite of monthly PHP values associated with low (<-0.5, dashed) and high (>0.5, dotted) DJF NAO index values. The mean value is also shown (solid line)

6. SUMMARY AND DISCUSSION

We evaluated the magnitude and the spatial extent of the statistically significant impact of the NAO mode on the precipitation field over the entire European continent. We then confirmed the relevance of this large-scale atmospheric circulation mode to winter precipitation and river flow in three important Iberian river basins, and to hydroelectric production over Iberia. The JFM mean river flow was shown to be better associated with 1-month leading (DJF) NAO index than is the simultaneous (DJF) river flow. To study temporal changes in the NAO–river-flow relationship, we compared the correlation coefficients obtained for three non-overlapping sub-periods: 1923 to 1947, 1948 to 1972, and 1973 to 1998. The highest correlation coefficients were obtained for the most recent period (1973–98) and, with magnitudes in the range −0.75 to −0.80, they can be regarded as highly significant (−0.76 for Douro, −0.77 for Tejo and −0.79 for Guadiana).

The analysis of the PHP of Spain (a surrogate of the river flows) and the NAO index shows similar results: the JFM PHP is more strongly related to the DJF NAO index than is the DJF PHP. The lagged correlation value over the period 1923–98 is −0.63, but it reaches −0.78 over the more recent 1973–98 period. A composite analysis shows that a 25% decrease in the JFM PHP is associated with positive NAO winters (DJF NAO index >0.5) and a 30% increase is associated with negative NAO winters (DJF NAO index <−0.5). In summary, this control exerted by NAO on the river flow regime has obvious consequences for all water resources in the region, and in particular it has a large economic impact due to the associated inter-annual variability of hydroelectric production within both Spain and Portugal.

The increase since the 1970s in the strength of the correlation is related to the observed strengthening of the NAO relationship with the region's winter precipitation (Table II). However, the increase in strength might also be related to the increase in water storage volume associated with the construction of major dams in the 1950s and 1960s (Daveau, 1988; Melo and Gomes, 1992). Results in Table III show that the correlation increase is larger at 1-month lag than it is for simultaneous correlations. This result might provide evidence for the expected effect of erecting large dams, viz. an increased time between precipitation episodes and the arrival of the corresponding flow to lower sections of the river basin. A recent study (Ramos and Reis, 2001) has shown that the construction of large dams in the Spanish sector of the River Tejo between the late 1950s and early 1970s has had an important effect in constraining the magnitude of the highest instantaneous runoff values entering into Portugal.

To check this hypothesis we performed a more detailed analysis to study the influence of the regulations of the Guadiana river basin in its flow regime. The average and the standard deviation of the river flow were compared for three different time periods: 1946–56, 1963–88 and 1990–98, chosen because these correspond to different stages of anthropogenic influence in the Guadiana river basin (Daveau, 1995; Brandão and Rodrigues, 2000). We conclude from results (not shown) the existence of a strong decrease during the 1990–98 period, in both the mean and the standard deviation, statistically significant at the 95% level when being compared with the previous periods' mean and variance. The magnitude of this decrease in the Guadiana river flow cannot be explained solely by a strong decrease in precipitation and/or increase in upstream water abstraction.

Problems with excessive use of water in the Guadiana are bound to arise, even if we disregard the previously mentioned decrease of this river's annual flow. In the Guadiana river basin, the combined storage capacity of all Spanish dams (9200 hm^3) is now equivalent to 200% of the long-term average annual flow reaching the Portuguese territory (Table I). In this context, the recently built dam of Alqueva might represent an anachronism. Located inside Portuguese territory, 50 km upstream of the Pulo do Lobo gauge station (see Figure 2), this dam will create the largest artificial lake in western Europe, with 200 km^2 area and a storage capacity of roughly 4200 hm^3, similar to the current average annual flow of Guadiana at Pulo de Lobo (Table I). Currently being filled up, this large investment is mainly for agricultural (and leisure) purposes, with the production of hydroelectricity being a minor component. The total accumulated storage volume will correspond roughly to 300% of the average annual flow currently reaching the reservoir.

We have clearly shown in Sections 4 and 5 that the impact of the NAO on precipitation, river flow and hydroelectric production is irregular, presenting a high inter-decadal variability. Recent studies have shown that, throughout the latest two decades, the northern centre of the NAO dipole (the Icelandic low) has moved closer to Scandinavia (Jung and Hilmer, 2001). This shift has major implications for the Northern Hemisphere climate in general (Lu and Greatbatch, 2002), and for the precipitation field over Iberia in particular (Rodó *et al*., 1997; Goodess and Jones, 2002). It is not obvious whether this variability is natural or induced itself by climate change. Using a multi-century control run, Osborn *et al*. (1999) have shown a remarkable range of inter-decadal variability in the magnitude of the association between NAO and Northern Hemisphere temperatures.

Despite these problems, we believe that the potential predictability of the NAO index and, consequently, of the precipitation field and river flow regimes over the Iberian Peninsula and the associated hydroelectric production provides large *potential* economic advantages. In fact, statistical (e.g. Gámiz-Fortis *et al.*, 2002; Rodriguez-Fonseca and Castro, 2002) and dynamical models are already in development to predict precipitation over Europe several months in advance. We believe that, based on NAO–rainfall and NAO–flow relationships, there is a large scope for further development of useful statistical and dynamical models. Such models should be developed with the double purpose of providing water resource managers in Iberia with seasonal forecasting tools and to assess changes in river flow regime under climate-change scenarios.

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