Hydrol. Earth Syst. Sci. Discuss., 8, C3099–C3116, 2011
www.hydrol-earth-syst-sci-discuss.net/8/C3099/2011/


Hydrology and Earth System Sciences Discussions

# *Interactive comment on* "The response of Iberian rivers to the North Atlantic Oscillation" *by* J. Lorenzo-Lacruz et al.

**J. Lorenzo-Lacruz et al.**

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Received and published: 29 July 2011

On the behalf of all the authors, we want to express our gratitude for the interesting comments and observations received from the reviewer, all of them aimed to improve substantially the quality of our work and the clarity of the presented results. Following we include a detailed letter where we respond to each one of the suggestions and concerns of the reviewer, explaining all changes introduced to the revised version of the manuscript.

-While the authors only analyze the effect of NAO on the interannual variability of monthly mean streamflow in IP, they do not explain in sufficient detail, in the Introduction section, why they restricted their analysis to this particular climate index, even



as they recognize the effect of ENSO on the variability of precipitation in Spain and Europe in general. Other indices, such as AMO and AO, may also affect this variability.

We focused on the NAO impacts on the streamflows of the Iberian Peninsula because it is widely recognized in hundreds of papers as the most influencing mode of variability affecting the climate in Western Europe as we noted in the manuscript. Moreover, we discarded ENSO due to its weaker relationship with European precipitation; AMO was not suitable to assess the interannual variability of streamflows since it is multidecadal; and finally AO is a different way to describe the same phenomenon that NAO does and they are very similar. These reasons are now stated in the revised manuscript. Furthermore, because the authors did not analyze all the interesting results deriving from Figures 2 and 3, the ensuing discussion on the relationship between NAO and the spatio-temporal variability of monthly mean streamflow is too brief and incomplete. The Results (sections 4.1 and 4.2) and Discussion sections must be expanded to provide more in-depth analysis and interpretation.

Sections 4 and 5 have been modified and reworked in order to fulfill the referee's concern.

II. Specific comments

1. Introduction Page 4461, lines 25-29; Page 4462, lines1-10 This paragraph should probably be moved to section 3.2 (page 4464) and the introduction should be reworked accordingly.

We think that the brief description of the spatio-temporal patterns of the NAO influence on the streamflows along Europe fits better with the Introduction section rather than with the Methodology section.

2. Study Area Page 4463, Study area The text in this section and in Figure 1 does not provide sufficient information on the various watersheds and stations analyzed. A table containing the following data should be provided as a complement to Figure 1

(see example below).

We appreciate this suggestion, also considered by us. For this reason we included the characteristics of the main river basins in a table as part of Figure 1 in the revised manuscript.

3. Dataset and Methodology Page 4465, lines 15-20 Sequences (duration) of missing data in the time series must be provided. Do they span more than two consecutive years?

We already clarified the requirements for the selection of the series (less than 10% of missing data and the belonging to the same river or river system) and the procedure to the gap-filling process. In general, missing data gaps are punctual and do not span more than two consecutive years.

Page 4466, lines 1-6 This section on standardization seems unclear. 1) Were all these probability distributions applied to each station?

All series were fitted independently to the most suitable probability distribution, according the Minimum Orthogonal Distance (MD) between the sample L-moments at site i and the L-moment relationship for a specific distribution from among the general extreme value (GEV), the Pearson type III (PIII), the loglogistic, the lognormal, the generalized Pareto and the Weibull distributions. The full description of the mentioned procedure can be found in Vicente-Serrano et al. (2011).

2) If not, how is it possible to compare series which were standardized according to different probability distributions?

Because using different distributions we achieve an accurate standardization minimizing skewness and kurtosis among series. More details about the underlying statistical theory and the standardization process can be found in Vicente-Serrano et al., 2011.

3) What is the rationale for using GEV's for monthly flow data? This distribution is generally used for extreme flows.



GEV is actually used for extreme flows. In our database, some southern Spanish rivers (Guadalquivir right bank tributaries and Andalusian sub-basins) present a flashy and ephemeral regime characterized by extreme high flows during concrete rainfall episodes (e.g. 2010 winter storms and floods in Andalusia) and low flows during the rest of the year. In general, GEV was used to standardize the series of these rivers.

Page 4467, line 20 Applying the term "non-stationarity" to correlation coefficients does not seem appropriate. This term is generally used for moments of a statistical series, such as the mean or the variance.

There are several research papers which use the terminology stationarity and non-stationarity (e.g. Llasat & Quintas, 2004; Vicente-Serrano & López-Moreno, 2008). Non-stationarity is commonly used to make reference to the changing role of NAO or other teleconnections on climate or hydrology. Thus, it has been accepted in many scientific publications.

Page 4467, line 22 1) It would be useful to clearly define the term "moving-window correlations".

We modified and completed the definition of the moving-window correlations as follows:

"To assess the non-stationariy influence of the NAO on Iberian streamflows we performed an analysis based on the use of moving-window correlations (Pearson's correlation coefficients) between the NAO and the SSIs for every gauging station. The result of the first calculation (1945–1965) was assigned to the middle year of this interval (1955). The second calculation was based on the years 1946-1966, and the process was repeated up to the years 1985–2005."

2) Why the use of 21 years in deriving these correlations?

Because we need a relative large interval to assess changes in NAO influence but without missing a long period of the available series (just 10 years at the beginning and at the end of the series).

Page 4468, line 11 Which criterion is used to determine the number of significant principal components?

For the selection of a new principal component, it must explain more than 5% of the variance. The 3rd PC in the case of the anomalies analysis explained the 6.4% of the total variance and so we included it, whereas the 3rd PC in the case of the moving-window correlations only added a 3.8% of new information and we discarded it. We have added a new paragraph in the revised manuscript to clarify this point, as follows:

"The criterion used to determine the number of significant Principal Components was the explained variance: for the selection of a new Principal Component it must explain more than 5% of the variance."

4. Results Sections 4.1 and 4.2. These two sections should be merged into a single one.

These two sections are now merged in the revised manuscript.

Figures 2 and 3 1) Map titles and legends are illegible. This must be improved.

We changed the size of the fonts in the titles and legends of Figures 2, 3 and 4 in the revised manuscript.

2) The order of maps in Figures 2 and 3 must be modified to be consistent with the way months are grouped into seasons. Maps should be arranged as follows:

We think that for an easier following of the explanations and for a better organization of the Figures, it is preferable the scheme used in the discussion paper, with a order of visualization from left to right instead of from top to bottom. In any case both possibilities could result adequate.

3) All points corresponding to non significant correlation coefficients should be removed to make maps more legible and easier to describe.

When representing non-significant correlations several spatial gradients appear in the



maps. Thus, we prefer to maintain them as they do not mask the significant correlations.

4) The legend pertaining to correlation coefficient values is not precise. For instance, does the size of the circle corresponding to a coefficient of 0.5 also represent all values larger than that threshold? Class limits for the coefficients of correlation must be defined.

The dimensioning of the size of the circles is actually precise. We used a constant proportionality rule to achieve an accurate representation. The size of the circle corresponding to a coefficient of 0.5 only represents correlations of 0.5; greater correlations are represented by greater circles. We decided to include the interval 0-0.5 in the legend because the great majority of the correlation values are between 0 and 0.5, and thus the restriction of the interval allows an easier comprehension of the dimensioning in the cartography.

Text in sections 4.1 and 4.2 The description of results presented in Figures 2 and 3 is short and does not address all of the important features observable in these two figures. Here is one possible example of how these two figures could be described: - In winter, NAO is negatively correlated with many stations at the IP scale, although this correlation is not homogeneous for the four winter months (Fig. 2). In December, at the beginning of the season, a difference is observed between the southern and central sectors (many stations correlated with NAO) and the northern sector of the IP (few stations correlated with NAO), whereas in March, at the end of the season, the opposite is true.

We have added the next paragraph in the revised manuscript:

"A clear spatio-temporal pattern was observed for the interaction, with significant negative correlations occurring throughout most of the IP during winter (December to March), with some spatial differences between months. In December, at the beginning of the season, only the Atlantic watershed and some Pyrenean sub-basins are under the influence of the NAO. During January and February almost the entire IP is under the NAO influence, whereas in March the response of some rivers of the Tajo, Guadiana, Júcar an Segura basins to the NAO weaken."

- During spring-summer (April to July), the number of stations which show a significant correlation with NAO decreases throughout the IP. Furthermore, in July, this correlation becomes positive, particularly in the Northwest.

This fact was already mentioned in the discussion paper:

"Nevertheless this relationship rapidly disappeared in spring. Positive correlations (mostly non-significant) were evident sporadically from April to July in the eastern part of the IP."

Moreover, positive correlations appear in the eastern and north-eastern part of the IP, not in the Northwest as the referee stated.

- During summer-fall (August to November), the number of stations which show a significant correlation with NAO increases gradually at the beginning of the season to reach a maximum in October, month during which the correlation is negative, as in winter. In addition, a difference is once again observed between the southern and northern sectors of the IP, as during the month of March. Thus, March and October are characterized by the same North-South difference. Finally, in November, the number of stations significantly correlated with NAO decreases with respect to October, and these stations are concentrated in the southwestern sector of the IP.

We have included a sentence to highlight the coincident pattern observed in March and October stressed by the referee.

"In contrast to the transition from winter to spring, the transition from late summer to autumn was gradual, with moderate negative correlations (R $\approx$ –0.35) becoming evident again in northern Iberia in late summer and the beginning of autumn. In October the NAO influence was evident in the basins in the Atlantic watershed (the central and



western parts of the IP) and the Pyrenean basins, configuring a similar North-South difference than the one observed in March. During November the area under the influence of the NAO decreased and was confined to the southwest of the IP. At the beginning of winter there was a reinforcement of the NAO signal, and a clear west–east pattern emerged during December, with significant negative correlations in the west that reached the basins on the western side of the Cantabrian Range, the Iberian Range and the Betic systems, which divide the IP into the Atlantic and the Mediterranean watersheds. This spatial configuration broadly reflected the climatic signal derived from the NAO–precipitation interaction during winter, which is enhanced in the Atlantic watershed sub-basins."

The spatio-temporal distribution of lagged correlations is similar to that just described, with the following differences: - In winter, the contrast described above for December is observed, although the number of stations which are significantly correlated with NAO decreases in the southern and central sectors. In contrast, in March, the North-South difference disappears as a result of the increase in the number of stations statistically correlated with NAO.

We have completed the explanation with the suggestion above this line:

"Slightly higher correlations (R $\approx$ –0.6) relative to the non-lagged correlations described above were observed during winter (from December to February), although the number of stations significantly correlated with the NAO decrease in the southern and central sectors at the beginning of the season."

- During spring-summer, the number of stations which are significantly correlated with NAO increases in April and, to a lesser extent, in May. The most notable fact is the disappearance of positive correlations in July.

We have completed the sentence related to the referee's advice:

"During spring the one-month lagged NAO signal disappeared throughout most of the study area; the exception was in the Duero basin, where significant correlations were still recorded during April and May. Non-significant positive correlations during summer were occasionally detected."

- During summer-fall, as in the previous season, the number of stations which are significantly correlated with NAO decreases, this decrease being particularly strong in October. In November, there is a slight North-South difference which is opposite to that observed in December.

We think that this transition was also already mentioned in the discussion paper:

"The reinforced response of streamflows to the NAO in the previous month did not occur until October and November, and this was restricted to the Duero and Tajo basins. In December, a southwards displacement of the hydrological response was observed, and this resulted in reinforcement of the November NAO influence across the southernmost basins of the Atlantic watershed. This occurred prior to the commencement of the highly active winter NAO period, when the IP was again completely under the influence of the NAO."

Page 4493, Fig.7 Why choose the month of March, which is characterized by a North-South difference? The months of January or February should have been used instead. In addition, given the symbols used, it is not possible to see whether or not coefficients of correlation are higher than during other months.

We kindly appreciate this suggestion also noted by other referee. In order to solve this problem (the North-South difference in the correlations) and the possible effects of the well-known decreasing trend in precipitation during March, we performed the same moving-window correlation analysis but this time by relating the winter NAO index (in order to account for the accumulated impacts of the NAO during its most active season) with the March SSI (which did not showed important differences in the correlations between the North and the South of the IP). This section has been rewritten as follows:



"To investigate the influence of the NAO on streamflow evolution, we first performed a moving-window correlation (21 years) analysis between the monthly Winter NAO index and the March SSI of each gauging station. A PCA was used to summarize the general temporal evolution of the NAO influence on streamflow. Figure 7 shows the temporal evolution of the three first principal components (left) and the correlations between their scores and the moving-window correlation series obtained for each gauging station (right). The first Principal Component explained approximately 28% of the variance. It was characterized by a low influence of the NAO influence on streamflow during the 1950s, 1960s and 1970s, and an enhanced response of streamflow to the NAO since the 1980s. Fitting this pattern were the Cantabrian basins, the Mondego basin, most of the Duero main course, the middle and upper Tajo and Guadalquivir basin tributaries, the majority of Júcar and Andalusian basins and some of the Pyrenean tributaries of the Ebro river. The second Principal component explained 23.8% of the variance. It was characterized by a strong NAO influence on streamflow during the 1960s and a stabilization of the response in recent years. The basins having this variability mode included the right bank Duero tributaries, the Tajo main course, much of the upper Ebro basin and the Segre river and its tributaries (Ebro basin). The third Principal Component accounts for 16.7% of the explained variance. It present a low response of the streamflows to the NAO during the 1950s and the 1960s, a enhanced response during the 1970s and a weakening of the influence to present. The sub-basins fitting this pattern are the headwaters of the Duero, Ebro and Tajo river, the Guadiana main course and the Guadalquivir lower reaches. These results show that in general the streamflow response to the NAO was highly variable in time, and that non-stationarity was the general pattern between 1945 and 2005."

5. Discussion Page 4474, section 5.2 Spatial and temporal variability This whole section must be reworked, as the authors did not provide an adequate description of the spatio-temporal variability of correlations in the Results section. They need to address all the factors which may affect the spatial and temporal variability of streamflow. Factors to consider when dealing with temporal variability

We do not share this criticism since we think that we discussed each of the following points highlighted by the reviewer.

1. Season-to-season variability

We explained the season-to-season variability in terms of water storage strategies and snowmelting processes as follows:

"The water management strategy relies on a large number of dams impounding the majority of basins in the IP, which explains the multi-temporal lagged relationships between NAO, precipitation and stream flows. Water is stored in reservoirs during the rainy period (winter and spring) to meet the water demand during summer, which reduces streamflows downstream of the reservoirs during winter and spring. This explains the close relationship of summer and autumn streamflow to the previous winter NAO, especially in the southern basins with larger impoundment capacities (Tagus, 11,012 hm3; Guadiana, 8635 hm3; and Guadalquivir, 8280 hm3): the majority of those rivers with retention capacity exceeding the mean annual discharge for the study period showed a sustained response to the winter NAO during the rest of the year."

"The strong correlations between the winter NAO index and streamflows during May, June and July in the Pyrenean sub-basins reflect the importance of snow accumulation and melting processes in the Pyrenean rivers (López-Moreno & García-Ruiz, 2004), and the inertia that these processes induce in the runoff yield."

We also discussed the seasonal variability of the extreme flows:

"Significant spatial differences were found between the Atlantic and Mediterranean basins. Winter positive anomalies in the Atlantic watershed were greater than those in the eastern basins adjacent to the Mediterranean Sea, but the intra-catchment variability and streamflow anomalies during extreme NAO phases (both positive and negative) were greater in the Andalusian basins, which is related to their intermittent fluvial regimes, small basin areas and orography. The PCA revealed three different patterns



of seasonality in streamflow anomalies during positive and negative NAO phases, with a clear spatial distribution. The general pattern depicts large streamflow anomalies during both positive and negative NAO phases, that spread throughout the whole year and along the entire IP and may be related to the general westerly circulation. The second pattern shows anomalies restricted mainly to winter months, when the NAO is more active, and solely during negative NAO phases. This pattern is observed for all river basins of the Atlantic watershed and reveals the importance of the shadow effect produced by the mountainous chains which divides the IP into the Atlantic and the Mediterranean watershed, blocking the advance of the humid flows coming from the Atlantic. The third pattern does not show a clear seasonality in the distribution of anomalies but it presents a well-defined spatial distribution, which may be related to northern flows coming from the Gulf of Biscay. These could be associated to the positive phases of the Western Mediterranean Oscillation as previously stated by Martín-Vide & López Bustins (2006).

We also discussed the persistence of the winter NAO influence:

"The water management strategy relies on a large number of dams impounding the majority of basins in the IP, which explains the multi-temporal lagged relationships between NAO, precipitation and stream flows. Water is stored in reservoirs during the rainy period (winter and spring) to meet the water demand during summer, which reduces streamflows downstream of the reservoirs during winter and spring. This explains the close relationship of summer and autumn streamflow to the previous winter NAO, especially in the southern basins with larger impoundment capacities (Tagus, 11,012 hm3; Guadiana, 8635 hm3; and Guadalquivir, 8280 hm3): the majority of those rivers with retention capacity exceeding the mean annual discharge for the study period showed a sustained response to the winter NAO during the rest of the year."

2. Month-to-month variability during a given season

We think that explaining the month to month variability for each season would increase significantly the length of the discussion without providing relevant information for readers. Thus, we prefer to do not enter in such degree of detail, in benefit of the presentation of the most important findings at the seasonal level.

3. The North-South contrast observed in March and October

We already discussed this point:

"We found an abrupt temporal transition from winter to spring and from summer to autumn in the NAO–streamflow relationship between the non-lagged and the one-month lagged correlations, which can be explained in terms of water management and atmospheric phenomena. This was exemplified during April and early autumn. During winter and spring, management practices are focused mainly on storing water; this results in decreased water releases, and hence decreased river discharges downstream of dams (López-Moreno, 2007). The relationship between the NAO and streamflow in April was non-significant for the non-lagged correlation, while for the one-month lagged correlation the relationship was significant in catchments located to the northwest. This difference was probably caused by seasonal weakening of the NAO as a result of a change in the position of the pressure centers (Kingston et al., 2006a), but also as a consequence of water management strategies focused on storing water resources in dams. The inverse was true for the transition from summer to autumn. During October the relative movement of the pressure centers associated with the NAO (Kingston et al., 2006a) generates inflow from the Atlantic, initially in the northwest (Duero basin) during October. Subsequently, a southward displacement of the influence occurs, covering the southwest during November (Trigo et al., 2008) and reaching its maximum influence and spatial extent during winter."

4. The change in the sign of correlations during spring-summer

This point is also discussed in the revised manuscript:

"The positive correlations between streamflow and the summer NAO, which were



mainly significant during July, are in agreement with the recent findings of Bladé et al. (2010), who found significant positive correlations between precipitation and the NAO during July and August in the central sector of the IP. This relationship apparently occurs because the positive phase of the summer NAO is related to cool, wet and cloudy conditions in southern Europe and the Mediterranean region (Folland et al., 2008)"

5. Interannual changes in correlation (before and after 1970)

We also discussed this point:

"The non-stationarity analysis highlighted three main patterns in the evolution of the NAO impact on streamflows over the last years. The first involved an increase in the impact of the NAO on streamflows since the 1980s in most parts of the IP, although it is more pronounced in the northwestern sector. These findings are similar to those of Vicente-Serrano and López-Moreno (2008), who reported an increase in the magnitude of negative correlations between the NAO and precipitation in southern Europe, which was closely related to shifts in the location of the Atlantic pressure centers. The second pattern involved a decrease in the correlations between the NAO and streamflows in the right bank Duero tributaries, the Tajo main course, much of the upper Ebro basin and the Segre river and its tributaries (Ebro basin). These basins have been subject to increased regulation/impoundment capacity, aimed at reducing the impacts of lack of precipitation and meet the demand for irrigating purposes. This increased capacity may explain the decreased sensitivity of streamflow to the NAO variability during extreme phases. The decrease in the sensitiveness to the NAO of the basins correlated with the Third Principal Component reported since the 1980s may be also related to the increased regulatory capacity in the river courses since the eighties. However, as-yet unresolved uncertainties remain in relation to this recently completed preliminary analysis, suggesting the need for more detailed investigations."

Factors to consider when dealing with spatial variability 1. West-East contrast (Continental effects?)

We mentioned the observed continental effects which generates a West to East pattern in the correlations:

"This phenomenon is enhanced during autumn, when the NAO is less active, with a topographic shadow effect causing the depletion of humidity in air masses crossing the barrier, and a consequent decrease in the correlation values between the two watersheds."

2. North-South contrast (Latitude effects?)

We explained the North-South contrast in terms of movement of the Atlantic pressure centers (which encompasses latitudinal effects) and water management strategies:

"We found an abrupt temporal transition from winter to spring and from summer to autumn in the NAO–streamflow relationship between the non-lagged and the one-month lagged correlations, which can be explained in terms of water management and atmospheric phenomena. This was exemplified during April and early autumn. During winter and spring, management practices are focused mainly on storing water; this results in decreased water releases, and hence decreased river discharges downstream of dams (López-Moreno, 2007). The relationship between the NAO and streamflow in April was non-significant for the non-lagged correlation, while for the one-month lagged correlation the relationship was significant in catchments located to the northwest. This difference was probably caused by seasonal weakening of the NAO as a result of a change in the position of the pressure centers (Kingston et al., 2006a), but also as a consequence of water management strategies focused on storing water resources in dams. The inverse was true for the transition from summer to autumn. During October the relative movement of the pressure centers associated with the NAO (Kingston et al., 2006a) generates inflow from the Atlantic, initially in the northwest (Duero basin) during October. Subsequently, a southward displacement of the influence occurs, covering the southwest during November (Trigo et al., 2008) and reaching its maximum



influence and spatial extent during winter."

3. Any orographic effect

The orographic effects are discussed in the revised manuscript:

"The spatial extent of the NAO influence on streamflow during winter and late autumn is largely determined by orography. The advance into the IP of southwesterly air masses associated with the NAO is facilitated by the gradual altitudinal increase and the smooth slopes of the lower Tagus, Guadiana and Guadalquivir valleys (Esteban et al., 2003). Although air masses progressively lose their humidity as they cross the IP, they are forced up by the topographic barrier to the east (the Cantabrian Range, the Iberian Ranges and the Betic systems), which separates the Atlantic and Mediterranean watersheds. Thus, the leeward sides of the mountain chains are less influenced by the NAO than the western part of the IP (Esteban-Parra et al., 1998; Muñoz-Díaz, 2003). This phenomenon is enhanced during autumn, when the NAO is less active, with a topographic shadow effect causing the depletion of humidity in air masses crossing the barrier, and a consequent decrease in the correlation values between the two watersheds."

"Orography may also explain why there was a significant correlation between the NAO and streamflow in the Pyrenean sub-basins during October and December, while in the other Mediterranean watersheds the correlations were not significant. Because of their north–south orientation the Pyrenean valleys act as humid corridors for the advance of air masses from the south. The mountainous topography induces their reactivation and generates orographic precipitation (Esteban et al., 2003)."

The conclusion section must be reworked to include a discussion of the foregoing

The conclusion section remains the same, since the changes made in the discussion do not alter the meaning and structure of the conclusions.

III. Technical corrections Page 4460, Line 20 Add “spatio-temporal” before “variability”

("the spatio-temporal variability")

"spatio-temporal" have been added before "variability" in the revised manuscript.

Page 4468, line 16 Replace "lineal" with "linear".

"lineal" was replaced by "linear".

1) Figure 3: The title of the map for the month of March is incorrect. Change "March NAO – March streamflow" to "March NAO – April streamflow".

The title of the map was changed.

Page 4486, Table 1 To be consistent with season definitions, the table must start with December and end with November.

In this case the table remains the same since we used the same order than the cartography to avoid incongruities.

Page 4492, Fig.6 Y-axes must be labelled (legend).

We labeled the Y-axis in the revised manuscript.

Page 4493, Fig.7 1) Y-axes must be labelled (legend) and years must appear below the figures. We labeled the Y-axis and the date labels appear below the figure in the revised manuscript.

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 8, 4459, 2011.