

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

J. Lorenzo-Lacruz et al.

jlorenzo@ipe.csic.es

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The authors want to express their 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.

-With respect to the methods, more details are needed to describe PCA in section 3.3.3. For instance, which procedure is used to perform PCA, S or T? It is also advisable to indicate the time resolution of the streamflow time series. The PCA results are not discussed and I think that this part is not required to understand the paper.

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However, the use of PCA for the lagged correlation coefficients is justified in the paper.

A paragraph explaining the procedure to perform the PCA (S mode) was already included in the methodology section of the discussion paper. Anyway, we believe that it was not well expressed in the text and we made a little change in order to clarify it:

"The S mode identifies regions in which the temporal variation of the hydrological variables has the same pattern. The S mode has been therefore used to identify general temporal patterns in the streamflow series (the observatories are the variables, and the time observations are the cases)."

We clarified in the revised manuscript the time resolution of the streamflow time series when performing the PCA:

"Because of the regional scale of the study we used a principal component analysis (PCA) to summarize the spatio-temporal variability of the streamflow anomalies detected during the positive and negative NAO phases at the monthly scale. To provide an estimate of where the NAO influence had remained stable and where it had changed, the same procedure was conducted with the 187 moving-window correlation series between the NAO and streamflows at the annual scale."

The PCA results are commented in section 4.4 (anomalies analysis) and 4.5 (non-stationarity analysis):

"The PCA (Fig. 6) revealed three components in the spatio-temporal variability of streamflow anomalies during the extreme NAO phases. The first principal component explained almost 40% of the total variance, and showed the most general spatiotemporal pattern of streamflow anomalies. It was characterized by positive streamflow anomalies during negative NAO phases (and vice versa) in all months of the year, although the anomalies were enhanced during late spring and summer. The spatial extent of this pattern included the entire IP, although it was more related to the main river courses. The second principal component explained 29% of the variance, and

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indicated large positive streamflow anomalies in winter and slight negative anomalies in summer during 5 negative NAO phases. The influence of the negative NAO phases was very low, with a clear non-linear behavior in the response of streamflow to the NAO. This component mainly represented the Atlantic watershed. The third principal component explained only 6.4% of the variance and it did not show a clear pattern related to the SSI anomalies in response to the positive and negative NAO phases. Nevertheless, this pattern was representative of some northeastern areas of the IP, where the correlation between the NAO and streamflow was quite low."

"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 presents a low response of the streamflows to the NAO during the 1950s and the 1960s, an 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 rivers, the Guadiana main

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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."

The PCA results of the non-stationarity analysis are discussed in section 5:

"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. However, as-yet unresolved uncertainties remain in relation to this recently completed preliminary analysis, suggesting the need for more detailed investigations."

We also have added the next paragraph in section 5 to discuss the PCA results related to the anomalies analysis:

"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

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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)."

-Figure 3 shows the one-month lagged Pearson's correlations between the SSI for a particular month and the NAO index for the previous month. Can the authors explain why the NAO drives streamflow in winter and not in spring? (line 289 - and following)?

We explained this phenomenon in terms of the water storage dynamics and the movement of the Atlantic pressure centers in the discussion section as follows:

"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

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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."

-Table 1 shows the percentage of gauging stations that registered significant differences between the average SSI anomalies generated during positive and negative NAO phases. The authors said that "It is noteworthy the high percentages (> 70%) of gauges in the large Atlantic basins (Duero, Tajo, Guadiana and Guadalquivir) with significant differences during winter and early spring..". However, the table shows that the differences are much lower in December than in January and February. Is there any explanation for that?

The explanation for the "low response" in December relies basically in methodological aspects, specifically in the way of calculation of the winter NAO index. The index was calculated averaging the NAO indices from December to March and it obviously does not fully represent the streamflows of December. The use of an averaged winter index is a standard procedure and its used here is justified as our scope was not to obtain a correlation value between monthly NAO index and monthly streamflows, but to observe how the global response of streamflows is during winter and also in the following months depending on NAO conditions.

-More interpretations are needed for the results of PCA in line 352. Figures 6 show the three PCs for positive and negative phases of the NAO - I wonder if this analysis is performed independently for the positive and negative phases. In this case, is the explained variance equal for the positive and negative phases? I am sorry for not understanding the objective of this part of this study.

We agree with that suggestion and we think that the interpretation of that results in

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the original manuscript was not enough complete. For this reason we have extended it. The analysis is performed taking into account the anomalies registered during positive and negative phases together. The explained variance accounts for the variability of both negative and positive anomalies. The objective of this analysis was to discern between anomalies produced during different months of the year and in different basins/watersheds of the study area, as a complement to figure 5.

-March is a month that shows a very significant decreasing trend for precipitation, and I wonder whether the authors have found this trend in the SSI time series and if it was removed before performing the analysis (page 372).

We appreciate the reviewer's comment, although we were aware about that problem. In fact, the analysis was performed after the de-trending of the series to avoid autocorrelation. We have included a new paragraph in the methodology section of the revised manuscript to explain it:

"To assess the impact of the NAO on surface water resources in the IP, monthly Pearson correlations between the NAO and the SSI were calculated for each gauging station. Prior to correlating the SSI series and the NAO index, we linearly de-trended the time series to take into account the autocorrelation. This approach minimized the influence of time series trend and multi-year to decadal signal variability on the strength and significance of the computed correlation and the deduced NAO predictability."

Anyway, due to a similar concern expressed by other referee, we decide to slightly change the analysis presented in this section. Instead of using the March NAO index in order to assess the non-stationarity of the NAO influence on the streamflows, we performed the same moving-window correlation analysis, this time by relating the winter NAO index (in order to summarize the NAO impact during its most active season) with the March SSI time series.

-PCA is applied to the correlation coefficient derived from different time series realizations between NAO and SSI. One can see in Figure 7 strong changes in the correlation

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coefficients with time. Is there an explanation for this? Are the correlation coefficients significant? I think it could be interesting to obtain correlation coefficients by using other NAO indices to demonstrate the significance of the non-stationarity of the NAO and SSI relationships.

The aim of this analysis was only to roughly illustrate the changes experienced in the relationship between the NAO and the streamflows. The first PC show a more climate-driven pattern, mainly associated with northern basins and related to the own NAO evolution. The decreasing dependence of the second and third PCs on the NAO could be related to the hyper-annual regulatory strategies practiced in the majority of the basins highly correlated with these components. Nonetheless, we stressed in the discussion section that further research is needed; here we only made a first approximation to this subject. The use of other NAO indices and the demonstration of the significance of the non-stationarity of the NAO-SSI relationships are beyond the objectives of this analysis, although present a great interest for future studies. Nevertheless several studies have recorded, using different NAO indices in its analysis, a non-stationary behavior of the NAO, which was also corroborated by us here.

-The authors present interesting results about the NAO SSI relationships for different months. However, the results of the PCA study when applied to streamflow anomalies need more interpretation or should be removed from the paper because they do not provide additional information for this work.

We added the next paragraph in the revised manuscript:

"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 nega-

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tive 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)."

Technical corrections In Line 212 1992 for NAO+ appears twice

The duplicity was corrected in the revised manuscript.

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