Differences in the non-stationary influence of the North Atlantic Oscillation on European precipitation under different scenarios of greenhouse gas concentrations

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1. Introduction

The North Atlantic Oscillation (NAO) is the leading mode of atmospheric circulation in the North Atlantic region [Hurrell et al., 2003], and is characterized by two pressure anomaly centers located near the Azores and Iceland. The NAO shows high interannual variability, and trends during some periods have also been observed [Hurrell, 1995]. Moreover, climate change simulations indicate changes in the NAO under different forcing conditions [e.g., Pinto et al., 2007]. This behavior could have marked implications for water resource availability in the future, mainly in southern Europe. Nevertheless, large uncertainties remain about the possible effects of the NAO with enhanced greenhouse gas concentrations. Stephenson et al. [2006] indicated that precipitation predicted under increasing 21st century greenhouse conditions would show changes of a higher magnitude than expected due to a more positive NAO index. These authors indicated that NAO trends do not seem to be a key contributor to climate model-predicted change in precipitation over Europe. It has also been shown recently that the NAO influence on European precipitation is non-stationary [Beranova and Huth, 2008], and differences in the NAO-precipitation relationship have been found for different periods as a consequence of the shifting behavior of the NAO pressure centers [Vicente-Serrano and López-Moreno, 2008].

2. Methodology

2.1. Database

The simulations of sea level pressure (SLP) for the North Atlantic region (20°–80°N, 90°W–40°E) and precipitation for Europe from the AOGCM CGCM 3.1 (T63) model (single run) provided by the Canadian Centre for Climate Modelling and Analysis (CCma, http://www.ccma.bc.ec.gc.ca/) were used [Flato et al., 2000] at a spatial resolution of 2.5° and monthly temporal resolution. We used four output scenarios: the IPCC pre-industrial (PI) and the 20th century experiment (20C) emission scenarios, which cover the period 1870–1999, and the B1 and A2 emission scenarios for the 2000–2099 period. Data were obtained from the Coupled Model Intercomparison Project (CMIP3) database at https://esg.llnl.gov:8443/index.jsp.

2.2. NAO Index Calculation

We obtained a NAO index from the SLP simulated outputs. The NAO is mainly active during the boreal winter, when it affects the climate over large areas of Europe [Wanner et al., 2001]. Therefore, in the present study we used winter data (December to March) to analyze the changing influence of the NAO on European winter precipitation.

Here we followed the approach of Jones et al. [1997] to calculate a NAO index as the normalized difference between the SLPs between the stations of Gibraltar (SW
Spain) and Reykjavík (Iceland). The closest grid points to Iceland (62.78°N, 22.5°W) and Gibraltar (37.67°N, 5.62°W) were used to calculate the NAO index in the four climate scenarios.

2.3. NAO-Precipitation Correlations

[7] To analyze the non-stationary response of European precipitation to the NAO, we calculated moving window correlations between the NAO and winter precipitation using Pearson’s correlation coefficient (r). A confidence level of $p < 0.05$ was chosen as indicative of significant correlations. The first calculation involved the window represented by the initial 31 years in the four model simulations (1870–1900 for the PI and 20C scenarios, and 2000–2030 for B1 and A2 scenarios). The result (r) was assigned to the central year of this interval (1885 and 2015, respectively). The second calculation was based on the window represented by the years 1871–1901 (PI and 20C scenarios) and 2001–2031 (B1 and A2 scenarios). This process was repeated up to the last year of simulation.

2.4. NAO Spatial Configurations

[8] To identify the spatial patterns of the NAO configuration and shifts over time in the positions and intensities of the surface pressure centers associated with the NAO dipole, we applied a moving window T-mode Principal Component Analysis (PCA) [Vicente-Serrano and López-Moreno, 2008]. We used the same 31-year periods used to calculate the NAO-precipitation moving window correlations. Independent moving window T-mode PCA analyses were applied to the data from the four scenario simulations. A correlation matrix was selected to provide an effective representation of variance within the dataset in the PCA. As the grids span from 20~80°N, different grid surface areas were adjusted by a weighting coefficient of the cosine of latitude.

[9] The analysis procedure was very similar to that used for the moving window correlations between the winter NAO and precipitation series. In this case, the first T-mode PCA from the SLP anomaly series was performed using data for the intervals 1870–1900 for the PI and 20C scenarios, and 2000–2030 for the B1 and A2 scenarios. T-mode PCA enabled the leading mode of variability in atmospheric circulation to be obtained, which was then assigned to the years 1885 and 2015, respectively, for the scenario pairs noted above. The analysis was continued using the moving window procedure and the displayed spatial pattern of the leading mode was always identified as the NAO pattern.

3. Results

[10] Figure 1 shows the evolution of the NAO index obtained for the 20th century under the 20C emission scenario, and for the 21st century for the B1 and A2 scenarios. There were no major differences in the NAO intensity between the 20th and 21st centuries, and no significant trends for the 21st century, and no significant differences between the A2 and B1 scenarios were found (one-way ANOVA analysis).

[11] Figure 2 shows the spatial distribution of Pearson’s correlation coefficients between the NAO indices and the winter precipitation, and the leading SLP pattern obtained from T-mode PCA for the whole period of the four emission scenarios. The pattern of NAO-precipitation correlations was very similar in the four simulations: positive correlations in northern Europe and negative correlations in southern Europe, in agreement to observations [Wanner et al., 2001]. However, some spatial differences were identified between the four emission scenarios. Under PI concentrations, positive and significant correlations were identified in large areas of northern Germany, Denmark, the British Isles and Scandinavia. Relative to the PI scenario, the surface area with positive and significant correlations was reduced under the 20C, B1 and A2 scenarios in northern Europe. Under enhanced greenhouse gas concentrations (A2 scenario), positive and significant correlation areas were noticeably reduced in Scandinavia. In southern Europe there were fewer changes among the four emission scenarios. Nevertheless, under increased greenhouse gas concentrations there was a reinforcement of the surface extent and magnitude of the significant correlations in the Iberian Peninsula and Italy, with very few differences between the B1 and A2 scenarios.

[12] The spatial pattern of the NAO was evident in the CGCM 3.1 (T63) model, and the few differences found among the four emission scenarios may be related to
differences in the patterns of the pressure centers that defines the NAO under the different scenarios. The PI and 20C NAO patterns show similar spatial configurations, with the north pressure centre (NPC) located over southern Iceland and extending to Scandinavia. This explains that the differences between the NAO-precipitation correlations under these emission scenarios are small. The spatial pattern of the NAO dipole changes under the B1 scenario since the NPC is displaced to the west, explaining the decrease in the magnitude of the NAO-precipitation correlation in central Europe and Scandinavia. In contrast, the South Pressure Centre (SPC) is displaced to the north in comparison to PI and 20C emission scenarios. This is in agreement with the higher magnitude of the NAO-precipitation correlation and spatial extent of significant correlations in the Iberian Peninsula, Italy and the Balkans. Under the A2 emission scenario the NPC was displaced more to the south relative to the B1 scenario since the NPC is displaced to the west, explaining the decrease in the magnitude of the NAO-precipitation correlation in central Europe and Scandinavia. In contrast, the SPC was clearly displaced to the north-west relative to the other emission scenarios.

Analysis of moving window correlations showed marked differences among the four emission scenarios (Figure 3). In the PI and 20C scenarios the spatial pattern of NAO-precipitation correlations changed noticeably. In the PI scenario correlations in southern Europe were very different among the 31-year periods analyzed. In general, periods with high and low correlations agreed with the observed pattern in the 20C emission scenario. The highest magnitude and surface extent of significant correlations was found in the 1900 slice, and the lowest correlations and surface extent was found between 1940 and 1960. Spatial variability was also high in northern Europe. For the PI scenario, positive and significant correlations extended to southern Germany in some periods (the 1940 slice), in agreement with the southern displacement of the SPC and NPC. The highest correlations recorded in northern Europe coincided with displacement of the NPC to Scandinavia (e.g. the 1920 and 1980 slices). This pattern was also observed under the 20C emission scenario. For example, the low precipitation correlations in southern Europe in the 1920, 1940 and 1960 slices coincided with displacement of the SPC to the eastern Mediterranean area. In contrast, the increased correlations in the 1980 slice in the Iberian Peninsula is related to displacement of the SPC to the west. The changes in the NAO-precipitation correlations in northern Europe were also in agreement with the displacement of the NPC.

The 31-year slices for the B1 and A2 emission scenarios also show some changes in the NAO-precipitation correlations among the different periods, and also some shifts in the spatial pattern of the NAO dipole. Although different, the spatial pattern and magnitude of correlations, both in southern and northern Europe, were more stable than observed for the PI and 20C scenarios. Nevertheless, the stability of the spatial pattern and magnitude of correlations between NAO index and precipitation between the 31-yr periods was higher for southern European areas than for northern Europe. Among the four scenarios, the A2 scenario had the most stable NAO pattern. There were few differences in the position and magnitude of the NAO pressure centers among different periods, which is in agreement with the small differences in the NAO-precipitation correlation pattern among the different 31-year periods. In the B1 scenario there was also lower spatial differences between the 31-yr periods in the NAO-precipitation correlation with respect to the PI and 20C emission scenarios.

It seems to have some relationship between the percentage of variance explained by the NAO and the magnitude and surface extent of correlations. In general, a smaller variance explained by the leading PC (NAO) transfers to some extent into generally weaker relationship with precipitation and vice versa. This is shown in the 1920 and 1940 slices of the PI scenario and the 1960 slice of the 20C scenario, in which the leading PC explained less than 30% of the SLP variance and it coincides with a decrease of the

Figure 2. (right) Spatial distribution of correlations between winter precipitation and the NAO index for the complete periods of the four emission scenarios. Dotted lines enclose areas with significant correlations ($p < 0.05$). (left) Leading principal component of winter SLPs obtained from T-mode PCA over the same periods. Units are PC scores. The percentage of variance explained by the leading component is also shown.
Figure 3. As in Figure 2, but for the Preindustrial, 20C, B1 and A2 emission scenarios and the 31-year periods. The year indicated on each map represents the midpoint of each period.
spatial extent of significant correlations between NAO and precipitation.

[16] Figure 4 shows the spatial distribution of variance values from the 31-year moving window NAO-precipitation correlation series. Higher variance values indicate a higher variability of the NAO-precipitation correlations throughout the emission scenario simulation. There were large differences among the four scenarios. Higher variance values were found for the PI and 20C emission scenarios. Central European areas had the largest variance values in these scenarios. There was a decrease in variability in the NAO-precipitation relationship in line with increased greenhouse gas concentrations, because under the B1 scenario and the A2 scenario in particular, the variance was noticeably reduced in central Europe. Moreover, in areas such as the Iberian Peninsula and the British Isles, changes in the non-stationary NAO influence on precipitation are not expected independently of the greenhouse gas emissions scenario.

4. Conclusions

[17] In this study we analyzed the influence of NAO on European precipitation under four different greenhouse gas emission scenarios. No major changes in the NAO index values were found between the B1 and A2 scenarios, and no noticeable differences to the NAO index under the 20C emission scenario were indicated. Some studies have suggested a higher frequency of positive phases in the NAO under increased greenhouse gas concentrations [e.g., Terray et al., 2004], but there is no general agreement about this as other studies did not show this trend [e.g., Dorn et al., 2003], and high uncertainty is generally assumed in pre-
dictions of change in the sign of the NAO under different emission scenarios [e.g., Osborn, 2004].

[18] More important than expected changes in the future evolution of the NAO are shifts in the spatial pattern of NAO-precipitation correlations. The scenarios showed a general decrease in the surface affected with significant positive correlations in northern Europe and an increase in the magnitude of negative correlations in southern Europe, in parallel to increased greenhouse gas concentrations. The differences are in agreement with shifts in the location of the NAO pressure centers. Even more important than the changes in the spatial patterns are the changes expected in the temporal stability of the NAO-precipitation relationship among the four emission scenarios. The PI and 20C scenarios showed large differences in the magnitude and spatial extent of the NAO-precipitation correlations among different periods, as a consequence of shifts in the position of the NAO pressure centers. This conclusion is not the result of this particular model artifact, since the results are in agreement with observations over the 19th and 20th centuries [Vicente-Serrano and López-Moreno, 2008]. Nevertheless, although the magnitude of the NAO-precipitation correlations in the B1 and A2 scenarios were lower in northern Europe and higher in southern Europe relative to the PI and 20C scenarios, the temporal variability was much lower, with high stability in the NAO-precipitation relationship throughout the analysis period. In addition, the NAO pressure centers appear to be more stable under increased greenhouse gas concentrations. This is consistent with the findings of Raible et al. [2006], who showed a more stable teleconnectivity in Europe using two different emission scenario simulations under increased greenhouse gas concentrations.

[19] Here we have used a single run of the GCM. Commonly ensembles of simulations from a given GCM are not available; although the availability of this data would be very helpful to illustrate the within-ensemble variability of results and to distinguish sampling variability from a climate-change signal. In any case, our results indicate that increasing greenhouse gas emissions may lead to a more stable influence of the NAO on European precipitation under similar NAO index values, implying a reduction in uncertainty related to climate prediction and downscaling processes.

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References

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