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NAO and solar radiation variability in the European North Atlantic region

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[1] We explore the relationship between the NAO and the solar radiation spatio-temporal variability in the European North Atlantic area during winter. Measured monthly sums of sunshine duration and short-wave downward solar flux reanalysis data have been used. Correlation analysis between the NAO index and the measured sunshine duration shows a dipolar pattern, with maximum positive values (+0.75) over the Iberian Peninsula, and maximum negative values (−0.71) over Norway. Reanalysis results confirm these findings. Composite analysis shows, for northern Europe, negative anomalies (−10% to −20%) associated with NAO > 1 and positive anomalies (10% to 20%) associated with NAO < −1; while for southern Europe anomalies are, respectively, 10% to 20% and −10% to −20%. A stronger influence is found during the NAO negative phase; particularly, the northern British Isles, Norway and the Iberian Peninsula present a significant non-linear response, with higher anomalies (10% to 20%) during this negative phase. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3359 Meteorology and Atmospheric Dynamics: Radiative processes. **Citation:** Pozo-Vázquez, D., J. Tovar-Pescador, S. R. Gámiz-Fortis, M. J. Esteban-Parra, and Y. Castro-Díez (2004), NAO and solar radiation variability in the European North Atlantic region, *Geophys. Res. Lett.*, *31*, L05201, doi:10.1029/2003GL018502.

1. Introduction

[2] The solar radiation measured at ground level can show low frequency temporal variability due to changes in solar input, atmospheric components such as aerosols and, particularly, cloudiness. Although there exist a complex relationship between solar radiation and clouds, the influence of the cloud cover variability on the low frequency solar radiation variability is likely, the most important. Several studies have established that the North Atlantic Oscillation (NAO) controls the storm track along the North Atlantic area [*Ulbrich and Christoph*, 1999; *Osborn et al.*, 1999]. Particularly during the negative phase of the NAO, a more southerly track is found, bringing more clouds to the southern part of Europe. On the other hand, during the positive phase a reduction of the cloud cover takes place in this area and there is an increase over central and northern Europe. The magnitude of the NAO influence on the cloud cover during the winter months and for the North Atlantic area was recently explored by [*Trigo et al.*, 2002].

[3] Given this well documented NAO-cloud-cover relationship, the existence of an influence of the NAO on the solar radiation measured at ground level would be obvious. But which is open to debate and is not so well documented is the magnitude of this influence. The aim of the present study is to explore the role of the NAO on the solar radiation (measured at ground level) spatial and temporal variability during the winter months and over the North Atlantic European area. Particularly, we try to quantify the magnitude of solar radiation changes related to the NAO. We analyze both measured monthly sums of sunshine duration (MSD hereinafter) and solar radiation reanalysis data. Furthermore, by making use of this two different solar radiation data sets a by-product of this work is to assess the ability of the NCEP/NCAR reanalysis to correctly capture the spatial structure of significant impacts of the NAO on the solar radiation fields of Europe.

[4] We first carried out a correlation analysis to explore the linear NAO-Solar-Radiation relationship. In a second part, we study by means of composite analysis the linear and non-linear component of the MSD anomalies response to the NAO phases.

[5] Throughout this paper we determine the significance of both the correlation and composites analysis results by use of 'Monte Carlo' (MC) simulations of the statistical procedures on surrogate data, and subsequently inspect the distribution of the correlation and composite values in the surrogate data. Following the same procedure explained in [*Gámiz-Fortis et al.*, 2002], an Auto-Regressive-Moving-Average (ARMA) model was fit to the monthly (Jan. trough Dec.) NAO index series. Then, using this model, 500 representative series of the NAO index were generated and the DJF values were taken. Finally, the correlations and composites are obtained using the 500 generated NAO index series, while maintaining unaltered both the MSD and downward solar radiation data. The spectral analysis of the winter-months NAO index series shows statistically significant oscillations of period around 2, 4, 6 and 8 years [*Gámiz-Fortis et al.*, 2002]. The use of an ARMA model to generate the surrogate data conserves these spectral properties, and thus ensures that the MC procedure can perform the Null hypothesis (the non existence of a NAO influence on the solar radiation in the North Atlantic area) test on suitable material: data series that are unrelated to the target series but which have the necessary similarity in

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statistical terms. Throughout this study, we report the percentages of trials that achieved a similar or lower correlation (for the correlation analysis) and mean composite value (for the composite analysis), thus enabling estimates of how likely the results are to be a non-random occurrence.

2. Data Description

[6] Data corresponding to the European Solar Radiation Atlas (ESRA) [*Scharmer and Greif*, 2000], have been analyzed. Monthly sums of sunshine duration (MSD), in hours, are available for 691 stations, covering the North Atlantic area, over the period 1981–1990. The sunshine duration is a proxy of the global solar radiation [*Iqbal*, 1983]. Based on these data, we have obtained a monthly 5° by 5° gridded dataset. Firstly, monthly anomalies were obtained for each station by subtracting the monthly 1981–1990 mean. Each grid value is obtained by averaging the values corresponding to the stations included in the grid. No weighting has been used. For all the grids, two or more stations are available. The use of gridded data has the advantage that the local effects on the spatial variability, which are not desirable in this mesoscale study, are partially removed. Monthly diagnostic surface downward solar flux from NCEP-NCAR CDAS-1 Reanalysis (MSR hereinafter), covering the period 1949–2002, has also been analyzed. The reanalysis data were derived through a consistent assimilation and forecast procedure that incorporated all available weather and satellite information [*Kalnay et al.*, 1996]. The data cover the North Atlantic area, having a resolution of 1.875° in longitude and 1.9° in latitude. December through February monthly values were analyzed both for the MSD and the MSR data. Finally, a monthly NAO index [*Hurrell*, 1995] was used to monitor the NAO.

3. Analysis and Discussion

3.1. NAO-Solar Radiation Correlation Analysis

[7] Figure 1 shows the sample correlation coefficients between the NAO index and the MSD field. A dipolar pattern can be observed: While most part of southern Europe presents positive correlations, most part of northern Europe presents negative values. The highest positive values (0.6 to 0.8) are located over the Iberian Peninsula (IP hereinafter) and north-western Africa; the maximum value (+0.75) corresponds to the central IP grid. Highest negative correlation (−0.6 to −0.8) are located over the northern British Isles, Norway and Denmark; maximum value (−0.71) correspond to Norway. Latitudes between 45° and 50°N present low correlation values. The area around Baltic sea and the central and eastern Mediterranean area also shows high correlation values, significant at 95% level.

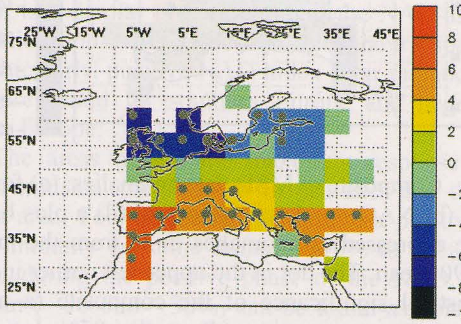

Figure 1. Monthly correlation (by ten) between the NAO index and the MSD data. The dot in the upper-left corner indicates local statistical significance at the 95% level. The meaning of this significance level is that, over the corresponding grid, the percentage of Monte Carlo trials performed on surrogate series that achieved smaller correlation is, at least, 95%.

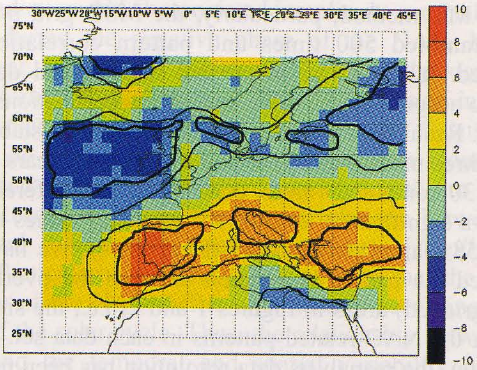

Figure 2. Monthly correlation (by ten) between the NAO index and the MSR data. The thin contours indicate areas of local statistical significance at 95% level and thick contours at 99% level; the significance levels meaning is the same as that of Figure 1.

[8] We have computed the field significance of the pattern in Figure 1. Using the 500 generated NAO index series, we have computed the number of grids in the MSD data base (among the 45 available) which locally have a significant correlation at the 95% at one time. In Figure 1, 26 of the 45 grids have a correlation significant at the 95% level. Results of the MC field significance experiments shows that only in 9 of the 500 experiments 26 or more of the grids showed a locally statistically significance at the 95 level. This means that the pattern showed in Figure 1 pass the MC field significance test at the 98.2% level.

[9] Correlation between the NAO index and MSR data have been also obtained, Figure 2 shows the results. As in Figure 1, positive values are found over the whole Mediterranean area while northern Europe presents negative values. The highest positive value (0.8) is found over the south-western part of the IP, while the highest negative values (up to −0.6) are found over the north of the British Islands. Note the low values of correlation, close to zero, found over the north of France and Germany. Overall, correlation values are similar to that shown in Figure 1, particularly over the Mediterranean area; for northern Europe amplitude are slightly lower.

[10] As a measure of the similarity between the data set, the pattern correlation, as defined by *von Storch and Navarra* [1995], has been computed between the MSD and the MSR data. To this end, the MSR data resolution has been reduced to match that of the MSD data. The pattern correlations have been computed only along the period 1981–90 and over the land area where MSD data are available. The significance of the results has been computed

using a MC method; particularly, the MSD grid positions was scrambled 500 times and pattern correlation was computed. It should be noted that this method does not take into account the possible spatial autocorrelations of the patterns. Results show that correlation pattern is stable both for the three months analyzed and over the ten years period. For the 30 computed values, correlations are different from zero on a significance level of 95%, having values ranging from 0.58 (Jan. 1984) to 0.63 (Dec. 1984). We have also computed the pattern correlation between the overlapping (and regridded) areas in Figures 1 and 2, i.e., the similarity between the NAO-related patterns in each data set. To this end, again, the reanalysis data resolution has been reduced. Significance of the results has been computed by the MC method: The MSD gridpoints in Figure 1 were scrambled 500 times and pattern correlation was computed. Results show a value of 0.75, significant at the 99% level. These result, along with the observation of Figure 1 and 2, and paying attention to the different spatial resolution of the data sets and the limited 10 years overlapping period, indicate that the downward solar flux reanalysis data correctly capture the spatial structure of the NAO impact on the solar radiation fields of Europe.

3.2. Composite Analysis

[11] In this section, composite patterns of MSD anomalies are obtained as a function of the state of the NAO. Figure 3a shows the composite for months in which the value of NAO index was NAO > 1 (14 cases) and Figure 3b for NAO < −1 months (10 cases). Additionally, Figure 3c shows the difference of the two maps 3a and 3b, which provides an estimation of the linear component of the MSD anomalies response to the NAO phases change. Finally, Figure 3d shows the summation of the 3a and 3b maps, which estimates the non linear component of this response. During NAO > 1 (Figure 3a), the MSD anomalies have a maximum positive value between 10% and 20% over the IP, northwestern Africa and the eastern Mediterranean region. Statically-significant negative anomalies of value between −10% and −20% are found over northern Britain and the Scandinavian area, reaching values between −20% and −30% over the area of the Baltic countries. During NAO < −1 (Figure 3b), the strongest positive anomalies are found over Norway (30% to 45%), and over the northern British Isles and the southern Scandinavian area (20% to 30%). On the other hand, maximum negative anomalies (−20% to −30%) are found over the IP.

[12] Note that although positive and negative NAO composite MSD anomalies show a similar but opposite sign pattern, anomalies associated with NAO < −1 are higher in absolute value than anomalies associated with NAO > 1 in most part of the study area. The differences between NAO > 1 and NAO < −1 (Figure 3c) show high negative values in the area between latitudes 55° and 65°N. Particularly, maximum negative differences (−45% to −60%) are found over northern Britain, Norway and the Baltic countries area. On the other hand, maximum positive anomalies differences (30% to 45%) are found over the IP. Differences are statistically significant at 95% level almost over the whole studied area. The summation of the NAO > 1 and NAO < −1 composites (Figure 3d) show maximum positive values (10% to 20%) in the north of the British

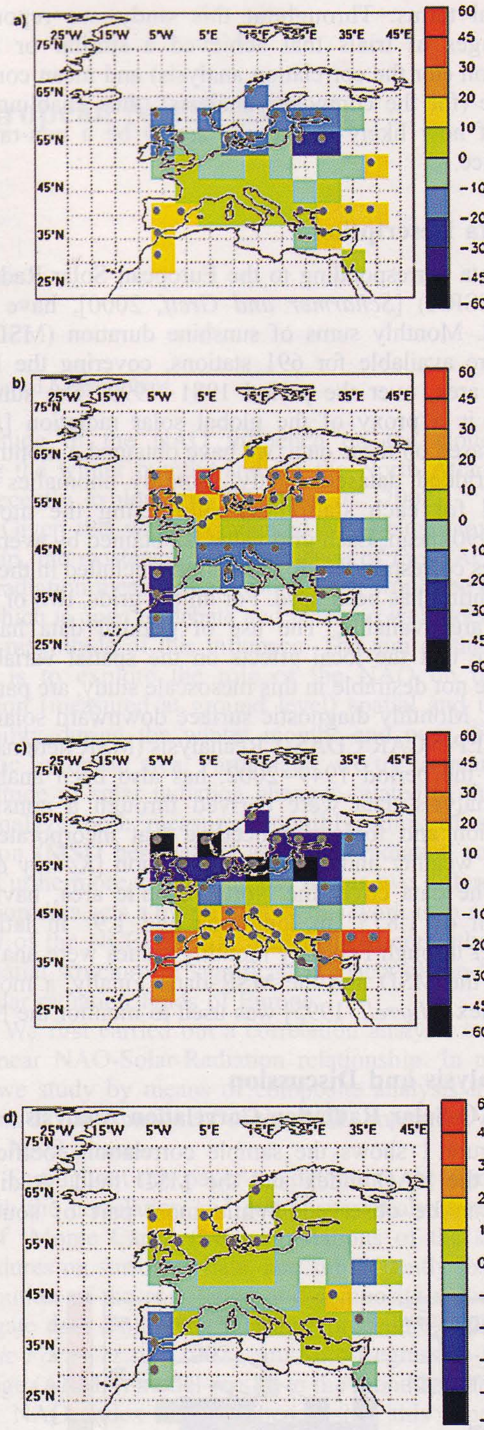

Figure 3. Composite of MSD data anomalies: (a) for NAO index >1, (b) NAO < −1, c) a minus b, (d) a plus b. MSD values are expressed as anomalies in % from the monthly 1981–1990 mean. The dot in the upper-left corner indicates local statistical significance of the composite (a and b), difference (c) or summation (d) at the 95% level. The significance levels meaning is the same as that of Figure 1 but for the composite value instead of the correlation value.

Isles and Norway, while over the IP maximum negative summations (−10% to −20%) are found. Statistical significance is higher than 95% in these three areas, which show the maximum non-linear response, being the amplitude of the response higher for the negative than for the positive phase of the NAO. A similar composite analysis was carried out using the MSR data. Results confirm those find using the MSD data.

[13] In a recent work [*Trigo et al.*, 2002] carried out an analysis of the cloud-cover-anomaly-NAO relationship during the winter. The spatial pattern of the NAO-related cloud variability found by these authors resembles the solar radiation spatial pattern found in this study. Particularly, results showed during positive NAO index winters maximum positive cloud cover anomalies of value +0.25 oktas over the North of the British Isles and the Scandinavian area, and maximum negative anomalies of value −0.2 oktas over southern Europe. The strength of the cloud-cover-NAO relationship is lower than that found for the solar radiation. For instance, the MSD anomaly during positive NAO index over the North of the British Isles is around −15%, while the cloud cover anomaly is around +4% (one okta means 12.5% change from the mean value). This indicates that influence of the cloud-cover on the solar-radiation measured at ground level is, probably, strongly non-linear. An approximately opposite pattern of anomalies was found during the negative phase of the NAO, but, over northern Europe, the negative cloud cover anomalies associated with the negative phase of the NAO were higher (in absolute value) than the positive cloud cover anomalies found during the positive NAO phase. They argued that this asymmetric response is caused by the lack of clouds during typical synoptic situations that characterize the negative phase of the NAO over Northern Europe, namely blocking anticyclones and easterly flow [*Wilby et al.*, 1997]. This strong lack of clouds in the northern British Isles and the Scandinavian area can explain the high positive MSD anomalies found over this area during the negative phase of the NAO (Figure 3b), higher in absolute value than the negative anomalies during the positive phase (Figure 3a), which lead to the nonlinear behavior showed in Figure 3d.

4. Concluding Remarks

[14] A significant influence of the NAO on the winter solar radiation spatial and temporal variability in the European North Atlantic region has been found in this study. The NAO-associated spatial pattern of variability of the solar radiation is a dipolar one, resembling the NAO-associated precipitation and NAO-associated temperature spatial pattern. Particularly, positive NAO index-solar radiation correlations are found for southern Europe and negative for Northern Europe.

[15] The areas having the maximum response are the Iberian Peninsula, the northern British Isles and the Scandinavian area. For the Iberian Peninsula, a positive increment in monthly sunshine duration (10% to 20%) can be expected during the positive phase of the NAO, while a decrement (−20% to −30%) can be found associated with the negative phase. Over the British Isles and the Scandinavian area, changes are similar but of opposite sign. The solar radiation NAO-associated amplitude anomalies are higher during the negative phase of the NAO, but this non-linear response is higher and statistically significant for the former areas. The way the NAO exerts an influence on the solar radiation variability is mainly by means of the control of the storm track, which lead to a cloud-cover spatial and temporal variability associated with the NAO.

[16] Recent works have reported relations between the NAO and solar-activity related parameters [*Thejll et al.*, 2003]. Particularly, *Kodera* [2002] showed that the spatial structure of the NAO differs significantly according to the phase of the solar cycle. Thus, the relationship between the NAO and the temporal and spatial variability of solar radiation measured at ground level could be highly complex, and more research is needed to have a complete description of this relationship.

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