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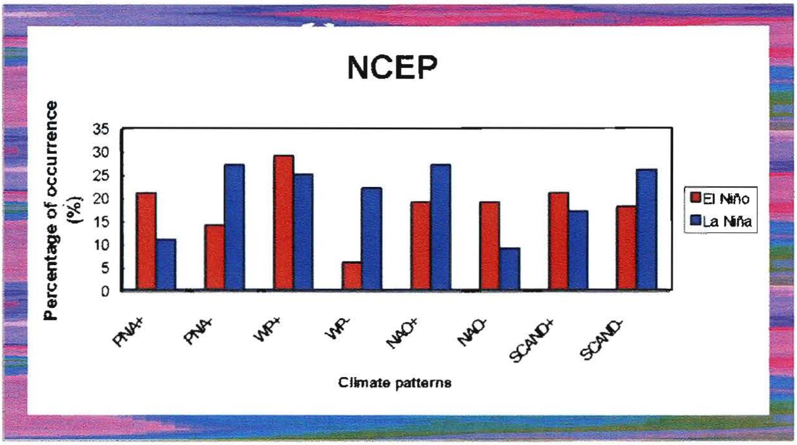
Low-frequency climate patterns and ENSO events for the period 1961-2000



Nota Técnica AEMCC N.º 2

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Low-frequency climate patterns and ENSO events for the period 1961-2000

Nota Técnica 2

Área de Evaluación y Modelización del Cambio Climático
Subdirección General de Climatología y Aplicaciones
Instituto Nacional de Meteorología

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1. Introduction and motivation

The El Niño-Southern Oscillation (ENSO) phenomena is primarily a coupled ocean-atmosphere phenomenon with effects that extend either via standing patterns over the entire tropics or via coherent large-scale low-frequency patterns over the midlatitudes (Cassou and Terray, 2001). Numerous studies have been devoted to documenting and understanding the impact of the ENSO phenomenon on global climate variability since the early 1980's (Trenberth et al., 1998). An important finding made in recent years is that the extratropical climate response to the tropical Pacific sea surface temperature (SST) anomalous forcing is nonlinear (Hoerling et al., 1997, 2001; Hannachi, 2001; Wu and Hsieh, 2003). As an example, observational studies and numerical models have demonstrated that North America wintertime climate has asymmetric response patterns during opposite phases of ENSO (e.g. Shabbar et al., 1997; Hoerling et al., 1997, 2001). In fact, a distinctive characteristic of North America climate response to ENSO is that there is an eastward phase shift of the circulation anomalies between the composites of warm ENSO episodes and the composites of cold episodes, with the two wave trains originating from different tropical sources (Wu and Hsieh, 2003; Hoerling et al., 1997).

There is ongoing evidence about the role of ENSO on the Euro-Atlantic climate, although its impact seems weaker and less robust than the corresponding on the Pacific region (Hurrell et al., 2003; Sutton and Hodson, 2003). Pozo-Vázquez et al. (2001) pointed out that the search of ENSO signals in the North Atlantic area presents many difficulties. Firstly, there are different types of El Niño and La Niña events, with different forcing characteristics that can lead to different responses of the extratropical atmospheric circulation. Second, climatological planetary atmospheric waves, natural noise and the complexity of the numerous feedbacks taking place can hide the signal of ENSO in the extratropics (Trenberth, 1997).

Some studies suggest that the relationship between ENSO Sea Surface Temperatures (SSTs) and North Atlantic climate is both non-stationary (Sutton and Hodson, 2003; Melo-

Gonçalves et al., 2005) and non-linear (Wu and Hsieh, 2004). More specifically, Sutton and Hodson (2003) have found evidence that the influence of the ocean on the interannual variability of North Atlantic climate has been non-stationary over the ninetieth Century. During the period 1910-1960 Atlantic SSTs were the dominant influence, whereas at other times ENSO was relatively more important. Wu and Hsieh (2004) discovered that while the linear impact of ENSO on the Euro-Atlantic winter Sea Level Pressure (SLP) is weak, the Neural Networks (NN) projection reveals statistically significant SLP anomalies over the Euro-Atlantic sector during both extreme cold and warm ENSO episodes. Several authors have argued that the impact on the North Atlantic can be characterized, at least in part, in terms of changes in the North Atlantic Oscillation (NAO) (Fraedrich, 1994; Pozo-Vázquez et al., 2001; Terray and Cassou, 2002). Though there is some discrepancy in the location of the atmospheric winter circulation anomalies, the studies by Pozo-Vázquez et al. (2001) and Cassou and Terray (2001) both found no statistically significant SLP anomaly patterns in the North Atlantic area associated with warm ENSO episodes, but both found a statistically significant SLP anomaly pattern resembling the positive phase of the NAO during cold episodes, suggesting a nonlinear association between Euro-Atlantic climate and ENSO. Moron and Ward (1998) and Moron and Gouirand (2003) mention that the relationships between ENSO and Euro-Atlantic climatic anomalies are weak and appear to have been unstable throughout the 20th Century. Concerning surface meteorological parameters, there is agreement on the existence of an impact of the ENSO phenomenom on the spring and autumn precipitation in the European area (Pozo-Vázquez et al., 2005) but on the other hand, although several studies are discussing the relationship between ENSO and European winter precipitation, there is no a general agreement in evaluating the importance of this influence. The impact of ENSO on the atmospheric circulation in the North Atlantic region and the temperature in Europe has been examined by some authors (e.g. Rogers, 1984; Huang et al., 1998; Dong et al., 2000) but these studies show different results (Wu and Hsieh, 2004).

In this context, one of the key purposes of this work is to try to assess a likely link between some selected hemispheric patterns in the Atlantic like the NAO and the Scandinavian (SCAND), and in the Pacific with the Pacific-North American (PNA), and the West Pacific (WP) patterns to ENSO polarity. Although traditionally, the impact of ENSO on circulation in the North Atlantic region has been restricted by some authors to the study of its association with the NAO, we extend the analysis study to other patterns like the SCAND pattern.

To give insight into the relation between ENSO events and the selected patterns, we evaluate the relative frequency of occurrence of the positive and negative phase of the teleconnections for El Niño and La Niña events together with the probability density function (PDFs) of the climate patterns during the cold and warm ENSO phases. Special emphasis is put on various aspects which may point to the non-gaussian behaviour of the climate patterns variability associated with each ENSO phase, such as the skewness and kurtosis of the patterns.

The paper begins with a description of the data sets in Section 2. Section 3 contains the methodology, while the main results are presented in Section 4. A summary and concluding remarks follow in Section 5.

2. Data

Gridded daily (12 UTC) 500-hPa geopotential height data from two quasi-independent reanalysis datasets over the period 1961-2000 have been used: the European Centre for Medium-Range Weather Forecast dataset (ERA-40 henceforth, Uppala et al., 2005) and the National Centers for Environmental Prediction Climate Prediction Center dataset (NCEP CPC, Kalnay et al., 1996). Daily anomalies are computed by removing the mean seasonal cycle at each grid point. The mean seasonal cycle is estimated as the sum of the annual average and the first four Fourier harmonics of the daily climatology. The analysis has been carried out for the extended winter season December-to-March, (DJFM henceforth). This season has been selected since the boreal winter shows the largest variability over the extratropical latitudes (e.g. Kushnir and Wallace, 1989; Blackmon et al., 1984). The spatial domain extends north of 20ºN.

To illustrate the influence of ENSO signals onto the patterns, every dataset has been subdivided into cold ENSO (La Niña) winters and warm ENSO (El Niño) winters according to the list of ENSO events created by the Canadian Meteorological Service. This list is available on http:/www.msc-smc.ec.gc.ca/education/lanina/comparing/enso1950_2002_e.html. These ENSO warm and cold winters are slightly different from other classifications such as provided by Thompson et al. (2002), although there is a general agreement.

3. Methodology

A standard empirical orthogonal function (EOF) analysis based upon the computation of the covariance matrix has been performed on the winter unfiltered Z500 daily anomalies (Wilks, 1995) to obtain the main modes of variability. A shortcoming of EOF analysis is that eigenvectors are mathematical constructions, constrained by their mutual orthogonality and the maximization of variance over the entire analysis domain. The use of EOFs can predispose the analysis to merging or blending patterns of variability that would be otherwise independent (Richman, 1986). An alternative to reduce the effect of this drawback consists in rotating the empirical orthogonal functions and the corresponding orthonormal principal component time series (PC). This way, the areas where the maxima of variability occur tend to be more concentrated. Prior to the eigenvector analysis, the height anomalies were weighted by the square root of the cosine of latitude in order to ensure equal weight to equal area.

Following this procedure we have used the varimax orthogonal rotation (RICHMAN, 1986) to obtain the corresponding climate patterns and we have considered 6 EOFs to rotate. This is the most widely used rotation technique and has been shown to produce statistically stable patterns (CHENG ET AL., 1995). The EOFs have been previously renormalized following the rule suggested by VON STORCH AND ZWIERS (1999). The renormalized EOFs then carry the units of the field and the PCs have variance 1.

A probability density function (PDF) was calculated for the different daily time coefficients associated to each mode. Each PDF is calculated with a Gaussian kernel density procedure using an algorithm based on the fast Fourier transform (SILVERMAN, 1986). The kernel density algorithm has a smoothing parameter, h, which is determined by a least squares cross-validation procedure. The impact of the smoothing parameter in the results has been assessed using a range of values ($0.25\ n^{-1/5} < h < 1.5\ n^{-1/5}$ where n is the number of data). For each climate mode, we have estimated the PDF for all years, and for all cold and warm ENSO years.

Moment measures of skewness and kurtosis to assess the non-Gaussian characteristics of the patterns have been employed. These measures present the advantage of their simplicity but nevertheless they are non-resistant and non robust and can be sensitive to outliers (HOSKING, 1990).

The standard $\sqrt{b_1}$ and b_2 tests have been used for evaluating skewness and kurtosis. Nevertheless, as some authors have pointed out there are several studies that have demonstrated that this test is not very reliable for discriminating between symmetric and asymmetric distributions in the presence of excess kurtosis. The main reason for the failure of the standard $\sqrt{b_1}$ test is that its variance formula is derived under the assumption of no excess kurtosis. We plan to use in a future work more robust and resistant techniques based on quantiles and L-moments (HOSKING, 1990).

4. Results

4.a. Characteristics of the climate patterns

The set of wintertime northern extratropics teleconnection patterns commonly identified in the literature (Wallace and Gutzler, 1981; Barnston and Livezey, 1987; Bell and Halpert, 1995) has been found in both datasets studied here. The main patterns identified are: North Atlantic Oscillation (NAO), Pacific North American (PNA), West Pacific (WP), Scandinavian (SCAND) and East Atlantic (EA). For the sake of simplicity, the following description focuses on the corresponding NCEP NAO, SCAND, PNA and WP patterns. ERA-40 patterns show similar features.

The NAO consists of a north-south dipole of anomalies, with one center located over Greenland and the other center of opposite sign spanning the central latitudes of the North Atlantic between 35ºN and 40ºN. Both phases of NAO are associated with basin-wide changes in the intensity and location of the North Atlantic jet stream and storm track, and in large-scale modulations of the normal patterns of zonal and meridional heat and moisture transport (Hurrell, 1995), which in turn results in changes in temperature and precipitation patterns often extending from eastern North America to western and central Europe (Rogers and van Loon, 1979). The NCEP NAO pattern (figure 1) differs from the corresponding obtained by the Climate Prediction Center (CPC henceforth), Barnston and Livezey (1987), in a westwards shift of the northern part of dipole meanwhile the southern part of dipole shows a northeastern displacement.

The Scandinavian pattern (SCAND) consists of a primary circulation center over Scandinavia, with weaker center of opposite signs over southwestern Europe and eastern Russia-western Mongolia. The SCAND pattern has been previously referred to as the Eurasian-1 pattern by Barnston and Livezey (1987). The positive phase of this pattern is associated with positive height anomalies, sometimes reflecting major blocking anticyclones, over Scandinavia and western

Russia, while the negative phase of the pattern is associated with negative height anomalies in these regions. The NCEP SCAND pattern (figure 2) differs from the corresponding CPC in a northwestern displacement of the southern centre. Less variability is associated in the location of the Scandinavian and Mongolian centers.

The PNA is a major pattern of the atmospheric low-frequency variability over the Northern Hemisphere which has centers of action near the North Pacific subtropical high, the Aleutian low, northwestern North America, and the Florida panhandle. The importance of the PNA for the North American climate arises from the fact that this pattern represents a departure from the mean tropospheric flow over the continent (Rodionov and Assel, 2001). The pattern has been found throughout the cool season (Barnston and Livezey, 1987) and at various levels in the troposphere (Hsu and Wallace, 1985).The NCEP PNA pattern (figure 3) differs from the corresponding CPC in a less extended Aleutian low.

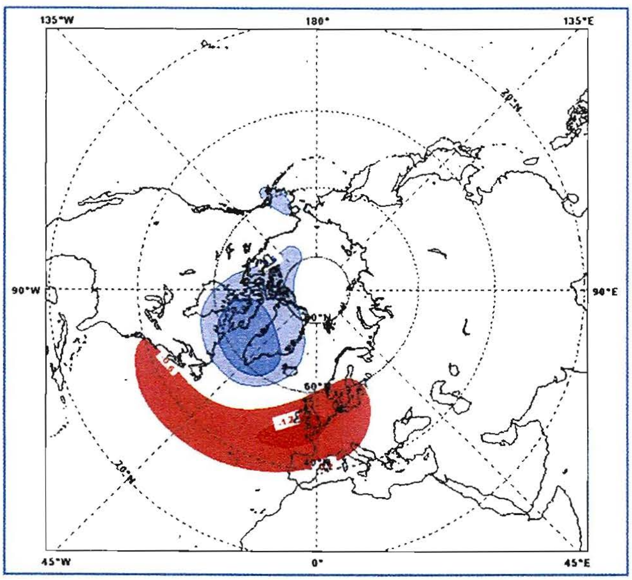


Figure 1. *NCEP NAO climate pattern. Contour interval is 0.6 hPa.*

The WP is a primary mode of low-frequency variability over the North Pacific in all months, and has been previously described by both Barnston and Livezey (1987) and Wallace and Gutzler (1981). During winter and spring, the pattern consists of a north-south dipole of anomalies, with one center located over the Kamchatka Peninsula and another broad center of opposite sign covering portions of southeastern Asia and the western subtropical North Pacific. Therefore, strong positive or negative phases of this pattern reflect pronounced zonal and meridional variations in the location and intensity of the entrance region of the Pacific (or East Asian) jet stream. The NCEP WP pattern (figure 4) differs from the corresponding CPC in a less extended southern dipole, shifted eastwards northern dipole exhibiting some kind of blending between East Pacific (EP) and WP CPC patterns.

The likely differences found with the CPC patterns may be mainly due to the different number of EOFs considered to rotate, while CPC takes into account 10 EOFs we have considered 6.

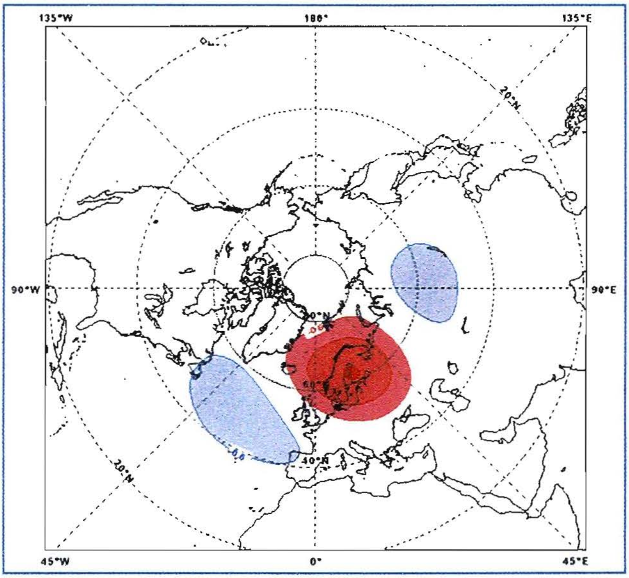


Figure 2. NCEP SCAND climate pattern. Contour interval is 0.6 hPa.

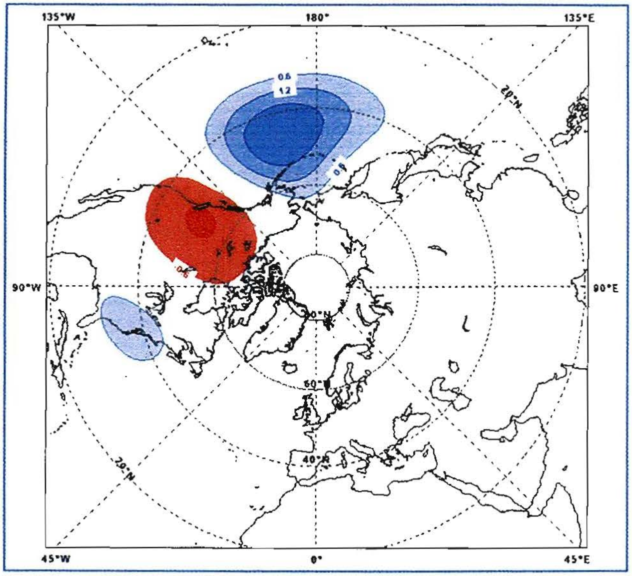


Figure 3. *NCEP PNA climate pattern. Contour interval is 0.6 hPa.*

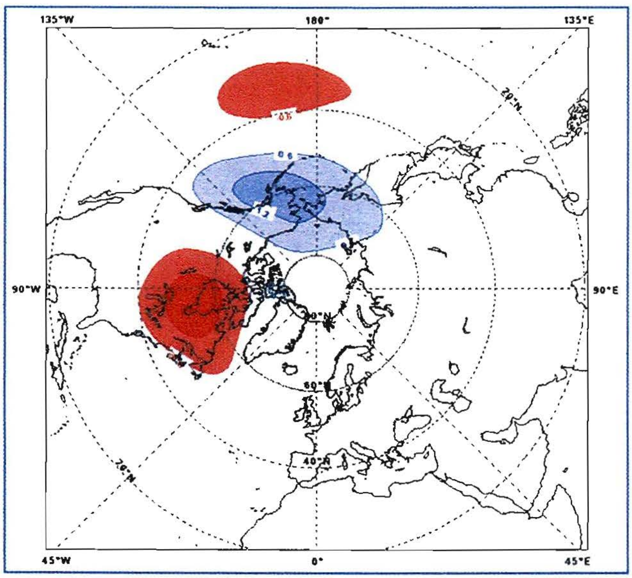


Figure 4. *NCEP WP climate pattern. Contour interval is 0.6 hPa.*

4.b. Relationships between ENSO events and climate patterns

In this study we first evaluate the relative frequency of occurrence of the positive and negative phase of the patterns during El Niño and La Niña winters. Secondly we assess the shape of the PDFs of the corresponding climate patterns of NCEP and ERA-40 together with the analysis of skewness and kurtosis (Table 1).

Climate patterns	Skewness		Kurtosis	
	NCEP	ERA-40	NCEP	ERA-40
PNA	-0.17	-0.15	-0.47	-0.49
WP	-0.26	-0.25	-0.08	-0.04
NAO	-0.44	-0.43	0.08	0.08
SCAND	0.08	0.08	-0.28	-0.24

Table 1. *Skewness and Kurtosis for the selected leading climate patterns of NCEP and ERA-40 reanalyses for the period 1961-2000. All the values are significant at 99%.*

As summarized in Figures 5 and 6, during El Niño winters the positive phase of the PNA, WP and patterns tends to occur more frequently than the negative one as was pointed out by several authors (Horel and Wallace, 1981), while the negative phase of NAO is more frequent than the positive one, especially noticeable in ERA-40. The behaviour of the negative phase of NAO is consistent with some published works where it has been observed that in case of strong El Niño phases, the North Atlantic storm track is shifted southward leading to positive pressure anomalies over northern Europe and negative ones over Central Europe (Fraedrich and Müller, 1992). These observational findings are also confirmed in modelling studies (May and Bengtsson, 1999; Cassou and Terray, 2001). As far as SCAND pattern is concerned, while the positive phase tends to occur more frequent than the negative for NCEP, the reverse is true for ERA-40. During La Niña winters the negative phase of PNA tends to occur more frequently than the positive in agreement with Mo et al. (1998) who emphasized that strong PNA patterns can be produced in non-ENSO years, while a strong warm or cold event does not always give the expected PNA response.

More recently, Rodionov and Assel (2001) mention that ENSO is not the only responsible for exciting the PNA. As far as NAO is concerned, in ENSO cold events, the positive phase of NAO tends to be favored in agreement with the literature. Different behaviour regarding SCAND is reported for ERA-40 and NCEP.

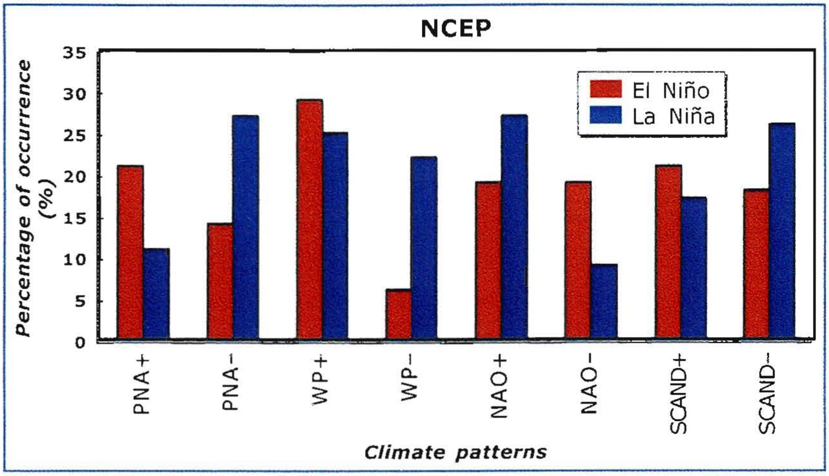


Figure 5. Percentages of frequencies of the positive and negative phases of the climate patterns corresponding to El Niño and La Niña events for NCEP dataset.

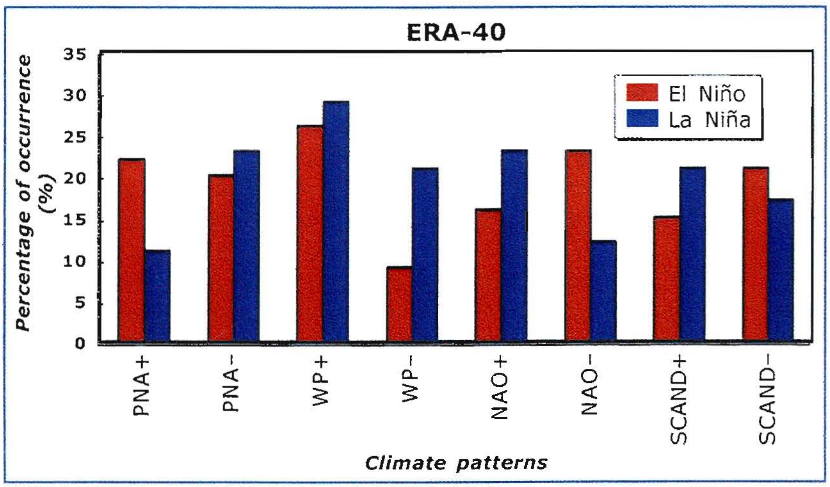


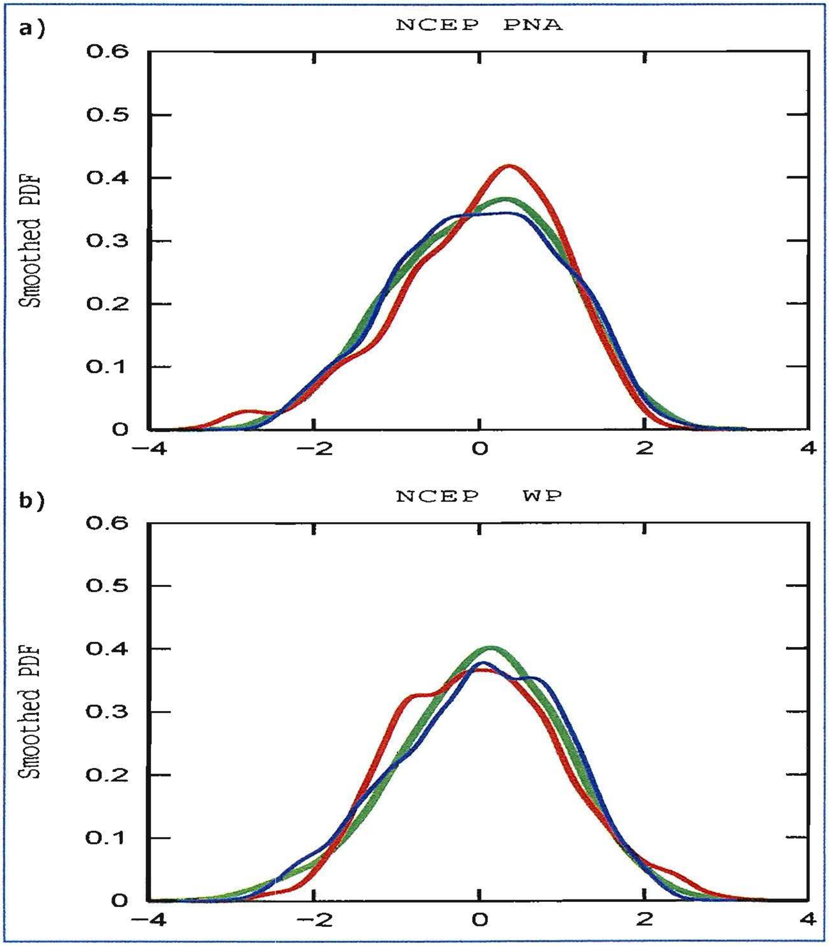
Figure 6. Same as Figure 5 but for ERA-40 dataset.

Our results indicate that the effects of La Niña are not exactly opposite to those associated with El Niño, which may be a consequence of the non-linear effect of ENSO on teleconnection pattern dynamics. As in Cassou et al. (2004), El Niño events might have less impact on the North-Atlantic European variability compared to La Niña events. The NAO-ENSO relationship is still an open question (Cassou and Terray, 2001) since it may well depend on the strength and the sign of the Pacific episodes. Also the effect of ENSO on the frequency of positive and negative patterns seems consistent with Palmer's (1999) hypothesis that the response of the atmosphere to external forcing is mainly a change in the frequencies, in his case of regimes.

We now analyze the shape of the PDFs of the considered climate patterns for NCEP (Figures 7a-7d) and for ERA-40 (Figures 8a-8d) together with the skewness and kurtosis parameters (Table 1). As it becomes clear, a different behaviour of climate patterns in warm and cold ENSO years is detected.

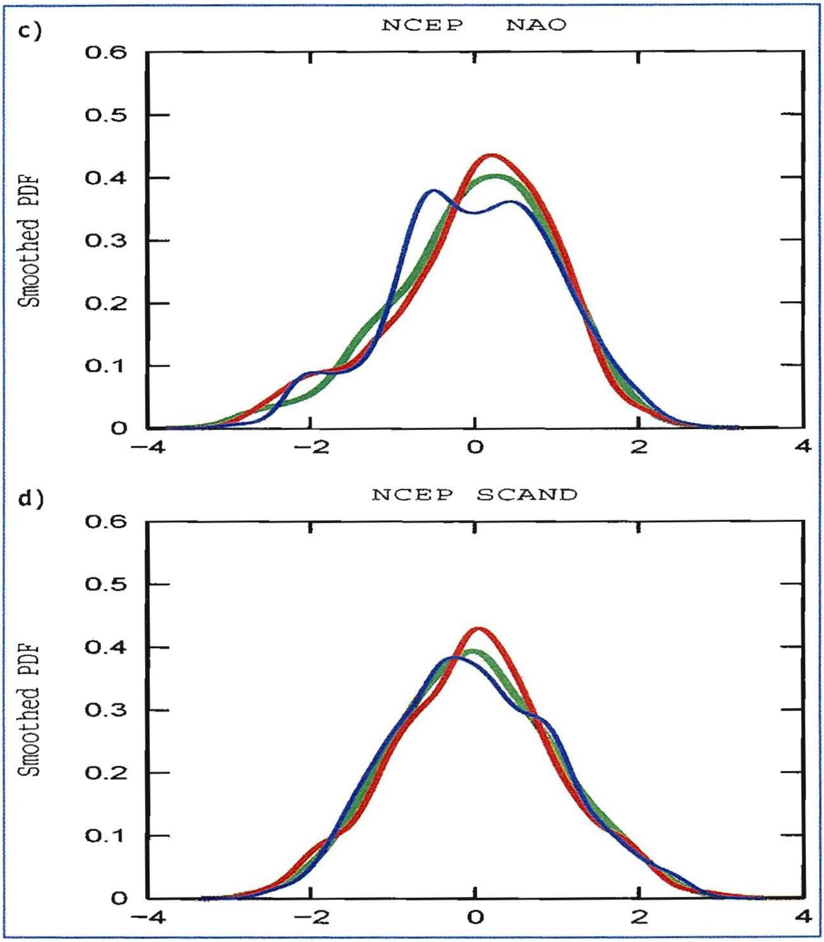
The daily NCEP PNA (Figure 7a) time series is asymmetric with negative skewness, so more extreme values are found when the mode is negative. This implies less variability in the positive PNA mode in agreement with the suggestion of Palmer (1988) that the atmosphere is more barotropically stable when is in this phase. During La Niña winters, there is a slight shift of the distribution to negative values, with reduction in the proportion of positive values and an increase in the number of negative values in agreement with Renshaw et al. (1998) who report also a shift in the PNA PDF toward more negative values during cold events. During El Niño winters, there is a distributional change with an increase in the number of positive cases. However, Renshaw et al. (1998) obtained little change in the observed PNA PDF. Working with daily data, less skewness for ERA-40 has been detected compared with NCEP data (Table 1). In case of ERA-40 El Niño (Figure 8a), a kind of bimodality has been observed.

The daily NCEP WP (Figure 7b) time series is asymmetric with a strong negative skewness. During El Niño, the PDF presents a secondary maximum in moderate negative values while in La Niña the PDF depicts a maximum corresponding to positive values. It shows a stronger response in El Niño for the WP compared with the PNA, a consistent result because this climate mode is strongly influenced by tropical Pacific SSTs. Compared with RENSHAW ET AL. (1998), the negative phase of WP is not favored in La Niña years. As a consequence, there is a notorious separation in the percentage of occurrence of



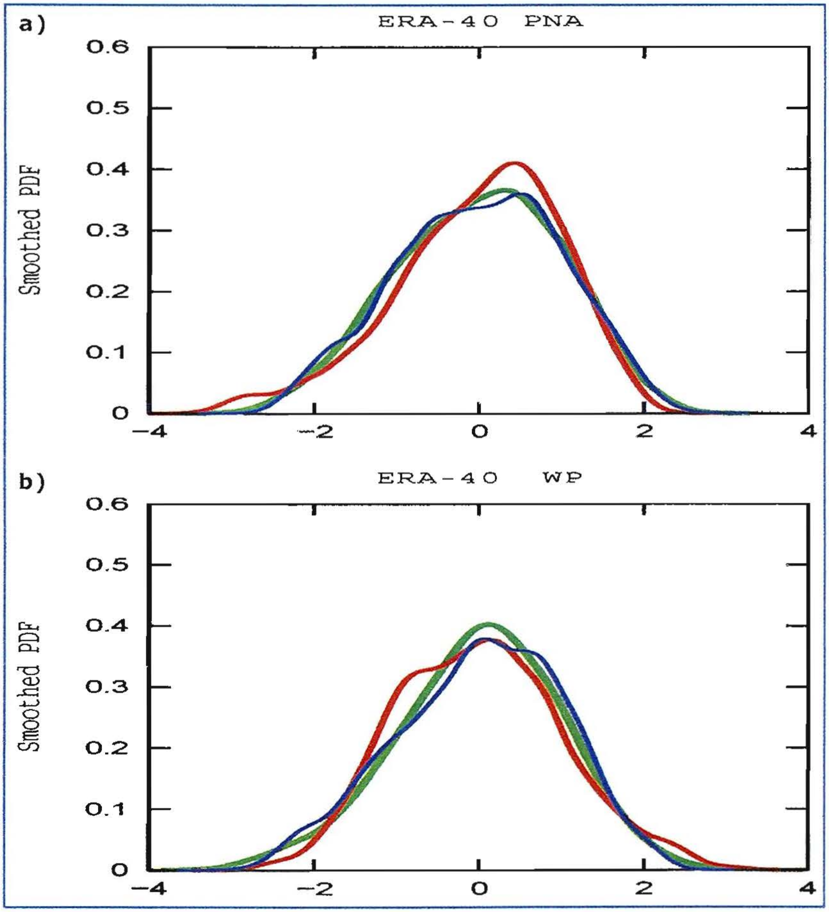
Figures 7a-7b. PDFs for the PNA and WP climate patterns for NCEP. Green line is calculated using all winter daily data, red line uses data from all El Niño winters and blue line uses data from La Niña winters.

positive and negative WP for El Niño winters (Figure 5). There is, thus, bimodality in El Niño in a direction, and bimodality in La Niña in the reverse direction. The link between El Niño events and the positive phase of WP pattern in nature has been identified in earlier studies such as LIVEZEY AND MO (1987) and HOREL AND WALLACE (1981).



Figures 7c-7d. *PDFs for the NAO and SCAND climate patterns for NCEP. Green line is calculated using all winter daily data, red line uses data from all El Niño winters and blue line uses data from La Niña winters.*

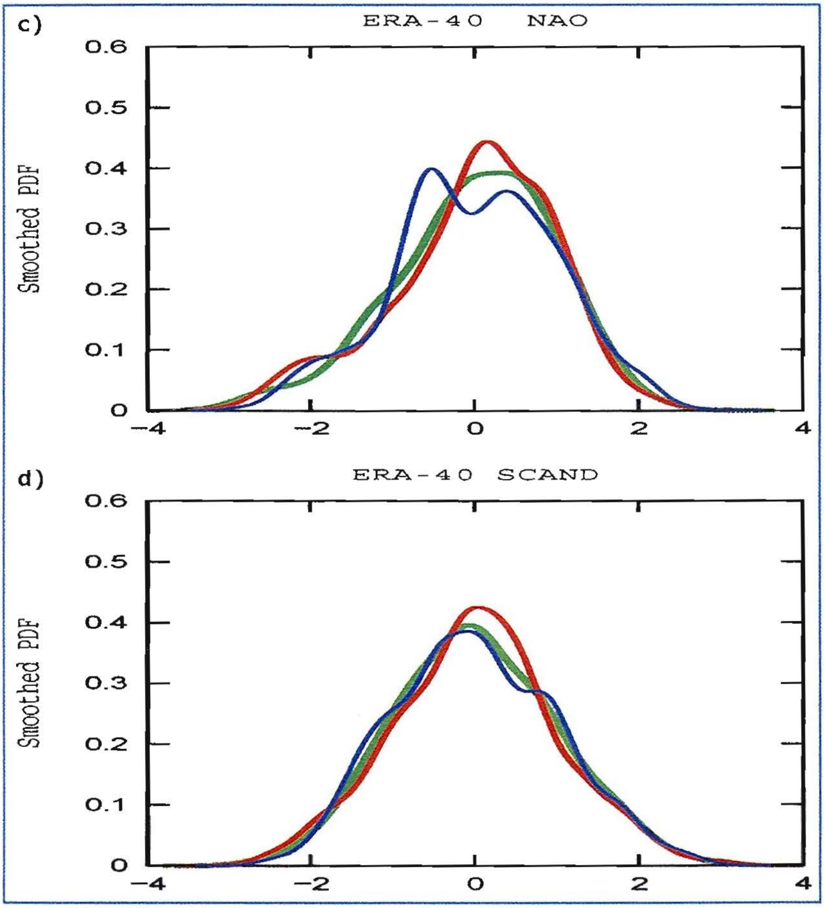
The daily NCEP NAO (Figure 7c) time series depicts the largest negative skewness. JUNG (2000) pointed out that the negative skewness of the NAO is also significant for monthly data. A large impact of La Niña is detected. There is a slight separation between El Niño and La Niña curves, mainly for negative values. Our results suggest bimodality in the cold ENSO phase while no such bimodality is found during the warm ENSO phase. There is apparently a reverse situation compared with MELO-GONÇALVES ET AL.



Figures 8a-8b. As Figures 7a-7b but for ERA-40 dataset.

(2005). They used winter mean (DJFM) 850 hPa geopotential height field over the Atlantic European Sector for the 1948-2001 period.

The daily NCEP SCAND (Figure 7d) time series presents almost no asymmetry. During La Niña, small shift to the left is detected compared with El Niño. There is more separation between the percentage of occurrence of frequencies of the negative and positive phases for La Niña.



Figures 8c-8d. As Figures 7c-7d but for ERA-40 dataset.

5. Summary and Conclusions

We analyzed here a 40-winter set of Z500 daily unfiltered anomalies from two datasets: ERA-40 and NCEP, to estimate first the impact of ENSO on a series of Northern Hemisphere climate patterns, isolated by REOF analysis and second the likely impact of the reanalysis used.

Our strategy is based on daily data, contrarily to the more usual method based upon monthly or seasonal data. The use of daily data is, in principle, beneficial because monthly data can hide important signals or processes. Furthermore, the existence and complexity of numerous non-linear feedbacks can hide the signal of ENSO in the extra-tropics when using averaged data.

Sensitivity to tropical SSTs associated with ENSO is analyzed first in terms of the shift in frequency of the occurrence of the opposite phases of a mode between warm or cold events. A change in the frequency of occurrence of the selected patterns as a function of ENSO phases has been detected. More influence of La Niña is detected for NAO, and in general for those patterns which have a signal in the Atlantic area while El Niño has more influence on the PNA pattern. Although as a general rule there is a noticeable similarity between the ERA-40 and NCEP datasets, some discrepancies appear mainly with the SCAND pattern.

The PDFs show a non-Gaussian shape in dipolar patterns like NAO and WP. It seems very plausible that this non-gaussianity is extremely important when considering the sensitivity to the ENSO phase, making these patterns especially sensible to the ENSO influences.

A predominant La Niña influence on European climate when compared with El Niño is observed. The physical mechanisms responsible for the asymmetry between El Niño and La Niña are still unclear. A need of investigating the dynamical causes behind the larger skewness of the dipolar patterns like NAO and WP, which may point to the non-linear character and the influence of ENSO is highlighted. The Euro-Atlantic climate anomalies have asymmetric responses to ENSO because they are non-linearly connected to it. How the Euro-Atlantic climate anomalies are physically linked to the tropical Pacific variability is still an open question. The PNA teleconnection may play a key role in the connection between the tropical forcing and the extratropical circulation response in the North Atlantic area. A possible mechanism could be attributed to the wave-wave interaction in the midlatitudes, e.g. the synoptic eddies and stationary waves.

As Wu and Hsieh (2004) recently insisted, it seems that unlike the response of North American climate to ENSO, where the linear component is important, the response of the Euro-Atlantic climate to ENSO is mainly non-linear. Our results seem to support those by Lau and Nath (2001) who showed that the influence of ENSO is not limited to the tropical Pacific but is also significant in the extra-tropical North Atlantic, a result that further supports the idea that the PNA mechanism plays an important role in the Atlantic response to ENSO.

These are preliminary results, in a next future we plan to extend the work evaluating the sensitivity of the results when more teleconnection patterns are taken into account.

6. Acknowledgements

The authors gratefully acknowledge the people involved in ERA-40 and NCEP reanalyses. Special thanks are due to J.M. Castanheira for kindly sending us Melo-Gonçalves et al. (2005) paper.

7. References

Barnston, AG and RE Livezey (1987): Classification, seasonality and persistence of low- frequency atmospheric circulation patterns. *Mon. Wea. Rev.*, 115, 1083-1126.

Bell, GD and MS Halpert (1995): Atlas of intraseasonal and interannual variability, 1986-1993, NOAA Atlas No 12, Climate Prediction Center, NOAA/NWS/NMC, Washington DC.

Cassou, C and L Terray (2001): Oceanic forcing of the wintertime low-frequency atmospheric variability in the North Atlantic European sector: a study with the Arpège model. *J. Climate*, 14, 4266-4291.

Cassou, C, L Terray, JW Hurrell and C Deser (2004): North Atlantic winter climate regimes: Spatial asymmetry stationarity with time and oceanic forcing. *J. Climate*, 17, 1055-1068.

Cheng, X, G Nitsbe, JM Wallace (1995): Robutness of low-frequency circulation pattern derived from EOF rotated analysis. *J. Climate*, 8, 1709-1713.

Dong, BW, RT Sutton, SP Jewson, A O'Neill, JM Slingo (2000): Predictable climate in the North Atlantic sector during the 1997-1999 ENSO cycle. *Geophys. Res. Lett.*, 27, 985-988.

Fraedrich, K and K Muller (1992): Climate anomalies in Europe associated with ENSO extremes. *International Journal of Climatology*, 12, 25-31.

Fraedrich, K (1994): An ENSO impact on Europe? *Tellus*, 46A, 541-552.

Hannachi, A (2001): Toward a nonlinear identification of the atmospheric response to ENSO. *J. Climate*, 14, 2138-2149.

Hoerling, MP, A Kumar, M Zhong (1997): El Niño, La Niña and the non-linearity of their teleconnections. *J. Climate*, 10, 1769-1787.

Hoerling, MP, A Kumar, T Xu (2001): Robustness of the nonlinear climate response to ENSO's extreme phases. *J. Climate*, 14, 1277-1293.

Horel, JD and J Wallace (1981): A rotated principal component analysis of the interannual variability of the Northern Hemisphere 500 mb height field. *Mon. Wea. Rev.*, 109, 2080-2092.

Hosking, JRM (1990): L-moments: analysis and estimation of distributions using linear combinations of order statistics. *Journal of the Royal Statistical Society*, Series B, 52, 105-124.

Hsu, HH and JM Wallace (1985): Vertical structure of wintertime teleconnection patterns. *Journal of the Atmos. Sci.*, 42, 1693-1710.

Huang, JP, K Higuchi, A Shabbar (1998): The relation between the North Atlantic Oscillation and El Niño-Southern Oscillation. *Geophys. Res. Lett.*, 25, 2707-2710.

Hurrell, JW (1995): Decadal trends in the North Atlantic Oscillation region temperatures and precipitation. *Science*, 269, 676-679.

HURRELL, JW, Y KUSHNIR, M VISBECK and G OTTERSEN (2003): An Overview of the North Atlantic Oscillation. The North Atlantic Oscillation: Climate Significance and Environmental Impact. *Eds. Geophysical Monograph Series*, 134, pp 1-35.

JUNG, T (2000): The North Atlantic Oscillation: variability and interactions with the North Atlantic Ocean and Artic sea ice. *Berihte aus dem Institut fur Meerreskunde*, Nr. 315.

KALNAY, E et al. (1996): The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, 77, 437-471.

LAU, NC, MJ NATH (2001): Impact of ENSO in SST variability in the North Pacific and North Atlantic seasonal dependence and role of extratropical sea air coupling. *Journal of Climate*, 14, 2846-2865.

LIVEZEY, RE and KS MO (1987): Relationships between monthly mean Northern Hemisphere circulation pattern and proxies for tropical convection. *Mon. Wea. Rev.*, 115, 3115-3132.

MAY, W, L BENGTSSON (1999): The signature of ENSO in the Northern Hemisphere midlatitude seasonal mean flow and high-frequency intraseasonal variability. *Meteor. Atmos. Phys.*, 69, 81-100.

MELO-GONÇALVES, P, AC ROCHA, JM CASTANHEIRA, JA FERRERIRA (2005): North Atlantic oscillation sensitivity to the El Niño/Southern Oscillation oscillation polarity in a large-ensemble simulation. Climate Dynamics DOI 10.1007/s00382-005-0001-z.

MO, R, J FYFE, J DEROME (1998): Phase-locked and asymmetric correlations of the wintertime atmospheric patterns with the ENSO. *Atmosphere-Ocean*, 36, 213-239.

MORON, V and MN WARD (1998): Enso teleconnection with climate variability in the European an African sectors. *Weather*, 53, 287-295.

MORON, V and I GOUIRAND (2003): Seasonal modulation of the ENSO relationship with sea level pressure anomalies over the North Atlantic in October-March 1973-1996. *International Journal of Climatology*, 23, 143-155.

PALMER, TN (1988): Medium and extended range predictability and the stability of the Pacific/North American mode. *Quart. J. Roy. Meteor. Soc.*, 114, 691-713.

PALMER, TN (1999): A nonlinear dynamical perspective on climate prediction. *J. Climate*, 12, 575-591.

POZO-VÁZQUEZ, D, MJ ESTEBAN-PARRA, FS RODRIGO, Y CASTRO-DIEZ (2001): The association between ENSO and winter atmospheric circulation and temperature in the North Atlantic region. *J. Climate*, 14, 3408-3420.

POZO-VÁZQUEZ, D, SR GÁMIZ-FORTIS, J TOVAR-PESCADOR, MJ ESTEBAN-PARRA, Y CASTRO-DÍEZ (2005): North Atlantic winter SLP Anomalies based on the autumn ENSO state. *J. Climate*, 18, 97-103.

RENSHAW, AC, DP ROWELL, CK FOLLAND (1998): Wintertime low-frequency variability in the North-Pacific sector 1949-93. *J. Climate*, 11, 1073-1093.

RICHMAN, MB (1986): Rotation of principal components. *J. Climatol.*, 6, 293-335.

RODIONOV, S and R ASSEL (2001): A new look at the Pacific/North American index. *Geophysical Research Letters*, 28, 1519-1522.

ROGERS, JC and H VAN LOON (1979): The seesaw in winter temperatures between Greenland and Northern Europe. Part II: Some oceanic and atmospheric effects in middle and high latitudes. *Monthly Weather Review*, 107, 509-519.

ROGERS, JC (1984): The association between the North Atlantic oscillation and the southern oscillation in the northern Hemisphere. *Monthly Weather Review*, 112, 1999-2015.

SHABBAR, A, B BONSAL, M KHANDESKAR (1997): Canadian precipitation patterns associated with Southern Oscillation. *J. Climate*, 10, 3016-3027.

SILVERMAN, BW (1986): Density estimation for statistics and data analysis. Chapman and Hall, London.

SUTTON, RT and DLR HODSON (2003): Influence of the ocean on North Atlantic climate variability. *J. Climate*, 16, 3296-3313.

TERRAY, L and C CASSOU (2002): Tropical Atlantic sea surface temperature forcing on the quasi-decadal climate variability over the North Atlantic Europe region. *J. Climate*, 15, 3170-3187.

THOMPSON, DWJ, MP BALDWIN, JM WALLACE (2002): Stratospheric connection to Northern Hemisphere winter time weather: implications for prediction. *J. Climate*, 15, 1421-1428.

TRENBERTH, KE (1997): The definition of El Niño. *Bull. Amer. Soc.*, 78, 2771-2777.

TRENBERTH, KE, GW BRANSTATOR, D KAROLY, A KUMAR, NC LAU, and C ROPELEWSKI (1998): Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures. *J. Geophys. Res.*, 103 (special TOGA issue), 14291-14324.

UPPALA, S (2002): ECMWF reanalysis 1957-2001, ERA-40 Project Series 3 Workshop on Reanalysis. ECMWF, Reading (UK). 62 pp.

VON STORCH, H, FW ZWIERS (1999): Statistical Analysis in Climate research. Cambridge University Press. 510 pp.

WALLACE, JM and DS GUTZLER (1981): Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Wea. Rev.*, 109, 784-812.

WILKS, DS, (1995): Statistical Methods in the Atmospheric Sciences: An Introduction. Academic Press, 467 pp.

WU, A and WW HSIEH (2003): Nonlinear interdecadal changes of the El Niño-Southern Oscillation. *Climate Dynamics*, 21, 719-730.

WU, A and WW HSIEH (2004): The nonlinear association between ENSO and the Euro-Atlantic winter sea level pressure. *Climate Dynamics*, 23, 859-868.

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