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Multidecadal modulation of El Niño influence on the Euro-Mediterranean rainfall

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[1] El Niño influence on the Euro-Mediterranean Rainfall (EMedR) has changed along the 20th century, and the reasons for this lack of stationarity, which represents an important issue in the climate change context, are still unclear. Here, the causes of this changing relationship are studied at interannual timescales. To this aim the EMedR is analyzed using observations from 1900 to 2008. Results confirm the lack of stationarity, showing how the teleconnections with El Niño appear modulated by multidecadal oscillations of the anomalous Sea Surface Temperature (SST) over the Atlantic and Pacific basins. The study presents statistically significant evidences about how the Atlantic Multidecadal Oscillation (AMO) seems to modulate El Niño teleconnection for late winter-spring, while modulation in fall could be controlled by the Pacific Decadal Oscillation (PDO). The results of this study have important implications in seasonal and decadal predictability, but they also represent a step forward in the understanding of the role of changes in the ocean mean state on the interannual teleconnections.

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1. Introduction

[2] El Niño-Southern Oscillation (ENSO) is the globally dominant climate mode at interannual timescales. Its influence over the Pacific and the tropics has been thoroughly analyzed [*Harrison and Larkin*, 1998; *Alexander et al.*, 2002; *Diaz and Markgraf*, 2000; *Wang*, 2004; *Wang and Picaut*, 2004; *McPhaden et al.*, 2006]. Nevertheless, over the North Atlantic sector, most of the studies point out to the North Atlantic Oscillation (NAO) as the leading pattern controlling its atmospheric variability. The NAO exerts its influence through Sea Level Pressure (SLP) fluctuations between the subpolar and the subtropical North Atlantic basin, modifying the stormtracks that reach the Euro-Mediterranean region [*Rogers*, 1997], and hence, the precipitation [*Rodwell et al.*, 1999; *Hurrell et al.*, 2003]. An interesting point is that, at interannual timescales, the regional atmospheric spatial pattern at surface levels over the Euro-Atlantic region associated with the Pacific El Niño presents a similar structure to the one associated with the NAO [*Brönnimann*, 2007; *García-Serrano et al.*, 2011]. In this way, although most of the NAO signal has an internal origin, external contributions associated with Sea Surface Temperature (SST) changes in the Pacific can have a determinant impact on the centers of action of the NAO. There are two possible ways to explain El Niño influence on the North Atlantic sector: by Rossby waves propagation due to changes in anomalous upper level convergence and divergence, or through the Walker and Hadley circulations [*Wang, C.*, 2002; *Brönnimann*, 2007]. A global teleconnection pathway from the Pacific region to Europe via the stratosphere has also been showed [*Ineson and Scaife*, 2009]. However, these signals are less well understood than those influencing on the Pacific due to the highly variable extratropical circulation of the Atlantic basin [*Trenberth et al.*, 1998; *Quadrelli and Wallace*, 2002].

[3] Previous studies have found nonstationary features in the impact of ENSO and NAO over Europe along the 20th century. These studies include interdecadal shifts in the location of NAO centers [*Vicente-Serrano and López-Moreno*, 2008], different impacts of ENSO before and after the 1970s [*Greatbatch et al.*, 2004], multidecadal variations in the relationship between ENSO and the western Mediterranean rainfall [*Mariotti et al.*, 2002], or a changing ENSO impact depending on the NAO and multidecadal oscillations of the SST over the Pacific [*Zanchettin et al.*, 2008]. However, none of these studies has restricted the analysis to the internannual signal, distinguishing in this way the multidecadal modulation of the interannual variability from the purely multidecadal variability not removed in the analysis.

[4] The present study focuses, for the first time, on the role that natural multidecadal modes, such as Atlantic Multidecadal Oscillation (AMO) [*Enfield et al.*, 2001] or Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997] play in the modulation of the El Niño influence on the leading interannual mode of the EMedR. Two remaining issues, which are still under debate, are analyzed in this paper: 1) the El Niño impact over the Euro-Mediterranean climate variability at interannual timescales; 2) the stationarity of this El Niño impact and related sources.

[5] The paper is divided as follows. Section 2 presents the data used and the methodology followed. In section 3 the results are showed. Finally, in section 4, a brief summary and discussion are presented, attempting to give some physical hypothesis supporting the non stationary relationships identified.

2. Data and Methods

[6] This work is performed analyzing gridded data and climate indices along the 20th century, all provided by observational databases and avoiding the use of reanalysis products due to errors and limitations inherent in the reanalyzed climate dataset.

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[7] The variables analyzed are precipitation, Sea Level Pressure (SLP) and Sea Surface Temperature (SST). Regarding rainfall, University of Delaware rainfall data (K. Matsuura and C. J. Willmott, Terrestrial precipitation: 1900–2008 gridded monthly time series, version 2.01, 2009, available at http://climate.geog.udel.edu/∼climate/html_pages/Global2_Ts_2009/README.global_p_ts_2009.html) from 1900 to 2008, and GPCC data [*Schneider et al.*, 2008] from 1901 to 2007, are used. Both databases are land-only and cover a global gridded domain with a 0.5 × 0.5 lat-long resolution. SLP comes from NCAR [*Trenberth and Paolino*, 1980], from 1899 to 2008 (0.5 × 0.5 lat-long resolution), while SST comes from two different datasets: ERSSTv3 [*Smith et al.*, 2008] from 1854 to present (2° × 2° lat long), and HadISST1 [*Rayner et al.*, 2003] from 1870 to present (1° × 1° lat long).

[8] Regarding the climate indices, Niño3.4, Atlantic Multidecadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO) are used in this study. Niño 3.4 index has been calculated with the SST databases mentioned above, computing the SST anomaly in the Equatorial Pacific region [5°S -5°N, 170°W-120°W]. Also with these SST datasets, AMO index is obtained as the ten-year running mean of detrended Atlantic SST anomalies north of the equator [*Enfield et al.*, 2001]; and PDO index is defined as the leading principal component of November to March detrended SST anomalies for the Pacific north of 20N latitude [*Mantua et al.*, 1997].

[9] In a preliminary study, the rainfall variability of the 12 possible 3-months seasons of the year, from JFM to DJF, is analyzed. The analysis is focused on the interannual seasonal precipitation over the Euro-Mediterranean region (iEMedR, [24°N-68°N, 15°W-35°E]), retaining the high frequency variability by computing the difference between the rainfall scores of one year and the next [*Stephenson et al.*, 2000]. This interannual filtering has been also applied for the SST and SLP (iSST and iSLP respectively). In a second step, the spatially coherent patterns that maximize the variance (thereafter called as "modes") of the iEMedR are determined in a linear way by applying a Principal Component Analysis (PCA/EOF [*Von Storch and Zwiers*, 2001]), as is suggested by *Zanchettin et al.* [2008]. Although they point to a switching behavior of ENSO effects driven by the Pacific Decadal Oscillation (PDO), they propose to focus on a few leading empirical orthogonal functions to reduce the degrees of freedom. Here, regression maps are computed projecting the iEMedR, iSST, and iSLP, onto the leading Principal Components (PC1s), and highlighting those gridpoints with significant correlation scores between the anomalous timeseries and the PC1s. Looking for the stationarity of El Niño impact, sliding windows correlation analysis between the PC1 and the Niño3.4 index is applied. Finally, periods with or without significant correlations are analyzed separately. Along the whole study, 95% confidence level of significance, which is determined by a non parametric Monte Carlo test with 400 permutations, is chosen.

3. Results

[10] We start by examining how the variability of the iEMedR has been organized during the whole 20th century. EOF analysis of this field is applied for all the possible 3-months seasons of the year, obtaining a similar spatial pattern for all of them. The leading mode is clearly separated (following *North et al.* [1982]) from the second one, for late winter-spring and fall months (Figures S1 and S2 in the auxiliary material).[1] For this reason, as representative of these two seasons, the analysis is focused in February-March-April (FMA) and October-November-December (OND). In particular, for FMA, the associated spatial pattern (Figure 1a) presents significant scores in central Europe, including the British Islands, opposite in sign to those over the Mediterranean region and northwestern Africa. In OND (Figure 1d), the leading mode is broadly similar to that obtained for FMA, although the Northern Scandinavia center gets significant and the Mediterranean center gets weaker. The regression of the anomalous iSST onto the PC1 (Figure 1c) presents, for FMA, a significant structure over the tropical Pacific in an El Niño type configuration, with the maximum anomalies over the Niño3.4 region. Over the North Pacific, an extratropical horseshoe pattern appears. Despite the similarities in the leading iEMedR mode for FMA and OND, the projection of the anomalous iSST onto the OND PC1 does not show any significant pattern over the tropical Pacific, although the map reveals an El Niño signal (Figure 1f). In both seasons the PC1s present a lack of stationarity in their variability, as it can be seen in the statistically significant changes in its variance along the 20th century (Figures 1b and 1e). In this way, and taking into account El Niño signal in the iSST regression maps, decadal changes in the PC1s amplitude could be related to changes in its relationship with the tropical Pacific, indicating a non stationary relationship with El Niño, in agreement with previous studies [*Mariotti et al.*, 2002; *Knippertz et al.*, 2003; *Greatbatch et al.*, 2004]. To assess the stationarity of this El Niño-iEMedR relationship, 21-year window moving correlations between PC1s and Niño3.4 index are computed for the whole 20th century (Figure 2), obtaining how the evolution of these correlations exhibits a clear multidecadal periodicity. Different windows are tested (Figure S3) and the results remain the same. On the one hand, for FMA, significant correlations appear in the beginning of the 20th century and after the 1960s, but not in the 1940s and 1950s. A highlighting result is the fact that these correlations evolve in

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL050049.

Figure 1. FMA and OND leading modes of iEMedR. FMA mode: (a) Leading empirical orthogonal function (EOF1; contours, ci = 0,1 mm per std in the PC) of the FMA anomalous rainfall (Delaware) over the EM region (24.25– 67.75°N/14.75°W-34.75°E). (b) Associated standardized principal component (PC1, referenced on the right axis) and its variance (black line, referenced on the left axis). (c) Regression map of anomalous iSST (ERSST) onto the PC1 (contours, ci = 0,05° per std in the PC) . Bottom Panel, OND mode: (d, e, and f) the same as Figures 1a, 1b, and 1c but for OND. In all the maps, shading represents statistical significant areas, according to a Monte Carlo correlation test at 95% confidence level. Blue bands in Figures 1b and 1e represent significant changes in the PC1 variance using the same test and threshold as in the maps.

phase with a low frequency SST pattern that agrees with the Atlantic Multidecadal Oscillation (AMO index, gray line in Figure 2 (bottom); see also regression map in Figure S4 in the auxiliary material). Another important result is how in OND the correlations evolve in phase with the Pacific Decadal Oscillation (PDO index as a gray line in Figure 2 (top) and regression map in Figure S4 in the auxiliary material), except for the last positive phase of PDO after

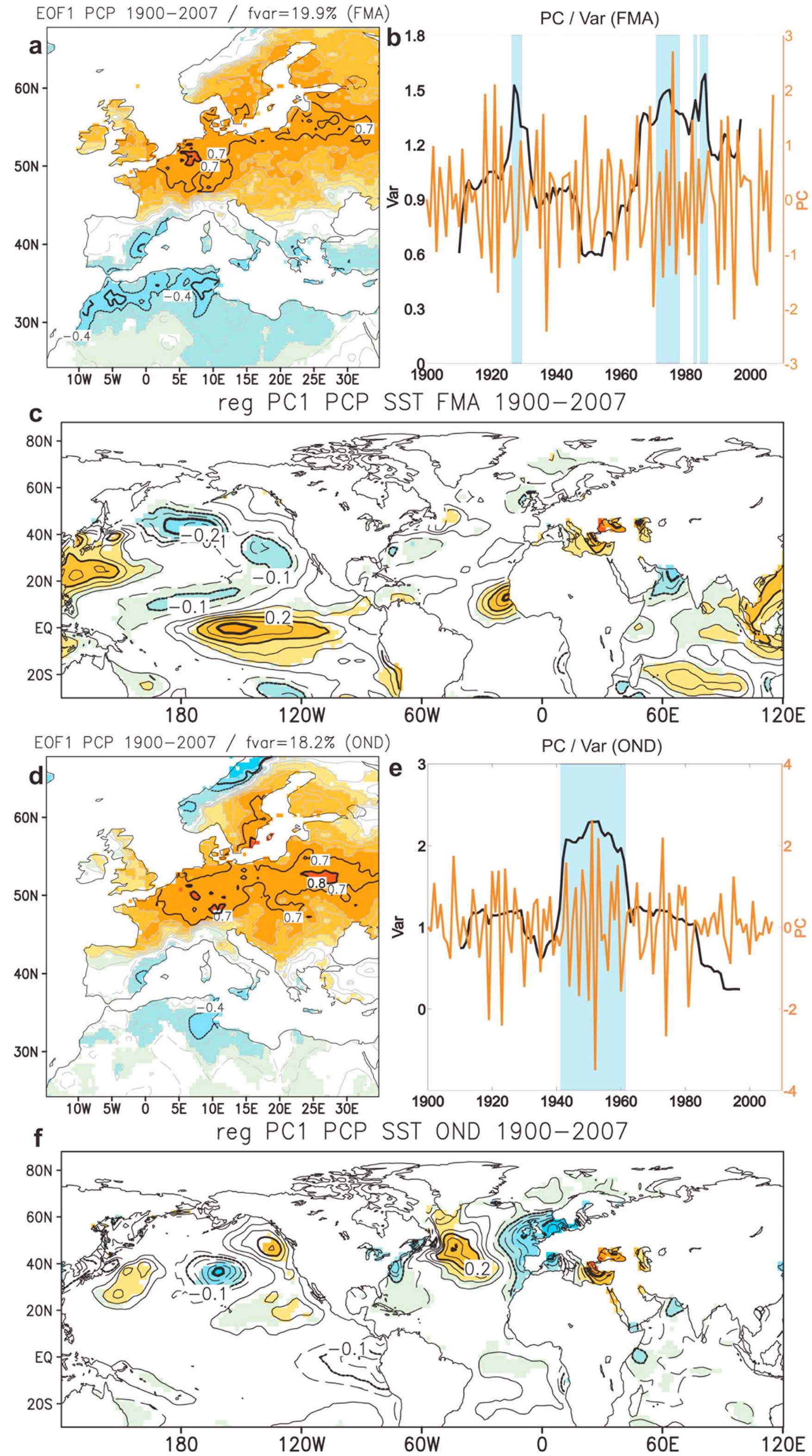

Figure 1

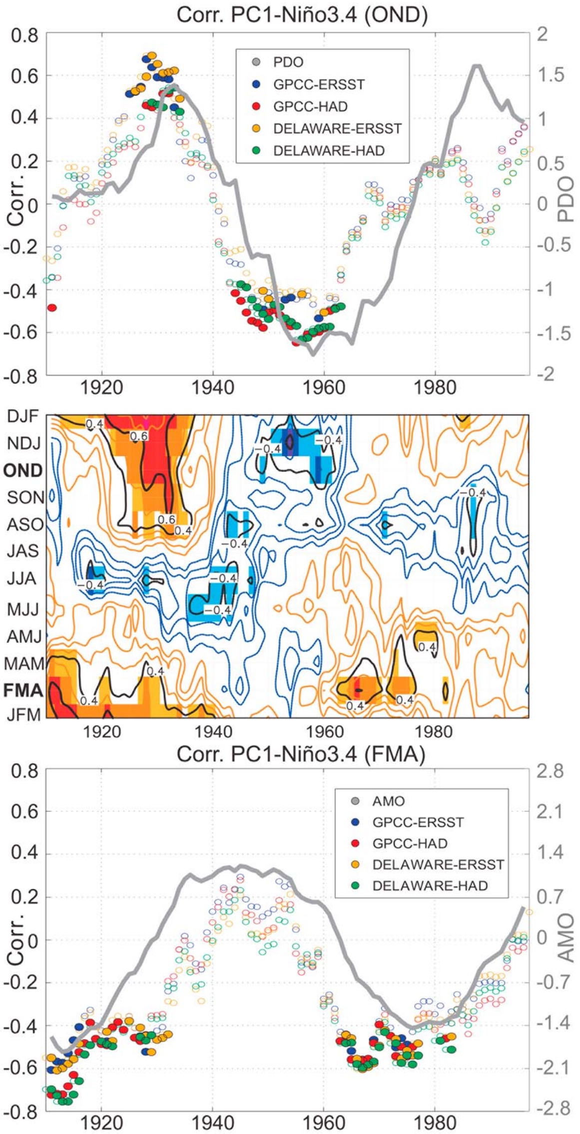

Figure 2. Correlations with Niño3.4 index. (top) Results for OND: 21 year moving window correlations (left axis) between the leading iEMedR PC1 and Niño3.4 index in OND for different PCP and SST datasets according to the legend. In grey line, the standardized PDO index based on *Mantua et al.* [1997] definition is plotted, referenced on the right axis. (middle) Results for all the year: 21 year moving window correlations between the leading iEMedR PC1 (Delaware) and Niño3.4 index (ERSST) for each of the 3 months seasons of the year. (bottom) Results for FMA: the same as the Figure 2 (top) but for FMA. In grey line, the standardized AMO based on *Enfield et al.* [2001]. The sign of the correlation has been changed to better show how the evolution of the correlations is in phase with the AMO. Fill dots and shaded areas represent periods with a 95% significant correlation according to a Monte-Carlo correlation test.

the 1970s, when the correlations do not reach the significant level. In the case of FMA, correlations with the Niño3.4 index appear significant only for negative phases of the AMO, but not for positive ones. In OND, the correlations are significant in both, negative and positives phases of PDO (except after the 1970's). It is important to mention that this multidecadal modulation of El Niño influence on the leading iEMedR mode in FMA and OND by both, AMO and PDO, occurs broadly for all the late winter-spring months and for all the fall months respectively (Figure 2 (middle) and Figure S5 in the auxiliary material). The next question is to try to formulate a hypothesis about the mechanism by which the link between El Niño and iEMedR changes at multidecadal timescales for each of the considered

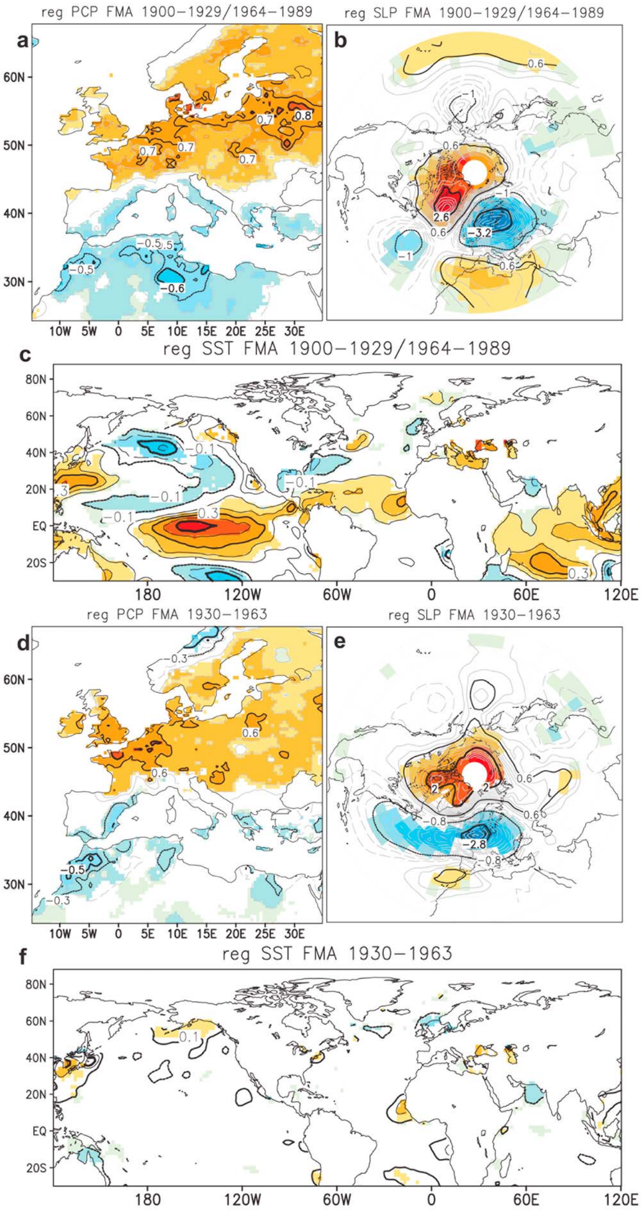

Figure 3. FMA Regression maps, for selected periods of the AMO, calculated between the PC1 and: (a) PCP (Delaware; contours, ci = 0,2 mm per std in the PC), (b) SLP (contours, ci = 0,2 hPa per std in the PC) , (c) SST (ERSST; contours, ci= 0,1° per std in the PC) for the period 1900-1929/1964-1989. (d, e, and f) The same as Figures 3a, 3b, and 3c but for the period 1930–1963. In all the maps, magnitudes correspond to one std dev of the PC. Statistical significant areas, according to a Monte-Carlo correlation test at 95% confidence level, are shaded.

seasons. To this aim, periods with or without significant correlations with the Niño3.4 index are analyzed separately, including in the analysis SLP data, which is the only available atmospheric variable with observations for the whole 20th century. For those years within an AMO negative phase (Figures 3a–3c), the iSST regression map projects an El Niño pattern over the Pacific, while over the Atlantic basin, the significant areas resemble the SST signal of the meridional gradient mode proposed by *Wang, C.* [2002]. The iSLP pattern presents a quadrupolar structure in the North Atlantic with a strong center over the Iberian Peninsula and Northern Africa. Over the Pacific, a positive significant center appears in the tropical region, reflecting the typical Southern Oscillation (SO) pattern. Nevertheless, for those years within positive AMO phase (Figures 3d–3f), when the El Niño-iEMedR relationship disappears, no El Niño signal is found in the ocean, the precipitation pattern weakens, and the iSLP pattern is confined to the Atlantic-European region resembling a NAO structure, mainly related to internally driven changes in the zonal flow.

[11] Similar analysis for the leading mode of OND shows the same precipitation pattern opposite correlated with El Niño phenomenon (Figures 4a–4f) depending on the PDO phase. In this way, the rainfall pattern obtained before the 1940s (positive phase of the PDO) in relation to a warm SST tongue in the tropical Pacific, appears after the 1940s (negative phase of PDO) in relation to a cold SST tongue; and the opposite. The iSST anomalies and the iSLP spatial patterns are broadly similar over the extratropics, except for the western Pacific and Asia iSLP signal, which could be associated with different atmospheric sources for this tropical-extratropical connection. After the 1970s (Figures 4g–4i), when another positive phase of PDO occurs, no significant El Niño signal appears and the precipitation pattern decreases with respect to the one identified in the positive phase of PDO before the 1940s.

4. Summary and Discussion

[12] This paper deals with the non stationary relationship between El Niño and iEMedR along the 20th century, focusing the analysis in “late winter-spring” and in fall seasons. The leading mode of the interannual rainfall presents a tripolar spatial structure with increased precipitation over central Europe, and the opposite over Northern Scandinavia and the Mediterranean. This mode is significantly related to El Niño in a nonstationary way, presenting a multidecadal modulation. Hence, the spatial projection of the anomalous iSLP onto this leading mode depends also on the decades considered and, for those decades in which the leading PC does not correlate with El Niño, the iSLP patterns presents a zonally symmetric structure, suggesting a configuration associated with internally driven changes in the zonal flow. On the opposite side, for those decades in which the leading PC correlates with El Niño, the iSLP pattern suggests the presence of a tropical forcing. This result agrees with *Ting et al.* [1996], who showed that the extratropical climate

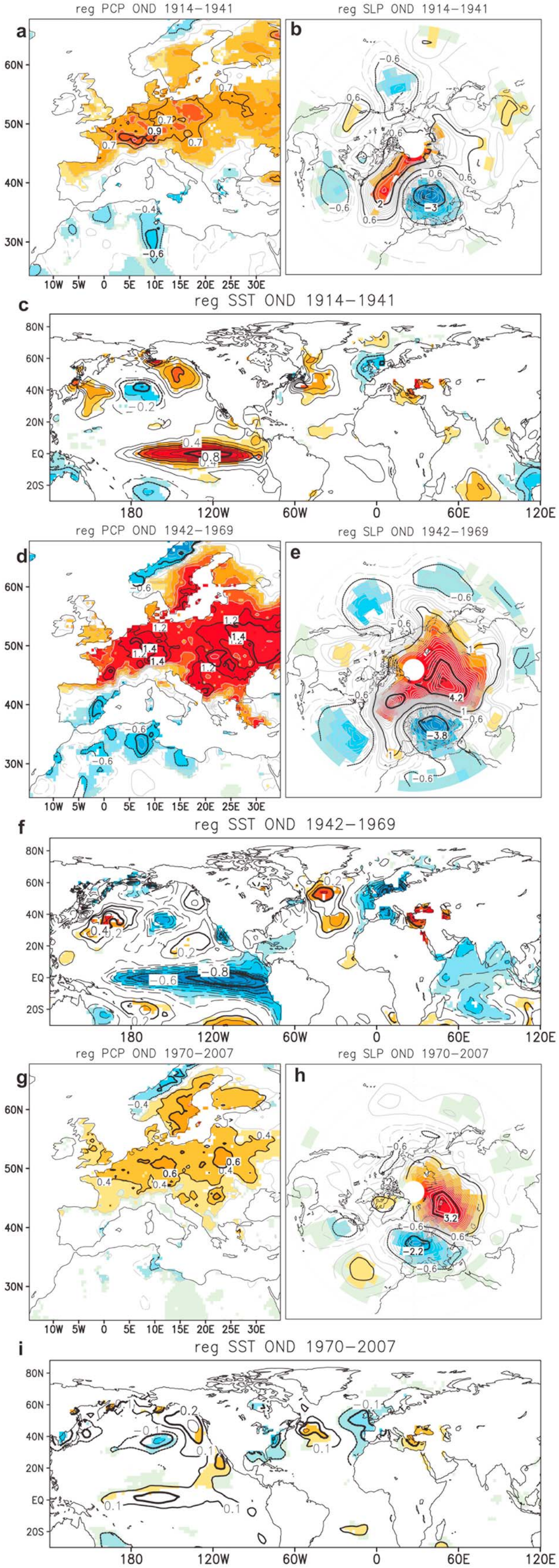

Figure 4. Regression maps in OND for selected periods. As Figure 3 but for particular periods of the PDO: (a, b, and c) correspond to the period 1915–1942, (d, e, and f) for the period 1943–1970 and (g, h, and i) for the period 1971–2008.

anomalies over the northern hemisphere could be understood as a linear combination of teleconnections associated with changes in the zonal mean flow and the ENSO states. This study also agrees with the fact that changes in the location of the anomalous tropical heat source would be producing differences in the extratropical teleconnection [*Ting and Sardeshmukh*, 1993].

[13] Multidecadal changes in the ENSO-EMedR relationship have also been found for these seasons by other authors [*Mariotti et al.*, 2002, *Knippertz et al.*, 2003, *Greatbatch et al.*, 2004], but none of them point to a specific multidecadal pattern as modulator of ENSO teleconnections. Using different methodologies and periods than the above mentioned authors, the present study adds a relevant result to the state of the art, which is the fact that the correlation between the leading interannual rainfall mode and El Niño appears modulated in phase with multidecadal variability patterns, such as AMO and PDO. In late-winter and spring, significant correlations with El Niño appear during negative phases of the AMO, being stronger over central Europe and the Mediterranean, whilst for positive phases of the AMO, the rainfall pattern is weaker. On the basis of this result, a possible mechanism to explain the role of AMO modulating the El Niño-iEMedR relationship in FMA, can be found from the study of *Wang, C.* [2002] due to the similarities in the SST patterns. Although the location of the centers of action could be different, the iSLP configuration identified here over the Pacific (Figure 3) is coherent with the Walker-Hadley mechanism [*Wang, C.*, 2002; *Cassou and Terray*, 2001] as the one linking the SSTs anomalies in the Atlantic and Pacific basins. Therefore, this Walker-Hadley mechanism could be enhanced during negative phases of AMO, getting significant the El Niño-iEMedR teleconnection. For positive phases of AMO, this mechanism is not effective and, thus, internal variability appears as the dominant mechanism. Our results also agree with *Sutton and Hodson* [2003], who suggested that the influence of the ocean on the interannual variability of the North Atlantic climate may have two causes: first, variations in the strength of ENSO, and second, SST changes in the Atlantic Ocean. In fall, the factor modulating the El Niño-iEMedR relationship points to decadal variability of the SST over the Pacific, appearing significant correlations for both, negative and positives phases of the PDO index. It is interesting how, in this case, the same rainfall structure is significantly correlated or anticorrelated with El Niño depending on the phase of the PDO. This change in the El Niño-iEMedR teleconnection could be associated with the reported decadal changes in El Niño behavior due to variations in the background state of the Pacific ocean [*Wang*, 1995; *Wang and An*, 2002], which in turn changes at multidecadal timescales in phase with the PDO. This result agrees with *Zanchettin et al.* [2008], who proposed that the low-frequency modulation of ENSO impacts on European wintertime rainfall (defined from October to March) is associated with multidecadal phases of the PDO via changes in the dynamical behavior of ENSO. The link between extra-tropical atmospheric circulation and central type El Niño events [*Di Lorenzo et al.*, 2010] may provide one additional hypothesis explaining the apparent multidecadal modulation of El Nino influences on iEMedR by the PDO. It is worth mentioning also that the different phases of the PDO are characterised by different frequencies of ENSO events [*Kiem et al.*, 2003; *Verdon and Franks*, 2006], a feature that could be further analyzed. Finally, considering that the global warming observed since 1970's are reproduced when models include anthropogenic effect [*Intergovernmental Panel on Climate Change*, 2007], human influence should be further study as a possible cause of the lack of significant El Niño impact on the fall iEMedR after this decade.

[14] This study is supported by observational analysis of both, ocean and atmospheric data, and it points to the fact of considering the changes in the mean state as a modulator factor of ENSO teleconnections, a result that has important implications in seasonal and decadal predictability. Although decadal fluctuations could be generated by physically varying teleconnections or by chance [*van Oldenborgh and Burgers*, 2005], the analysis performed in the present study for specific phases of both, AMO and PDO, points to a physically coherent modulation of the El Niño-iEMedR relationship by changes in the ocean background state. Nevertheless, further analysis discerning the nonlinear responses, and sensitivity experiments with General Circulation Models (GCMs), are necessary to investigate the underlying dynamics and to test the hypothesis inferred here from the observations.

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References

Alexander, M. A., et al. (2002), The atmospheric bridge: Influence of ENSO teleconnections on air-sea interaction over the global oceans, *J. Clim.*, *15*, 2205–2231, doi:10.1175/1520-0442(2002)015<2205:TABTIO>2.0.CO;2.

Brönnimann, S. (2007), Impact of El Niño–Southern Oscillation on European climate, *Rev. Geophys.*, *45*, RG3003, doi:10.1029/2006RG000199.

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 ARPEGE model, *J. Clim.*, *14*, 4266–4291, doi:10.1175/1520-0442(2001)014<4266:OFOTWL>2.0.CO;2.

Diaz, H., and V. Markgraf (Eds.) (2000), *El Niño and the Southern Oscillation: Multiscale Variability and Global and Regional Impacts*, Cambridge Univ. Press, New York, doi:10.1017/CBO9780511573125.

Di Lorenzo, E., et al. (2010), Central Pacific El Niño and decadal climate change in the North Pacific, *Nat. Geosci.*, *3*, 762–795, doi:10.1038/ngeo984.

Enfield, D. B., A. M. Mestas-Nuñez, and P. J. Trimble (2001), The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S., *Geophys. Res. Lett.*, *28*, 2077–2080, doi:10.1029/2000GL012745.

García-Serrano, J., B. Rodriguez-Fonseca, I. Bladé, P. Zurita-Gotor, and A. de la Cámara (2011), Rotational atmospheric circulation during North Atlantic-European winter: The influence of ENSO, *Clim. Dyn.*, *37*, 1727–1743, doi:10.1007/s00382-010-0968-y.

Greatbatch, R. J., J. Lu, and K. A. Peterson (2004), Nonstationary impact of ENSO on Euro-Atlantic winter climate, *Geophys. Res. Lett.*, *31*, L02208, doi:10.1029/2003GL018542.

Harrison, D. E., and N. K. Larkin (1998), El Niño-Southern Oscillation sea surface temperature and wind anomalies, *Rev. Geophys.*, *36*, 353–399, doi:10.1029/98RG00715.

Hurrell, J. W., Y. Kushnir, G. Ottersen, and M. Visbeck (2003), An overview of the North Atlantic Oscillation, in *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, *Geophys. Monogr. Ser.*, vol. 134, edited by J. W. Hurrell et al., pp. 1–35, AGU, Washington, D. C., doi:10.1029/134GM01.

Ineson, S., and A. A. Scaife (2009), The role of the stratosphere in the European climate response to El Niño, *Nat. Geosci.*, *2*, 32–36, doi:10.1038/ngeo381.

Intergovernmental Panel on Climate Change (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.

Kiem, A. S., S. W. Franks, and G. Kuczera (2003), Multi-decadal variability of flood risk, *Geophys. Res. Lett.*, *30*(2), 1035, doi:10.1029/2002GL015992.

Knippertz, P., U. Ulbrich, F. Marques, and J. Corte-Real (2003), Decadal changes in the link between El Niño and springtime North Atlantic Oscillation and European-North African rainfall, *Int. J. Climatol.*, *23*, 1293–1311, doi:10.1002/joc.944.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079, doi:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2.

Mariotti, A., N. Zeng, and K.-M. Lau (2002), Euro-Mediterranean rainfall and ENSO: A seasonally varying relationship, *Geophys. Res. Lett.*, *29*(12), 1621, doi:10.1029/2001GL014248.

McPhaden, M. J., S. E. Zebiak, and M. H. Glantz (2006), ENSO as an integrating concept in Earth science, *Science*, *314*, 1740–1745, doi:10.1126/science.1132588.

North, G. R., T. L. Bell, R. F. Cahalan, and F. J. Moeng (1982), Sampling errors in the estimation of empirical orthogonal functions, *Mon. Weather Rev.*, *110*, 699–706, doi:10.1175/1520-0493(1982)110<0699:SEITEO>2.0.CO;2.

Quadrelli, R., and J. M. Wallace (2002), Dependence of the structure of the Northern Hemisphere annular mode on the polarity of ENSO, *Geophys. Res. Lett.*, *29*(23), 2132, doi:10.1029/2002GL015807.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, *108*(D14), 4407, doi:10.1029/2002JD002670.

Rodwell, M. J., D. P. Rowell, and C. K. Folland (1999), Oceanic forcing of the wintertime North Atlantic Oscillation and European climate, *Nature*, *398*, 320–323, doi:10.1038/18648.

Rogers, J. C. (1997), North Atlantic storm track variability and its association to the North Atlantic Oscillation and climate variability of northern Europe, *J. Clim.*, *10*, 1635–1647, doi:10.1175/1520-0442(1997)010<1635:NASTVA>2.0.CO;2.

Schneider, U., et al. (2008), *Global Precipitation Analysis Products of the GPCC*, Global Precip. Climatol. Cent., Offenbach, Geramny.

Smith, T. M., R. W. Reynolds, T. C. Peterson, and J. Lawrimore (2008), Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006), *J. Clim.*, *21*, 2283–2296, doi:10.1175/2007JCLI2100.1.

Stephenson, D. B., V. Pavan, and R. Bojariu (2000), Is the North Atlantic Oscillation a random walk?, *Int. J. Climatol.*, *20*, 1–18, doi:10.1002/(SICI)1097-0088(200001)20:1<1::AID-JOC456>3.0.CO;2-P.

Sutton, R. T., and D. L. R. Hodson (2003), Influence of the ocean North Atlantic climate variability 1871–1999, *J. Clim.*, *16*, 3296–3313, doi:10.1175/1520-0442(2003)016<3296:IOTOON>2.0.CO;2.

Ting, M.-F., and P. D. Sardeshmukh (1993), Factors determining the extratropical response to equatorial heating anomalies, *J. Atmos. Sci.*, *50*, 907–918, doi:10.1175/1520-0469(1993)050<0907:FDTERT>2.0.CO;2.

Ting, M., M. P. Hoerling, T. Xu, and A. Kumar (1996), Northern Hemisphere teleconnection patterns during extreme phases of the zonal-mean circulation, *J. Clim.*, *9*, 2614–2633, doi:10.1175/1520-0442(1996)009<2614:NHTPDE>2.0.CO;2.

Trenberth, K. E., and D. A. Paolino (1980), The Northern Hemisphere sea-level pressure data set: Trends, errors, and discontinuities, *Mon. Weather Rev.*, *108*, 855–872, doi:10.1175/1520-0493(1980)108<0855:TNHSLP>2.0.CO;2.

Trenberth, K. E., G. W. Branstator, D. Karoly, A. Kumar, N.-C. Lau, and C. Ropelewski (1998), Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures, *J. Geophys. Res.*, *103*(C7), 14,291–14,324, doi:10.1029/97JC01444.

van Oldenborgh, G. J., and G. Burgers (2005), Searching for decadal variations in ENSO precipitation teleconnections, *Geophys. Res. Lett.*, *32*, L15701, doi:10.1029/2005GL023110.

Verdon, D. C., and S. W. Franks (2006), Long-term behaviour of ENSO: Interactions with the PDO over the past 400 years inferred from paleoclimate records, *Geophys. Res. Lett.*, *33*, L06712, doi:10.1029/2005GL025052.

Vicente-Serrano, S. M., and J. I. López-Moreno (2008), Nonstationary influence of the North Atlantic Oscillation on European precipitation, *J. Geophys. Res.*, *113*, D20120, doi:10.1029/2008JD010382.

Von Storch, H., and F. Zwiers (2001), *Statistical Analysis in Climate Research*, Cambridge Univ. Press, Cambridge, U. K.

Wang, B. (1995), Interdecadal changes in El Niño onset in the last four decades, *J. Clim.*, *8*, 267–285, doi:10.1175/1520-0442(1995)008<0267:ICIENO>2.0.CO;2.

Wang, B., and S. I. An (2002), A mechanism for decadal changes of ENSO behavior: roles of background wind changes, *Clim. Dyn.*, *18*, 475–486, doi:10.1007/s00382-001-0189-5.

Wang, C. (2002), Atlantic climate variability and its associated atmospheric circulation cells, *J. Clim.*, *15*, 1516–1536.

Wang, C. (2004), ENSO, Atlantic climate variability and the Walker and Hadley circulations, in *The Hadley Circulation: Present, Past and Future*, *Adv. Global Change Res*, vol. 21, edited by H. F. Diaz and R. S. Bradley, pp. 173–202, Kluwer Acad., Dordrecht, Netherlands, doi:10.1007/978-1-4020-2944-8_6.

Wang, C., and J. Picaut (2004), Understanding ENSO physics: A review, in *Earth's Climate: The Ocean–atmosphere Interaction*, *Geophys. Monogr. Ser.*, vol. 147, edited by C. Wang et al., pp. 21–48, AGU, Washington, D. C., doi:10.1029/147GM02.

Zanchettin, D., S. W. Franks, P. Traverso, and M. Tomasino (2008), On ENSO impacts on European wintertime rainfalls and their modulation by the NAO and the Pacific multi-decadal variability described through the PDO index, *Int. J. Climatol.*, *28*, 995–1006, doi:10.1002/joc.1601.

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