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A mechanism for the multidecadal modulation of ENSO teleconnection with Europe

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Abstract El Niño phenomenon is the main oceanic driver of the interannual atmospheric variability and a determinant source of predictability in the tropics and extratropics. Several studies have found a consistent and statistically significant impact of El Niño over the North Atlantic European Sector, which could lead to an improvement of the skill of current seasonal forecast systems over Europe. Nevertheless, this signal seems to be non-stationary in time and it could be modulated by the ocean at very low frequencies. Hence, the seasonal climate predictability based on El Niño could be variable and only effective for specific time periods. This study considers the multidecadal changes in the ocean mean state as a possible modulator of ENSO-European rainfall teleconnection at interannual timescales. A long control simulation of the CNRM-CM5 model is used to substantiate this hypothesis and to assess if it can be relevant to explain the non-stationary behavior seen in the twentieth century. The model reproduces the leading rainfall mode over the Euro-Mediterranean region, and its non stationary link with El Niño. This teleconnection has been identified in coincidence with changes of the zonal mean flow at upper levels, which influence the propagation of the waves from the tropics to extratropics through the atmosphere and, hence, to explain the changing impact over Europe. However, the non-stationary impact observed along the twentieth century could also be related to the observed changes in the interannual oceanic forcing signal itself. The results obtained suggest, for both hypotheses, an important role of the natural internal variability of the ocean at multidecadal timescales.

Keywords Atmospheric teleconnection · ENSO · European rainfall · Multidecadal modulation

1 Introduction

The climate variability over the North Atlantic European Sector (NAES) is mainly linked to the North Atlantic Oscillation (NAO; Van Loon and Rogers 1978; Wallace and Gutzler 1981), which is characterized by a Sea Level Pressure (SLP) seesaw between the Azores high and the Icelandic low (Walker 1924). This fluctuation between subpolar and subtropical North Atlantic latitudes influences the stormtracks, and hence, the associated precipitation regime (Rodwell et al. 1999; Hurrell et al. 2003). Although the NAO is mainly associated with internal atmospheric variability, it is also influenced by changes in Sea Surface Temperature (SST), which could lead to predictability at seasonal to interannual time scales (Czaja and Frankignoul 1999; Hurrell et al. 2003). Several studies have found a consistent and statistically significant ENSO signal on the European climate (Fraedrich and Müller 1992; Moron and Plaut 2003). Interestingly, its low-level atmospheric pattern is similar to the one associated with the internal NAO (García-Serrano et al. 2010). In general, El Niño tends to be associated with a negative phase of the NAO (Brönnimann

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2007). This raises the issue of a robust detection of the atmospheric response to ENSO as the forced response projects onto the leading mode of internal variability. Furthermore, an additional factor is that the influence of the NAO (Hilmer and Jung 2000; Lu and Greatbatch 2002; Vicente-Serrano and López-Moreno 2008) and ENSO (López-Parages and Rodríguez-Fonseca 2012; Greatbatch et al. 2004; Mariotti et al. 2002; Zanchettin et al. 2008) over the North Atlantic European climate, has not been stationary along the twentieth century. Hence, the seasonal climate predictability could be variable and only effective for specific time periods, contributing in that way to the poor skill of current seasonal forecast systems over Europe (Van Oldenborgh and Burgers 2005).

A recent study of López-Parages and Rodríguez-Fonseca (2012, hereafter LPRF12) indicates, using observational data of rainfall, SLP and SST along the twentieth century, that the leading mode of interannual rainfall in the European region is significantly correlated with El Niño during some particular decades whilst, in others, there is no link with any large scale oceanic pattern. The spatial structure of the associated SLP field was similar to the traditional NAO. However, to better determine the dynamical link, the study of upper atmospheric levels is crucial, as was demonstrated by García-Serrano et al. (2010). ENSO influence over NAES can take place through different mechanisms which could include the alteration of the thermally driven overturning atmospheric circulation (Wang 2002, 2004; Wang and Enfield 2003; Ruiz-Barradas et al. 2003), downstream propagation of Rossby waves, including or not the stratosphere (Hastenrath 2003; Cassou and Terray 2001; Honda et al. 2001; Castanheira and Graf 2003; Ineson and Scaife 2008), or combinations of these mechanisms. The former occurs by the alteration of the Walker and Hadley circulations in relation to changes in the convection. The latter is explained through changes in the vorticity due to the meridional displacement of the flow at upper levels as a result of the divergence associated with the convection in the tropics. This vorticity disturbance triggers Rossby waves propagating over the extratropics and altering the atmospheric circulation over remote regions. In this way, a non-stationary impact of ENSO over Europe should be related to a non-stationary behavior of one (or both) of the previous mechanism. Recent studies have also found noticeable differences in the impacts of the two major ENSO patterns, Eastern and Central Pacific events (Kug et al. 2009; Kao and Yu 2009; Choi et al. 2011), the former being representative of the most intense El Niño events and the latter linked with the most intense La Niña ones (Dommenget et al. 2012). In this study non-Linear impacts of ENSO are not analyzed, each kind of episodes could be related to different non-stationary features of the abovementioned mechanisms (An and Wang 1999; Fedorov 2000; An 2009; Choi et al. 2011; Yeh et al. 2011). A possible hypothesis that could explain the changing impact of ENSO over the NAES is associated with a modulation of the teleconnection by which the forcing signal is transmitted to the target area depending on the background state. Hence, an interesting issue to be explored here is the influence of oceanic low frequency variability modes, such as Atlantic Multidecadal Oscillation (AMO, Enfield et al. 2001), or Pacific Decadal Oscillation (PDO, Mantua et al. 1997), in the modulation of the atmospheric teleconnection mechanisms at interannual timescales. In this sense, LPRF12 found how the correlation between the leading rainfall mode in Europe and the anomalies over the Niño3.4 region evolves at multidecadal timescales in phase with AMO, and PDO, depending on the season considered. Building on these previous studies, the main questions we wish to address in the present work are as follows: (1) is there any SST multidecadal pattern, internal to the ocean, that could be able to modulate the ENSO teleconnection with Europe? (2) How does this SST pattern modulate the teleconnections? (3) What are the associated dynamical mechanisms? (4) Is there any preferred phase of these multidecadal SST modulating patterns for which the ENSO-Europe teleconnection is more efficient?

Therefore, the present study is mainly related to the non-stationary influence of ENSO over the NAES and how the internal variability of the slowly variant background state of the ocean can modulate this teleconnection.

The available literature suggests January to March as an appropriate season to study the ENSO influence over Europe (Brönnimann 2007), being convenient to separate the weak ENSO-related circulation over the North Atlantic in early winter with the much stronger one during mid-late winter (Toniazzo and Scaife 2006; Gouirand et al. 2007). Even in the North Pacific, the canonical Tropical Northern Hemisphere pattern (TNH, Mo and Livezey 1986; Barnston and Livezey 1987; Livezey and Mo 1987; Trenberth et al. 1998) related to ENSO is not completely established until January (Bladé et al. 2008). For these reasons this work is focused on the non-stationary ENSO-European rainfall teleconnection in late winter early spring, selecting the season February–March–April, according to LPRF12. A complete analysis cannot be carried out using only observations due to the shortness of the record and limited sampling of multidecadal SST modes. It is thus of interest to use a model approach where the non-stationary behavior could be assessed on multi-centennial simulations. To this aim, a long coupled simulation with constant pre-industrial forcing has been analyzed to complement the observational analysis. If the changes identified in the ENSO-European rainfall relationship along the twentieth century could be reproduced only considering the internal variability of the climate system, it would suggest that the responsible mechanism of the non-stationary behavior is not necessarily related to anthropogenic changes.

The paper is organized as follows. We begin by presenting the data and methods used (Sect. 2). In Sect. 3 the covariability of European rainfall and tropical SSTs is analyzed for observations. The same analysis is applied to a long control simulation of the CMIP5-CM5 coupled model in Sect. 4. In Sect. 5, observed and modeled composites maps of different fields are compared to each other. Then, in Sect. 6, some plausible hypotheses of the non-stationary features identified are presented and finally, in Sect. 7, a brief summary is presented.

2 Data and methods

This work is focused on the interannual precipitation over the Euro-Mediterranean region (iEMedR; 24°N–68°N, 15°W–35°E), in late winter-early spring (February–March–April, FMA).

Two different observational databases have been used: University of Delaware rainfall data (Matsuura and Willmott 2009, version 2.01, http://climate.geog.udel.edu/climate/html_pages/), and Global Precipitation Climatology Centre data (GPCC; Schneider et al. 2008). Both data are monthly climatology of precipitation spanning the whole twentieth century and the beginning of the twenty-first century. They are land-only in coverage and are based on interpolated data from stations. Regarding the SST data, 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) have been used. To pose a possible dynamical mechanisms and be able to compare it with the model outputs, atmospheric fields from the twentieth century Reanalysis V2 data provided by the NOAA/OAR/ESRL PSD (Boulder, Colorado, USA; http://www.esrl.noaa.gov/psd/), have also been used.

The climate model data are provided by a long control coupled simulation (hereinafter PICTRL) of the CNRM-CM5 model (cf. Voldoire et al. 2013). This model includes the ARPEGE-Climat (v5.2) atmospheric model (1.4° × 1.4°, 31 vertical levels, being 26 of them in the troposphere), the NEMO (v3.2) ocean model (ORCA1°, 42 vertical levels), the ISBA land surface scheme and the GELATO (v5) sea ice model coupled through the OASIS (v3) system. The PICTRL analyzed here is an 800 year long simulation where all external forcings (solar, volcanic and anthropogenic Greenhouse Gases and aerosols) are kept constant at their observed values of 1850.

Regarding the methodology, a Maximum Covariance Analysis (MCA, or Singular Value Decomposition; Bretherton et al. 1992) has been applied to identify the modes that explain the maximum covariance between the anomalous Euro-Mediterranean rainfall and tropical SST (20°N–20°S). Each mode comprises two spatial structures (singular vectors), two time series (expansion coefficients; U and V for the predictor and predicted field respectively), and the covariance fraction, which is a measure of the percentage of covariability explained by each mode. The most common procedure when analyzing MCA results is to plot the projection of the predictor field (tropical SSTs here), and the field to predict (Euro-Mediterranean rainfall), on the standardized U, obtaining in that way the homogeneous and heterogeneous maps respectively. Along this study some composite maps also based on U have been obtained, being 1 standard deviation of U the threshold selected in PICTRL, and 0.75 standard deviation in observations. This difference in the threshold is considered to balance the number of cases selected in both, model and observations. These composites have been calculated to analyze the changes in the spatial patterns depending on the time period, and also to infer possible related dynamical mechanisms.

To retain only the interannual variability for all the fields analyzed here, periods longer than 7 years have been subtracted by applying a temporal filter based on a Discrete Fourier Transform. Looking for the stationarity of El Niño impact, different sliding window correlation analysis have been applied along the study, using 21 year as the reference window, for comparison with previous studies.

The correlation statistical significance has been determined by a non parametric approach using a Monte-Carlo test with 400 permutations. The spatial patterns significance has been also determined by non parametric approaches such as, Monte-Carlo test, or Wilcoxon-Mann–Whitney test (Wilks 2005).

3 Rainfall-SST covariability: observational results

As it was shown in LPRF12, the teleconnection between El Niño and the European rainfall leading mode of variability in late winter-early spring seems to be non-stationary on time, changing along the twentieth century in phase with the Atlantic Multidecadal Oscillation (AMO). The leading EOF is shown in Fig. 1a, which is consistent with the ENSO signal over the European rainfall (Fraedrich and Müller 1992; Moron and Plaut 2003; Pozo-Vazquez et al. 2005). In order to delve into the existence of this impact and to discard it as a statistical artifice, a time index based on this leading EOF has been used. This index has been calculated as the difference of area-average rainfall over Western Europe and Western Mediterranean region. These areas are two centers of actions of the leading EOF (black boxes in Fig. 1a), and they do not coincide with those in the second and third modes of variability (see Figure A1 of supplementary material). Time correlation between

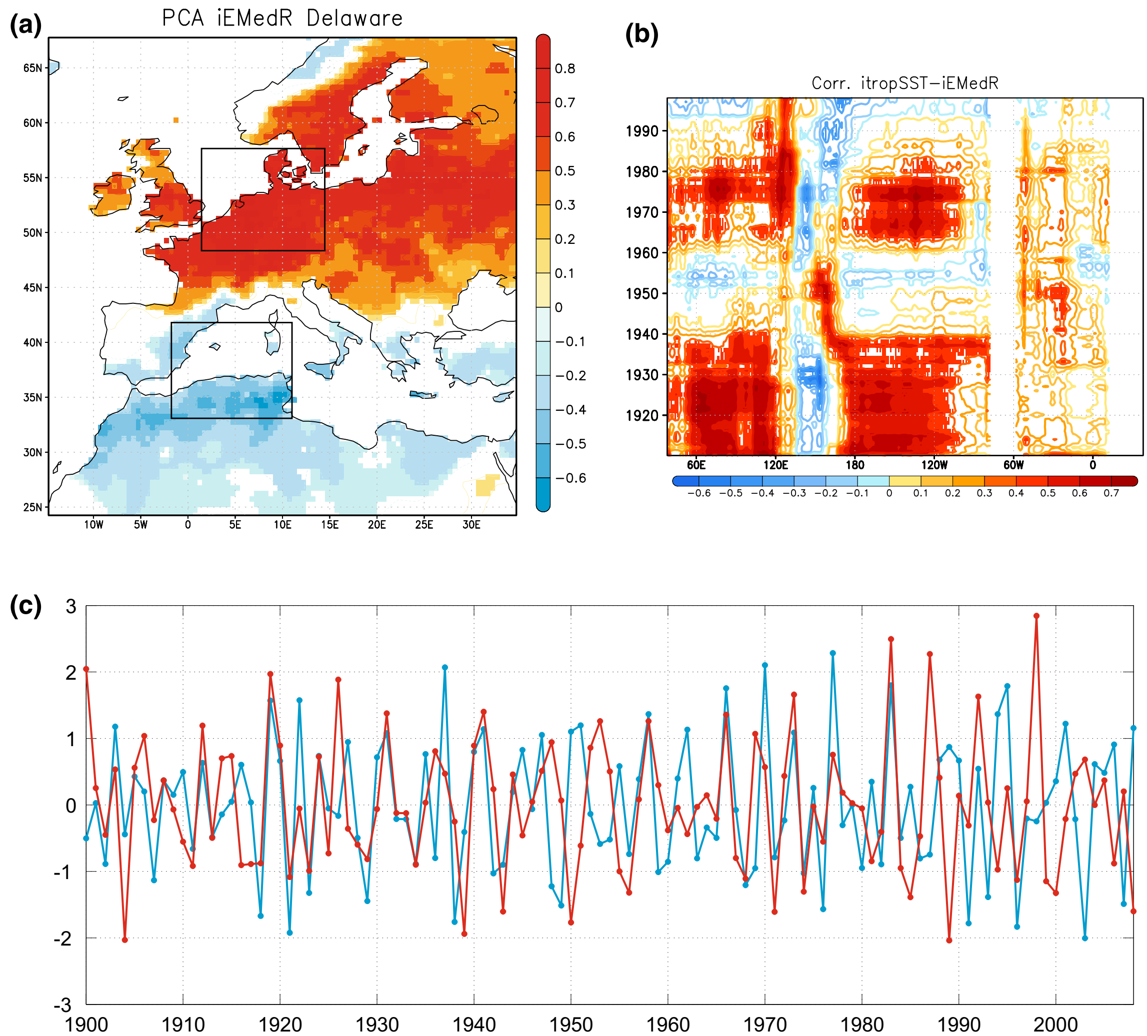

Fig. 1 **a** Leading rainfall empirical orthogonal function over the Euro-Mediterranean region (EOF1, standardized rainfall per standard deviation in the associated PC1). **b** 21-Years sliding windows correlation between the PC1 and tropical SSTs (5°S–5°N). **c** Standardized PC1 (*blue*) and Niño34 (*red*) Indices. *Black boxes* in (**a**) indicate the regions used to calculate the rainfall index mentioned in the manuscript (Western Europe minus Western Mediterranean). Statistical significant areas, according to a Monte-Carlo test at the 95 % level, are *shaded*

the leading PC and the above-mentioned index is 0.83, which supports the absence of a mathematical artifact in the calculation of the leading EOF. The link with the equatorial SSTs is, moreover, non-stationary on time (Fig. 1b). Thus, strong correlations with the whole Indo-Pacific equatorial basin are positive from 1900s to 1940s and from 1960s to 1980s. However, for the years in between and, in the beginning of the twenty-first century, the correlations are weaker and of opposite sign. For the whole twentieth century, the SST pattern coincides in sign in the Pacific and Indian oceans, while being opposite over the Maritime Continent. Although the magnitude of the correlation scores slightly differs between HadISST and ERSST (not shown), in both cases the maximum values are located over the Niño3.4 region, as in LPRF12. In agreement with Fig. 1b, the Euro-Mediterranean rainfall PC1 and the Niño3.4 index (Fig. 1c) broadly correlate from 1900 to 1940 (0.47), and from 1965 to 1984 (0.42) approximately, while they are mainly anticorrelated from 1944 to 1964 (−0.23), and from 2003 to 2008 (−0.73).

The previous results reinforce those of LPRF12 and show how, although the dipolar rainfall pattern identified as EOF1 is present along the whole observational period, it might be enhanced and potentially predictable when its relation with tropical SSTs is stronger. It also shows that this link mainly takes place in the twentieth century during negative phases of AMO. As it was indicated in Sect. 2, MCA is a discriminant analysis tool which is very useful for finding coupled patterns in climate data and, thus, for

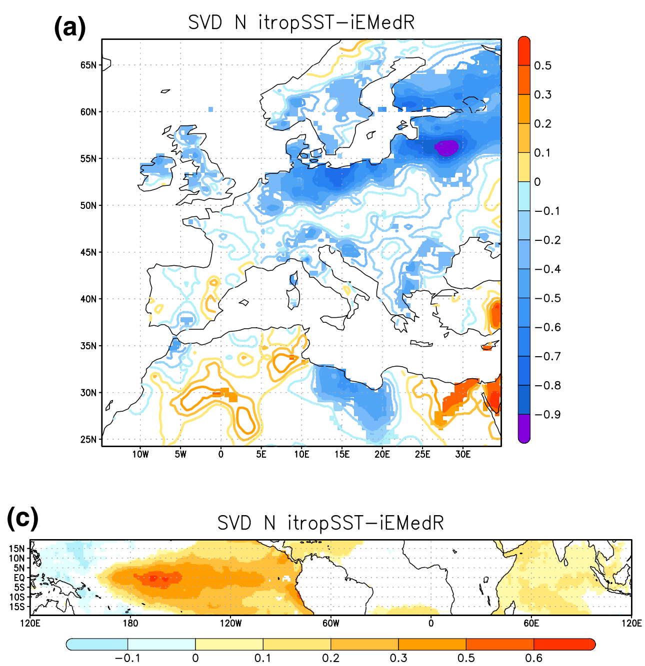

Fig. 2 Homogeneus (*bottom*) and heterogeneous (*up*) regressions maps of respectively SST (° per std. deviation in U) and rainfall (standardized rainfall per standard deviation in U) onto the MCA SST expansion coefficient (U) obtained for N and P periods. On the *left* (**a**, **c**) the leading covariability mode for observed N periods (1944–1964 and 2003–2008) and, on the *right* (**b**, **d**), the same for observed P periods (1900–1940 and 1965–1984)

determining the most frequent predictors for a variable to predict. With the purpose of confirming the changing coupling between rainfall and SST, two different MCA analyses linking the Euro-Mediterranean rainfall and the tropical SST have been performed selecting two different samples according to the changing relationship previously identified. The first sample covers the periods 1944–1964, and 2003–2008, which correspond to the years with negative correlations between rainfall and Niño3.4 (Fig. 1c). The second sample (1900–1940 and 1965–1984) corresponds to the periods with positive correlations between the same indices. Hereinafter these periods will be referred as N (Negative correlations) and P (Positive correlations) periods respectively.

The leading mode of covariability for the P period (Fig. 2b, d), which explains 31.1 % (28.3 % for ERSST) of the total covariance, resembles the link identified in LPRF12 (see Fig. 1 of LPRF12). The spatial correlation between the rainfall anomalous pattern obtained in LPRF12 and that obtained here from the MCA_P is 0.88 (0.85 for ERSST). On the other hand, for N periods (Fig. 2a, c), the leading mode, which in this case explains 23.3 % (21.6 % for ERSST) of the total covariance, shows a similar SST pattern than in P periods, but in relation to a completely different rainfall pattern. The spatial correlation between the rainfall pattern from LPRF12 and that obtained here from the MCA_N is −0.61 (−0.59 for ERSST). These rainfall maps obtained for each MCA broadly coincide with the simple regression of rainfall anomalies on the Nino3.4 index (see Figure A2 of supplementary material) for the selected periods. Although the tropical SSTs for both MCAs are similar, it is worth to highlight the enhanced signal identified in P over the Tropical North Atlantic (TNA) and the Maritime continent regions. This issue will be discussed in Sect. 5.

As the observed changing link between rainfall and tropical Pacific SSTs appears in phase with the AMO, and this oceanic mode is internal to the ocean, a long coupled control simulation has been used to test if this non-stationary relationship could be reproduced by the model multidecadal internal variability without any changes in external forcing.

4 Model performance

It is first necessary to assess the ability of the model to reproduce the leading mode of observed interannual rainfall variability. The observed and simulated modes present a similar spatial pattern (Fig. 3a), with significant scores in central Europe, including the British Islands, and the surrounding areas of the Baltic Sea. These anomalies are opposite in sign to those over the Mediterranean region, the northwestern Africa, and the north of Scandinavia. This leading rainfall

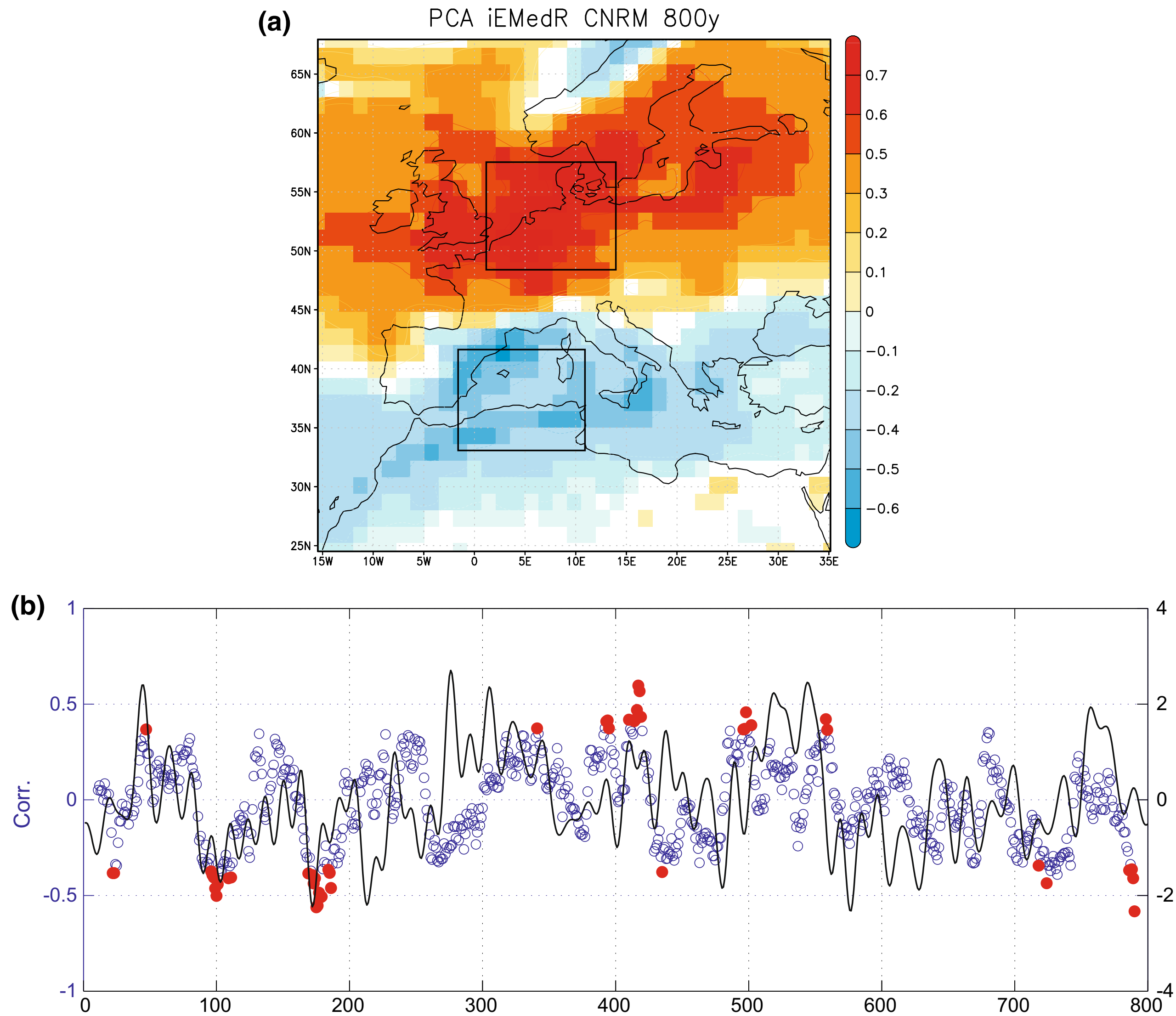

Fig. 3 **a** Leading empirical orthogonal function in PICTRL over the Euro-Mediterranean region (EOF1, standardized rainfall per standard deviation in the associated PC1). **b** 21-Years sliding windows correlation between the interannual rainfall PC1 and the Niño3.4 index (*dots*), and PC1 of an EOF analysis of the low frequency SSTs (*black line*, for which only higher periods than 13 years have been considered). *Fill dots* and *shaded areas* represent 95 % significance according to a Monte-Carlo test

mode can be described through the same simple index previously used in observations (see black boxes in Fig. 1a). In this case PC1 is correlated at 0.89 with the defined index. Slight differences with observational EOF1 are found in the intensity and location of the centers of action, and in the decrease of the explained variance by the leading mode (19.2 % in observations and 14.4 % in PICTRL). This fact is probably explained by the large difference in the number of years analyzed in observations (109 years) and PICTRL (800 years). In spite of this decrease in the explained variance, the leading mode of PICTRL is well separated to the second one according to the criteria of North et al. (1982). Looking for the stationarity of the rainfall mode, 21-yr window sliding correlations have been calculated here (Fig. 3b) between the rainfall leading PC and the Niño3.4 index, indicating a quasi-cyclic behavior in the relationship and, as a consequence, periods with positive, negative, or even no correlation. This time evolution is highly similar to the leading PC of the low frequency SST variability of the model (Fig. 3b). PICTRL, which is a long control simulation, is a useful tool to assess the time evolution identified in the moving correlations (see also Figure A3) and its possible connection with multidecadal modes such as AMO, as was proposed in LPRF12.

As in the observations, two different, and opposite, relationships emerge between rainfall and El Niño along the PICTRL, suggesting the existence of different underlying dynamics that alternate at multidecadal timescales. To further analyze this issue, periods with negative (N, 169 years)

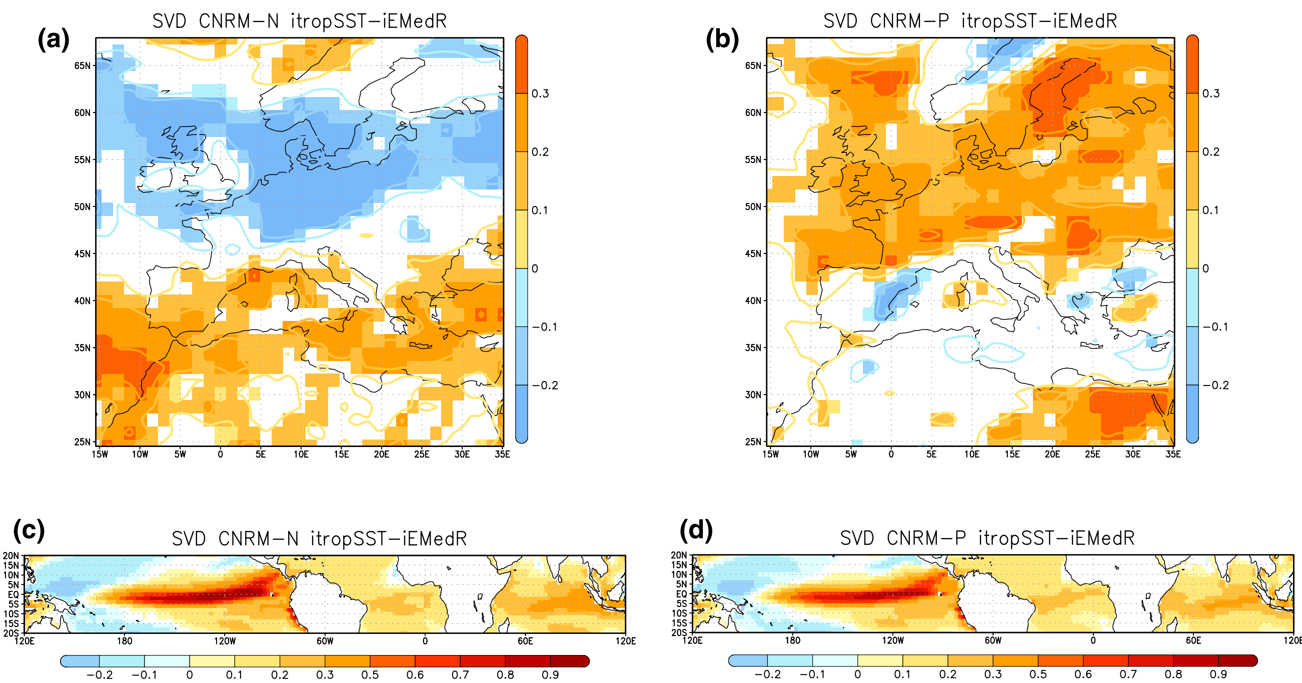

Fig. 4 Same as Fig. 2 but for the long control run in the model CNRM-CM5 (PICTRL)

and positive (P, 137 years) significant correlations have been analyzed separately.

MCA analysis between model anomalous rainfall and tropical SSTs has been performed for P and N. The leading modes of covariability account for 20.0 % and 21.9 % of the total variance, respectively. The resultant oceanic patterns (Fig. 4c, d) resemble the ones obtained in observations (Fig. 2c, d). However, unlike it happens in observations, the model ENSO signal is almost the same in P and N, putting forward how in PICTRL, the interannual SST forcing seems to be stationary. Nevertheless, its impact on rainfall is opposite in P and N periods over central Europe and the Mediterranean region. The spatial correlation between the rainfall patterns obtained for each period and the EOF1 for the whole PICTRL (Fig. 3a) are −0.90 and 0.71 for N and P respectively, reinforcing the idea of a changing impact over the Euro-Mediterranean area for the same tropical forcing.

In the next section the atmospheric variables related to the leading modes of covariability obtained for N and P periods are analyzed in order to infer different hypothesis for the dynamical mechanisms involved in the teleconnection.

5 Dynamical mechanisms in the teleconnection

Several composites maps have been calculated for each time period and for different variables involved in the above mentioned mechanisms. The expansion coefficient of tropical SSTs (hereinafter U) from each MCA has been used to perform “high minus low” composites maps as the difference between events for which U is greater than (high events), or lower than (low events) an imposed threshold (see Sect. 2).

The observational results are represented in Fig. 5 for N and P periods. In both cases, a warming (cooling) in El Niño and a extratropical horseshoe pattern over the North Pacific (Fig. 5a, b) appears in relation to an anomalous upper level divergence (convergence) over the central equatorial basin (Fig. 5c, d) and a weakening (strengthening) of the subtropical Pacific anticyclone. However, the tropical divergence together with its rotational response is clearly enhanced in P periods (Fig. 5c, d), as a consequence of the stronger El Niño amplitude in decades in which the north Atlantic is cooler than the south Atlantic, as it happens in P periods (Dong et al. 2006; Zhang et al. 2011). In agreement with Wang (2002), El Niño signal over the Pacific appears together with a heating in the Tropical North Atlantic (TNA), in association with a weakening of the Azores high (Fig. 5f). The connection takes place through changes in the Walker and Hadley circulations, as it can be seen by the Atlantic anomalous upper level convergence over South America and divergence over the TNA region (Fig. 5d). As the TNA region highly influences the ENSO-related atmospheric response over the NAE sector (Mathieu et al. 2004), its stronger signal for selected P periods, a time period with a stronger relation of El Niño with the rest of the tropical basins (Losada et al. 2010, 2012), could explain the non stationary impact of El Niño over the European climate.

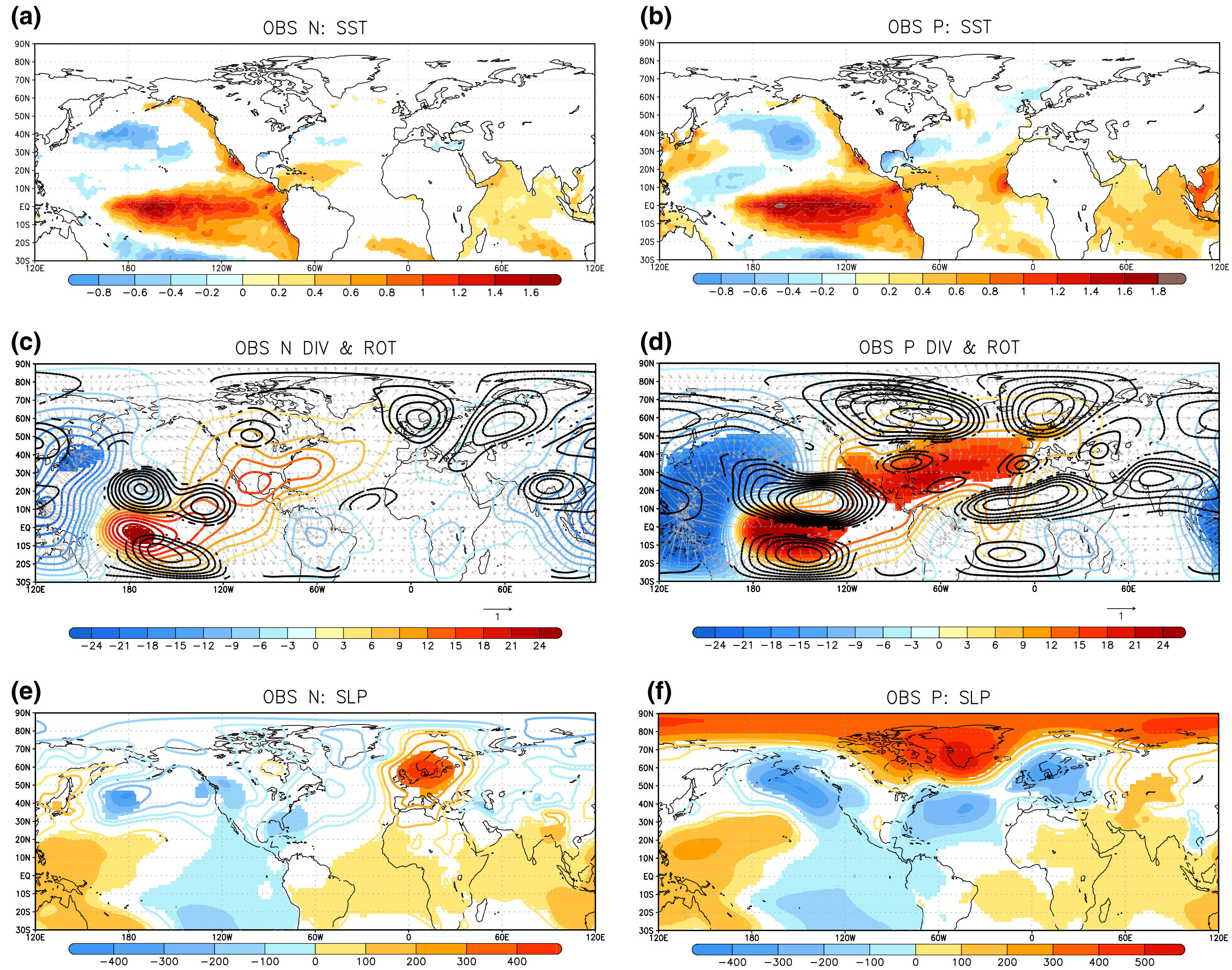

Fig. 5 High (higher that 0.75) minus low (lower that −0.75) composites maps, in N and P periods, based on the first SST MCA standardized expansion coefficient U for **a**, **b** HadISST (°); **c**, **d** potential velocity (in colour, 10^5 m^2 s^{-2}), streamfunction (*black contours*, $ci = 10^6$ m s^{-2}), and divergent wind (*arrows*, m s^{-1}) at 200 hPa, and **e**, **f** sea level pressure (Pa). Statistical significant areas, according to a Monte-Carlo test at the 95 % level, are *shaded*. In **c** and **d** only the 95 % significant streamfunction is contoured (being *solid lines* positive values and *dashed lines* negative ones)

This feature could, however, be also associated with the multidecadal variability of the Atlantic Warm Pool that is known to vary in phase with the AMO (Wang et al. 2008b). In general, the significant differences identified over the extratropical Atlantic and Pacific suggest a changing influence of the atmosphere on the underlying ocean (Fig. 5a, b). Regarding the tropical Indo-Pacific basin, warmer SSTs are observed in P from the Maritime continent to the Japan Islands. Thus, Rossby Wave Sources over these regions might be intensified in response to the warmer ocean. Moreover, in P as well, a stronger longitudinal gradient seems to take place over the west equatorial Pacific, in agreement with Meng et al. (2012), who have related it to a weakening of the Walker Circulation in association with a warmer Indian ocean. As a consequence of the changes in the tropical upper level divergence, an anomalous rotational circulation appears to balance the variation in the planetary vorticity to preserve the potential vorticity. For both, N and P periods, two twin anticyclones straddling the equator over the tropical Pacific reflect the typical Gill-type atmospheric response to equatorial anomalous heating (Gill 1980). However, only for P periods, the wavetrain propagating from the tropical Pacific resembles the well known TNH pattern. Moreover, a strong negative center of action also appears in P over Scandinavia. The whole quadrupolar atmospheric pattern over the North Atlantic-European sector has a quasi-barotropic structure (Fig. 5d, f) except for the Iberian Peninsula center that is not significant at surface levels. This configuration is coherent with the leading mode of upper level streamfunction in mid-winter obtained by García-Serrano et al. (2010), and related to El Niño extratropical rotational atmospheric response. Complementary to that study, in which the stationary behavior is not discussed, this spatial structure (see Figs. 1, 3 of that paper) is found here just for selected P periods. The centre of action located over Scandinavia in P might be due to a split of the ENSO wavetrain originated in the tropical Pacific, as was suggested by García-Serrano et al. (2010) for January–February. The appearance of this pattern over the North Atlantic (Fig. 5d, f), and the role of low frequency changes in the ocean on its nonstationary behavior, will be further analyzed below.

For N decades, however, in agreement with a weaker heating at surface and a weaker divergent flow at upper levels, the TNH pattern weakens and the resultant configuration over North-Atlantic Europe (Fig. 5c) is different. At surface (Fig. 5e), the strong center of action located over the North Sea resembles an atmospheric blocking pattern. Thus, it seems that these blocking structures could be favored in N periods, in agreement with recent results putting forward an enhancement of the frequency of blocking events under positive phases of the AMO (Häkkinen et al. 2001).

Model results are represented in Fig. 6 for N and P periods. Contrary to the observations, the SST patterns and the associated perturbation of the divergent flow are highly similar to each other (Fig. 6a, b). The stronger influence in P of the atmosphere on the extratropical Atlantic and Pacific basins is, however, well reproduced by the model. The significant divergence signal over the North Atlantic, which is found in PICTRL for both N and P, resembles the response found just for P in observations. The significant upper level convergence over the equatorial Atlantic for PICTRL (Fig. 6c, d) appears in relation to an underlying warming (Fig. 6a, b), indicating the dominant influence of the remote warming in comparison with the local warming (which would induce divergence at upper levels). A significant velocity potential signal is also identified in PICTRL over the Indian Ocean, being slightly stronger for P periods. A striking feature is that these similar divergent responses for P and N are related to different rotational responses over the NAES (Fig. 6c, d). Over this region, the wave pattern at upper levels seems to significantly reach the European continent in P, the response being broadly the same as the one identified in observations at surface (Figs. 5f, 6f) and upper levels (Figs. 5d, 6d). Conversely, in N, the North Atlantic region is less perturbed by the TNH pattern and a dipolar configuration emerges at surface (Fig. 6e), resembling an internally driven NAO configuration and not the blocking pattern that appears in the observations (Fig. 5e).

Previous works have documented changes in the location of the actions centers of the NAO along the twentieth century (Hilmer and Jung 2000; Lu and Greatbatch 2002; Vicente-Serrano and López-Moreno 2008). Thus, our results could suggest an additional non-stationary external forcing over the NAES that could contribute to the documented changes in the observed NAO structure.

In agreement with the above mentioned results, it seems that the model is able to reproduce the observed impact of ENSO over the Northern Hemisphere and the Euro-Mediterranean region, at least, for selected periods (P). However, although the mechanism could be related to the Walker-Hadley atmospheric bridge and the TNH pattern, a different extratropical response occurs in relation to almost the same tropical heating in PICTRL for N periods (see Figure A4 of supplementary material). At this point a question emerges: if the forcing from the tropical Pacific SSTs is considered stationary in PICTRL, why the impact over the European rainfall is so different? A plausible explanation is that the zonal mean flow at upper levels, which influences the propagation of Rossby waves (Hoskins and Ambrizzi 1993), changes due to variations of the low-frequency oceanic forcing. This issue is analyzed in the next section.

6 Contribution of mean state changes to the interannual teleconnection

As it has been previously shown, tropical heating associated with El Niño is similar in N and P periods for PICTRL, so the distinct signals identified for each kind of period could reasonably be attributed to variations in the mean state. The characteristics of a control simulation make easier the inference of the role of low frequency SST internal variability because external forcings are constant and thus not considered. According to the results obtained in PICTRL, the changes in El Niño teleconnection observed over the North Atlantic and the Euro-Mediterranean region could be explained through changes in the internal mean state (not forced by the GW).

The rotational flow at upper levels previously plotted in Figs. 5d and 6c, d is presented in Fig. 7 in a north polar stereographic projection, identifying a similar configuration for those periods with a significant divergence flow signal associated with ENSO (P and N in PICTRL and P in observations). Nevertheless, the TNH pattern over the NAE sector is clearly weaken in PICTRL for N periods (Fig. 7a), while in P (Fig. 7b), the configuration over the North Atlantic is significantly stronger and highly similar with the observations (Fig. 7c). According to the basic Rossby Wave Theory proposed by Hoskins and Ambrizzi (1993), the planetary waves are always refracted towards latitudes with higher Rossby wavenumbers (Ks). As a consequence, positive anomalies of Ks indicate regions with a reinforced waveguide. Thus, the northward displacement of the Indo-Pacific jet in P (Fig. 8a), and its related Rossby waveguide

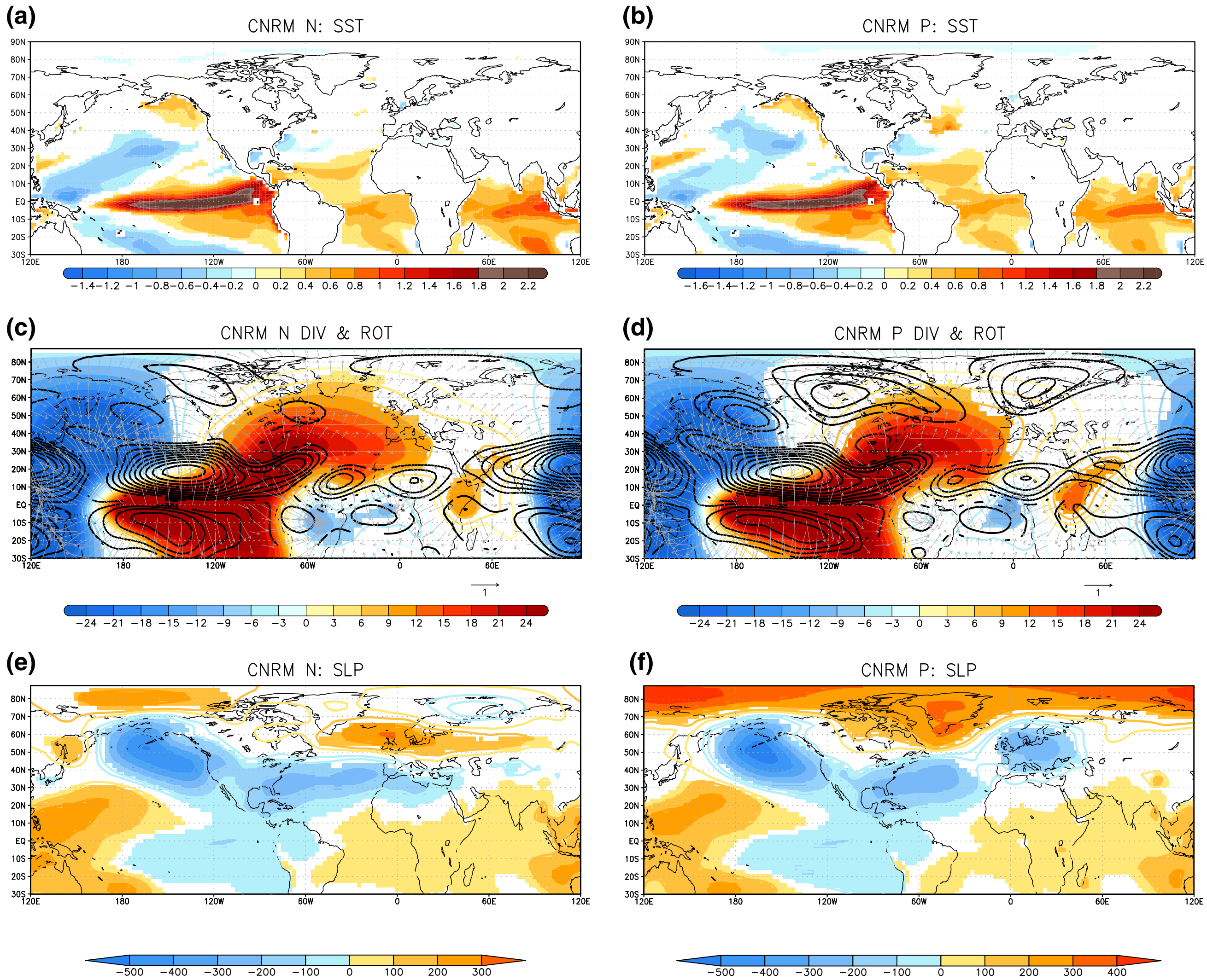

Fig. 6 Same as Fig. 5 but for the long control run in the model CNRM-CM5 (PICTRL). Here, higher values than 1 (U > 1 standard deviation) and lower values than −1 (U < −1 SD) have been considered for the composites maps

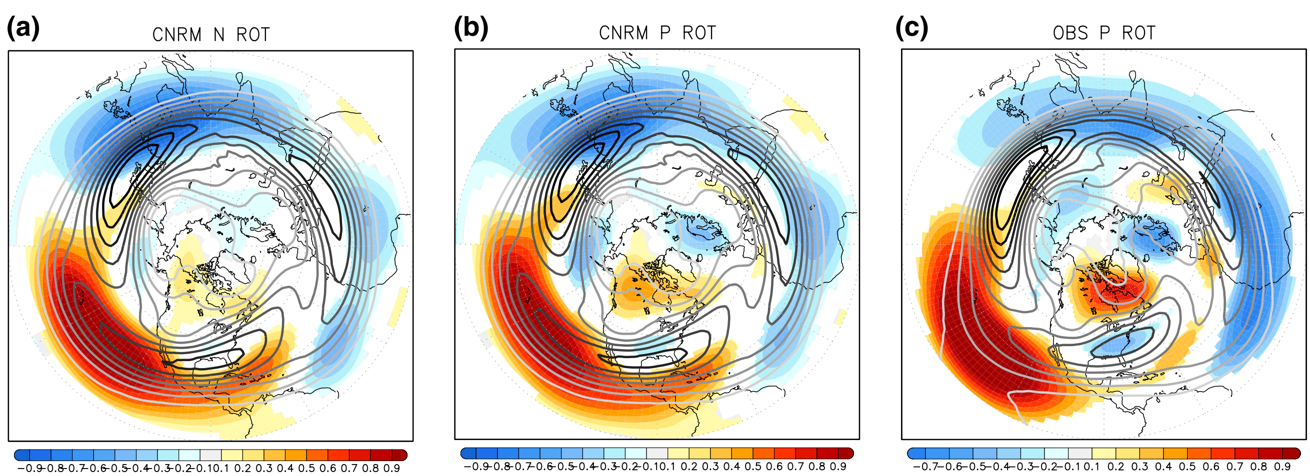

Fig. 7 Same composites maps of streamfunction (*shaded*; 10^7 m s^{-2}) as in **a** Fig. 6c, **b** Fig. 6d, and **c** Fig. 5d. In contours the zonal mean flow at 200 hPa (contours, ci = 5 m s^{-2}), being the maximum and minimum value represented 10 and 50 m s^{-2} in each case

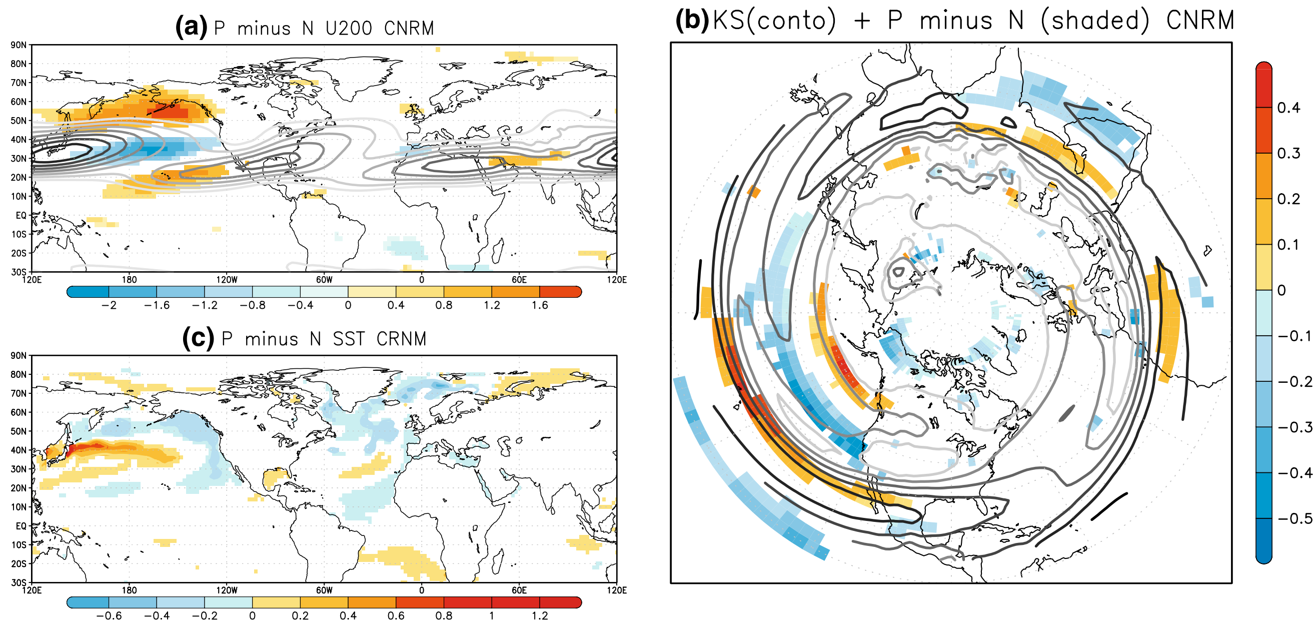

Fig. 8 High (P periods) minus low (N periods) significant composites maps in PICTRL for **a** zonal mean flow at 200 hPa (m s^{-1}), **b** mean Rossby wavenumber at 200 hPa (Ks) and **c** SST (°). The climatological zonal mean flow (**a**) and the climatological mean Rossby wavenumber (**b**) at 200 hPa are also shown in contours levels, being the maximum and minimum value represented 20 and 50 m s^{-1} (ci = 5 m s^{-1}) in the former case, and 3 and 8 (ci = 1) in the latter case. Only the 90 % statistical significant areas, according to the Wilcoxon-Mann–Whitney test, are plotted

(Fig. 8b), over the North Pacific, can explain the enhanced propagation of the disturbances to higher latitudes for P periods in the model. Hence, a stronger ENSO-related rotational atmospheric pattern over the NAES (García-Serrano et al. 2010) is identified (Fig. 7b). This difference could explain the non-stationary impact on rainfall between P and N periods in the model. The rotational flow configuration shown in Fig. 7 is also coherent with a remote displacement of the disturbances along the northern hemisphere due to the above-mentioned waveguide effect of the zonal mean flow (Hoskins and Karoly 1981; Branstator 1992, Hsu and Lin 1992; Hoskins and Ambrizzi 1993; Ambrizzi et al. 1995; Branstator 2002). Thus, it seems that a more efficient waveguide effect and so, a stronger hemispheric response, could also contribute in P to the above mentioned ENSO-related rotational impact over the North Atlantic.

These changes in the zonal mean flow are related to the underlying ocean multidecadal variability (Fig. 8c), which signal appears significant over the North Pacific and Atlantic basins, resembling typical multidecadal variability patterns associated with the well known PDO (Mantua et al. 1997) and AMO modes (Knight et al. 2005). As the jet streams are partially caused by the meridional temperature gradient in the earth's atmosphere, a significant change in their location could be expected if the underlying ocean temperature varies along the time. Thus, the non-stationary impact over the NAE sector identified in PICTRL could ultimately be explained by changes in the zonal mean flow forced by the slowly variant component of the ocean.

The observational results point to the same impact over the NAES for P periods, in agreement with López-Parages and Rodríguez-Fonseca (2012). Some slight differences appear, however, in the location of the extratropical centers of action in PICTRL (Fig. 7b) and observations (Fig. 7c), with a westward displacement in the former case. This fact could be explained by both, the more westerly location of the forcing region (see Figs. 5, 6), and the less elongated Indo-Pacific jet (Fig. 7b, c), in the model.

7 Summary

In this paper the link between the leading mode of interannual anomalous rainfall in the Euro Mediterranean region and El Niño found in López-Parages and Rodríguez-Fonseca (2012) has been further investigated using a long control simulation of the CNRM-CM5 model. The aim of the study is to find if the observed multidecadal modulations of ENSO teleconnections with Europe can be reproduced by the internal low frequency variability of the coupled system without invoking any role for anthropogenic forcing. The study is focused on the late-winter early spring, which is a characteristic season in which ENSO exerts an influence over North Atlantic and Europe (Brönnimann 2007; Zhang et al. 2011). The working hypothesis is that ENSO teleconnections are not stationary and the multidecadal natural variability of the ocean acts as a modulator, in agreement with the results of López-Parages and Rodríguez-Fonseca (2012).

In this way, the correlation between the observed Euro-Mediterranean rainfall and ENSO is stronger in some decades (P) than in others (N). For P, broadly in coincidence with twentieth century negative phases of AMO, an increase of rainfall over central Europe and a decrease over the Mediterranean area occurs jointly with a warming over the tropical Pacific and Indian basins, and a cooling over the Maritime continent. As the correlations obtained evolve in phase with the AMO, which is a natural internal variability mode of the ocean, a long coupled control simulation has been considered as a useful dataset to analyze the internal effect in the observed modulation.

In particular, the CNRM-CM5 model long control simulation has been used. This model reproduces the observed leading rainfall mode and its non-stationary link with El Niño, confirming in this way that the natural variability has an effect in modulating the impacts of El Niño in the extratropical North Atlantic region.

In the above-mentioned P periods two dynamical mechanisms are contributing to the ENSO teleconnection. Thus, alteration of the thermally driven direct circulation (Wang 2002), and the ENSO related rotational North Atlantic mode (Garcia-Serrano et al. 2010), significantly affect the surface European rainfall in both, model and observations. The resultant configuration over the NAE sector has been previously associated with a non-stationary forcing from the tropics (Greatbatch et al. 2004), but also with a teleconnection pathway via the stratosphere (Ineson and Scaife 2008). In the latter work it is argued that the response over the NAES in late winter is explained by the occurrence of sudden stratospheric warming's, and so, a good representation of the stratosphere become crucial. Here, the same impact has been reproduced by a model which do not fully represent stratospheres processes ("low-top model"). Then, although the stratosphere could play also an important role, the teleconnection could be reproduced through tropospheric mechanism if the non-stationary features are considered. Nevertheless, this does not exclude a possible significant role for the stratosphere that could be analyzed in a similar setup with high-top models.

The ENSO related rotational flow impact is modulated, in PICTRL, by changes in the zonal mean flow at upper levels forced by the ocean. Hence, the surface signal over the NAES changes as well, resembling in N periods a negative phase of the NAO. The observed N periods, coinciding with positive phases of the AMO, are characterized by a weakening of the ENSO signal. As a consequence, the previously commented mechanisms are also weakened and, an atmospheric blocking pattern appears in relation to an El Niño signal over the tropical Pacific. This link between ENSO and the enhanced frequency of blocking events under positive phase of AMO (Häkkinen et al. 2001) should be further investigated in the future.

Although this study is focused on late winter and early spring, non stationarities modulated at multidecadal timescales takes place from autumn to spring (see Fig. 2 of LPRF12). Thus, similar changes in the zonal mean flow forced by the ocean could also explain the changing impact identified in these seasons. This seasonal time difference in the nonstationary ENSO-NAES teleconnection is a task to be further researched in future works.

Our results thus point to an important role (although not unique) of the multidecadal changes in the zonal flow forced by natural internal oceanic variability, in the modulation of El Niño effect on the European rainfall. As a fraction of the oceanic variability is linked to the Atlantic Meridional Overturning Circulation that is projected to weaken in the twenty-first century, it is possible that the interaction between El Niño and Europe change again in the next decades. Another explanation to the nonstationary impact of the same ENSO signal over the NAES could be related to a changing SSTs background state of the tropical Pacific, which in turn could be also forced by the Atlantic Ocean (Sutton and Hodson 2007). To get further insight into these issues, and to investigate nonlinear responses, sensitivity experiments with General Circulation Models (GCMs) should be also done in the future.

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