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Predictability of the spring rainfall in Northwestern Iberian Peninsula from sea surfaces temperature of ENSO areas

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Abstract The influence of sea surface temperature (SST) of the ocean on seasonal rainfall in Northwestern Iberian Peninsula is studied for the period 1951–2006. Seasonal correlations were calculated for all seasons and different lags applied on SST. A test for field-significance considering the properties of finiteness and interdependence of the spatial grid was applied to avoid correlations by chance. The most significant and repetitive correlation is found between SST over Equatorial Pacific and spring rainfall. The correlation is maintained for different lags, and the common area that satisfies the criteria for statistical field significance is coincident with ENSO area. A forecast scheme is developed to predict spring rainfall anomalies based in SST over ENSO area in precedent seasons. An analysis of principal components was also carried out to obtain the main modes of the Pacific Ocean and their influence on spring rainfall in NWIP. This study concludes that for the period 1951–2006 the negative phase of ENSO, "La Niña", almost always announces dry springs in NW Iberian Peninsula. However, the positive phase of ENSO, "El Niño", does not anticipate the appearance of wet springs.

1 Introduction

The Atlantic part of the Iberian Peninsula is an area located in Northern Hemisphere mid-latitudes. This location implies a great oceanic influence on its climate, particularly important in its northwestern corner. Rainfall is a critical issue in Northwestern Iberian Peninsula. On the one hand the region produces an important percentage of

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Spanish hydroelectric energy since the productivity of Galician rivers is especially high in terms of discharge compared to the basin extent (deCastro et al. 2006). On the other hand, soil characteristics (Martínez Cortizas and Pérez Alberti 2000; Vega et al. 2006) make the region prone to short duration droughts. To maximize hydroelectric productivity and avoid water shortages it is very useful to have any information on seasonal rainfall anomalies. In general, ordinary weather forecast is limited to one or two weeks. However, in some regions, the average weather is influenced in a predictable way by slowly varying boundary conditions, such as sea surface temperature (SST), ice or land conditions. These factors can have a local or a remote effect (teleconnections). In the Atlantic area of the North Hemisphere, NAO (North Atlantic Oscillation) is the dominant pattern of atmospheric circulation variability. Other teleconnection patterns appearing in this area (Barnston and Livezey 1987) are: EA (East Atlantic), EA/WR (East Atlantic/ Western Russia), SCA (Scandinavian Pattern), and POL (Polar/Eurasia Pattern). Previous studies (Lorenzo and Taboada 2005; deCastro et al. 2006, 2008a, b) have proved that some climatic variables like coastal upwelling (directly linked to wind speed) and rainfall are influenced by several of these indices. However, the non-stationarity of the teleconnection patterns (Trigo et al. 2004; deCastro et al. 2006; Vicente-Serrano and López-Moreno 2008) compel us to seek new forecasting tools such as the sea surface temperature (SST)., since different SST patterns can induce different rainfall patterns. Thus, the passage of a cold front over a cold ocean area induces the stabilization of the air column, diminishing associated rainfall, while a positive SST anomaly increases rainfall, via enhanced evaporation and the decrease of the vertical stability. In this way SST is an important variable to be taken into account to make rainfall forecasting.

Forecasting models have been explored considering the associations between precipitation and lagged SST of different regions of the Atlantic area of Europe (Philips and McGregor 2002; Philips and Thorpe 2006). In a previous work Lorenzo et al. (2010) showed the skill of the North Atlantic SST to forecast rainfall in the NW area of the Iberian Peninsula at monthly scale. This predictability can be explained in terms of the relationship between SST fluctuations and NAO strength in the North Atlantic (Rodwell et al. 1999). As we mentioned above, NAO is the leading pattern of weather and climate variability over the North Hemisphere (Hurrell 1996). Nevertheless, other areas of the world ocean could also influence rainfall anomalies in Iberian Peninsula. It is well known that El Niño-Southern Oscillation (ENSO) has a significant correlation with rainfall in the Mediterranean area (Rodó et al. 1997). Recently, some studies have obtained the impacts of ENSO in other areas of Europe (van Oldenborgh et al. 2000; Brönnimann 2007). Areas outside Equatorial Pacific can also play a non-negligeable role on rainfall anomalies in NWIP. For example SST anomalies at the Indian Ocean modifies Asian summer monsoon and this modification influences atmospheric circulation in Northern Hemisphere, by means of a Rossby-wave disturbance that spreads the influence of Asian summer monsoon all over the Northern Hemisphere (Rodwell and Hoskins 1996; Hoerling et al. 2004; Black and Sutton 2006).

The aim of the present study is to analyze the relationship between the global SST and seasonal rainfall in Northwest of Iberian Peninsula. The present study is structured as follows: The data sets and methodology are described in Section 2. In Section 3, the main results are presented. The areas of the world ocean with the greatest influence on seasonal rainfall variability in NW Iberian Peninsula are identified. These correlations are analyzed to elaborate appropriate multiple regression models to predict the anomalies of rainfall. Conclusions are drawn in Section 4.

2 Materials and methods

The NW corner of the Iberian Peninsula is located in Northern Hemisphere mid-latitudes (Fig. 1). Therefore its rainfall has a marked seasonality (Martínez Cortizas and Pérez Alberti 2000; deCastro et al. 2006; Lorenzo et al. 2010). In autumn and winter the jet stream is in its lower latitudes (Gallego et al. 2005; Gimeno et al. 2007). This causes many cold fronts associated to lows traveling across the Atlantic to affect this area leaving great rainfall quantities (28% in winter and 35% in autumn). In spring those events tends to diminish, but in average this season is responsible for 24% of annual rainfall (Martínez Cortizas and Pérez Alberti 2000; Lorenzo and Taboada 2005; deCastro et al. 2006). Minimum values lower than 300 mm season^{-1} are observed in summer (Gómez-Gesteira et al. 2011).

Monthly precipitation data in mm from 1951–2006 were obtained from the database CLIMA of the University of Santiago de Compostela with data from the Agencia estatal de Meteorología (AEMET) and the Regional Government of Galicia that are distributed throughout the territory of Galicia [42° N to 44° N, 10.5° W to 6° W]. These data underwent a quality control procedure with substitutions made for poor quality and some missing data, similar to the one used in the NCDC (National Climate Data Center of the National Oceanic and Atmospheric Administration, NOAA) for GHCN (Global Historical Climate Network) database (Peterson et al. 1998). Quality control for these series of data gave a result of only 1% of missing data and 90% of correlation with neighbor stations. Four meteorological stations have been considered according to their length in time. Table 1 summarizes the geographic characteristics of the meteorological stations. The average rainfall of

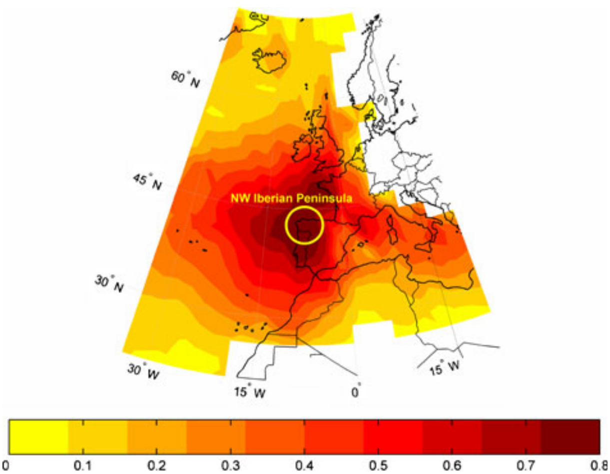

Fig. 1 Area positively correlated between the monthly rainfalls averaged in NW Iberian Peninsula and the monthly precipitation data of the area [35–65° N, 35° W–30° E] obtained with GPCP covering the period December 1979–December 2004. The *color scale* indicates the value of the Pearson correlation index. Values higher than 0.23 have a significance level of 95%

Table 1 Meteorological stations with rainfall data from 1951 to 2006

Station	Altitude (m)	Latitude	Longitude
A Coruña	58	43°22′	−8°25′
Santiago	367	42°53′	−8°25′
Salcedo	40	42°24′	−8°38′
Ponteareas	50	42°10′	−8°29′

the four stations was considered as representative of the rainfall of the study area. Averaging rainfalls corresponding to the four stations is a valid procedure because the four time series are closely correlated, being the lowest correlation ($r^2 = 0.90$) observed between stations 1 and 4.

Precipitation data from the marked area (35–65° N, 35° W–30° E) were also retrieved from the Global Precipitation Climatology Project (GPCP) of the Global Energy and Water Cycle Experiment (GEWEX) for the period December of 1979 and December of 2004 (http://lwf.ncdc.noaa.gov/oa/wmo/wdcamet-ncdc.html/). This database provides monthly mean precipitation data in mm on a 2.5° × 2.5° latitude-longitude grid. The correlation between averaged precipitation and GCPC data show that this rainfall can be considered representative of rainfall across the South Western Europe (Fig. 1).

Monthly rainfall totals were expressed as anomalies relative to the period 1951–2006 The rainfall anomaly index adopted in the present study is defined as NWIPR (Northwestern Iberian Peninsula Rainfall):

$$NWIPR = 100 \sum_{i=1}^{N} \left(X_i \middle/ \overline{X}_i \right). \qquad (1)$$

X_i is the monthly rainfall anomaly at one station in mm, $\overline{X_i}$ is the station's mean annual rainfall in mm and N is the number of stations (Philips and McGregor 2002; Lorenzo et al. 2010).

SST data were retrieved from the Earth System Research Laboratory (ESRL) of NOAA, (http://www.cdc.noaa.gov/). The version3 of the extended reconstructed sea surface temperature (ERSST) was considered. This database was constructed using the most recently available International Comprehensive Ocean-Atmosphere Data Set (ICOADS) SST data and improved statistical methods that allow stable reconstruction using sparse data. Monthly averaged data are located in a 2° × 2° grid. In the present study, data from January 1951 to December 2006 were considered.

Sea level pressure (SLP) data belong to the National Center for Atmospheric Research (NCAR) reanalysis data (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html) with a resolution of 2.5° × 2.5° latitude–longitude.

The different Niño indices used along the text were obtained from the Climate Prediction Center of the NOAA (http://www.cpc.noaa.gov/data/indices/). The Pacific Decadal Oscillation (PDO) PDO index used in the text was obtained from the web page http://jisao.washington.edu/pdo/PDO.latest.

For the seasonal study months were grouped according to the standard climatological seasons in the study area: winter (January, February and March, JFM), spring

(April, May, June, AMJ), summer (July, August, September, JAS) and autumn (October, November, December, OND).

All series used were linearly detrended and normalized by the corresponding standard deviation prior to the statistical analysis to eliminate the long-term trend. The Pearson product-moment correlation coefficient r was considered to quantify the linear association between the SST of each $2° \times 2°$ grid square and NWIPR. The significance of the coefficient was assessed to be greater than 95% by means of Student's t test (Trauth 2006). As it is possible to obtain a statistically significant correlation by simply correlating two random number series a test for field-significance was applied considering the properties of finiteness and interdependence of the spatial grid (Livezey and Chen 1983; Wilks 1995). Finiteness is defined as the dimensionality of the grid. On the other hand, the value of SST of one grid square is not independent of the value of the SST of neighbouring grid squares. Therefore a criterion of interdependence of the spatial grid was also considered (Livezey and Chen 1983; Wilks 1995; Philips and McGregor 2002; Lorenzo et al. 2010).

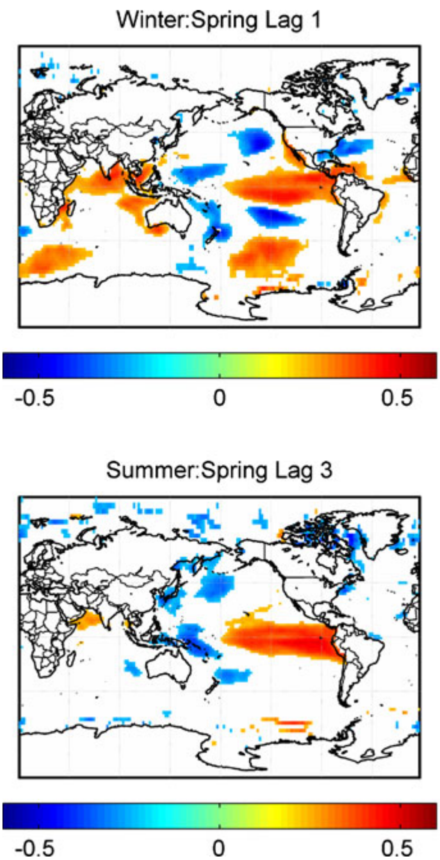

Fig. 2 Spatial distribution of correlation between seasonal SST and spring NWIPR. The correlations shown here present a significance level of 95%. Lag *j* is the lag considered for SST

3 Results

Seasonal SST/NWIPR correlations have been calculated for every season with lags from 1 to 4. Only spring data (Fig. 2) fulfill the finiteness and interdependence criteria mentioned above for several lags. Spring NWIPR is significantly correlated with SST corresponding to the previous winter, fall, summer and spring, being the equatorial Pacific and the Indian Ocean the most significant areas. In Fig. 2 one can observe spots of negative correlations located on western areas of the Pacific Ocean and positive correlations around Indian Peninsula and in the Eastern and Equatorial Pacific Ocean. The present study will be focused on the search for repetitive patterns showing a common area of correlation. Thus a positive correlation is observed between spring NWIPR and the previous winter and autumn SST in the Equatorial and Indian Ocean. This correlation is restricted to the Equatorial Pacific when considering the previous summer and spring. Considering the whole preceding year, the common area with significant correlation with spring NWIPR is the Equatorial Pacific Ocean shown in Fig. 3. The common area overlaps with the areas used to calculate the Niño3 [5° S–5° N], [90° W–150° W] and Niño1 + 2 [0–10° S], [80°–90° W] indices (see Fig. 3).

The correlation between spring NWIPR and the Niño3 and Niño1 + 2 indices oscillates depending of considered lags between 0.35 and 0.4 with a significance level of 99%.

According to these results, a linear regression model was developed.

Linear regression attempts to model the relationship between two variables by fitting a linear equation to observed data. One variable (x) is considered to be an explanatory variable, and the other (y) is considered to be a dependent variable. Using model results, when an additional value of x is provided without its accompanying value of y, the fitted model can be used to make a prediction of the value of y (Wilks 1995).

In the present study the regression models were elaborated using as input (explanatory) values the mean SST corresponding to the area composed by the regions

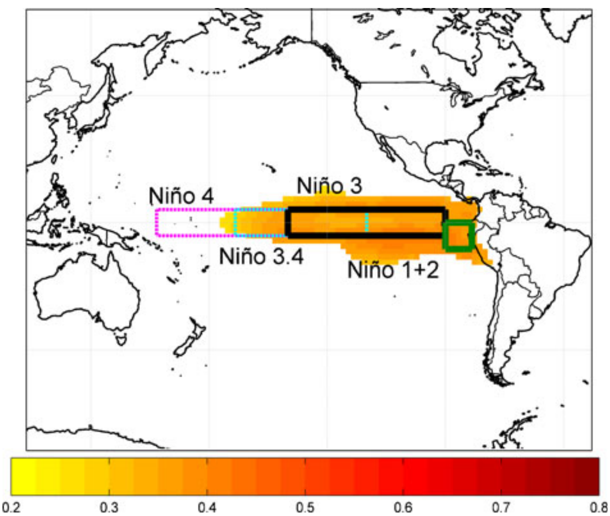

Fig. 3 Areas considered to elaborate the different Niño indices superimposed on the area with significant correlations in the four graphs depicted in Fig. 2

Table 2 Stepwise regression model of spring rainfall anomaly considering the SST of the area Niño3 and area Niño1 + 2

Area SST	Period	Equation	Correlation
Niño3	1951–2006	$NWIPR = a * SST_3L1 + b * SST_3L2 + c * SST_3L3$ $a = 0.0970; b = -0.0373; c = 0.4942$	0.42
Niño1 + 2	1951–2006	$NWIPR = a * SST_{1+2}L1 + b * SST_{1+2}L2 + c * SST_{1+2}L3$ $a = 0.0139; b = 0.5229; c = 0.1661$	0.45

The input variables are the mean values of SST for the two areas of SST. *SSTiL*
SSTi area of SST (Niño3 or Niño1 + 2), *Lj* lag considered for each term, *Correlation* the correlation value between the spring NWIPR real and the spring NWIPR predicted by the regression models. Both values have a significance level of 99%

used to calculate the Niño3 and the Niño1 + 2 indices. The output (dependent) variable is the value of the spring NWIPR (see Table 2). Correlation values on the order of 0.45 with a significance level of 99% were obtained between the spring

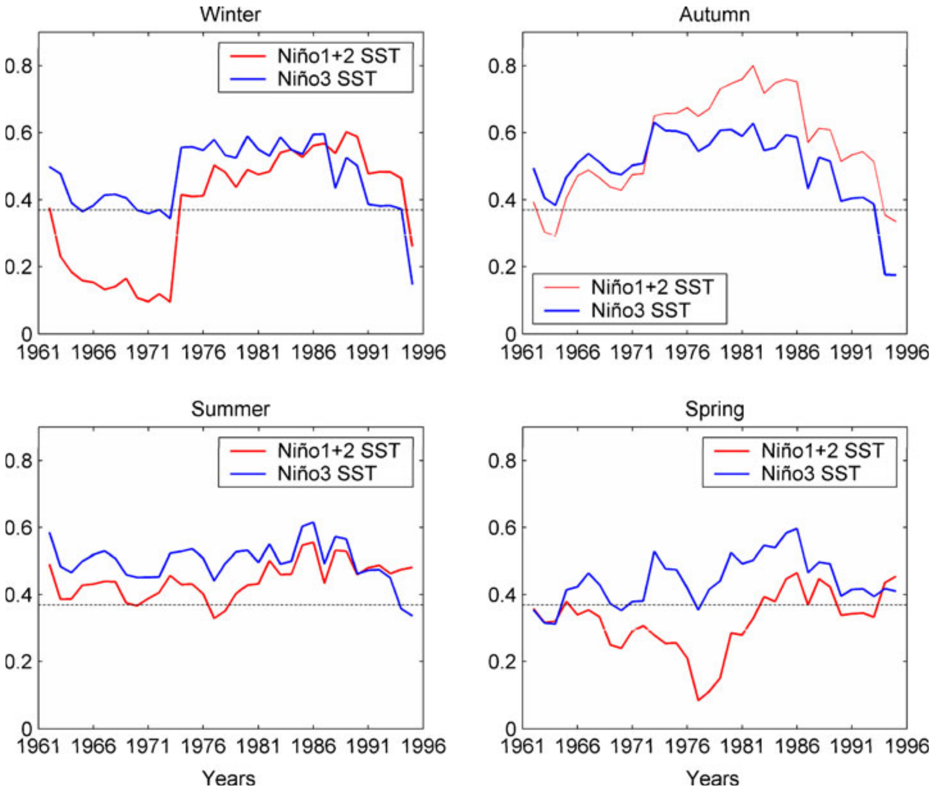

Fig. 4 Correlation between spring rainfall and SST of the areas used to calculate the Niño3 and the Niño1 + 2 indices. The significance at the 95% level is shown (*dotted lines*). A moving window of 21 years from 1951 to 2006 for each season was used. Note that the years before 1962 and after 1995 were discarded since they were not central to a whole interval of data. The years shown in the *X* axis correspond to the center years of the moving windows

NWIPR obtained with the regression models and the real values of the spring NWIPR.

It is a well known fact that the influence of ENSO on precipitation in Europe has varied over time (Knippertz et al. 2003; van Oldenborgh and Burgers 2005). In order to analyze changes in correlation between Niño3 index and precipitation along the studied period 21-year sliding means were used to calculate the evolution of the correlation between index in different seasons with NWIPR of the next spring (see Fig. 4). The period of 21 years has been elected as a period long enough to remove high frequency events and short enough not to be affected by low-frequency interdecadal variations. This period is similar to those used in ENSO impacts over Europe (Diaz et al. 2001). Results show important changes in the correlations during the 1970s, especially during the winter season. This change can be related to the atmospheric circulation change occurred in the Northern Hemisphere in 1976/77 (Trenberth 1990). This change in the correlation between ENSO and the European climate had been previously noted by other authors (Knippertz et al. 2003; Greatbatch et al. 2004; Mariotti et al. 2005; Pozo-Vázquez et al. 2005; deCastro et al. 2006; Brönnimann 2007).

Murphy and Winkler (1987) established the use of contingency tables to verify forecasts. A contingency table is essentially a display format used to analyze and record the relationship between two or more categorical variables. A categorical forecast is a forecast of the occurrence or non-occurrence of a specific event, which must be clearly defined. For example, rainfall can be considered as a discrete predictand, assuming only rainfall higher or lower than normal. Only the values that were outside the interval $<NWIPR> \pm 1/2\sigma$ (NWIPR) were considered, since they correspond to those events which can be potentially more harmful, giving rise to floods and droughts. Following the forecast of higher normal (+) or lower normal (−), the event will actually occur or not. This leads to four possibilities as lay out in the Table 3. The contingency tables (Table 3) show that the years with negative SST anomalies in the Equatorial Pacific (‘La Niña’ event), the probability of a dry spring in the NW Iberian Peninsula are very high with a hit rate between 83% and 100%. However, the years with positive anomalies in the Equatorial Pacific (‘El Niño’ event) do not give significant differences between dry and humid spring obtained a similar value between hit rate and false alarm in the contingency tables (see Table 3).

A complementary analysis through a study of Principal components has also been carried out. The Principal Components of SST were calculated at a seasonal scale inside the area of the Pacific Ocean (Hoerling et al. 2001) limited by the coordinates [50° N–56° S], [144° E–286° E]. A technique PCA in S-mode was used (adopting

Table 3 Contingency tables calculated using stepwise regression models of spring rainfall anomaly shown in Table 2 to forecast extreme rain events in spring

	Forecast (−)	Forecast (+)
Niño3 model		
Observed (−)	9	0
Observed (+)	5	8
Niño1 + 2 model		
Observed (−)	10	2
Observed (+)	5	7

NWIPR higher normal (+), NWIPR lower normal (−)

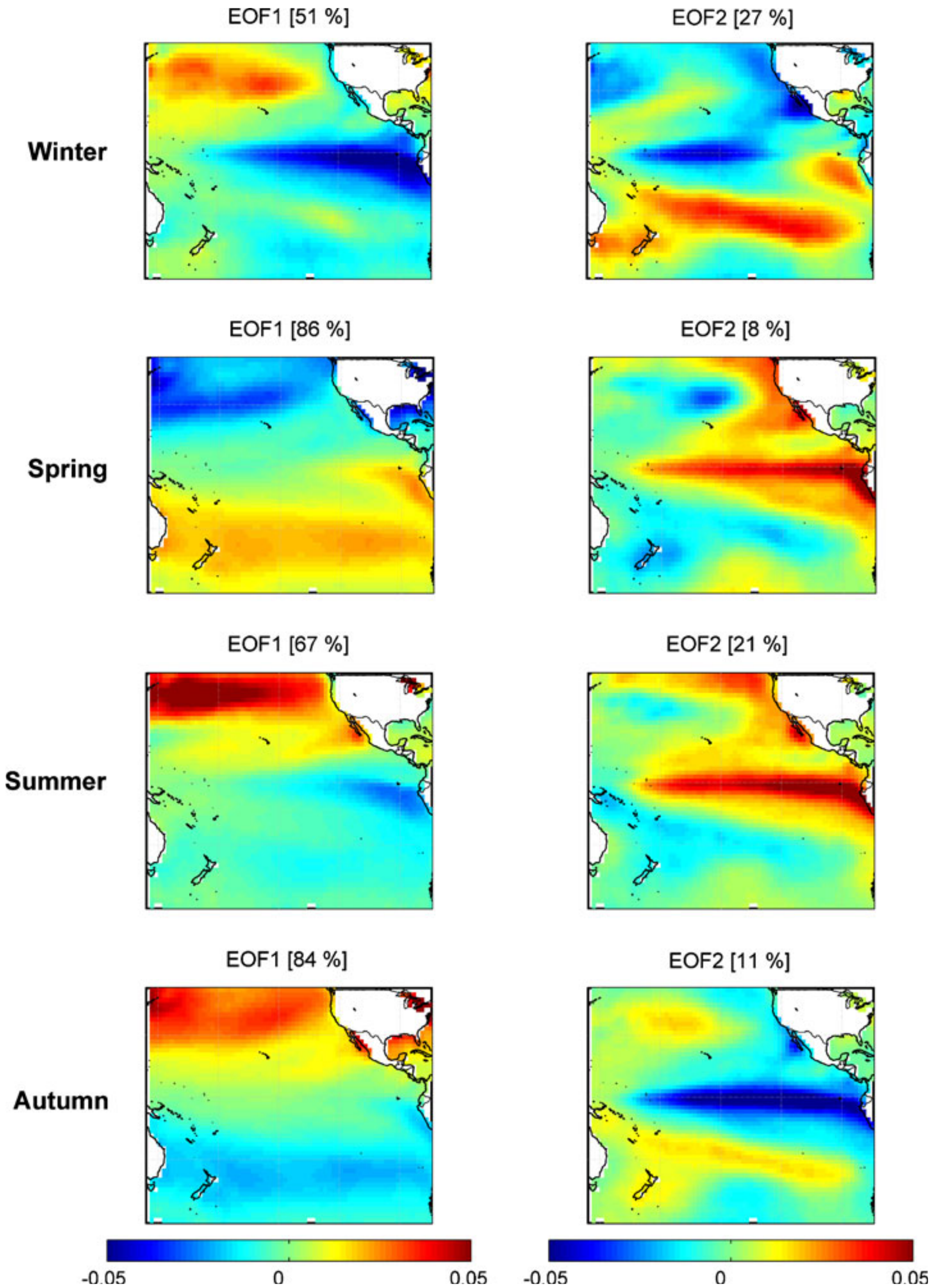

Fig. 5 First two leading EOFs for winter (JFM), spring (AMJ), summer (JAS) and autumn (OND). EOFs were calculated with SST data corresponding to the area [50° N–56° S], [144° E–286° E]. The respective variance (%) explained by each EOF is also depicted

Table 4 Correlation between the first two seasonal PCs of the SST and spring rainfall

Spring NWIPR:PC	PC 1	PC 2
Winter	−0.39	−0.34
Spring	0.23	0.37
Summer	−0.42	0.40
Autumn	−0.16	−0.42

All values have a significance level equal or higher than 95%

the terminology by Richman 1986) which means that the eigenvector describes the spatial pattern of the modes and the PCs describe the time variations. In this analysis, more than 78% of the total variance is contained in EOF1and EOF2, whereas the rest of the EOFs do not play a significant role. This means that most of the variability in the data set can be described by only two modes. The two main EOFs with its variance are shown in Fig. 5 for each season. In addition, Table 4 summarizes the correlations between the PCs of the two first modes and spring rainfall anomalies in NW Iberian Peninsula. The EOF1 in winter and EOF2 in the rest of seasons show the characteristic signature of the El Nino-Southern Oscillation (ENSO); there is a warming/cooling of the tropical Pacific Ocean and a cooling/warming in the western Pacific with small changes elsewhere depending on the ENSO's Phase (El Niño/La Niña). In addition, the correlation between these PCs and the ENSO index shows values around 0.95 with significance level of 99%. The spring, summer and autumn EOF1s present a zonal pattern of temperature which resembles to the Pacific Decadal Oscillation's (PDO) with a zonal pattern fingerprints more visible in the North Pacific/North American sector. In this case the correlation between these PCs and the PDO index show values around 60% with significance level of 99%. Finally the EOF2 of winter appears as a mix of the two patterns ENSO and PDO without a clear definition. In this case the correlation between ENSO and this PC has a value of 0.77 while with the PDO index the correlation is 0.36, both with a significance level of 99%.

Considering the correlation values in Table 4, a regression model was developed to predict spring NWIPR values from the values of the dominant modes of the Pacific Eq. 2:

$$\mathrm{NWIPR} = a^{*}\mathrm{EOF1winter} + b^{*}\mathrm{EOF2Autumn} + c^{*}\mathrm{EOF1summer} \tag{2}$$

where $a = 0.0087$; $b = -0.2368$; $c = -0.2084$. Here the input variables are the PCs with higher correlation with NWIPR of each previous season (see Table 4). This regression model provides a correlation between the predicted data and observed data of 0.46 with a significance level of 99%. The contingency tables elaborated with the Eq. 2 (Table 5) confirm the results observed in Table 3. In general, dry springs in NW of Iberian Peninsula are better forecasted than wet springs.

Table 5 Contingency tables calculated using stepwise regression model of spring rainfall anomaly shown in Eq. 2 to forecast extreme rain events in spring. NWIPR higher normal (+), NWIPR lower normal (−)

	Forecast (−)	Forecast (+)
Observed (−)	10	0
Observed (+)	4	7

The correlation between Niño3 index and SLP calculated over the region [10–80° N], [60° W–80° E] for the period 1951–2006 was carried out to look for some dynamical reason underlying the observed behavior. Figure 6a shows a negative correlation between winter Niño3 index and spring SLP in the area north of the Iberian Peninsula. This means that negative SST anomalies in the Equatorial Pacific are related with high pressures settled over North Sea area which blocks the passage of cold fronts associated with lows travelling across the North Atlantic and vice versa. This correlation is qualitatively maintained when considering the Niño3 index of preceding autumn, summer or spring. A similar correlation is observed when the Niño1 + 2 index is used instead of Niño3 (not shown). When the previous analysis is performed separating 'El Niño' years (15 cases) and 'La Niña' years (12 cases; Fig. 6b and c) a strong positive correlation between 'La Niña' events and the high pressures over the Iberian Peninsula and Mediterranean area can be observed. However, the 'El Niño' years do not show a significant correlation with the spring SLP over the studied area for this period. Therefore when ENSO has a La Niña phase the spring will be dry. Nevertheless when the ENSO has an El Niño phase the rainfall will not have a defined pattern.

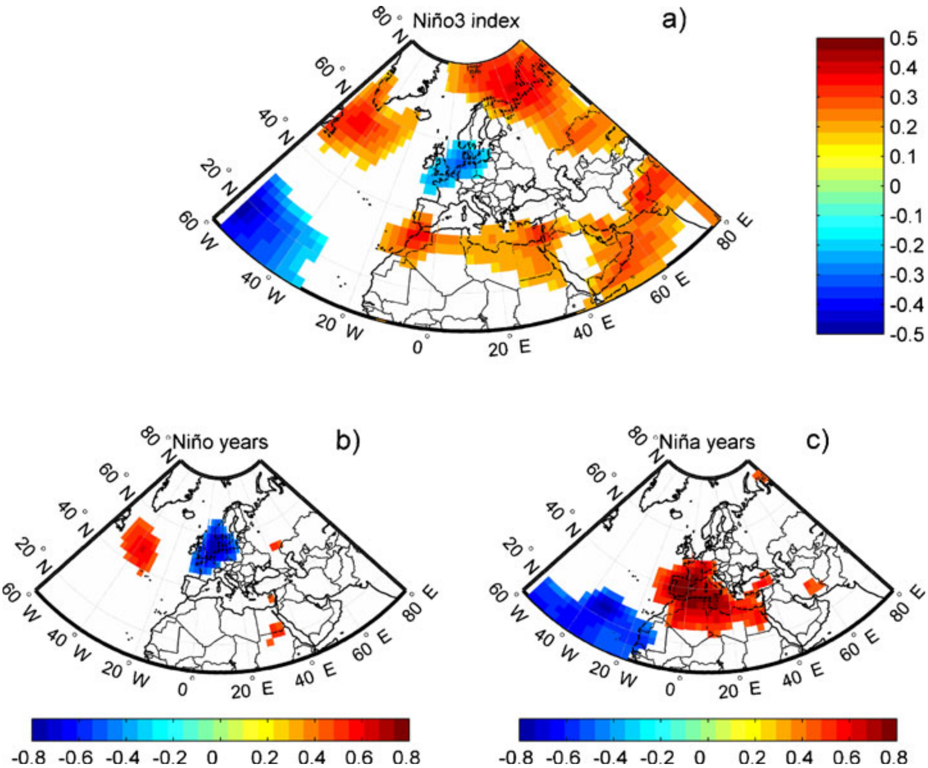

Fig. 6 **a** Correlation between winter Niño3 index and spring SLP field in the area of study from 1951 to 2006; **b** The same as in (**a**) but only for 'El Niño' years; **c** The same as in (**a**) but only for 'La Niña' years. A significance level of 95% was considered in all subplots

4 Conclusions

Pacific Ocean SST has been proven to be a suitable variable to forecast spring rainfall anomalies in NW Iberian Peninsula for the period 1951–2006. The area is related with the regions used to calculate the Niño3 and Niño1 + 2 indices. The effect of these areas on rainfall seems to be mediated by the appearance of a blocking high centered at North Sea, extending from Ireland and Great Britain to Central Europe. Results show significant correlation, higher than 45%, when combining different indices and lags. In particular, 'La Niña' years almost always announce dry springs in NW Iberian Peninsula (between 83% and 100% of hit rate). However, 'El Niño' years do not anticipate the appearance of wet spring (around 55% of hit rate).

One important outcome of this work is that the Equatorial Pacific area has some relation with spring rainfall in NW Iberian Peninsula. Because of the progress that has been made in its prediction, the relation between ENSO and climate in NW Iberian Peninsula is of interest with respect to potential seasonal predictability and the results can be extended to Southwestern Europe.

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