Nonstationary interannual teleconnections modulated by multidecadal variability

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Abstract
The present work shows observational evidence of changes in atmospheric teleconnections of West Africa (WA) and the Euro-Mediterranean (EM) areas with remote regions. We show that the impact of the tropical Sea Surface Temperature (SST) anomalies over the WA precipitation has changed in the late 1970s, which is relevant for seasonal predictions in this area. These changes coincide with a nonstationary link between the interannual variability of the tropical Atlantic and Pacific basins. Also, the link between the Pacific El Niño and the EM rainfall in late winter-spring has changed throughout the 20th century. Our results give evidence of nonstationarities of both types, atmospheric and oceanic, occurring during negative phase periods of the Atlantic Multidecadal Oscillation (AMO). Hence, the results obtained here point out a physical coherent modulation of interannual variability by multidecadal variability. These multidecadal modes also appear to influence the variability of explosive cyclones (EC) over the EM region. Finally, to further understand the AMO and its possible influence over the interannual variability, the ability to reproduce a coherent AMO in General Circulation Models (GCMs) has been analysed. Results show that both the simulated and observed AMO patterns are consistent.
Keywords: Teleconnection, Rainfall, SST, Nonstationarity, ENSO, Equatorial Mode, AMO, CMIP5, West Africa, Euro-Mediterranean region, Extratropical cyclones, Explosive cyclones.

No-estacionariedad de teleconexiones interanuales modulada por variabilidad multi-decadal

Resumen
Este trabajo muestra evidencias observacionales de cambios en los mecanismos de teleconexión atmosférica que afectan a África occidental (WA) y al área Euro-Mediterránea (EM), con otras regiones remotas. Se ha mostrado como el impacto de las anomalías de temperatura superficial del mar (SST) tropical en la precipitación en África occidental, ha cambiado a finales de los 1970s, lo cual es relevante para la mejora de las predicciones estacionales en dicha región. Estos cambios coinciden con una relación no estacionaria entre la variabilidad interanual del Atlántico y Pacífico tropical. Por otro lado, la conexión entre El Niño del Pacífico y la precipitación en la región EM a

finales de invierno y durante la primavera ha cambiado a lo largo del siglo XX. Nuestros resultados muestran no estacionariedades, tanto en la atmósfera como en el océano, coincidentes con fases negativas de la Oscilación Multidecadal del Atlántico (AMO). Los resultados aquí obtenidos apuntan a una modulación físicamente coherente de la variabilidad interanual por la variabilidad multidecadal. También se ha mostrado como los modos multidecadales mencionados afectan a la variabilidad de las ciclogénesis explosivas (EC) sobre la región EM. Finalmente, con el objetivo de comprender la variabilidad de la AMO y su posible papel modulador, la capacidad de los Modelos de Circulación General (GCMs) para reproducir el patrón de la AMO, también ha sido estudiada. Dicho patrón sobre el Atlántico Norte es consistente en observaciones y simulaciones.
Palabras clave: Teleconexión, Precipitación, SST, No estacionariedad, ENSO, Modo ecuatorial, AMO, CMIP5, África occidental, Región Euro-Mediterránea, ciclón extratropical, ciclogénesis explosiva.

Summary: 1. Introduction. 2. Nonstationarities in the ocean. 3. Nonstationary teleconnections in WA and EM. 4 Evaluation of multidecadal variability modes from the state of the art GCMs. 5. Summary and conclusions. 6. Acknowledgements. 7. References.

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1. Introduction

A teleconnection mechanism is a causal relationship between the climate variability of remote regions in the globe, which produces anomalous climate behaviour in the target region. Teleconnections are of great importance in climate variability for several reasons. Firstly, they produce an atmospheric link between distant regions over the entire globe (Wallace and Gutzler, 1981; Barnston and Livezey, 1987). Secondly, annual/decadal prediction methods can be developed using teleconnection patterns of high thermal inertia like SSTs (Rodwell et al., 1999). Finally, some temporal series from proxy data can be reconstructed using these mechanisms.

The regions where the teleconnection mechanisms are triggered are called forcing regions. There, strong ocean-atmosphere interactions are usually observed, with a strong vertical air lift causing a rapid influence over the upper troposphere (i.e. changes in the vorticity field). As a consequence, the anomalies from the forcing region are propagated in the upper troposphere as Rossby waves and the teleconnection is established (Branstator, 1983; Hoskins and Ambrizzi, 1993; Honda et al., 2001, 2005).

Some teleconnection mechanisms are of special interest due to the strong socioeconomic impacts they frequently produce over the target regions. Clear examples of these impacts can be found in West Africa (WA) and the Euro-Mediterranean (EM) areas, which are carefully analysed in this study. On one hand, the country economies over WA are mainly based on agriculture and thus highly influenced by climate conditions. As a consequence, the improvement of seasonal predictability tools remains as a great challenge in this area. On the other hand, the EM region is considered as a vulnerable region in the current global warming context. Particularly, the study of the EM rainfall variability has become important due to the growing risk of water shortage (Hulme et al., 1999).

In the last years the science community has shown a growing interest in the time evolution of some teleconnection mechanisms. Two of them are the teleconnections related to WA and EM regions, where nonstationary climatic conditions have been found since the 19th century. Along this study these previous works are presented for each target region.

This study represents an updated review of the recent and ongoing research carried out by the TROPA (TROPical Atlantic variability) group, which belongs to the consolidated UCM research group Micrometeorology and Climate Variability in the Geophysics and Meteorology department of the Complutense University of Madrid. Here, the nonstationarity of different oceanic and atmospheric teleconnections mechanisms is provided, with a main focus in the impact over the WA and EM regions. These results represent a step forward in the understanding of the role of the ocean mean state as a modulating factor of the atmospheric interannual teleconnections.

The paper is structured as follows. The analysis of the nonstationary teleconnection between the tropical Atlantic and Pacific oceanic interannual variability is provided in section 2. The modulation of the interannual teleconnections of WA and EM with remote regions is studied in section 3. In section 4, the ability of state-of-the-art General Circulation Models (GCMs) to reproduce the Atlantic Multidecadal Oscillation (AMO) pattern is given. A brief summary and discussion conclude this article.

2. Nonstationarities in the ocean

The eastern Tropical Atlantic and Pacific Oceans present interannual oscillations of SST, which are associated with their leading modes of variability called Equatorial Mode or Atlantic Niño and El Niño-Southern Oscillation (ENSO), respectively, which have worldwide impacts (Zebiak et al., 1993; Bjerknes, 1969; Philander, 1990). Previous works have reported the influence of the mean state of the Tropical Pacific in ENSO phenomena, through changes in its spatial structure, intensity, frequency and type (Federov and Philander, 2000; Wang and An, 2002; Lee and McPhaden, 2010; Choi et al., 2010). On the other hand, long-term variations in the Tropical Atlantic SST modify the zonal equatorial gradient and eastern equatorial variability (Tokinaga and Xie, 2011; Polo et al., 2013a). In this way, the Equatorial Mode has also suffered changes in its characteristics and impacts after the 1970s (Polo et al., 2008; Rodríguez-Fonseca et al., 2009; Losada et al., 2010a,b; Mohino et al. 2011b).

The connection between the Tropical Atlantic and Pacific interannual variability, as well as the nonstationarity of this relation is still under debate (Polo et al., 2008; Rodríguez-Fonseca et al., 2009; Ding et al., 2012; Martín-Rey et al., 2012). In order to study the stationarity of the Atlantic influence on the Pacific along the whole 20th century, we analyse the ensemble mean of 9 simulations which were run in a similar way to the one performed by Rodríguez-Fonseca et al. (2009) but for a longer period [1871- 2002] (hereafter *SimAtlVar*). The Indo-Pacific Ocean is fully coupled and observed SSTs are prescribed over the Atlantic Ocean with climatological SSTs elsewhere. The running correlation between equatorial Atlantic indices (Atl3 index [SST over 20W-0E, 3N-3S] and Atl4 index [SST over 40W-20W, 3N-3S]) in summer (JJAS) and the equatorial Pacific Niño3 index [SST over 150W-90W, 5N-5S] in winter months (DJFM and FMAM) during the 20th century is shown in Figure 1a,e. Significant negative correlations appear not only after the 1970s but also at the beginning of the 20th century in both modelled data and observations. These results indicate that the interannual variability of the Tropical Atlantic and its impact on the Pacific depend on the decades considered. In addition, interdecadal modulation of this Atlantic-Pacific relationship is interpreted from the correlation analysis; thus, for some decades, the Atlantic is linearly related with the Pacific and for other decades there is no relation or very weak relation. Another way to illustrate that is given by the Figure 1 (b-d,f-h). The scatter plots of Niño3 versus Atl3 indices for the different periods reveal that, in the periods where the correlation becomes statistically significant, the dispersion can be linearly fitted with a negative slope therefore, positive anomalies in Atl3 region are related to negative ones in Niño3 region and vice versa (red lines). On the contrary, this linear regression becomes weaker (even positive correlation for the observations) in the period previous to 1970 (blue lines, Figure 1). Although the model shows different periods of the actual significant correlation between indices, the decadal modulation of the connection is defined. Interestingly, the model and the observation shows similar behaviour from 1970, period when a warming over the equatorial Atlantic has been reported (Tokinaga and Xie, 2011) and an increase of variance over tropical Pacific has been identified (Federov and Philander, 2000; An, 2009).

The multidecadal modulation of this Atlantic-Pacific Niños connection, with the leadership of the Atlantic, can contribute to the improvement of the ENSO prediction. Frauen and Dommenget (2012) analyse the effect of considering the Atlantic and Indian basins in the simulation of the ENSO events, concluding that the inclusion of the initial conditions of the Tropical Atlantic is crucial for the ENSO predictability. Furthermore, Keenlyside et al. (2013) using climate models obtain a better prediction of the ENSO phenomena taking into account the knowledge of the equatorial Atlantic SST in the previous months.

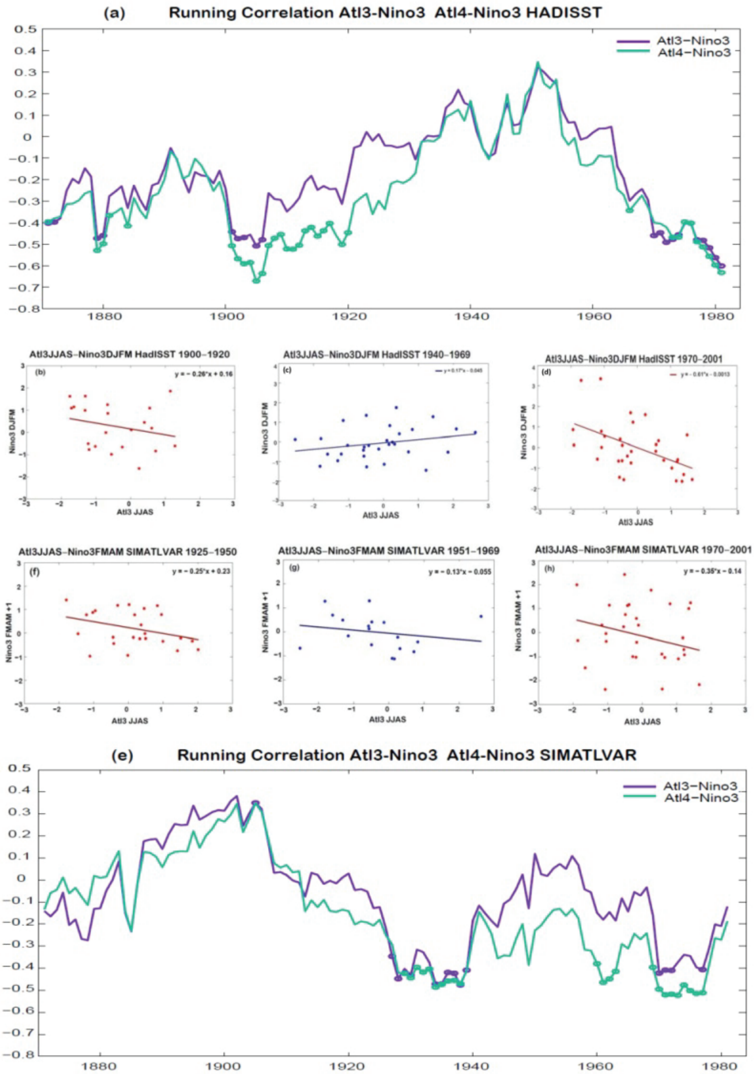

Fig. 1. a) 20-yr running correlation between the observed summer (JJAS) Atl3 [SST averaged over 20W-0E,3N-3S] and Atl4 [SST averaged over 40W-20W,3N-3S] and observed winter (DJFM) Niño3 [SST averaged over 150W-90W; 5N-5S] indices from 1871-1890 to 1981-2000 period. Significant values exceeding 90% confidence level are shown in dots. b) Scatter plot of the indices Atl3 and Nino3 for the period [1900-1920] c) Same as b) but for the period [1940-1969] d) Same as b) but for the period [1970-2001]. e)-h) same as a)-d) but for the simulated Nino3 index in FMAM (year +1) for appropriated chosen periods. Observational data come from HadISST (Rayner et al., 2003).

3. Nonstationarities in the atmospheric teleconnections

In this section the results of TROPA group regarding the atmospheric teleconnection mechanisms associated with the climate variability of WA and the EM region are analysed in detail.

3.1. West Africa

The WA rainfall shows variability at different time scales. At intraseasonal time scales there are two main peaks of periodicity at 15 and 40 days (Janicot and Sultan, 2001), the latter of which has been connected to the Madden Julian Oscillation (e.g. Matthews, 2004).

At decadal time scales, the precipitation over the Sahel region showed periods of high rainfall (1950s and 1960s) followed by periods of severe drought (1970s and 1980s). This decadal variability has been related to SST variability amplified by land-surface processes (e.g. Giannini et al., 2003). Also, the effect of the Indian Ocean over WA rainfall seems to operate mainly at decadal time scales (Shinoda and Kawamura, 1994; Bader and Latif, 2003; Giannini et al., 2003, 2005; Paeth and Friederichs, 2004).

In between, at interannual time scale, many works have shown a connection between variability of SST in the different ocean basins and WA rainfall. In the tropics, the Atlantic and Pacific basins have been shown to affect West Africa rainfall at this time scale (e.g. Giannini et al., 2003; Rowell, 2001).

Many works have highlighted the connection between SST warmer than average in the eastern Equatorial Atlantic and increased rainfall over the Gulf of Guinea (GG) (e.g. Janicot, 1992; Shinoda and Kawamura, 1994; Rowell et al., 1995; Ward, 1998; Giannini et al., 2003, 2005; Polo et al., 2008; Mohino et al., 2011b). These SST anomalies are characteristic of the main mode of variability of the tropical Atlantic Ocean at interannual scales, the Atlantic Niño or Equatorial Atlantic Mode (Zebiak, 1993). Simulations with global and regional Atmospheric General Circulation Models (AGCMs) can reproduce this WA rainfall response to the Equatorial Mode (Janicot et al., 1998; Vizy and Cook, 2002; Paeth and Friederichs, 2004; Giannini et al., 2003, 2005; Losada et al., 2010a). An Atlantic Niño (warm phase of the Equatorial Mode) reduces the SLP gradient between the Saharan Heat Low and the warmer than average Equatorial Atlantic (Losada et al., 2010a). This, in turn, drives southwards the Intertropical Convergence Zone (ITCZ) (Janicot et al., 1992, 1998), leading to a precipitation dipole with increased rainfall over the GG and reduced rainfall over the Sahel (Janicot, 1992, 1998; Ward, 1998; Vizy and Cook, 2002; Paeth and Friederichs, 2004; Losada et al., 2010a; Mohino et al., 2011b). However, some studies only show a positive connection of the Atlantic Niño with rainfall over the GG, with no significant loadings over the Sahel (Giannini et al., 2003, 2005; Polo et al., 2008).

Regarding the Pacific basin, some early works did not show a statistically significant relationship between ENSO and summer rainfall over WA (Ropelewski and Halpert, 1989; Kiladis and Diaz, 1989; Shinoda and Kawamura, 1994). Nevertheless, more recent works using observations and model simulations show that warmer than average SSTs over the tropical eastern Pacific in boreal summer are related to a decrease of precipitation over the Sahel (e.g., Folland et al., 1986; Palmer, 1986; Palmer et al., 1992; Rowell et al., 1995; Janicot et al., 1996, 1998; Ward, 1998; Rowell, 2001; Camberlin et al., 2001; Janicot et al., 2001; Giannini et al., 2003; Moron et al., 2003, 2004; Dai et al., 2004; Mohino et al., 2011a). This reduced Sahel rainfall would be linked to a weakened WA monsoon due to large-scale subsidence (Mohino et al., 2011a) caused by a change in the Walker Circulation (Janicot et al., 1996, 1998) or propagation of equatorial waves (Rowell, 2001). Other authors suggest that this reduction could be connected to a general warming of the tropical troposphere (Giannini et al., 2001; Neelin et al., 2003). The connection between WA rainfall and SST anomalies over the Pacific basin seems to have strengthened after the 1970s (Trzaska et al., 1996; Janicot et al., 1996, 2001; Mohino et al., 2011b).

Both, Atlantic Niño and ENSO, the leading modes of Tropical Atlantic and Pacific SST variability respectively, are known to have an impact on the WA rainfall. However, both oceanic basins have suffered a change in their variability/feedbacks processes for certain periods (Federov and Philander, 2000; An, 2009; Tokinaga and Xie, 2011; Richter et al., 2013), which presumably affects their teleconnections. For instance, Rodríguez-Fonseca et al. (2009) have found how the Atlantic Equatorial Mode is negatively correlated with the Pacific ENSO since late 1960s. The authors, using observations and partially-coupled simulations considering the prescribed observed SST in the Atlantic as the only external forcing, showed how an Atlantic Niño could activate the deep convection over the equatorial Atlantic, altering the Walker Circulation and linking both basins through an atmospheric bridge. The subsidence over the equatorial Pacific creates anomalous surface divergence, which, in turn, modifies the thermocline depth, setting up the conditions for the development of a Pacific La Niña. This atmospheric bridge proposed as the mechanism responsible for the interbasin connection was confirmed using climate models (Losada et al., 2010b; Ding et al., 2011). More recently, Polo et al. (2013b) have deeply analysed the oceanic mechanisms at work in the connection between the Atlantic Niños and Pacific Niñas (and vice versa) established after the 1970s. They found that the surface wind divergence over the central Pacific strengthens the trades in the western equatorial Pacific, piling up warm water in this region and deepening the thermocline. The thermocline shallows east of the divergence propagating eastward as a Kelvin wave from autumn to winter. The impact on SST in the eastern Pacific appears some months later as a consequence of the Bjerknes feedback that is established after the wave reaches the American continent (Polo et al., 2013b). Martín-Rey et al. (2012) confirmed this impact of the Atlantic in the tropical Pacific variability modes using the simulations performed by Rodríguez-Fonseca et al. (2009). They found that the equatorial Atlantic SST in summer impacts on the winter Tropical Pacific SST allowing the thermocline feedbacks to be more active after 1970s. Besides, since the 1970s, the spatial pattern of the Equatorial Mode presents a westward extension of the SST anomalies up to the Atlantic-4 region [40W-20W, 3N-3S] covering the whole equatorial band. On the other hand, the leading mode in the previous decades is characterized by a warm tongue in the eastern Atlantic and negative anomalies in north and south subtropical Atlantic (Polo et al., 2008; Rodríguez-Fonseca et al., 2009).

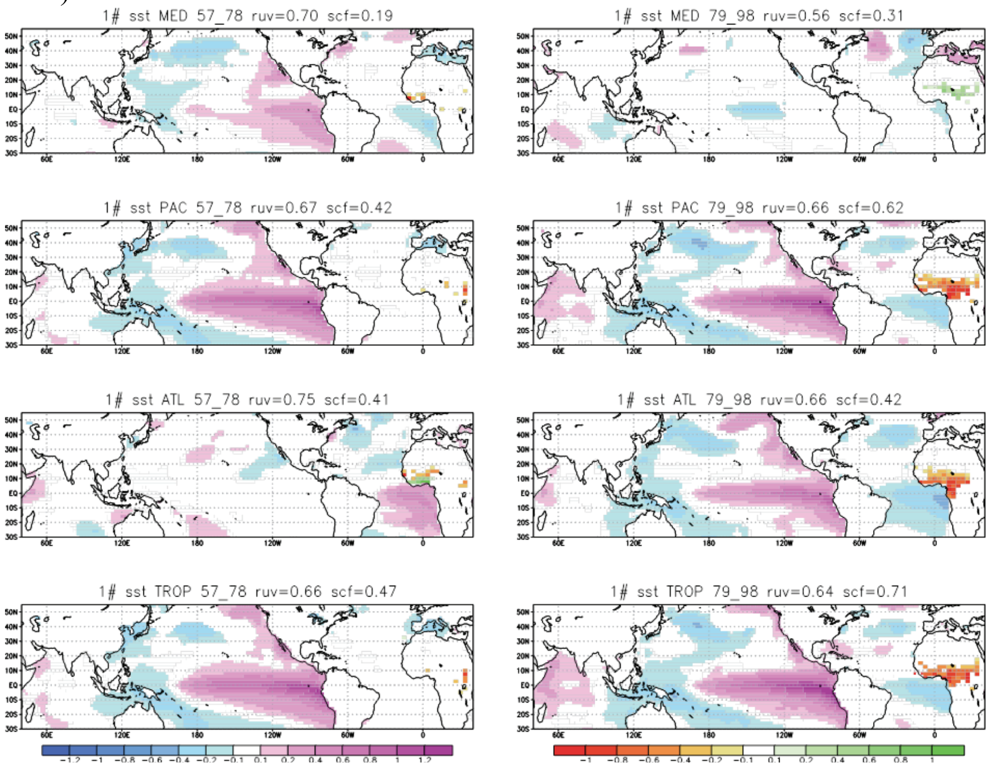

Fig. 2. June to September (JJAS) SST and rainfall regression patterns associated with the leading extended maximum covariance analysis (EMCA) mode obtained between the Mediterranean (first row), Pacific (second row), Atlantic (third row), and global Tropics (fourth row) and the West African rainfall for the period before and after the 1970s. The squared covariance fraction and SST-rainfall correlation score is indicated at the top of each map. Only regions 95% statistically significant under a t-test are gridded. Right and left colour bars correspond to the rainfall and SST, respectively. (Modified from Rodríguez-Fonseca et al., 2011). Rainfall and SST data come from CRU (Hulme 1992) and HadISST (Rayner et al., 2003) respectively.

Mohino et al. (2011b) investigates the relationship between tropical SSTs and summer Sahelian rainfall – both before and after the 1970s – using observations and an ensemble of five AGCMs, by performing Extended Maximum Covariance Analysis (EMCA; Polo et al., 2008) between SSTs in the tropical Atlantic and Pacific oceans and summer precipitation in WA for two periods of time (1957-1978 and 1979-1998). Their results reveal that, before the 1970s, the pattern of rainfall anomalies associated with the Atlantic Niño is a dipole with anomalies of opposite sign in the GG and the Sahel but, after the 1970s, the pattern is no longer of the dipole-type. Instead, a warming (cooling) of SSTs in the GG appears associated with a monopole-type of positive (negative) rainfall anomalies in WA together with weak impacts on the Sahel (Figure 2, third row). They also show that the correlations between the tropical Pacific SSTs and WA precipitation are higher after the 1970s (Figure 2, second row). Furthermore, Mohino et al. (2011b) results show that, after the 1970s, the patterns of covariability between WA precipitation and SSTs in each of the basins have similar and significant projections outside the basin considered, presenting an El Niño-like pattern in the Atlantic together with a La Niña-like pattern in the Pacific.

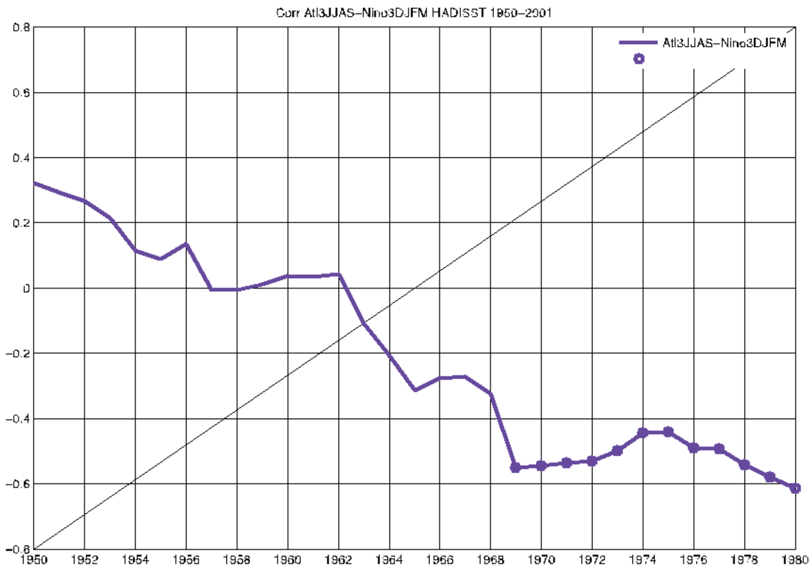

Fig. 3. Twenty year lead-lag correlation, running one year from 1952–1972 to 1981–2001, between the observed summer Atl3-index (June–July–August–September) and observed Niño-3-index in winter (December-January-February-March). Dots denote those correlations between the Niño3 and the Atl3 index that are 90% Monte Carlo test.

Following Mohino et al. (2011b) results, Rodríguez-Fonseca et al. (2011) investigate the change in the relationship of the global tropical oceans and the WA Monsoon before and after the 1970s. They apply the same EMCA technique to global tropical SSTs (from 20ºN to 20ºS) and summer precipitation in WA. Their results are focused on the summer season (JJAS) only, and show that after the 1970s there appears a dominant mode of covariability between global tropical SSTs and WA precipitation that explains the 60% of the covariance and that relates a decrease (increase) of precipitation in the whole WA with anomalously cold (warm) SSTs in the GG and the Maritime Continent, and anomalously warm (cold) SSTs in the eastern tropical Pacific and the Indian Ocean (Figure 2, fourth row). The seasonal evolution of this mode shows the maximum loadings of SST anomalies in the tropical Atlantic during spring, which are related to a dipole of rainfall anomalies in WA; from July on the pattern of precipitation presents a monopolar structure, and the mode shows a decrease of the anomalies in the GG, as the SSTs in the eastern Pacific and Maritime Continent become more important (Losada et al., 2012). This pattern of SST anomalies is consistent with the results by Rodríguez-Fonseca et al. (2009), who reported that after the 1970s the Atlantic Niño (Niña) is associated with a La Niña (El Niño) in the Pacific, a relationship that didn't hold before the 1970s (Figure 3).

Both Mohino et al. (2011b) and Rodríguez-Fonseca et al. (2011) hypothesize that the changes in the relationships between WA rainfall and tropical SSTs at interannual time scales before and after the 1970s could be due to the concomitant impact of SST anomalies of the Atlantic and Pacific basins after the 1970s. Losada et al. (2012) validate this hypothesis by performing a set of AGCM experiments with two different models, prescribing the spatial pattern of SSTs of the tropical global mode both in the global tropical ocean (GT experiment) and in the Atlantic and Indo-Pacific tropical basins separately (TA and IP experiments respectively). Their results show that the impact of the individual ocean basins on WA rainfall seems to be relatively stationary over time, with the tropical Atlantic producing a dipole of anomalous precipitation over WA and the Indo-Pacific affecting Sahel precipitation in summer (Figure 4 a-d, e-h). After the 1970s, interferences between the impacts of SSTs from each of the tropical ocean change the pattern of WA precipitation. In spring the SST anomalies of the Indo-Pacific reinforce the impact of the Atlantic SSTs in WA rainfall, producing a strong dipole of precipitation anomalies. Conversely, in summer, the influence of SSTs of the Indo-Pacific basin over the Sahel is opposite to that of the Atlantic SSTs, leading to the weakening and disappearance of the anomalous dipole of precipitation when the two basins are considered together (Figure 4 i-l). Results from the GT experiment are similar to the sum of the TA and IP (Figure 4 m-p), meaning that the precipitation response over WA to tropical SST anomalies is mostly linear.

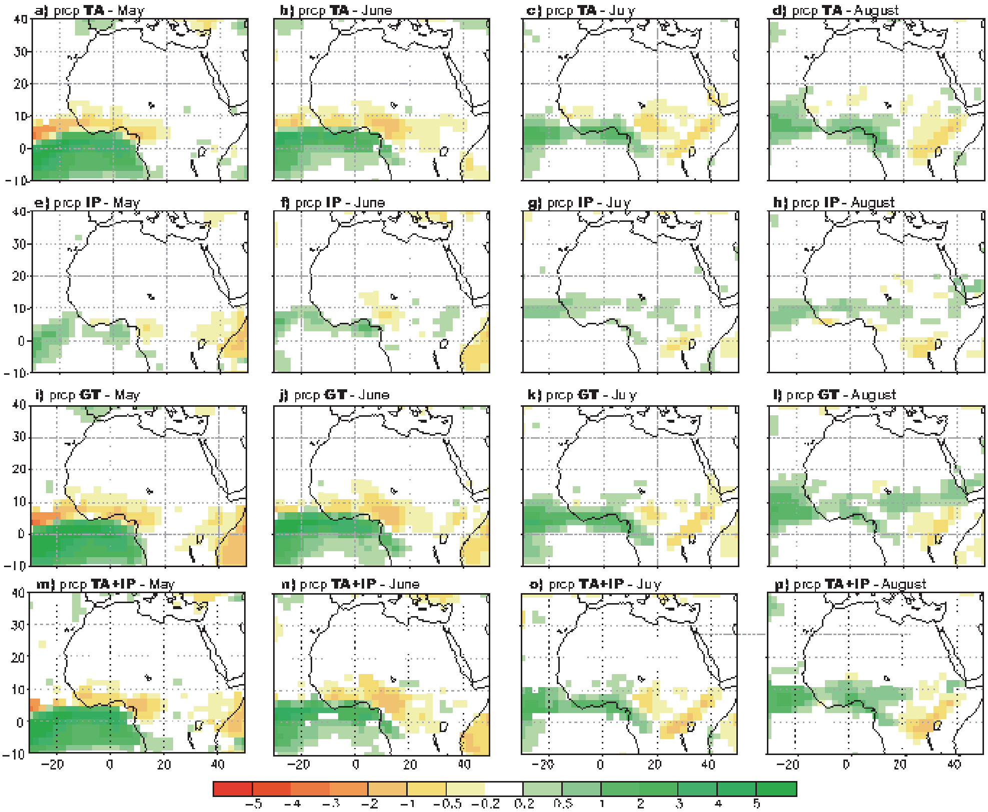

Fig. 4. May to August monthly-mean anomalies of precipitation (mm/day) a-d) for TA; e-h) IP and; i-l) GT experiments; and m-p) sum of TA and IP experiments, calculated as the difference between the mean of the sensitivity experiments from the two models and the control simulations. Only the regions where the ratio of mean to standard deviation of the models is larger than one are showed. (Modified from Losada et al., 2012). Rainfall data come from CMAP (Xie and Arkin, 1997).

Outside the tropics, several works have also pointed out a positive connection between SST anomalies over the Mediterranean and Sahel rainfall, associated to an increased north-easterly moisture transport from the eastern Mediterranean (Rowell, 2003; Raicich et al., 2003; Fontaine et al., 2010; Fontaine et al., 2011). Mohino et al. (2011b) and Rodríguez-Fonseca et al. (2011) investigate the relationship between Mediterranean SST and WA precipitation before and after the 1970s (Figure 2, first row) as well, finding that before the 1970s Mediterranean SST anomalies are related to precipitation anomalies in a very small region of the GG, while after the 1970s a warming in the Mediterranean is related to an increase of precipitation over the Sahel, in agreement with other studies (Polo et al., 2008; Fontaine et al., 2010). Also, before the 1970s the

Mediterranean SST could be a fingerprint of a more global pattern of SST; while after the 1970s Mediterranean SST anomalies related to WA precipitation is an isolated pattern.

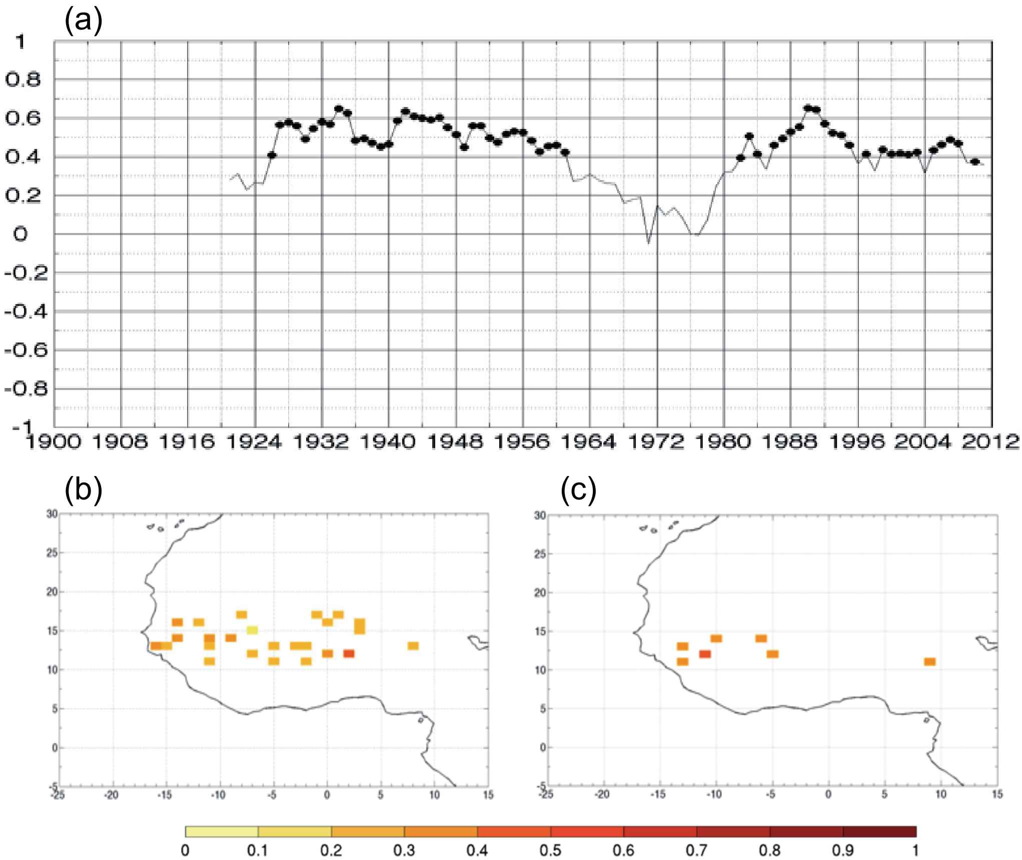

Fig. 5. a) 20 years moving window correlation between expansion coefficients U (SST) and V (PCP) of the leading co-variability mode among SST in lag 3 (AMJ) and PCP in lag 0 (AMJ) from MCA. The black dots mark the significant correlation period. (Second row) Validation of the hindcast in terms of the significant correlation between observed and modelled precipitation for the significant b) and no significant c) correlation according a) periods. All values are 90% significant under a Monte Carlo test. Rainfall data come from GPCC data (Schneider et al., 2008).

The "switch off" and "on" of the influence of some oceanic basins on the WA rainfall variability can have an important application for predictability issues. In this way, if the covariability of the SST and rainfall anomalies does not hold on during the whole period of study, the use of the entire time series for predicting rainfall from SSTs could diminish the accuracy of statistical predictions (Suárez, 2012). This can be seen in Figure 5a in which the moving correlation between the expansion coefficients for the leading mode of covariability between rainfall in Sahel and SSTs in the Pacific shows how during the central years of the 20th century the Pacific seems to have no significant influence on the Sahelian rainfall. Using just those years for which there is a significant relation between the expansion coefficients of the Maximum Covariance Analysis (MCA) (Figure 5b), the prediction is better than the case in which there is not a significant influence (Figure 5c).

3.2. Euro-Mediterranean

The climate variability over the EM sector is usually related 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).The specific study of the Mediterranean climate, however, becomes more complex due to its geographical location, between the tropics and mid-latitudes, which causes the existence of two different underlying dynamics associated with these two areas (Lionello et al., 2006). Besides the NAO, others patterns, as the East Atlantic (EA, Krichak et al., 2002; Fernandez et al., 2003) or the Scandinavian pattern (SCAND, Xoplaki, 2002), influence the climate of the Mediterranean region.

Although the NAO is mainly associated with internal and almost unpredictable variability, it is also influenced by SSTs, which might increase its predictability (Hurrell et al., 2003). In that sense, it has been found a consistent and statistically significant ENSO signal on the European climate (Fraedrich and Müller, 1992; Moron and Plaut, 2003). Interestingly, its regional atmospheric spatial pattern at surface levels presents a similar structure to the one associated with the NAO (García-Serrano et al., 2010). In general, El Niño tends to be accompanied by a negative phase of the NAO, which does not mean that all the negative NAO comes from a El Niño (Brönimann, 2007). In this way, it is not easy to make the difference, at surface levels, between the ENSO and NAO signals, and hence, between spatial patterns associated to forced (predictable) or internal (unpredictable) variability in the atmosphere. This issue becomes even more complex considering that both, the influence of the NAO (Hilmer and Jung, 2000; Lu and Greatbatch, 2002; Vicente-Serrano and López-Moreno, 2008) and the influence of ENSO (López-Parages and Rodríguez-Fonseca, 2012; Greatbatch et al., 2004; Mariotti et al., 2002; Zanchettin et al., 2008) over the North Atlantic European sector, have not been stationary along the 20th century. In that sense, the importance of forced signal like ENSO over the North Atlantic European and the Mediterranean regions might be only large for selected intervals.

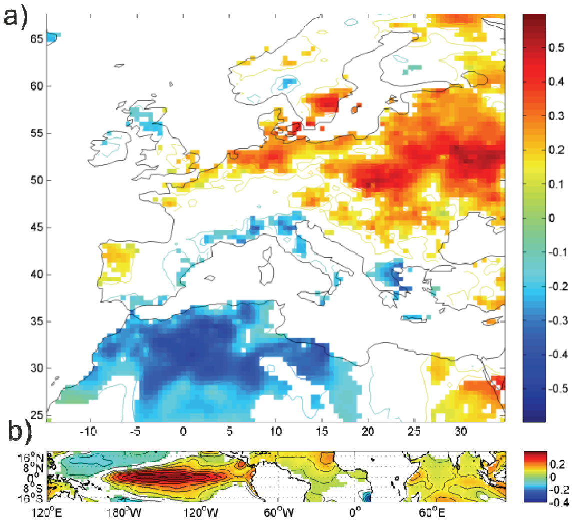

Fig. 6. FMA leading mode of covariability between iEMedR and itropSST: a) heterogeneous rainfall pattern and b) homogeneous SST pattern. Only regions 95% statistically significant under a Monte-Carlo test are shaded. Rainfall data come from University of Delaware (Matsuura & Willmott, 2009).

In this work the link between the EM rainfall (iEMedR) and the SST in the tropics (tropiSST, [20ºN-20ºS]), for late winter and spring, and at interannual time scales, is determined by performing a MCA between these fields. The leading mode of covariability, which explains 17% of the total variance, is shown in Figure 6. The heterogeneous rainfall pattern presents significant anomalies over central east Europe, opposite in sign to those over the Mediterranean region and the northwest Africa. The associated homogeneous tropiSST pattern presents a significant structure over the tropical Pacific in an El Niño-type configuration. Over the subtropical Atlantic basin, two different signals of iSST, with opposite signs, appear for both hemispheres. This response could be related to changes in the trade winds. Regarding the variability of the link between iEMedR and tropiSST, the statistically significant changes identified (Figure 7a) in the variance of both expansion coefficient (hereafter V_pcp and U_sst respectively) point to a lack of stationarity of the leading mode obtained in the MCA. To assess this issue, 21-year window sliding correlations have been computed between V_pcp and U_sst (Figure 7b). The resultant correlation presents a nonstationary behaviour. The link between U_sst and V_pcp is statistically significant from 1900 to 1930, and from 1960 to 1990, while the relationship significantly decreases in the middle of the 20th century and after the 1990s. The same result is obtained if U_sst is replaced by the Nino3.4 index (SST averaged between 120W-170W in longitude and 5N-5S in latitude). Additionally, different Principal Component Analysis (PCA) have been done (not shown) for short periods (around 20 years) along the 20th century to analysed how the variability of iEMedR has changed. These “short PCA” shows, before the 1930s and after the 1960s, a dipolar iEMedR pattern, which broadly coincide to the one obtained from MCA, related to El Niño. However, for the decades in between, the iEMedR pattern previously mentioned seems to be weaker, and no significant El Niño signal is found in relation to it. All the previous results indicate that the dipolar iEMedR pattern analysed mainly appears when the relationship between iEMedR and tropiSST occurs. An interesting result is the fact that this link takes place coinciding with negative phases of the AMO[1]. Many questions about the reasons of this nonstationary teleconnection remain open, as the origin of the modulating factors. In this sense, López-Parages et al. (2013, in preparation) have analysed a long Coupled GCM control run, in which only the internal variability of the system is considered, and have obtained similar results to the observed ones (López-Parages and Rodríguez-Fonseca, 2012). This suggests that ENSO teleconnections with the leading rainfall pattern in the European sector are not stationary and that there is a multidecadal modulator factor, internal to the climate system, which switches on and off this connection. The causes of this multidecadal modulation are still unresolved and sensitivity studies are needed to further corroborate the posed hypothesis.

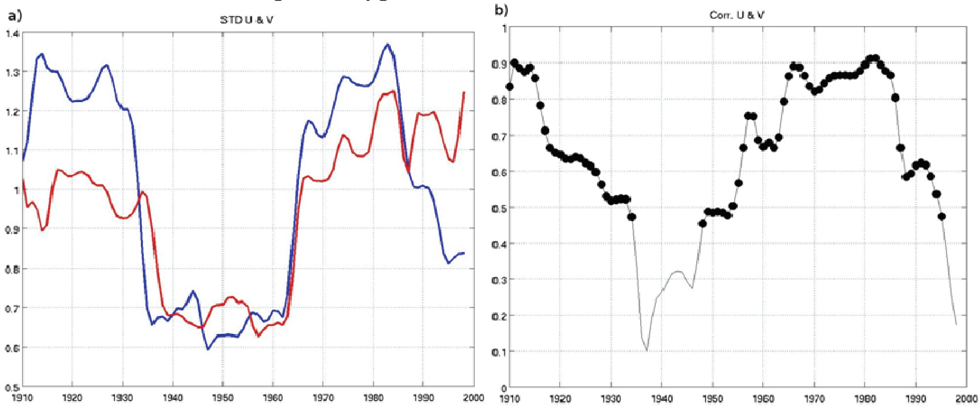

Fig. 7. a) 21years moving window standard deviation of iEMedR expansion coefficient (V_pcp; blue line) and itropSST expansion coefficient (U_sst, red line), b) 21 years moving window correlation between V_pcp and U_sst. Fill dots in panel b represent periods with a 95% significant correlation according to a Monte-Carlo test.

The EM day-to-day local weather is highly sensitive to the passage of North Atlantic extra-tropical cyclones, particularly in winter. The NAO fluctuation between subpolar and subtropical North Atlantic latitudes influences on the stormtrack, and hence, the precipitation regime (Rodwell et al., 1999; Hurrell et al., 2003). Thus, the analysis of extratropical North Atlantic cyclones is a good approach to study the NAO.

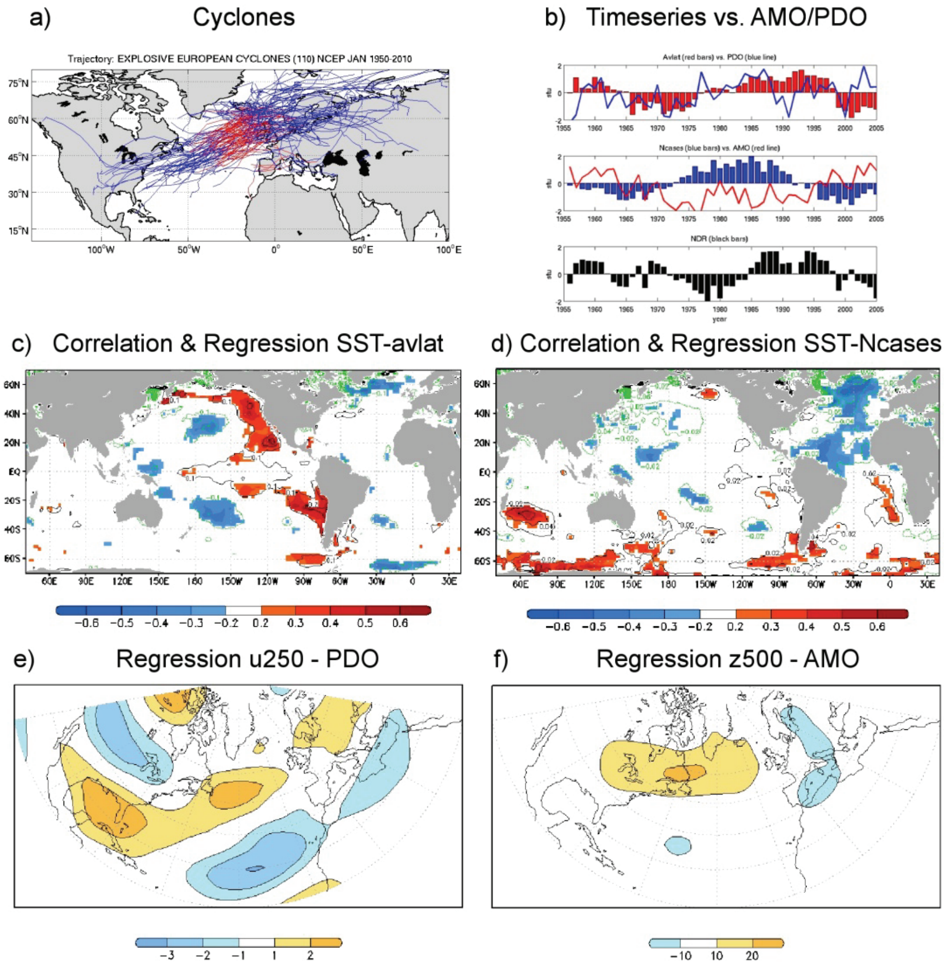

Fig. 8. a) Explosive cyclones (110 cases) in the vicinity of Europe (with any part of their NDR segments overlapping the latitude-longitude box [20W-40E, 30N-65N])). Whole cyclone trajectory in blue, NDR segments in red. b) Standardised time-series (11yr running means) and SST indices: Average latitude of cyclones (avlat, red bars) and PDO SST index (blue line) on the top. Number of cases (Ncases, blue bars) and AMO SST index (red line) on the centre. Average cyclone NDR (NDR, black bars) on the bottom. c) Correlation (blue-red shadings, above 90% confidence level using a double-tailed t-test) and regression of SST (January, in K) on to the avlat time-series. d) Same as c) but for Ncases. e) Regression of u250 on to the 11-yr running mean PDO index (in m s-1). f) Same as e but for z500/AMO (in gpm). Time interval: January a) 1950 - 2010 b)-d) 1956-2005 e)-f) 1950 – 2003.

Extratropical North Atlantic cyclones generally develop near the East coast of North America, intensify over the ocean and reach Europe during their final life-cycle stages (Trigo, 2006, Pinto et al., 2009). Hazardous wind gusts and precipitation events leading to strong socio-economic impacts (Della-Marta et al., 2009) are often associated with cyclones featuring large deepening rates (e.g., EC, Sanders and Gyakum, 1980) as extensively reported in the literature (Ulbrich et al., 2001; Liberato et al., 2011; Fink et al., 2012; Rivière et al., 2012). From a meteorological point of view, the study of the dynamical factors that appear to foster explosive cyclogenesis in the NA (Wang and Rogers, 2001; Hanley and Caballero, 2012; Gómara et al., 2013) helps to improve predictions of these damaging events and mitigate their associated impacts. From a climatic perspective, it is also of high importance the analysis of the long-term (decadal/multidecadal) variability of their associated characteristics to assess their potential impacts under present-day and forthcoming climate scenarios (Pinto et al., 2012).

Using the NCEP reanalysis data, EC (NDR ≥ 1 Bergeron; eq. (1) from Lim and Simmonds, 2002) in the vicinity of Europe have been selected through an automatic tracking method (Pinto et al., 2005) on the period January 1948 – 2010 (Figure 8a). For the selected EC, an 11-year running mean (considering all cyclones within each 11-yr window) has been applied to the time series of Number of cases (Ncases), average latitude (avlat) and average NDR, with linear trends removed, to account only for natural (non-anthropogenic) multidecadal variability of such variables (Figure 8b, bars). To describe both the Pacific Decadal Oscillation (PDO[2]) (Mantua and Hare, 2002) and AMO (Knight et al., 2005) variability two different monthly indices have been used (Figure 8b, lines).

The spatial correlation and regression (contours) maps between the filtered time series of the EC characteristics and global SSTs (monthly means, 1956 - 2005) have been subsequently performed (Figure 8(c,d)). In Figure 8c a significant correlation is observed between a positive phase of a PDO-like pattern over the North Pacific and the average latitude of EC affecting Europe (avlat). Conversely, the (increasing) number of EC over Europe in Figure 8d appears to be highly correlated with a negative phase of the AMO in the NA. These results are confirmed by the PDO and AMO monthly indices, which feature correlation values of 0.2812 (95%, t-test) and -0.4967 (99%, t-test) with the avlat and N cases time series, respectively (Figure 8b). The results derived from the NDR analyses are not shown as they do not provide any relevant outcome. In order to assess the possible physical mechanisms underlying the two proposed SST-EC modulations, a regression analysis of the monthly jet stream's intensity (u250) and geopotential height (z500) data (January) onto the PDO and AMO indices has been carried out. Figure 8e depicts how a PDO positive phase (1 standard deviation) is linked with a dipole of u250 anomalies (in m s^{-1}) downstream in the NA and over the EM sector, probably associated with a northward displacement of the eddy-driven jet.

This is consistent with a poleward shift of the EC tracks as reported in Figure 8b (top). Finally, the z500 field regressed on to the AMO index exhibits a wide area of positive anomalies spanning over the NA storm track region [40-60N, 80-10W] in Figure 8f. As a consequence, the number of developing cyclones (including EC) during a negative AMO phase is expected to increase over this area, thus enhancing the frequency of EC downstream in the storm track over Europe. Nevertheless, further analysis is needed to confirm whether the proposed mechanisms hold in a centennial control run of a coupled (ocean-atmosphere) model.

4. Evaluation of multidecadal modes of variability in state of the art GCMs

The AMO is usually considered as an internal variability mode of the Atlantic Ocean SST, related to changes in the thermohaline circulation (Knight et al., 2005). Nevertheless, recent works indicate that the observed AMO has also been affected by external radiative forcings, like those produced by anthropogenic aerosols and volcanoes (Ottera et al., 2010; Booth et al., 2012; Terray, 2012). This pattern shows alternating phases of warm and cold SST anomalies across the northern Atlantic basin, with an oscillation period of 50 -70 years (Kerr, 2000). During the 1860s-1880s and 1940s-1960s the AMO was in a warm phase, and the 1900s-1920s and 1970s-1990s are decades characterized by a cold phase (Enfield et al., 2001).

As it was shown, the analysis of observational records suggests that the AMO plays an important role in the modulation of the teleconnections of the Mediterranean (López-Parages and Rodríguez-Fonseca, 2012) and WA (Losada et al., 2012) with remote regions such as the tropical Pacific (Polo et al., 2013a). Therefore, to further understand the teleconnections between the Atlantic and the surrounding regions and the processes that induce and modulate them, it is useful to analyse the simulations of GCMs and their ability to reproduce an AMO-like SST pattern on the Atlantic basin.

The results of historical and preindustrial control (piControl) simulations of twelve GCMs (CNRM-CM5, CSIRO-Mk3-6-0, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, HadGEM2-ES, inmcm4, IPSL-CM5A-LR, MIROC5, MIROC-ESM-CHEM, MPI-ESM-LR and MRI-CGCM3) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) have been analysed. The historical simulations cover much of the industrial period (since the mid-19th century) and include the evolution of the external forcing (natural and anthropogenic). And the piControl run, which simulates several centuries without external forcing and fixed boundary conditions, is used to obtain the internal variability of the model when it reaches the equilibrium (Taylor et al., 2011).

In order to isolate the internal SST variability of the Atlantic in the historical runs and in the observations we must first remove the large-scale signal associated with global processes (Meehl et al., 2004). For this purpose, we define the global warming index (GW) as the annual mean SST anomaly averaged over the 60°N - 60°S region, low-pass filtered with a 40 years frequency cut-off (a Butterworth filter of order 10 was used). For those models run in ensemble mode, we first average the surface temperature (TS) data for all the ensemble members.

The spatial pattern related to the GW signal is calculated by regression of the TS anomaly field onto the GW time series. We finally get a residual TS anomalous field by subtracting the product of the GW spatial pattern times the GW time series to the TS anomaly field. For models run in ensemble mode, we use just one member for the calculation of the residual TS field.

From the residual SST anomaly of the observations and the historical outputs, we obtain the AMO index computing the average throughout the North Atlantic (0-60°N and 0-80°W). In the case of piControl outputs, the index is obtained from the original SST anomaly field. All the time series are standardized and a 13-year low-pass filter is applied to isolate the multidecadal variability.

The TS patterns associated with the AMO are obtained as the regression of the anomalous original TS field onto the AMO index of each model separately (not shown). The average of the regression maps of all the models show a horseshoe shaped North Atlantic warming pattern which is reproduced by all models in both experiments, as well as in the observations (Figure 9).

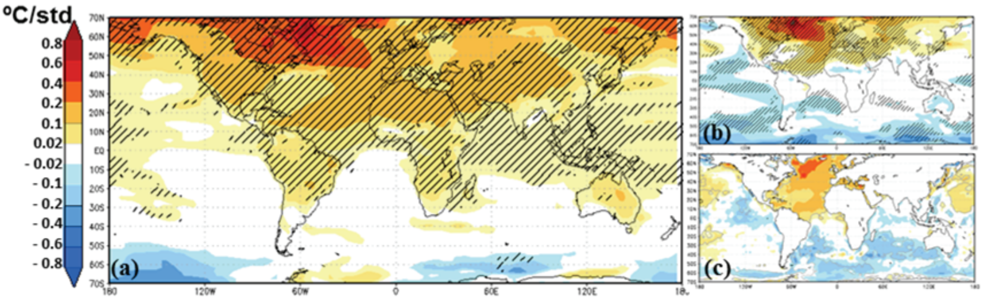

Fig. 9. (a) Average of the twelve regression maps of each model of annual mean surface temperature anomaly (ºC/std.) of the historical experiment onto the AMO index obtained from the low frequency filtered residual SST. (b) Same as (a) but for the piControl run and with an AMO index calculated from the low frequency filtered original SST. Hatched area in (a) and (b) indicates the regions where the regression rate of at least 8 of the 12 models has the same sign. (c) Regression of the observed SST anomaly (ºC/std.) onto the AMO index obtained from the residual SST of HadISST1 database. Gray contour marks 95% significant correlation regions (according to a *t* test).

However, out of the Atlantic basin, there are discrepancies among the different models. Moreover, the mean historical AMO pattern is warmer than the piControl one. This could suggest that the methodology followed with these historical runs is not able to completely extract the forced component of the variability. There could also be a net effect of the external forcing on the dynamics of the AMO (Trenberth et al., 2007).

The analysis of the Fourier transform of the AMO indices (not shown) highlights a periodicity of about 50-70 years in the AMO index of the observations, in accordance with bibliography (Kerr, 2000). However, the simulations produce different results. Some models (CSIRO-Mk3-6-0-ESM2G GFDL, GFDL-ESM2M, GISS-E2-H and HadGEM2-ES) have similar periodicities in historical and piControl simulations. Others (CNRM-CM5, inmcm4 and MIROC5) show a periodicity of the AMO of more than 100 years in the piControl AMO indices, which is probably too long to be characterized by the historical runs. The rest of the models show no characteristic periodicity in the AMO index. Furthermore, all the indices obtained from the outputs of the models have a power spectrum of the Fourier transform much weaker than the index of the observations. Except GFDL-ESM2G, that shows a peak with a period of around 80 years, slightly more intense than the peak of the observations.

5. Summary and conclusions

In this study some works carried out by the TROPA group along the last years are shown to bring together some interesting results about the nonstationary behaviour of interannual variability. By examining observational and modelled results it has been highlighted the important role of decadal and multidecadal variability modes in the modulation of interannual variability. The results obtained have been organized on the ocean interannual variability, on the one hand, and on the atmospheric interannual variability, on the other hand. The latter results have been focused on the impact over the West Africa and the Euro-Mediterranean regions, whose interannual variability seem to be highly affected by the phase of the AMO. The importance of AMO has carried on to determine the ability of GCMs to reproduced a realistic AMO-like SST pattern.

In particular, the main results obtained in our investigation are:

1) A robust link between tropical Atlantic and Pacific SSTs has been found for selected decades, at the beginning of the 20th century and after the 1970s.
2) A changing impact over the WA rainfall is identified before and after the 1970s. Before that decade, a dipole-type pattern appears in relation to the Atlantic Niños. After the 1970s, the WA rainfall pattern change into a monopole-type associated

to a concomitant influence of tropical Atlantic and Pacific SSTs. This issue has been validated by performing a set of AGCM experiments.

3) The link between the Mediterranean SST and the WA rainfall has also change before and after the 1970s, with a weak impact over the GG before, and an increased impact over the Sahel after, that decade.

4) The nonstationarity of the SST influence of certain oceanic regions on precipitation in WA can improve the statistical predictability by selecting the most suitable predictors depending on the period in which we want to predict.

5) Over the EM region, a nonstationary link between the iEMedR and the tropiSST is identified. Thus, a dipolar rainfall pattern is reinforced when the relationship between the rainfall and the tropical SSTs occurs. This link takes place in coincidence with negative phases of the AMO along the 20th century.

6) Multidecadal modes have also shown to influence the EM region through the change in variability of the EC. In this way, the average latitude of EC affecting Europe seems to be associated with the PDO through changes of the jet stream intensity. Instead, the variability in the number of EC points to a modulation by the AMO.

7) Most GCMs do not reproduce a well-defined periodicity of the AMO. In addition, they reproduce a warmer TS pattern in the historical simulations than in the piControl, possibly connected to a remaining external forcing in the North Atlantic variability. Despite these differences, the characteristic SST pattern of the AMO in the North Atlantic reproduced by the models is consistent in both simulations and in observations.

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