Interaction between the West African Monsoon and the summer Mediterranean climate: An overview

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Abstract
Although in the framework of the global climate research the Mediterranean climate variability and the West African Monsoon (WAM) dynamics have been considered for a long time as "passive" systems, i.e., prone to the influence of large scale ocean and atmospheric variability, over the last decade many studies have been dedicated to the WAM-Mediterranean interaction and the active role of these climate systems has been highlighted. This article presents the WAM-Mediterranean teleconnection through an overview of the recent literature, describing the observational evidences and the dynamical mechanisms underlying this climate teleconnection. The influence of the Mediterranean Sea thermal anomalies on the WAM dynamics has been robustly demonstrated, and a WAM modulation of the atmospheric circulation over the Euro-Atlantic sector has been highlighted. On the other hand, the direct effects of the WAM dynamics on the Mediterranean climate still need to be more clearly understood.
Key words: Climate, Teleconnection, Mediterranean, West Africa, Monsoon.

Interacción entre el Monzón de África Occidental y el clima Mediterráneo en verano: Artículo de revisión

Resumen
La variabilidad climática de la región Mediterranea y la dinámica del Monzón de África Occidental (MAO) han sido considerados durante mucho tiempo como sistemas pasivos por la comunidad científica, es decir, como regiones objeto de la influencia de la variabilidad atmosférica y oceánica de gran escala. Sin embargo, durante la última década diversos estudios se han centrado en la interacción del MAO y la región mediterránea, destacando el papel activo de ambos sistemas climáticos. En este trabajo se presenta una profunda revisión de la literatura reciente acerca de las teleconexiones entre el MAO y la región del Mediterráneo, describiendo las evidencias observacionales y los mecanismos dinámicos que subyacen en esta teleconexión climática. La influencia del contraste térmico del Mar Mediterráneo en la dinámica del MAO se ha demostrado claramente. Sin embargo, aunque se ha apuntado a una modulación de la circulación atmosférica en el sector Euro-Atlántico por el MAO, todavía es necesario comprender más claramente los efectos directos de la dinámica del MAO en el clima Mediterráneo.
Palabras clave: Clima, Teleconexión, Mediterráneo, África Occidental, Monzón.

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1. Introduction

In the framework of the global climate research, the Mediterranean climate variability and the West African Monsoon dynamics (WAM) are mostly considered as "passive" systems, prone to the influence of large scale ocean and atmospheric variability. In this context, the Mediterranean climate appears to be influenced by both midlatitude and tropical circulation patterns as underlined by Lionello (2012). Thus, from September to May during the cold season, three main atmospheric modes affect the Mediterranean region, namely, the North Atlantic Oscillation (NAO; Wallace and Gutzler, 1981), the Eastern Atlantic/Western Russia pattern (EA/WRUS; Barnston and Livezey, 1987) and the Scandinavian pattern (SCAND; Barnston and Livezey, 1987). At this period of the year, the NAO is widely considered the most important source of climate variability over Europe and Mediterranean through changes induced in the North Atlantic storm track activity. A related index, defined as the leading Principal Component of the 500 hPa geopotential height anomalies in the North Atlantic sector, exhibits centres of action near the Azores islands and Iceland (Hurrell et al., 2003) and is positively correlated with rainfall in northern Europe and negatively with rainfall in southern Europe (Marshall et al., 2001). The EA/WRUS mode shows a 3-centre east-west pattern spanning from the British islands to northeast China: it affects the winter temperature variability in the western Mediterranean region, and is positively (negatively) correlated with the rainfall over central and eastern Mediterranean Sea, eastern North Africa and Middle East (Iberian Peninsula and northern Mediterranean coast) (Xoplaki, 2002). The SCAND mode is characterized by a positive pressure anomaly north of the Scandinavian Peninsula and affects the Mediterranean region mainly in winter: it is associated with wet precipitation anomalies in the western and central basins and cold temperatures over the whole Mediterranean region (Xoplaki, 2002). Interesting associations with the El Nino/Southern Oscillation (ENSO) have been also observed, both at the interannual and multidecadal time scales. Thus Mariotti et al. (2002) showed that the interannual variability of rainfall in the Euro-Mediterranean sector is influenced by ENSO in finding significant correlation patterns in central and eastern Europe during winter and spring, and in western Europe and the Mediterranean region during autumn and spring. Shaman and Tziperman (2011) demonstrated that the interannual rainfall variability over the Mediterranean region is linked to ENSO variability in the eastern Pacific via an eastward-propagating atmospheric stationary barotropic Rossby-wave train. Moreover, Lopez-Parages and Rodriguez-Fonseca (2012) recently highlighted how the teleconnection with the ENSO appears modulated by multidecadal oscillations of the Sea Surface Temperature (SST) over the Atlantic and Pacific basins, namely the Atlantic Multidecadal Oscillation (AMO) in late winter-spring and the Interdecadal Pacific Oscillation (IPO) in autumn. In summertime, by contrast, the European climate is mainly affected by the Asian monsoon system, through the thermal excitation of a Rossby-wave pattern to the west, interacting with the southern flank of the mid-latitude westerlies and producing an adiabatic descent localized over the eastern Sahara and Mediterranean (Rodwell and Hoskins 1996; Tyrlis et al., 2013).

The WAM circulation originates in late spring in the Gulf of Guinea when the sea-land energy contrasts near the surface turn the tropical low-level easterly and northeasterly flows to southwesterly, advecting ocean moisture inland and triggering the monsoonal rainfall up to the Sahelian belt. The WAM is fully developed in summer (from July to September, JAS) when the southwesterly moisture flux converges onto the Sahel, and retreats in early autumn. Its variability covers a wide range of time scales, from intraseasonal (Sultan et al., 2003) to decadal (Lebel and Ali, 2009) and is sensitive to both local forcing and remote influences. Thus Mohino et al. (2012) demonstrated that part of the intraseasonal rainfall variability over WAM is related to the Madden-Julian Oscillation (MJO) through the westward propagation of convection anomalies developed over the Indian Ocean. At the interannual time scale, climate variability depends more directly on the sea-land contrasts, i.e., the stronger energy gradients intensifying the monsoonal circulation and the inland penetration of the precipitation belt up to the Sahel, while the weaker limit the precipitation to the Guinea coast. In this respect, Joly and Voldoire (2010) pointed out the importance of SST in the Gulf of Guinea for the moist static energy content in the lower troposphere driving the monsoonal circulation and Losada et al. (2009) described the negative impact of the positive (warm) phase of the Atlantic Equatorial mode (the so-called Atlantic Niño) on the WAM precipitation. At larger spatial scale, Raicich et al. (2003) highlighted a connection between the WAM and the Indian monsoon through the circulation over the eastern Mediterranean driven by the Indian monsoon activity: the intensification of the climatological northeasterly flow crossing the eastern Mediterranean increases the convection over the Sahel. The linkage role of the Mediterranean between the WAM and the Indian monsoon has been also pointed out by Fontaine et al. (2011b) and Fontaine and Pham (2012). At longer timescales (multiannual to multidecadal) the global SST anomalies are recognized as the main driver of WAM variability (Folland et al., 1986). The relationship with the ENSO has been therefore extensively explored and periods of strong and weak correlations between WAM and ENSO have been identified by Janicot et al. (2001). These authors showed in particular, a significant negative impact of positive (warm) ENSO phases on the WAM precipitation after the 1970s. More recently, Mohino et al. (2011) specified the role of the main global SST modes in driving the multidecadal variability of the WAM precipitation, highlighting the prominent role of AMO and IPO compared to the SST Global Warming. They found that the positive (negative) AMO (IPO) phases act positively (negatively) on the WAM precipitation, modulating the drying trend induced by Global Warming.

The first attempts to identify interactions and feedbacks between the Mediterranean climate and the WAM dynamics date back to the beginning of the 21st century. Firstly, Rodwell and Hoskins (2001) showed that the Mediterranean-type climates may be induced remotely by the monsoon system, although they specified that the African monsoon role is marginal compared to the action of the Asian monsoon. Then Rowell (2003) demonstrated in a seminal work the positive influence of Mediterranean SST anomalies on the WAM precipitation through northerly moisture advection from the Mediterranean toward the Sahel. Over the last decade many other works have been dedicated to the WAM-Mediterranean interaction and the existence of this teleconnection is now widely accepted. This paper presents an overview of the WAM-Mediterranean teleconnection on the basis of some results recently published in the literature. Section 2 describes the influence of the Mediterranean Sea on the WAM variability and Section 3 the possible impact of the WAM dynamics over the North Atlantic and Europe, in Section 4 the general picture is drawn and some near future research lines are outlined.

2. Mediterranean influence on the West African Monsoon

The connection between the Mediterranean SST and the WAM precipitation has been underestimated until the seminal work by Rowell (2003) who explored this relationship using both observational and Atmospheric General Circulation Model (AGCM) data. Based on the observation that years with warmer than average SST are often wetter over the Sahel, whereas years with cooler than average SST tend to be drier, this author used idealized numerical simulations for providing evidence that the observed statistical link between the Mediterranean and the African Sahel is due to an influence of the former on the latter and can therefore be viewed as an atmospheric response to thermal Mediterranean forcing. These experiments were conducted using the HadAM3 version of the UK Meteorological Office climate model, in which the model was forced by anomalous (warmer than average and colder than average) SSTs in the Mediterranean and climatological SST elsewhere. In the "warm" experiments a positive significant response on the JAS Sahelian rainfall is observed. In years when the Mediterranean SST is warmer than average, increased evaporation leads to enhanced moisture content in the lower troposphere that is advected southwards into the Sahel by the low-level mean flow across the eastern Sahara. The resulting increased moisture convergence over the Sahel feeds the convective activity leading to increased precipitation. The responses of the 850 hPa wind, humidity and moisture flux fields in the "warm" experiments are displayed in Figure 1. Each of these responses is reversed in the "cold" experiments.

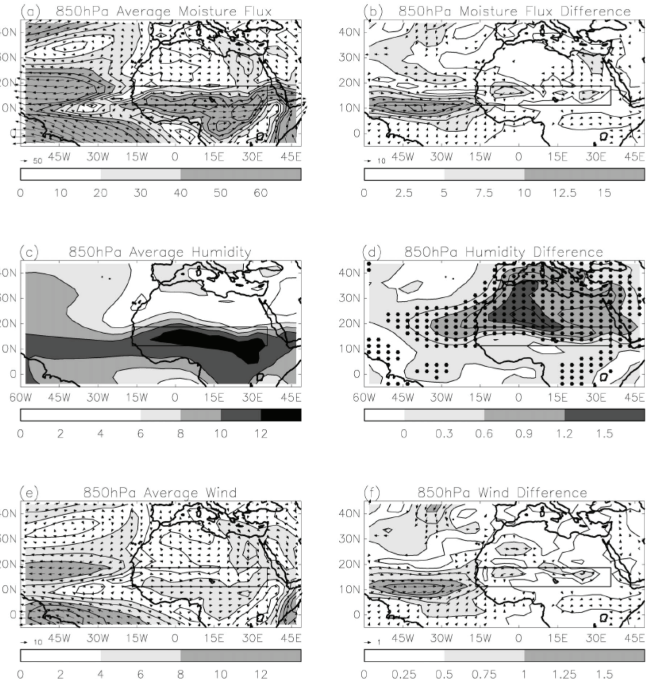

Fig. 1. (a) Average 850 hPa moisture flux (m/s g/kg), (b) composite difference of 850 hPa moisture flux, (c) average 850 hPa specific humidity (g/kg), (d) composite difference of 850 hPa specific humidity, (e) average 850 hPa winds (m/s), (f) composite difference of 850 hPa winds. All data are JAS means, composite differences are computed as the average of “warm” minus “cold” experiments. In (b) and (f) vectors are only plotted where the null hypothesis of zero difference between either the zonal or meridional components can be rejected (at the 5% significance level with a two-tailed test); and in (d) points where this null hypothesis can be rejected are indicated by a solid hexagon. Sahel location is marked by a rectangular box. Reproduced from Rowell (2003).

Several recent empirical and numerical studies supported the hypothesis of a connection between Mediterranean and WAM. So, Jung et al. (2006) found significantly increased Sahelian rainfall deriving from enhanced evaporation in the Mediterranean Sea, in simulating the response to the Mediterranean SST anomalies in summer 2003 over Europe and Africa. In complement, Peyrille et al. (2007) and Peyrille and Lafore (2007) emphasized the major role of thermal contrasts between the Mediterranean and the Sahara in describing the local circulations and mechanisms favouring the northward migration of the monsoonal rain belt, through a 2-D zonally-symmetric model and case studies. Studying the relationship between weather regimes in the Euro-Atlantic and Mediterranean sector and the West African rainfall, Polo et al. (2011) suggested that the Mediterranean SST anomalies could be a precursor in the change of frequency of the weather regimes associated to wet and dry conditions in the Sahel.

The WAM-Mediterranean connection has been also investigated in a multi-model environment in the framework of the African Monsoon Multidisciplinary Analysis (AMMA-FP6) program (Redelsperger et al., 2006). In this context, Fontaine et al. (2010) further detailed the dynamical mechanisms underlying the connection through the analysis of numerical experiments from the ARPEGE-Climat3, ECHAM4, LMDZ4 and UCLA7.3 models. By simulating anomalously warm and cold situations in the Mediterranean, the authors provided evidence that anomalous warm events favour enhanced flux convergence and upward motion along the ITCZ, a strengthening of low-level moisture advection, and a more northward location of ascending motion in West Africa. The JAS meridional cross sections of the moisture fluxes simulated by ARPEGE-Climat3 are displayed in Figure 2: the consequent intensification of the monsoonal circulation leads to wet anomalies over West Africa. Moreover, these authors indicate that thermal variability observed in the two Mediterranean basins has unalike impacts: in the western Mediterranean, SST is statistically associated with the atmospheric deep convection over the Gulf of Guinea, while in the eastern Mediterranean the SST variability forces the atmospheric circulation over the North African subcontinent. Thus, anomalous eastern Mediterranean warm conditions are linked to a northward migration of the monsoon system accompanied by enhanced south-westerly flow and weakened northeasterly climatological wind.

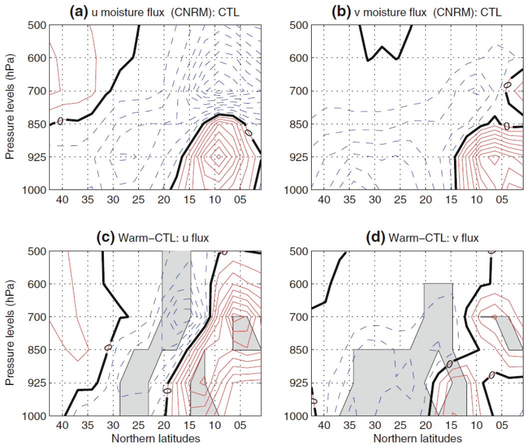

Fig. 2. JAS meridional cross sections of mean and composite moisture fluxes from ARPEGE-Climat3 over the longitudinal window 20°W-30°E. (a, b): zonal and meridional mean components from the control runs; (c, d): composite differences between the "warm" and control simulations. The solid (dashed) contours refer to the positive (negative) differences. In (c, d), shadings are superimposed when composite differences are significant at 90% regarding a Student t-test. Reproduced from Fontaine et al. (2010).

Time evolution of the connection has been also described. Thus, Gaetani et al. (2010) explored specifically the time evolution of the WAM-Mediterranean relationship and associated mechanisms at a subseasonal time scale, by analysing the daily outputs from the AMMA-FP6 sensitivity experiments. A positive precipitation response to warmer than average conditions in the Mediterranean Sea is found in the Sudano-Sahelian belt in August-September. The proposed dynamical mechanism is based on the modifications produced by the SST forcing in the moisture content in the lower troposphere. A warmer eastern Mediterranean in August-September feeds the lower troposphere with additional moisture favouring the northerly moisture transport and associated convergence over the Sahel. Furthermore, warmer SST is linked to a strengthening of the Saharan heat low and to an enhancement of the moist static energy meridional gradient over West Africa, which favours the northward displacement of the monsoonal front. The warm-cold differences in the lower troposphere specific humidity and moisture transport divergence are displayed in Figure 3. One can see, in particular, that rainfall anomalies are concentrated in August-September when the monsoonal circulation is fully developed inland so that the effect of northerly moisture transport from the Mediterranean is maximized.

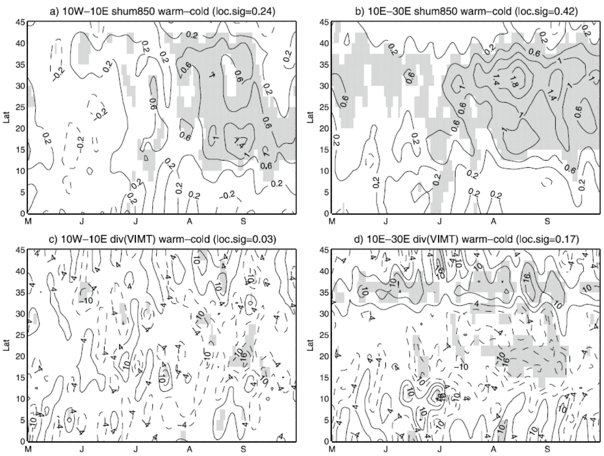

Fig. 3. May-September time-latitude diagram of the ensemble-mean 850 hPa specific humidity (g/kg) averaged between (a) 10°W and 10°E and (b) 10°E and 30°E, warm-cold composite. May-September time-latitude diagram of the ensemble-mean vertical integrated moisture transport divergence (10^{-6} m/s) averaged between (c) 10°W and 10°E and (d) 10°E and 30°E, warm-cold composite. Shaded contours are the differences 90% significant after a Student's t-test; in parentheses are the percentages of field significance regarding a local test at 90%. Reproduced from Gaetani et al. (2010).

Furthermore, at a multidecadal time scale and after removing the impact of the global SST over the 20th century, Fontaine et al. (2011a) highlighted that the eastern Mediterranean and the Indian Ocean dominate the WAM-SST relationship, both in terms of intensity and time stability, with a growing importance of the Mediterranean at the end of the 20th century. Statistical analysis shows that positive SST differences between the eastern Mediterranean and the Indian Ocean favor the strengthening of the convergence between the northeasterly moisture transport from the eastern Mediterranean and the southwesterly moisture transport from the eastern equatorial Atlantic, leading to a rainfall excess over the whole Sudan-Sahel. Associated changes in the atmospheric circulation along the meridional and zonal planes are observed, specifically, a subsidence above 10°N-18°N associated with air ascents above the Saharan thermal lows, upward anomalies on the western and eastern Sahel reinforcing the atmospheric ascents in upper levels, a low-level subsidence anomaly by 30°E-40°E weakening the normal uplifts consistently with the Indian cooling, and a reinforcement of the Tropical Easterly Jet over 0°-20°E.

3. The active role of the West African Monsoon

The influence of the monsoon system on the Mediterranean climate in summer suggests that the WAM can play an active role in the teleconnection. This hypothesis has been investigated by Rodwell and Hoskins (2001), studying the relationship between the climatological annual cycle of the summer anticyclones and the global monsoon system using numerical simulations. They argued that the subtropical circulation in summer comprises a set of weakly interacting monsoon systems, each characterized by seasonal rains, a low-level jet, a subtropical anticyclone to the east, and subsidence to the west. The equatorward portion of each subtropical anticyclone is interpreted as the Kelvin-wave response to the monsoon heating over the continent to the west, while the Rossby-wave response to the west of the monsoon, interacting with the midlatitude westerlies, produces a region of adiabatic descent. Specifically, adiabatic descents over the eastern Mediterranean and subtropical Atlantic are observed when monsoonal heating sources are prescribed in the model over Africa and Asia, although the African source weakly affects the response induced by the Asian source.

However, interactions between the summer Euro-Atlantic circulation and the convective activity of the WAM and in the tropical Atlantic have been reported by several authors. Black et al. (2004) suggested possible teleconnections of the recent strong heat wave event in 2003 in Europe to remote signals: an intensification of the Azores high, a Rossby-wave pattern from tropical America and a northward shift of the West African ITCZ. Additionally, Cassou et al. (2005) supported the hypothesis of a tropical-extratropical connection influencing the summer atmospheric circulation in the Euro-Atlantic sector. They showed that the European heat waves can be associated with the occurrence of two specific summertime atmospheric circulation regimes over North Atlantic, namely the “blocking” and “Atlantic low” patterns and presented evidence that during summer of 2003 the excitation of these two regimes was significantly favoured by the anomalous tropical Atlantic heating related to wetter-than-average conditions in both the Caribbean basin and the Sahel. The estimated 2003 anomalous heating has been used by the authors to force the NCAR CAM2/CLM2 model in numerical sensitivity experiments aiming to reproduce the North Atlantic circulation regimes. In Figure 4 the precipitation anomalies observed during summer 2003 are represented through the Outgoing Longwave Radiation (OLR) along with the different occurrences of the circulation regimes in the forced and control simulations. There is evidence of a relationship between wet conditions in the tropical belt and significant increased frequency of the "blocking" and "Atlantic low" patterns, while the frequency of the "NAO-" and "Atlantic ridge" patterns, which are related to cold anomalies over Europe, result significantly reduced. These results have been recently substantiated by Douville et al. (2011), who used a numerical study to show the tropical control on the boreal summer midlatitude stationary waves. Furthermore, Fontaine et al. (2011c) observed that the increase and northward migration of the monsoonal rainfall in northern Africa since the mid-90s is accompanied by a reorganization of the circulation with increasing subsidence in high troposphere over the Mediterranean and increasing ascendance in the African ITCZ.

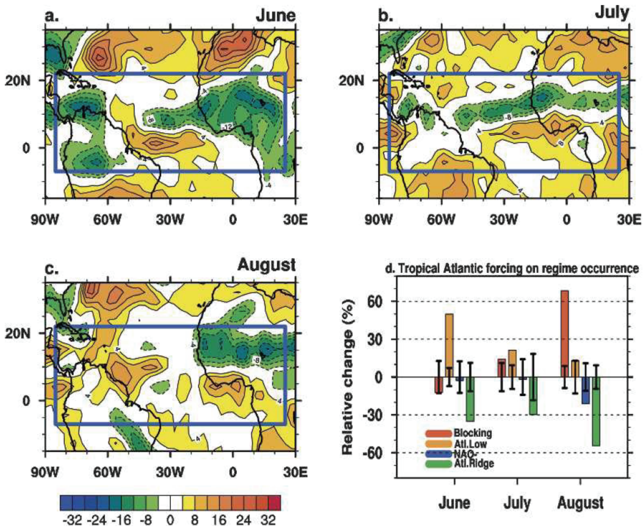

Fig. 4. (a)-(c) Observed OLR anomalies. Greenish (orange) colours correspond to enhanced (reduced) convective activity or wetter (drier) conditions. The blue box shows the tropical domain where the diabatic heating perturbations are estimated and further imposed in model experiments. Contour interval is 4 W/m2. (d) Relative change (%) of occurrence of the circulation regimes due to the prescribed tropical forcing in the atmospheric model. The error bars indicate the range of uncertainty due to internal atmospheric variability as given by one standard deviation of the within-ensemble variability. Reproduced from Cassou et al. (2005).

The WAM influence on the interannual variability of the summer atmospheric circulation over North Atlantic and Europe has been specifically investigated by Gaetani et al. (2011) over the period 1971-2000. The authors demonstrated the statistical association between the observed Euro-Atlantic circulation and the WAM variability, with anomalies of reinforced convection in the Sudan-Sahel region related to positive North Atlantic Oscillation (NAO) phases and subsidence over eastern Mediterranean. Moreover, they analysed a set of sensitivity experiments performed through the Arpege-Climat4.6 model using the so-called "grid-point nudging" technique, where the simulated atmospheric fields over the WAM region are relaxed towards the ERA40 reanalysis. The model relaxation leads to a correction of the regional biases and a more realistic description of the climate variability within the "nudged" domain, therefore possible improvements in the description of the climate variability outside the "nudged" domain can be interpreted as a response to the "real" climate variability. A covariance analysis of the precipitation in West Africa and atmospheric circulation over the Euro-Atlantic sector is presented in Figure 5 as the Singular Value Decomposition (SVD) (von Storch and Zwiers, 1999) of OLR and 500 hPa geopotential height (Z500). The comparison with the control simulation shows an improvement in the description of the midlatitude interannual variability, when the Arpege-Climat4.6 model is "nudged" in the WAM region. Specifically, the NAO-like dipole is repositioned in a more realistic configuration along the meridional direction, although the centres of actions are shifted too north compared to the ERA40 data, and its intensity and extension are better reproduced. A sizable effect is observed in the subtropical North Atlantic, with a strong monsoon related to high-pressure anomalies over the Azores and to positive NAO phases. It is hypothesized that changes in the monsoonal convection have a direct impact in the meridional overturning circulation over Africa and Atlantic, intensifying the northern Hadley cell and increasing subsidence over the Azores, although the response in the model is weaker than in ERA40.

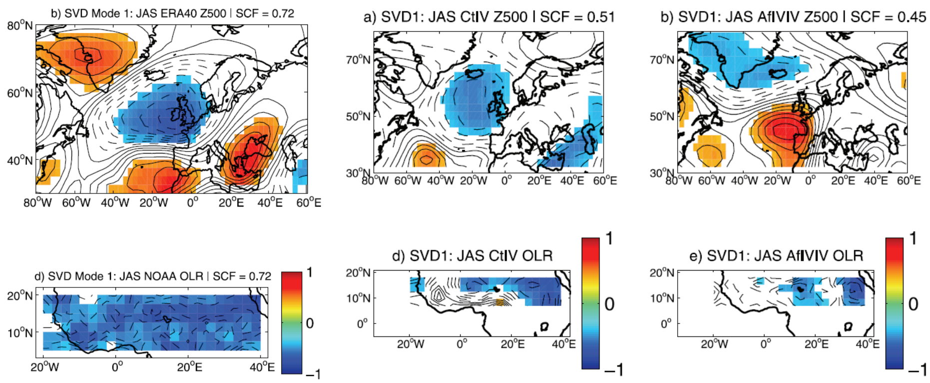

Fig. 5. SVD analysis applied to JAS OLR in northern tropical Africa and Z500 in the Euro-Atlantic sector, first mode displayed through heterogeneous correlation maps: ERA40 and NOAA data (left), control (middle) and "nudged" (right) simulations. Contour interval is 0.1, solid (dashed) contours indicate positive (negative) values, colour shadings are the correlation values 95% significant. Reproduced from Gaetani et al. (2011).

4. Summary and perspectives

The evidence of a sizable influence of the Mediterranean Sea on the WAM variability at different time scales is nowadays widely documented by studies based on observations and climate models. The most important actor in the teleconnection is the moisture excess in the lower troposphere over the Mediterranean fed by anomalously warm SSTs. The moisture is transported towards the Sahel on the climatological northerly flow crossing the eastern Mediterranean, favouring convection and convergence in the eastern Sahel and the northward displacement of the ITCZ in the western Sahel, with consequent wet anomalies. The moisture dynamics over northern Africa and the Mediterranean is presented in Figure 6. The teleconnection appears to be more effective at, and just after, the peak of the rainfall season (August-September), when the monsoonal front is fully developed inland and the interaction with the northerly moisture advection is maximized. Because of the role of the northerly climatological flow, the eastern Mediterranean is mainly involved in the teleconnection with the Sahel, while the western Mediterranean linked to the convective activity over Gulf of Guinea (e.g. Fontaine et al., 2010; Gaetani et al., 2010). The understanding of this teleconnection is particularly relevant for the predictability of the WAM precipitation interannual to multidecadal variability, because, at these time scales, SST is the main forcing. Specifically, Gaetani and Mohino (2013) recently reported a robust improvement in the decadal predictability of the Sahel precipitation in coupled climate models capable to correctly describe the SST variability at a regional scale. So a specific effort towards a more detailed modelling of the Mediterranean Sea dynamics could effectively impact the climate prediction over the Sahel.

On the other hand, a modulation action of the WAM dynamics on the circulation at midlatitudes has been pointed out along with the related indirect effects over Euro-Atlantic sector, and two alternative or additional mechanisms have been hypothesized. First, the excitation of a Rossby-wave pattern produced by the tropical convection activity, which influences the North Atlantic circulation regimes, causing warm anomalies over Europe related to wet conditions in the Sahel (see Cassou et al., 2005). Second, an intensification of the meridional overturning circulation related to strong monsoonal dynamics, which induces subsidence and warm anomalies at the subtropical latitudes (see Gaetani et al., 2011). However, the robustness of the second mechanism along with the evidence of a direct effect on the Mediterranean region still needs to be substantiated. The clarification of the role of the WAM in determining the climate variability over the Euro-Mediterranean region in summer is a relevant issue for the climate prediction in that region, which is considered a hot-spot in the context of the climate change, with a projected increase of climate extremes (IPCC, 2007). This is a particularly difficult task, due to the intrinsic difficulties in modelling the tropical convection, and the "nudging" technique appears to be promising in this respect (see Douville et al., 2011; Gaetani et al., 2011).

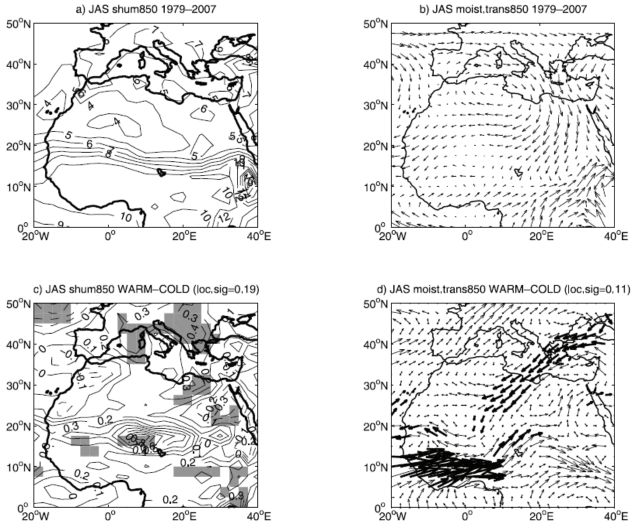

Fig. 6. The 1979-2007 JAS climatology of (a) 850 hPa specific humidity (g/kg) and (b) 850 hPa moisture transport (g/kg m/s). JAS warm-cold Mediterranean composite of (c) 850 hPa specific humidity (g/kg) and (d) 850 hPa moisture transport (g/kg m/s). Shaded contours and bold arrows are the differences 90% significant after a Student's t test; in parentheses are the percentages of field significance regarding a local test at 90%. Reproduced from Gaetani et al. (2010).

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