Influence of atmospheric circulation on turbulent air-sea heat fluxes over the Mediterranean Sea during winter

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[1] The influence of the winter atmospheric circulation on the turbulent variables of the air-sea boundary layer in the Mediterranean Sea is investigated. We examine the effects of several climatic indices and the corresponding large scale atmospheric patterns on the above variables by using a correlation analysis. The spatial characteristics and the behavior of the turbulent variables are also examined based on standard deviation and EOF analysis. Two main types of response to the index-specified atmospheric patterns have been identified: (1) A relatively uniform response of the entire basin associated with the influence of the East Atlantic pattern and (2) opposite responses in the western and eastern sub-basins linked mainly to the intrabasin SLP. The latter is a combined effect of the first four modes of atmospheric variability in the North Atlantic/Eurasia region, the North Atlantic Oscillation (NAO), the East Atlantic Pattern (EA), the Scandinavian Pattern (SCAND), and the East Atlantic-West Russia Pattern (EAWR). The two identified responses of the Mediterranean Sea to the atmospheric forcing are also in accordance with the primary modes of variability of the turbulent variables that result in the EOF analysis. All of the statistically independent indices (NAO, EA, SCAND, EAWR) have to be considered in order to fully account for the modulation of the turbulent variables in the Mediterranean Sea. As an example we refer to the mechanism through which, independent modes of atmospheric variability contributed to the Eastern Mediterranean Transient event between 1987 and 1995.

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1. Introduction

[2] The turbulent components of the air-sea heat fluxes, the latent and sensible heat, and the atmospheric variables associated with them are essential for the energy transfer from the ocean to the atmosphere and vice versa. Energy transfer to the atmosphere takes place mainly by means of evaporation (release of latent heat) and heat conduction (sensible heat). Reversely, energy can be transferred from the atmosphere to the ocean through sensible heat flux, condensation, and surface wind stress. The turbulent components are also crucial in determining the surface fluxes variability over the global ocean [*Alexander et al.*, 2002]. The latter is considerably evident in the Mediterranean Sea where the turbulent air-sea heat fluxes substantially regulate the variability of the air-sea heat budget [*Garrett et al.*, 1993; *Josey*, 2003; *Papadopoulos et al.*, 2012]. Furthermore, anomalies of turbulent fluxes affect the ocean climatology as they can determine critical characteristics of the marine boundary layer. For example, the SST spatial distribution and the vertical stability of the surface layers are directly associated with the turbulent fluxes feedback. In particular, during winter the turbulent parameters play an important role in the preconditioning and actual formation phase of the intermediate and deep water masses, a process of high climatic importance for the thermohaline conveyor belt and the deep layer oxygenation in the Mediterranean Sea [*Madec et al.*, 1991; *Haines and Wu*, 1995; *Roether et al.*, 1996; *Theocharis et al.*, 1999]. In other cases, sensible and latent heat affect the precipitation regime in the Mediterranean Sea [*Lolis et al.*, 2004]. For these reasons, the turbulent parameters of the marine boundary layer have a strong impact on the climatic regime of the Mediterranean Sea.

[3] In general, turbulent surface exchanges are affected by atmospheric circulation [*Bond and Cronin*, 2008; *Konda et al.*, 2010] as well as SST variability. On a global scale, atmospheric forcing along with SST regime regulates the turbulent fluxes. The influence of large-scale atmospheric circulation on the climate variability over the Mediterranean region has been addressed in terms of several teleconnection patterns as the North Atlantic Oscillation (NAO) [*Hurrell*, 1995], the Eastern Atlantic Pattern (EA) [*Wallace and Gutzler*, 1981], the East Atlantic-West Russia Pattern

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(EAWR) [*Krichak et al.*, 2002], the North Sea Caspian Pattern (NCP) [*Kutiel and Benaroch*, 2002], the North Africa-West Asia Pattern (NAWA) [*Paz et al.*, 2003], the Mediterranean Oscillation Index (MOI) [*Conte et al.*, 1989] and the eastern Mediterranean teleconnection pattern (EMP) [*Hatzaki et al.*, 2007]. *Josey et al.* [2011, hereinafter JST11] examined the impacts of the four leading independent modes of variability over the North Atlantic/Eurasia region (NAO, EA, SCAND and EA/WR) on the heat budget of the Mediterranean Sea and its sub-basins using the NCEP/NCAR and ARPERA reanalyses. They found that two patterns are the most influential for the heat budget of the Mediterranean Sea: the EA pattern influences the net heat flux in a relatively uniform manner across the whole basin while the EA/WR pattern has a dipole effect with approximately equal and opposite impacts on the eastern and western sub-basins.

[4] Among the aforementioned indices, NAO is the most extensively studied. *Ben-Gai et al.* [2001] link NAO with changing patterns of temperature and pressure anomalies over Israel during the second half of the 20th century. They find high correlation coefficients of −0.8 and +0.9 between NAO and smoothed (5 year running mean) cool season temperature and surface pressure anomalies in Israel, respectively. *Tsimplis and Josey* [2001] manifest a link between sea level variability in the Mediterranean Sea and NAO in terms of atmospheric pressure anomalies and changes in evaporation and precipitation. *Zervakis et al.* [2004] identify a relation between NAO and changes of the thermohaline circulation in the Aegean Sea. *Feliks et al.* [2010] discover a synchronization between climate conditions and NAO in the eastern Mediterranean. *Kazmin et al.* [2010] attribute the large-scale atmospheric forcing on the long-term SST variability in the Aegean and Black Seas from 1980 to 2000 to positive NAO and EAWR. *Romanou et al.* [2010] report that NAO affects the precipitation and SST regime only over the western and central Mediterranean Sea. *Chronis et al.* [2011] examining climatological variables over the eastern Mediterranean during summer find a significant impact of NAO on temperature, meridional wind, and cloudiness. On the contrary, *Feidas et al.* [2004] argue that NAO explains a small proportion of the temperature variance in the Greek region (eastern Mediterranean) only in winter. It is, therefore, inappropriate index for explaining the temperature variability in the Greek region. In addition, *Lionello and Sanna* [2005] point out that the SLP patterns associated with the sea wave regime in the Mediterranean reveal structures different from NAO. *Papadopoulos et al.* [2012] identify poor correlation between NAO and air-sea heat fluxes in the Aegean Sea. At the same time, some other indices show a clear influence on the Mediterranean climate. *Schröeder et al.* [2010] demonstrate that episodes of deep water formation in the western Mediterranean are closely related to the EA pattern. *Ruiz et al.* [2008] find correlation higher than 0.7 between radiation terms and winter MOI values in the eastern Mediterranean basin. They also obtain correlation values smaller than 0.7 between the heat flux terms and the NAO index. As mentioned above, JST11 suggest that EA and EAWR have a major impact on the Mediterranean Sea surface heat budget. *Krichak and Alpert* [2005] reveal connections between the Mediterranean precipitation regime and the EAWR phases. The studies of *Kutiel et al.* [2002] and *Gündüz and Ozsoy* [2005] substantiate that NCP has higher impact than NAO on the Mediterranean climate. *Paz et al.* [2003] introduce the NAWA index and associate its phases with distinctive precipitation and air temperature regime over the eastern Mediterranean region. Last, *Hatzaki et al.* [2007] introduce the EMP and describe its influence on the Mediterranean wind regime. Despite of its high climatic importance, the western basin of the Mediterranean has been included to a limited number of studies dealing with the impacts of large scale atmospheric circulation on marine and atmospheric parameters. From the above studies, the JST11 is the most conclusive and well documented study since it examines the impact of independent modes of atmospheric variability on the heat budget of the Mediterranean Sea. JST11 explains precisely the physical mechanisms through which each mode affects the heat exchange over the basin. Therefore, the results of JST11 are fundamental and we refer to them at several points in the present article.

[5] The study at-hand examines the influence of large scale atmospheric circulation on the latent and sensible heat, wind stress, air temperature, and specific humidity over the Mediterranean Sea. In comparison to JST11, who have examined the relationship between the atmospheric indices and the Mediterranean heat budget, as mentioned above, this study examines in detail the impact of the four leading modes (NAO, EA, SCAN and EA/WR) on latent and sensible heat, wind stress, air temperature and specific humidity, while we additionally examine their spatial characteristics. Therefore, we provide indicative information on the impact of the atmospheric circulation on the turbulent parameters of the Mediterranean air-sea energy exchanges. Moreover, the influence of some additional indices as the NCP, NAWA, and EMP is investigated with respect to their relation with the four leading independent modes of atmospheric variability. Apart from the aforementioned climatic indices whose impact on the Mediterranean Sea climate has been found in the existing literature, we also investigate the potential influence of the Arctic Oscillation Index (AO) [*Thompson and Wallace*, 1998; *Rogers and McHugh*, 2002]. Plus to prior studies, we introduce a testing intrabasin index, hereafter conventionally called the Mediterranean Index (MI), which represents the anomaly of sea level pressure (SLP) difference between South France (5E, 45N) and Levantine Sea (30E, 35N). Although this index is proximate to the Mediterranean Pressure Index (MPI, SLP difference between Marseille and Mersa Matruh) introduced by *Raicich et al.* [2003], the MI presents a stronger influence on the turbulent fluxes than MPI. The MI is anticipated to capture the effect of the intrabasin SLP field on the turbulent parameters over the Mediterranean Sea. The spatial distribution of the correlation coefficients (r) between the employed indices and the latent heat (LH), sensible heat (SH), wind stress (WS), air temperature (TA), and specific humidity (QA) during the cold period of the year is discussed.

[6] The study gives special attention to the relation of the considering indices with the four leading independent modes (NAO, EA, SCAND, EAWR) and to the physical mechanism that they represent. Furthermore, the spatial characteristics of the turbulent variables are investigated for associating those with the correlation analysis results. We consider that this inclusive overview can be a useful background for understanding the mechanisms governing the Mediterranean

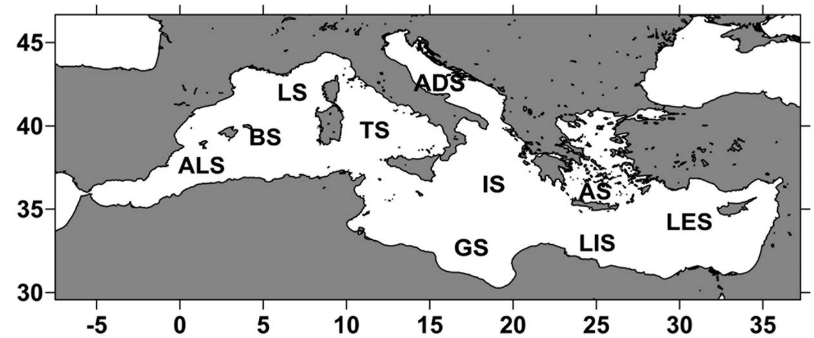

Figure 1. Map of the main regional sub-basins of the Mediterranean Sea. ALS, Alboran Sea; BS, Balearic Sea; LS, Ligurian Sea; TS, Tyrrhenian Sea; ADS, Adriatic Sea; GS, Gulf of Sirte; IS, Ionian Sea; LIS, Libyan Sea; AS, Aegean Sea; LES, Levantine Sea.

Sea climate. Besides, a better knowledge of the characteristics of the turbulent variables and their dependence on the large and regional scale atmospheric circulation contributes to a better assessment of the projected climate scenarios for the Mediterranean region. This assessment becomes critical due to the high vulnerability of the Mediterranean Sea to the global warming effects [*Intergovernmental Panel on Climate Change*, 2007].

[7] The paper is organized as follows. Data and methodology approach are presented in section 2. Section 3 provides a brief description of the employed atmospheric indices, the results that are based on the correlation analysis, and the spatial characteristics of the studied variables. Finally, section 4 presents the concluding remarks and brings up issues that remain under speculation.

2. Data and Methods

[8] Monthly mean values of the four prominent modes of low-frequency variability over the North Atlantic and Eurasia (NAO, EA, EAWR, SCAND) are obtained by the NOAA/CPC archive for the 53 years 1958–2010. We are using the same index that used by JST11 enabling a useful comparison of results that is discussed in the section 3. In addition, AO values are also obtained by the same archive. For the same period, we calculate the NCP according to *Kutiel et al.* [2002], NAWA according to *Paz et al.* [2003], and EMP according to *Hatzaki et al.* [2007] by making use of monthly mean geopotential height (for NCP and EMP) and SLP (for NAWA) from NCEP/NCAR re-analysis data set [*Kalnay et al.*, 1996]. Using monthly SLP values from the same data set we calculate the testing MI index. We also use monthly mean values for the latent and sensible heat, wind stress, air temperature, and specific humidity, obtained from the Objectively Analyzed Air–Sea Fluxes project (OAFlux) [*Yu et al.*, 2008] of the Woods Hole Oceanographic Institution. This archive also covers the same period (1958–2010) with a grid resolution of 1° in both latitude and longitude. We select the OAFlux data set since the latent and sensible heat from this data set display good statistical agreement when they are compared to in situ observations over the eastern part of the Mediterranean Sea (Aegean Sea) [*Papadopoulos et al.*, 2010]. Moreover, the OAFlux data set provides reasonable spatial resolution and extended time series. Although it provides a much better spatial resolution, OAFlux is not fully independent from NCEP/NCAR re-analysis data set used by JST11. This could be a reason for the similar results obtained by the two studies.

[9] The impact of the selected indices on the turbulent parameters for the cold season of the year (November to March) is investigated by performing a grid point Pearson correlation between the indices and the monthly anomalies of the studied variables. Only the statistically significant correlation coefficients (here greater than 0.12) at a confidence level of 95% are presented. To make the inter-comparison easier, we maintain the same scale for all the correlation maps and variables. For the air-sea turbulent heat fluxes, we adopt the oceanographic convention, according to which positive heat flux represents heat gain by the sea and vice versa. In order to study the spatial characteristics of the turbulent variables, we employ standard deviation and Empirical Orthogonal Functions (EOF) analysis. The modes of EOF analysis are presented as homogeneous correlation maps [*Bjornsson and Venegas*, 1997] with the same scale for easier interpretation. The major sub-basins of the Mediterranean Sea are shown in Figure 1. It has to be noted that correlation and EOF analyses are performed after the removal of the local linear trend at each grid point.

3. Results and Discussion

3.1. The Climatic Indices

[10] In order to give a concise description of the employed climatic indices and their relationship to the atmospheric circulation, we first present correlation maps between the indices and the SLP. The correlation patterns identify the centers of action and reveal the general atmospheric circulation relevant to each index during the cold period of the year. The correlation maps between the indices and the SLP are shown in Figure 2. The NAO pattern shows the well-known two opposite centers of action over Iceland and Azores islands. Positive NAO values are linked to a stronger Azores subtropical anticyclone and a deeper Icelandic Low. The EA pattern has a major influence on the North Atlantic, west of the British Isles, and a minor opposite influence over north Africa and west Asia. Negative values of EA favor higher pressure over north Atlantic and transfer cold air masses mainly over the western Mediterranean basin. EAWR has a less strong impact than NAO and EA on the SLP with a tripole consisting of three successive centers of

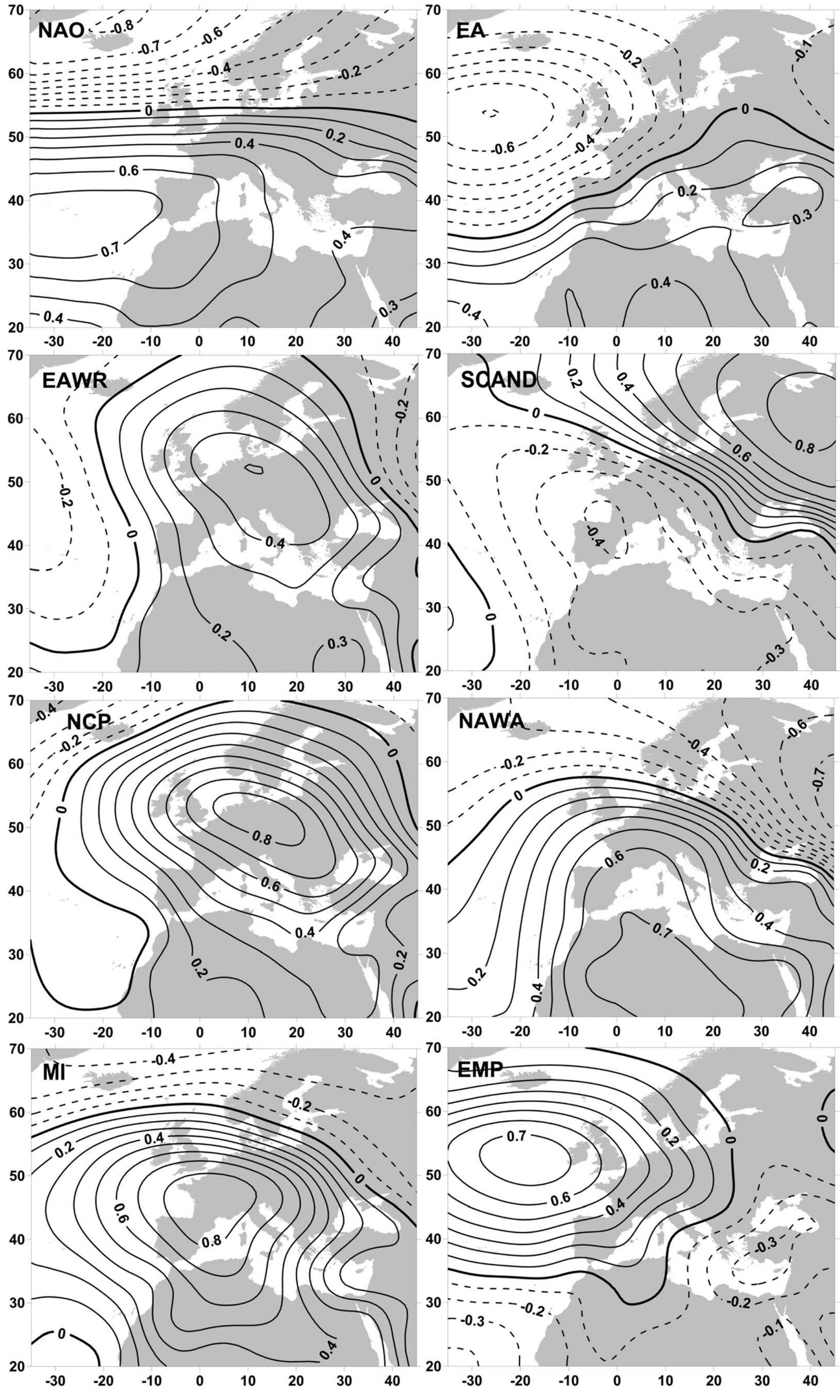

Figure 2. Correlation maps between indices and SLP during the cold period of the year.

Table 1. Correlation Coefficients ⟨r⟩ Between the Four Prominent Modes of Atmospheric Variability in the North Atlantic/Europe Region and the Rest of the Employed Indices in this Study During the Cold Period of the Year[a]

Index	NAO	EA	SCAND	EAWR
NCP	**0.21**	−0.08	0.01	**0.64**
NAWA	**0.32**	**0.28**	**−0.58**	**0.47**
MI	**0.46**	**−0.17**	**−0.32**	**0.33**
EMP	0.06	**−0.70**	−0.01	0.02
AO	**0.72**	**0.14**	**−0.33**	**0.18**

[a]Boldface indicates statistically significant values.

action in a zonal direction over the north Atlantic, central Europe, and western Russia. Positive phase of EAWR favors northerlies over eastern Mediterranean and southerlies over western Mediterranean. The SCAND pattern [*Rogers*, 1990] affects the northwestern Russia and in an opposite sense the Iberian Peninsula. Positive SCAND promotes the southerlies over the entire Mediterranean Sea. The NCP is similar to the EAWR pattern but has a stronger impact on the SLP over central and north Europe. Alike to EAWR, positive NCP is associated with cold airflowing over eastern basin and warm air over western basin. NAWA shows two centers of action, the first over the entire north Africa and the second over Russia. Positive phase of NAWA favors transfer of cold air masses over the eastern Mediterranean. MI shows some similarity to NCP and EAWR and during its positive phase cold air masses are transferred over the entire eastern basin. Finally, the EMP pattern shows centers of action similar to EA and AO (not shown) is similar to NAO but affects the entire Mediterranean basin in a uniform manner.

[11] Apart from the centers of action of the employed indices we also investigate if NCP, NAWA, MI, EMP, and AO can act independently from the four primary modes NAO, EA, SCAND, and EAWR. Table 1 presents the correlation coefficients between the four prominent modes of low-frequency variability over the North Atlantic/Eurasia region with the rest of the indices employed in this study. NAO, EA, SCAND, and EAWR can act independently as modes resulted by the same EOF analysis. The NCP pattern shows a strong relation with EAWR and a weaker relation with NAO. The NAWA pattern correlates better with SCAND and EAWR than with NAO and EA. The intrabasin MI correlates moderately with NAO, weakly with SCAND and EAWR, and negligibly with EA. The EMP seems to have a strong connection with EA and AO is strongly correlated with NAO and weakly with EA, SCAND, and EAWR. The coefficients of the Table 1 reveal that the NCP, NAWA, MI, EMP, and AO are related more or less with at least one primary mode of the atmospheric variability over the North Atlantic/Eurasia region. Notwithstanding they cannot act independently from the primary modes, each of them represents a different atmospheric circulation pattern and their potential to affect the turbulent fluxes in the Mediterranean Sea merits investigation.

3.2. Spatial Characteristics

[12] The spatial characteristics of the turbulent variables are examined using standard deviation and EOF analysis. The spatial characteristics of the turbulent components, LH and SH, are presented in Figures 3 and 4. LH exhibits its highest variability over the Ligurian Sea (Figure 3a). The Aegean and the Levantine also show high standard deviation values. Interestingly, the Ligurian, the Aegean, and the Levantine Seas are all water formation areas. In accordance with that, high standard deviation suggests that conditions favoring extreme heat loss by the sea in climatic time-scales occur in these areas. The coastal areas of North Africa and the northernmost parts of the Adriatic and Aegean Seas are the places of the lowest variability. The first three EOFs of the LH account for 46%, 25% and 6% of the total variance, respectively. The EOF1 (Figure 3b) is a coherent mode with maximum amplitudes over the central Mediterranean. The second EOF (Figure 3c) exhibits an out-of-phase relationship between the western and the eastern basin. The third EOF (Figure 3d) shows a more complex dipolar but weaker mode with a rather zonal phase separation. SH exhibits high variation over the north Aegean Sea, north Adriatic Sea, and the Gulf of Lions (Figure 4a). EOF1 of SH has a predominantly east-west gradient ranging from values of 0.2 close to Gibraltar to almost 1 at the eastern limit of the basin (Figure 4b), yet exhibits an in-phase mode. EOF2 (Figure 4c) shows same characteristics with those of LH EOF2, whereas the opposite phases of EOF3 are between NW and SE Mediterranean Basins (Figure 4d). The first three EOFs of the SH account for 46%, 24% and 13% of the total variance. The modes of variability for the LH and SH described here are similar to those given by *Ruiz et al.* [2008]. WS displays high variability over the Gulf of Lions, the Sicily Straits and the northernmost part of Levantine Sea (Figure 5a). Similarly to LH and SH, the first EOF of the WS (Figures 5b) is a coherent mode but exhibits maximum amplitudes over the Adriatic and central Mediterranean. On the other hand, EOFs 2 and 3 (Figures 5c and 5d) are comparable to those reported for LH and SH. The first three EOFs of the WS, account for 41%, 20%, and 8% of the total variance. Regarding the TA, the maximum standard deviation is found at the northernmost parts of Adriatic and Aegean Seas and the minimum variation around the coast of Egypt and Libya (Figure 6a). The first three EOFs of the TA (Figures 6b–6d), accounting for 50%, 24%, and 11% of the total variance, respectively, resemble their counterparts of SH as the two variables are intimately related. Last, the QA has higher variation over the Aegean and Levantine Seas and minor along the coastal regions of North Africa (Figure 7a). The first EOF of QA (49%) is coherent with maximum amplitudes over the Ionian and Aegean Seas (Figure 7b). The second EOF (27%) is similar to those reported for the rest of the turbulent variables with the dipolar configuration of opposite phases between the west and the east sub-basins (Figure 7c). The third EOF of QA (7%) exhibits three successive (positive-negative-positive) phases over west, central and east sub-basins, respectively (Figure 7d).

3.3. Correlation Analysis

[13] In our analysis, we present the grid point correlation between the indices, NAO, EA, EAWR, NCP, NAWA, and MI, and each one of the turbulent variables. The rest of the indices are omitted since the AO and SCAND exhibit significant correlation values at very few grid points in the Gulf of Lions and the northernmost part of the Adriatic Sea, and the EMP presents almost the same correlation patterns with

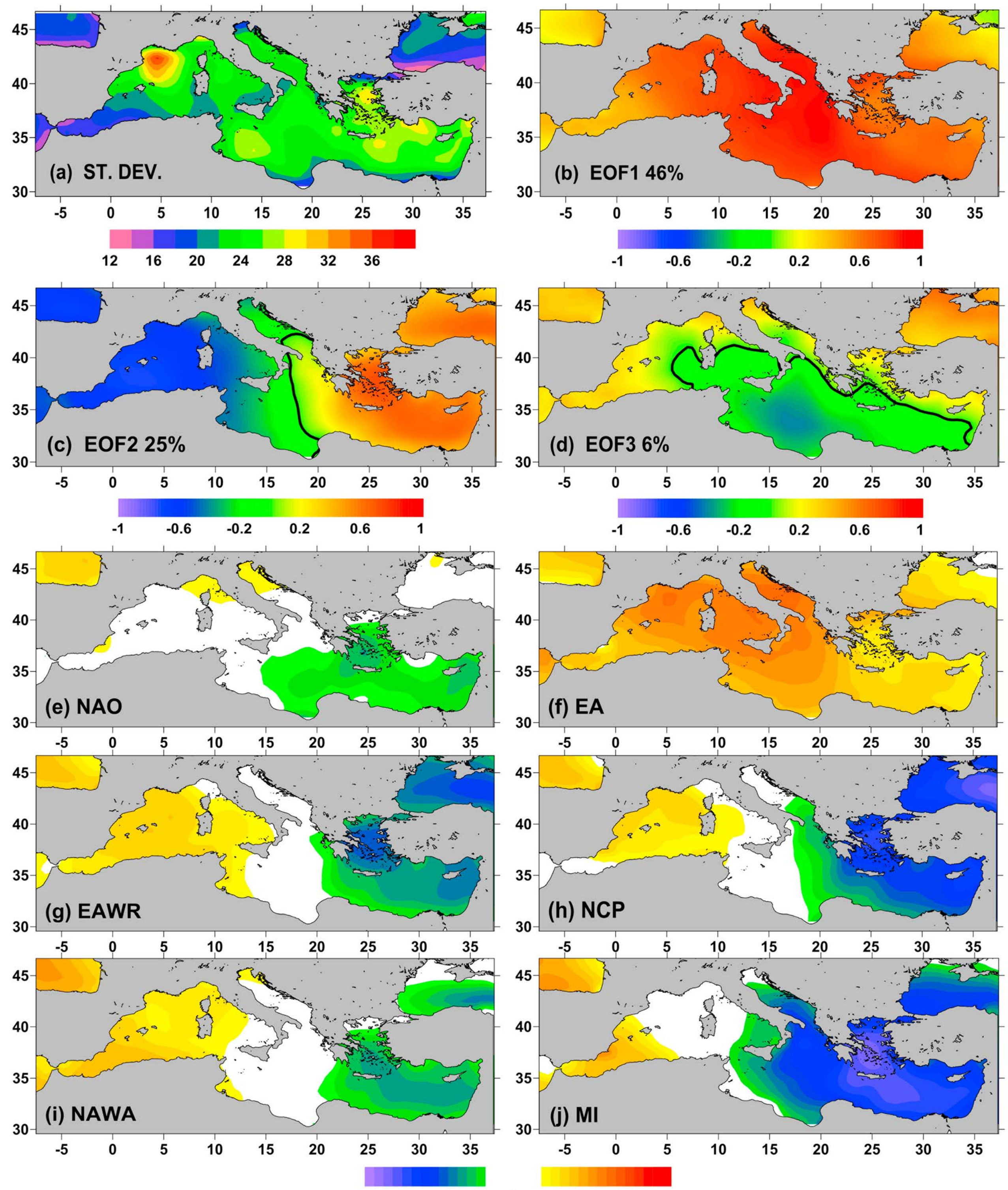

Figure 3. (a) Standard deviation (in W/m^2) for the latent heat during winter. (b–d) The first three EOFs presented as homogeneous correlation maps with the explained variance. The thick black line in EOF maps is the zero line. (e–j) Spatial distribution of correlation coefficients between the latent heat and the selected indices (only the significant coefficients at a confidence level 95% are plotted).

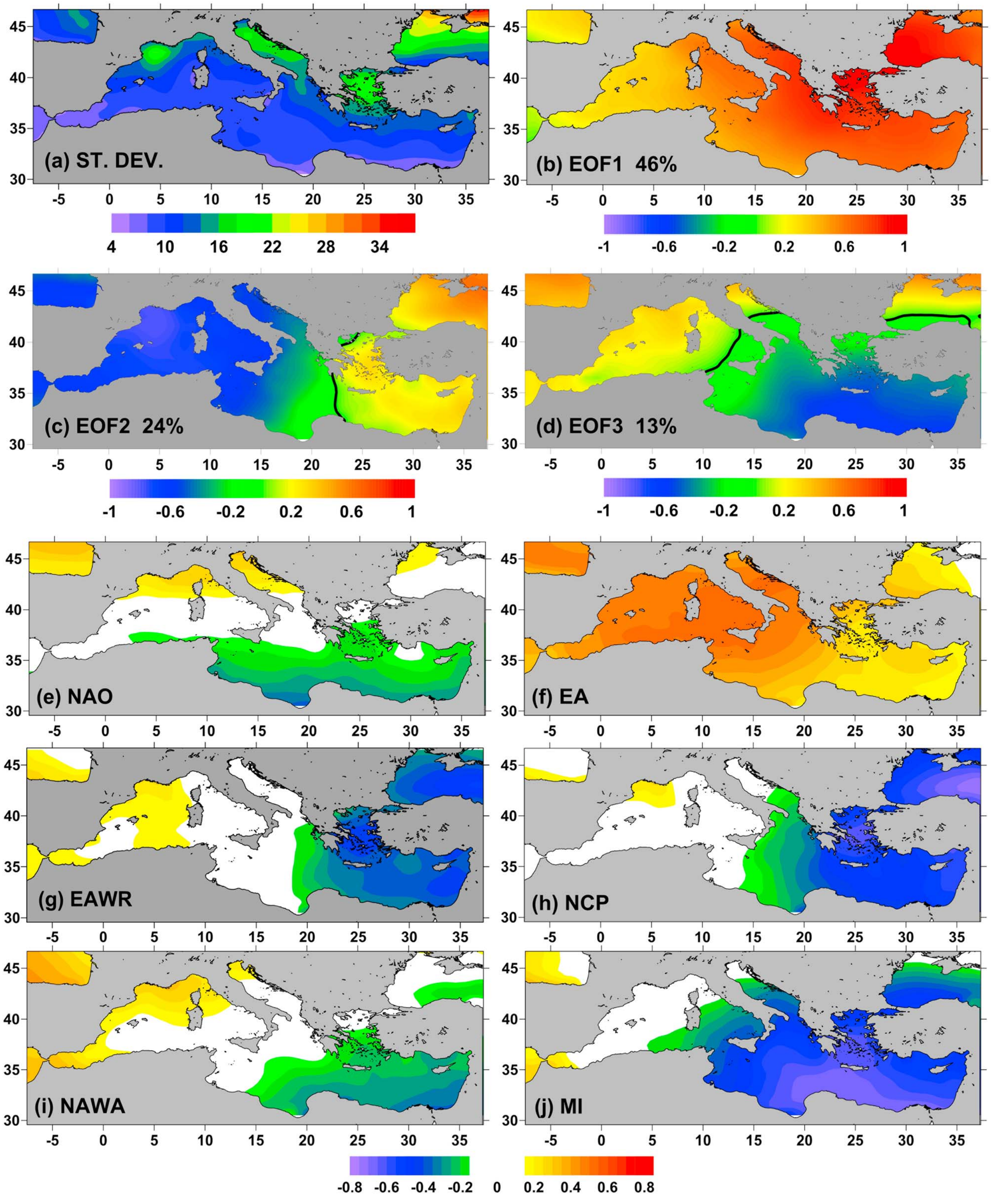

Figure 4. As in Figure 3 but for the sensible heat (W/m^2).

those of the EA index (quantitatively and qualitatively). Figures 3e–3j present the correlation maps between the climatic indices and the LH. The NAO shows weak negative correlation over the eastern Mediterranean and statistically insignificant (therefore not shown) positive correlation over the Western Mediterranean. Thus, positive NAO phases may enhance the heat loss in the eastern sub-basin and decrease the heat loss in the western sub-basin. The opposite occurs during negative NAO phases. The EA displays a coherent positive correlation with maxima over the North Adriatic

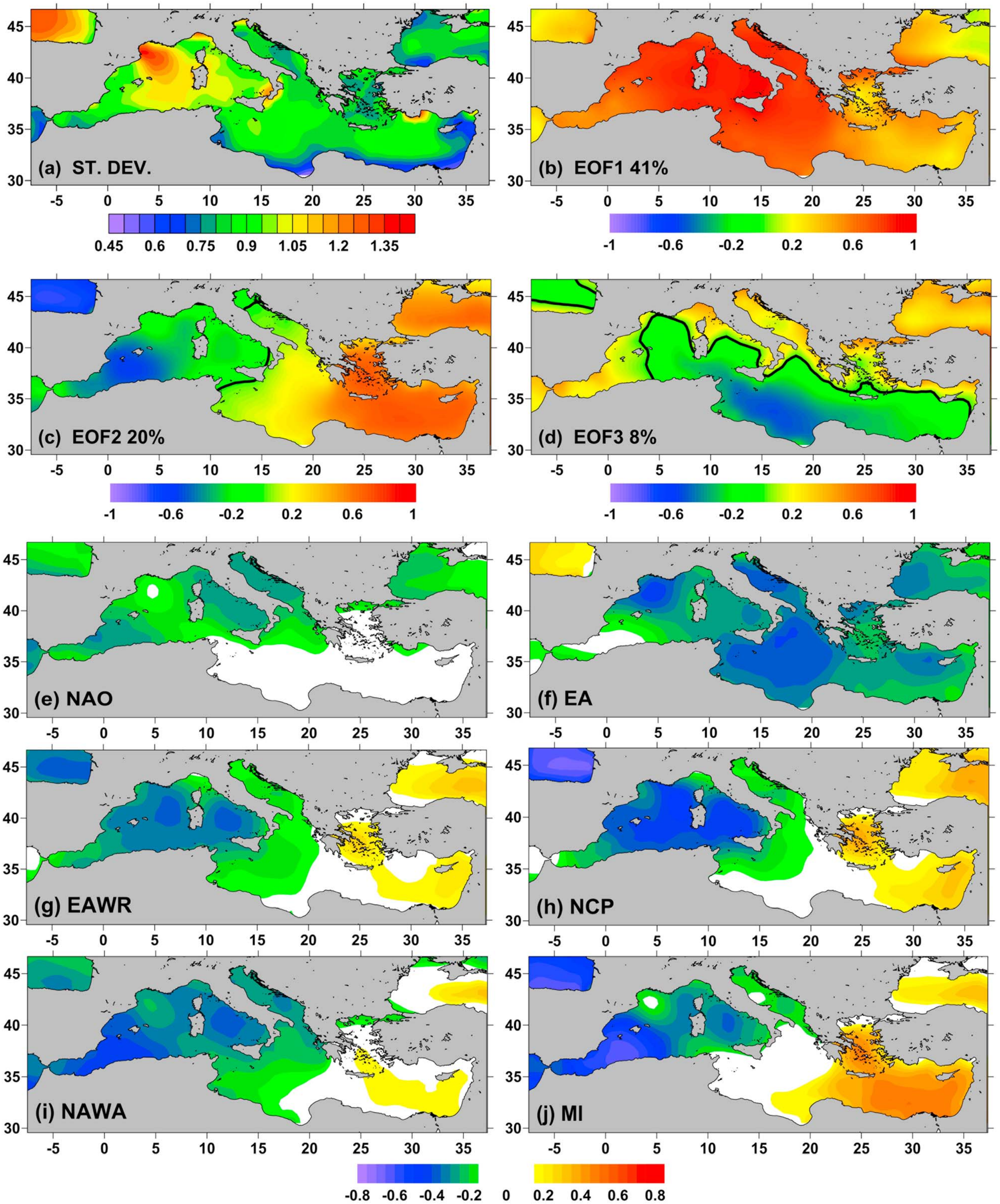

Figure 5. As in Figure 3 but for the wind stress (m/s).

and Ligurian Seas indicating lower heat loss during its positive phases over the entire basin and vice versa in agreement with the results obtained from JST11. The rest of the indices (EAWR, NCP, NAWA and MI) present weak positive correlation over the western sub-basin and stronger negative correlation over the eastern sub-basin. Positive (negative) phases of these indices are linked to lower (higher) heat loss by the sea in the Western Mediterranean and higher (lower) in the eastern Mediterranean. Especially for the EAWR, identical results for its behavior were obtained by JST11.

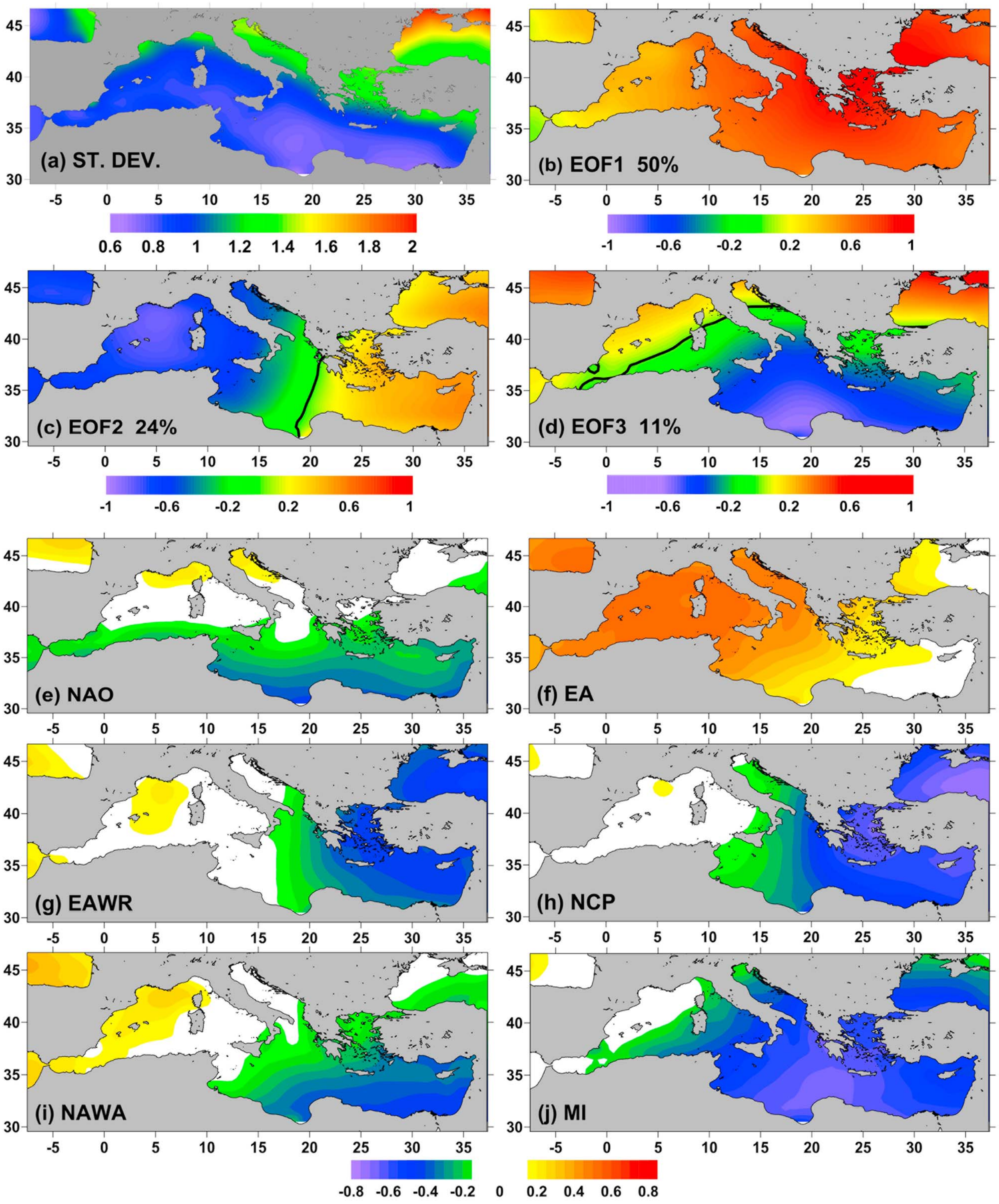

Figure 6. As in Figure 3 but for the air temperature (°C).

Very similar patterns are shown on the correlation maps between the indices and the SH (Figures 4e–4j) except that NAO presents a rather north-south than a west-east phase change. WS correlates in a similar way with all of the indices but in the opposite sense (Figures 5e–5j). Thus, positive (negative) phases of NAO, EAWR, NCP, NAWA and MI promote stronger (weaker) winds over the eastern sub-basin and weaker (stronger) over the western sub-basin. The correlation maps for TA (Figures 6e–6j) and QA (Figures 7e–7j) follow the characteristics of the LH and SH patterns. In general, positive (negative) phases of NAO, EAWR, NCP, NAWA and MI favor higher (lower) TA and QA values over

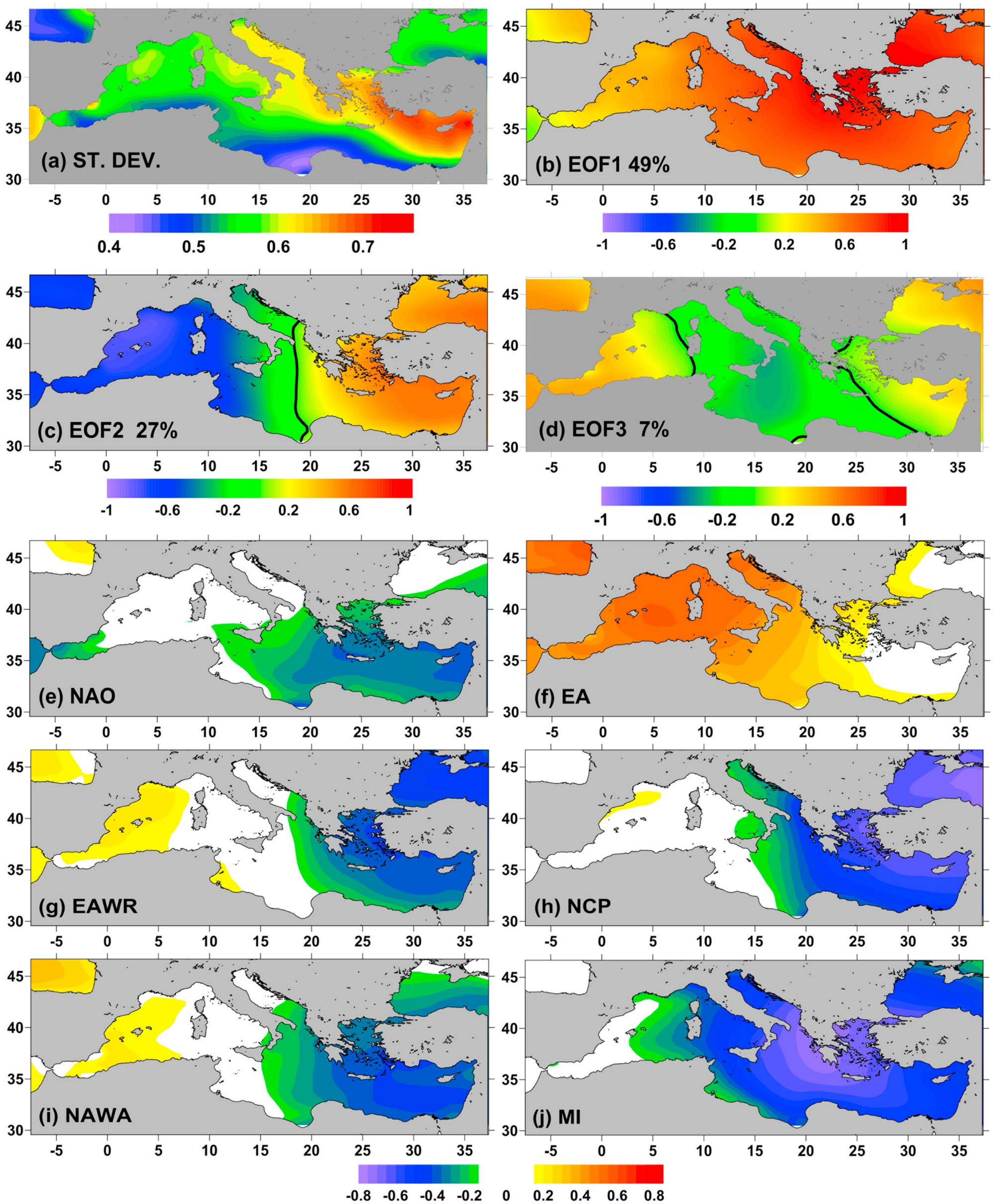

Figure 7. As in Figure 3 but for the specific humidity (gr/Kgr).

the western part of the Mediterranean Sea and lower (higher) over the eastern part. Accordingly, positive (negative) phases of EA favor higher (lower) TA and QA over the entire basin that is also in agreement with the JST11 results.

[14] Table 2 summarizes the major characteristics of the correlation between the climatic indices and the turbulent variables. The majority of the correlation maps present two domains of opposite sign over the west or northwest and the east or southeast Mediterranean sub-basins respectively.

Table 2. Summary of the Characteristics of Correlation Maps[a]

		Lowest CC		Highest CC	
Index	Type	Value	Area	Value	Area
		Latent Heat			
NAO	M	−0.3	Aegean Sea	–	–
EA	M	–	–	0.45	Adriatic Sea
EAWR	D	−0.45	Aegean Sea	0.30	Balearic Sea
NCP	D	−0.59	Aegean Sea	0.33	Balearic Sea
NAWA	D	−0.36	Libyan Sea	0.21	Balearic Sea
MI	D	−0.69	Aegean Sea	0.40	Alboran Sea
		Sensible Heat			
NAO	D	−0.36	Ionian Sea	0.26	Ligurian Sea
EA	M	–	–	0.51	Tyrrhenian Sea
EAWR	D	−0.44	Aegean Sea	0.28	Ligurian Sea
NCP	D	−0.64	Aegean Sea	0.27	Ligurian Sea
NAWA	D	−0.40	Libyan Sea	0.26	Ligurian Sea
MI	D	−0.71	Libyan Sea	0.22	Alboran Sea
		Wind Stress			
NAO	M	−0.31	Alboran Sea	–	–
EA	M	−0.42	Balearic Sea	–	–
EAWR	D	−0.37	Balearic Sea	0.27	Aegean Sea
NCP	D	−0.48	Balearic Sea	0.38	Aegean Sea
NAWA	D	−0.46	Alboran Sea	0.24	Levantine Sea
MI	D	−0.65	Alboran Sea	0.52	Libyan Sea
		Air Temperature			
NAO	D	−0.29	Libyan Sea	0.29	Ligurian Sea
EA	M	–	–	0.58	Alboran Sea
EAWR	D	−0.43	Aegean Sea	0.22	Ligurian Sea
NCP	D	−0.66	Aegean Sea	0.16	Ligurian Sea
NAWA	D	−0.41	Levantine Sea	0.32	Alboran Sea
MI	M	−0.67	Ionian Sea	–	–
		Specific Humidity			
NAO	M	−0.43	Levantine Sea	–	–
EA	M	–	–	0.54	Alboran Sea
EAWR	D	−0.42	Aegean Sea	0.25	Balearic Sea
NCP	D	−0.67	Aegean Sea	0.16	Balearic Sea
NAWA	D	−0.50	Libyan Sea	0.24	Alboran Sea
MI	M	−0.74	Ionian Sea	–	–

[a]The Type column presents the type of correlation pattern: M, monopole, D, dipole. The remainder of the table shows the lowest negative and the highest positive ⟨r⟩ values and the sea areas where they were detected.

Only seven out of 30 maps exhibit a coherent correlation pattern, five of them related to the EA pattern and two (TA and QA) to MI. All of the other correlation maps exhibit a pattern of two distinct domains of opposite correlation sign, yet this is not seen in every case since only the statistically significant correlation levels (>0.12) are plotted. Interestingly, among the examined indices, NAO presents the lower impact than any other index on all variables except QA. The strongest correlation between NAO and QA is detected in the Levantine Sea (r = −0.44, Figure 6e). The unique characteristics of the EA are the consistent one-phase correlation pattern and the broad coverage of the Mediterranean basin with statistically significant correlation with all the turbulent parameters. The EA does not show as high correlation values as other indices and therefore a strong local influence for all of the turbulent parameters. However, the large spatial extent of its significant correlations throughout the Mediterranean makes it the most influential index on the turbulent parameters, as JST11 have also demonstrated. The major influence of EA is detected on the air temperature over the west basin (Alboran Sea, highest r = 0.57, Figure 5f). The EAWR, NCP and NAWA always present two similar out-of-phase domains of influence (west-east). Again, it has to be noted especially for the EAWR index, the two opposite phases are in accordance to JST11 findings. The three indices are similar in structure representing a general west-east SLP gradient (mainly EAWR and NCP, Figure 2). This strongly suggests that indices of zonal pressure gradient exhibit a dipolar pattern of inverse correlation between the western and eastern part of the Mediterranean Sea. Among all of the indices, the intrabasin MI displays locally the strongest correlation with all the turbulent variables. The maximum correlation of MI is with the specific humidity in the Ionian Sea (highest r = −0.74, Figure 6j). The influence of MI on the specific humidity is remarkably higher over the eastern Mediterranean with r values ranging from 0.55 to 0.75 (considering absolute values).

[15] All of the indices, apart from the MI, have a much stronger effect on the eastern part of the Mediterranean than on the western part of it. Opposite correlation is usually detected between the west basin (Balearic and Ligurian Seas) and the east basin (Aegean and Libyan Seas). Consequently, these areas are the ones that are affected the most by the atmospheric indices we consider in the entire Mediterranean. Interestingly, the Adriatic Sea, usually located between domains of opposite correlation sign, is significantly affected mostly by EA and in the cases of SH and TA, by MI.

[16] NAO usually exhibits opposite correlation between the north-northwest and the south-southeast Mediterranean Sea and affects much more the eastern than the western part. Positive phase of NAO is associated with lower LH, SH, TA and QA over the south-southeastern part of Mediterranean basin and lower WS over the western part. Conversely, positive phases of EA favor higher LH, SH, TA and QA and lower WS almost over the entire Mediterranean Basin. EAWR, NCP, NAWA and MI exhibit impressively similar correlation maps, indication of not being independent between each other. In general, positive phases of these indices favor lower LH, SH, TA and QA and higher WS over the eastern part of the Mediterranean Sea and vice versa. On the other hand, positive EAWR, NCP, NAWA and MI values are associated with higher LH, SH, TA and QA and lower WS over the western part. Especially, MI shows an one-phase correlation pattern with apparent influence only over the eastern part of the Mediterranean for TA and QA. The positive phase of MI favors lower TA and QA over the eastern basin and vice versa. This behavior of MI can be explained by the propagation of high pressures over the continental Europe [*Papadopoulos et al.*, 2012]. Higher than average pressure over South France and lower pressure over the Levantine Sea cause an almost zonal, strong SLP gradient favoring cold and dry northerlies over the eastern part of the Mediterranean Sea that reduce the values of TA and QA.

4. Conclusions

[17] The spatial characteristics of the turbulent variables (LH, SH, WS, TA, QA) over the Mediterranean Sea display a similar behavior. The coherent first mode of variability (EOF1) plays the dominant role accounting for about half of the total variance for each variable. Despite its coherent pattern, the amplitudes of the first EOF are apparently higher over the Ionian and Aegean Seas implying a differentiation

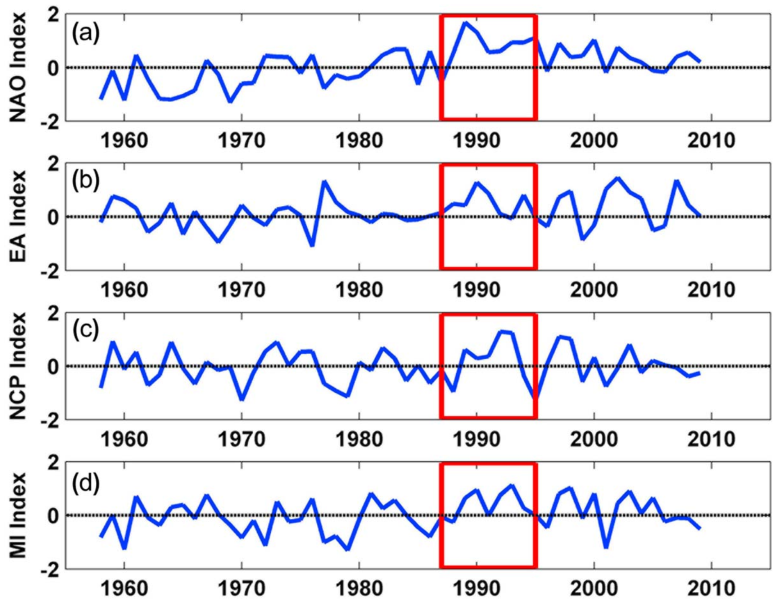

Figure 8. Time series of the mean winter values (DJF) for the (a) NAO, (b) EA, (c) NCP, and (d) MI indices. The red box encompasses the period of the observed changes in the deep waters of the eastern Mediterranean Sea.

between the west and the east parts of the Mediterranean. The second EOF indicates an out-of-phase relationship between west and east basins. The two leading modes of variability account for ~70% of the total variance for all of the studied variables. The third EOF accounts for less than 10% in all cases and exhibits a rather north-south out-of-phase domain. The three EOF patterns reflect on the size and morphology of the Mediterranean basin. In comparison to the open oceans, the Mediterranean Sea is so small to exhibit a main coherent oscillation of the turbulent variables as revealed by their first EOF. Regarding its geomorphology, the Mediterranean is elongated enough to favor frequent zonal oscillation as implied by the second EOF of most of the variables. Since the length of the basin is much greater than its width, a small fraction of the total variance is linked to a meridional oscillation as the third EOF usually reveals.

[18] The correlation between the turbulent variables and the selected climatic indices manifests a different response of the variables to the atmospheric forcing at the various parts of the Mediterranean Sea. Opposite response to the atmospheric forcing is observed mostly between the Ligurian and Aegean Seas. Balearic and Ligurian Seas in the west sub-basin and Aegean and Libyan Seas in the east, display the greater dependence on the climatic indices implemented in this study. The intrabasin MI locally exhibits the highest impact on all variables indicating the significant role of the regional SLP field. However, this mode is under the combined influence of the primary atmospheric modes as is inferred from the correlation of MI with NAO, EA, SCAND, and EAWR (Table 1). The NCP yields also a significant dipolar correlation pattern affecting mainly the east Mediterranean basin, while the EAWR shows similar domains of influence on the studied variables but weaker influence than NCP. The EA is dominant only over the central basin but shows the most extensive spatial influence in the Mediterranean basin, yet it exhibits lower maximum ⟨r⟩ values than the NCP and MI. The NAWA and particularly the NAO exhibit the weaker impact on the turbulent fluxes. Nevertheless, they are much more influential just out of the Mediterranean Sea (over the adjacent Black Sea and Biscayan Gulf). In terms of an entire basin approach, the EA is the most influential index for the Mediterranean Sea as is also shown by JST11 for the Mediterranean heat budget. For the eastern and western sub-basins individually, JST11 find that the EA and EA/WR modes are dominant; the EA results in heat budget anomalies of the same sign in each sub-basin while the EA/WR produces anomalies of about equal and opposite sign in each sub-basin. The magnitude of the heat budget anomalies lie in the range of 15–30 W/m^2.

[19] In the present article, the highest calculated ⟨r⟩ values are hardly greater than 0.7 (that statistically explains the local 50% of the total variance). Nonetheless, the NAO, EA, EAWR and SCAND are uncorrelated due to their orthogonality (as they are modes of the same EOF analysis) and the rest of the indices show a great variation in correlation to one another. For indices which are uncorrelated to one another, each one has its own independent contribution to the total variance of a given turbulent parameter. In other words, at any given time, some indices can decisively modulate the climate of the Mediterranean and some others may be inactive. As a result, this "partial contribution model" can explain a considerable fraction of the total variance. A manifestation of the partial action of the indices can be found in the period between 1987 and 1995. During this period, a significant change in the deep water formation over the eastern Mediterranean took place within the Aegean Sea and as a result the Aegean deep water displaced the traditional Adriatic Sea deep water [*Roether et al.*, 1996]. The period 1987–1995 is uniquely characterized by simultaneous positive mean values of NAO, EA, NCP, and MI with values 0.72, 0.58, 0.36, and 0.45, respectively (Figure 8). From our analysis, EA affects

much more the Adriatic than the Aegean Sea and the opposite occurs for NAO, NCP, and MI. We examine the coupling effect of EA with each one of NAO, NCP, and MI. EA and NAO are orthogonal modes, whereas based on the correlation coefficients of Table 1 we infer that EA can act independently from NCP and exhibits a weak correlation, hardly above the level of significance, with MI. The positive phase of EA favored positive turbulent fluxes feedback mainly over the Adriatic Sea hindering or decreasing the intensity of the deep convection there. In contrast, positive NAO, NCP, and MI favored the enhancement of heat loss in the Aegean Sea. This unique, over our studied period, combination between EA from the one side, and the NAO (or the related but NAO dependent indices NCP and MI) from the other, may have contributed to a lasting intermission or a lower rate of production of the Adriatic deep water formation and a simultaneous intensification of the Aegean Sea deep convection [*Theocharis et al.*, 1999; *Roether et al.*, 2007]. Further research is required to establish the extent to which this combination of modes contributed to this change in eastern Mediterranean convection sites.

[20] Regardless of how much variance the partial contribution model can explain, some speculation arises on the existence of more centers of influence on the turbulent fluxes over the Mediterranean Sea. The existence of additional factors that can affect the climate of the Mediterranean should be given further attention in terms of searching for indices or even better, physical mechanisms with stronger influence than those stated in this paper. Such physical mechanisms may include the winter behavior of the thermal Middle East and Arabian Peninsula Lows, the low-frequency atmospheric disturbances throughout subtropical North Africa and a more complex oscillation-like mode including the Azores and Siberian Highs, and the Icelandic and Eastern Mediterranean Lows. In addition, further investigation has to be undertaken on the local effects that may modulate the turbulent variables and their relation with the large scale atmospheric forcing.

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