CLIMATIC INDICES INFLUENCING THE LONG TERM VARIABILITY OF MEDITERRANEAN HEAT AND WATER FLUXES: THE NORTH ATLANTIC AND MEDITERRANEAN OSCILLATIONS

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ABSTRACT: Interannual to interdecadal precipitation (P), evaporation (E), water deficit (E-P) and total heat flux have been correlated with North Atlantic Oscillation (NAO) and Mediterranean Oscillation (MO) indices to explore the influence of large-scale atmospheric forcing in the Mediterranean water and heat budgets variability. Basin-averaged precipitation decrease from mid-60s to late-80s clearly corresponds to a switch from a low to a high state of both indices. E-P variability is not so well correlated with the atmospheric indices due to the different sensitiveness of E and P that leads to correlations of opposite sign in the Eastern and Western sub-basins. The effectiveness of NAO and MO indices is rather similar for P and E-P but the regional MO index has turned out to be a more successful indicator of interdecadal evaporation and net heat flux because from mid 70s to early 90s there is a considerable discrepancy with NAO index. Since the MO centre remains rather steady, it influences most of the Mediterranean all year round, then becoming more suitable for monitoring long term water and (especially) heat budgets variability.

Keywords: Heat and water budgets, long-term variability, atmospheric forcing, climatic indices, Mediterranean Sea.

INTRODUCTION

The Mediterranean Sea (Figure 1), a semi-enclosed basin that extends over 3000 km in longitude and over 1500 km in latitude with an area of $2.5 \cdot 10^{12}$ m^2, communicates with the Atlantic Ocean through the Strait of Gibraltar and with the Black Sea through the Turkish Bosphorus and Dardanelles Straits. Semi-enclosed basins such as the Mediterranean are suitable for the characterisation of heat and water fluxes since they make a budget closure feasible. Evaporative losses (E) are not balanced by precipitation (P) and river runoff (R) and an Atlantic inflow through the Strait of Gibraltar is necessary to balance the freshwater and salt budgets. The circulation in the Mediterranean Sea is influenced to a large extent by the heat and freshwater air-sea exchanges which depend on the meteorological and oceanic conditions (Tsimplis et al., 2006). The heat and water budgets play a key role in dense water formation and hence in the Mediterranean Thermohaline Circulation (Bethoux et al., 1999). As a consequence, they affect the characteristics of the Mediterranean water masses and then may potentially influence the Atlantic Ocean circulation via changes in the properties of the Mediterranean Outflow (Bethoux et al., 1999; Potter and Lozier, 2004; Artale et al., 2005; Millot et al., 2006). For these reasons, the improvement of our knowledge of heat and water budgets and their long-term variability is a challenge for the scientific community of the Mediterranean region and is thought to be crucial to understand the Mediterranean circulation and climate and their evolution under climate change.

--------------------------------Approximate location of Figure 1--------------------------------

A great number of studies have dealt with the Mediterranean heat (Bethoux, 1979; Bunker et al., 1982; May, 1986; Garrett et al., 1993; Gilman and Garrett, 1994; Castellari et al., 1998; Matsoukas et al., 2005; Ruiz et al., 2008; Sanchez-Gomez et al., 2011; Criado-Aldeanueva et al., 2012) and water (Bethoux, 1979; Peixoto et al., 1982; Bryden and Kinder, 1991; Harzallah et al., 1993; Gilman and Garrett, 1994; Castellari et al., 1998; Angelucci et al., 1998; Béthoux and Gentili, 1999; Boukthir and Barnier, 2000; Mariotti et al., 2002; Mariotti, 2010; Sanchez-Gomez et al., 2011; Criado-Aldeanueva et al., 2012) budgets but only in the recentmost ones, which use longer datasets, the attention focused on the interannual variability and its forcing mechanisms. For instance, Criado-Aldeanueva et al. (2012) report three different periods in the precipitation and evaporation anomalies: from early 50s to late 60s, a positive trend is observed that changes to negative until late 80s when it changes sign again. This variability also reflects in the total heat flux exchanged between the ocean and atmosphere and suggests a 40-year period multi-decadal oscillation related to long-term atmospheric forcing that needs further investigation.

Indices of large-scale climate modes provide an integrated measure of weather linked more to the overall physical variability of the system than to any individual local variable. Among these indices, the North Atlantic Oscillation (NAO) is one of the most prominent modes of the northern hemisphere climate variability (Walker and Bliss, 1932; van Loon and Rogers, 1978; Barnston and Livezey 1987; see Hurrell et al., 2003 for a recent review). It consists of a dipole of the sea level pressure over the North Atlantic-European region with one centre reflecting the Iceland low and the other the Azores high. Both phases of the NAO (stronger and weaker dipole) are associated with basin-wide changes in the intensity and location of the North Atlantic jet stream and storm track and in large-scale modulations of the normal patterns of zonal and meridional heat and moisture transport, which in turn results in changes in temperature and precipitation patterns over extended areas, including the Mediterranean sea (Walker and Bliss 1932; van Loon and Rogers 1978; Rogers and van Loon 1979; Hurrell 1995; Serreze et al., 1997; Dai et al., 1997; Mariotti et al., 2002; Mariotti and Arkin, 2007). Interest in NAO has been recently renewed because a trend towards its positive phase, especially in the last two or three decades, has been observed.

Although very important, NAO is not the only mode of variability of the northern hemisphere: the Artic Oscillation (AO), defined as the first leading mode from the EOF analysis of monthly mean height anomalies at 1000 hPa poleward of 20ºN, is highly correlated with NAO in the Atlantic region because of the overlap of their spatial patterns in this sector and could be candidate for monitoring the large-scale atmospheric forcing instead of NAO. But the results of Ambaum et al. (2002) show that the NAO has a separated set of physical processes involved in its variability that makes it more robust and physically relevant and has therefore been preferred for this study.

Conte et al (1989) suggested the possible existence of a Mediterranean Oscillation (MO) as a consequence of the dipole behaviour of the atmosphere in the area between the Western and Eastern Mediterranean. Differences in temperature, precipitation, circulation and other parameters between both basins were attributed to this MO and an index to measure the intensity of this dipole-like behaviour was proposed (Conte et al., 1989; Kutiel et al., 1996; Maheras et al., 1999; Supic et al., 2004; Suselj and Bergant, 2006). Some aspects of the Mediterranean climate variability have been reported to be better reflected by the MO index (Supic et al., 2004), including the flow exchange through Gibraltar (Gomis et al., 2006). More recently, Papadopoulos et al. (2012) stated that the MO index captures to a certain extent the influence of other independent modes of low-frequency atmospheric variability such as the East Atlantic (EA), the East Atlantic-West Russia (EA-WR) or the Scandinavian (SCAND) patterns over the Mediterranean and hence provides a valuable measure of the atmospheric impact on the basin.

In contrast to NAO, that has been extensively studied, only a few previous works focus on the MO index and more research is required, especially to assess its influence in heat and water budgets in the Mediterranean Sea, which is the objective of this work. To this aim, we correlate interannual to interdecadal precipitation, evaporation, water deficit (E-P) and total heat flux with atmospheric indices (NAO and MO) and perform a composite analysis to establish the relative importance of their positive and negative phases in the climatic variables. The work is organised as follows: section 2 describes the data and methodology; section 3 presents and discuss the results both from a regional and global approach and finally section 4 summarises the conclusions.

DATA AND METHODOLOGY

Since there is no unique way to describe the spatial structure of the NAO or MO, it follows that there is no universally accepted index to describe the temporal evolution of the phenomenon. Most recent NAO or MO indices are derived either from the simple difference in surface pressure anomalies between various locations (Rogers, 1984; Conte et al., 1989; Hurrell, 1995; Jones et al., 1997; Slonosky and Yiou, 2001; see Jones et al., 2003 for a comparison between several station-based indices) or from the

Principal Components (PC) time series of the leading Empirical Orthogonal Function (EOF) of sea level pressure or some other climate variable (Suselj and Bergant, 2006; Gomis et al., 2006; Mariotti and Arkin, 2007; see Hurrell and Deser, 2010 for a review of diverse methods). A disadvantage of the station-based indices is that they are fixed in space and are significantly affected by small-scale and transient meteorological events that introduce noise (Trenberth, 1984; Hurrell and van Loon, 1997) whereas the PC time series approach is more optimal representation of the full spatial pattern (Hurrell and Deser, 2010) and will be used in this work unless differently stated.

The monthly NAO index from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) has been retrieved. Its calculation is based on the Rotated Principal Component Analysis (Barnston and Livezey, 1987) applied to monthly mean standardized 500-mb height anomalies for 20ºN-90ºN (see http://www.cpc.ncep.noaa.gov/data/teledoc/teleindcalc.shtml for a detailed description). The MO pattern has been computed as the first PC mode of normalised sea level pressure anomalies across the extended Mediterranean region (30ºW-40ºE in longitude, 30ºN-60ºN in latitude) which exhibits a single centre located over the Central and Western Mediterranean (Figure 1), fairly steady in all seasons. The MO index is then obtained as the corresponding time coefficients of the first PC mode. Since we define the positive phase when sea level pressure anomaly above the Mediterranean is positive, MO and NAO indices are positively correlated.

Monthly means from January 1948 to February 2009 of precipitation, evaporation and surface heat fluxes have been retrieved from the National Center for Enviromental Prediction-National Center of Atmospheric Research (NCEP-NCAR) reanalysis project

(NCEP hereinafter, Kalnay et al., 1996), which is run at T62 spectral resolution (approximately a grid size of 1.9ºx1.9º) with 28 sigma levels. Auxiliary data of monthly mean sea level pressure and air temperature at 2.5ºx2.5º for the period 1948-2009 have also been retrieved from NCEP database. Despite the uncertainties derived from the use of reanalysis, Mariotti et al. (2002) showed that NCEP data exhibit good agreement when compared with observational datasets at interannual to inter-decadal time scales in the Mediterranean area. Moreover, the use of reanalysis allows the construction of homogeneous time series (both in time and space), this leading to a better representation of the basin-scale structures, which are the aim of this work. Seasonal means have been computed by averaging JFM (winter), AMJ (spring), JAS (summer) and OND (autumn) monthly data and Mediterranean spatially-averaged time series have been obtained by averaging all grid points over the sea.

Linear correlation maps have been used to identify coupled patterns between the climatic variables and the atmospheric NAO and MO indices. The statistical significance of the correlation has been computed by transforming the correlation matrix in a *t*-student distribution with N-2 degrees of freedom, where N is the number of element of the analysed time series. Time filtering into low and high frequency components is achieved using a 5-year running mean to take into account the long time scale effects of the indices. Linear regression has also been used to quantify NAO (and MO) related anomalies of the climatic variables. A complementary composite analysis has also been performed to add robustness to the correlation results and highlight the asymmetries between the positive and negative phases of the indices. First, we select those years in which NAO and MO indices are in the upper (positive phase) and lower (negative phase) quartiles over the period 1948-2009 and analyse their influence in the climatic variables in terms of the average standard deviation anomalies during both phases with respect to the complete time series on each grid point (Mariotti and Arkin, 2007). Only the points where the results are statistically different from zero (according to a *t*-Student test at 95% significance) have been represented.

RESULTS AND DISCUSSION

Precipitation

Figure 2 displays the correlation between annual precipitation and winter NAO (panel A) and annual MO (panel B) indices for the period 1948-2008. The most effective (seasonal or annual) index will be selected for each variable hereinafter. A relatively high (anti)correlation (above 0.5) is observed in the Algeric-Balearic and Aegean and northern Levantine sub-basins (more evident for MO index). However, only in ~60% of the Mediterranean, precipitation and atmospheric indices are significantly correlated on annual basis with a mean absolute correlation, |corr|, about 0.4 (see table 1). The correlation increases in winter (or even the entire rainy period, October-March), especially for MO index, with wide regions close to -0.6 and a mean absolute value of 0.48 (not shown). Up to 80% of the basin (except the South-Eastern sub-basin) is significantly correlated in this season, when P is generally linked to storm-track activity captured by atmospheric indices. In summer, most of precipitation across the Mediterranean region is of convective origin and is poorly correlated with the large-scale atmospheric variability.

---------------------------------Approximate location of Figure 2---------------------------------

To further research the relationship between precipitation and the positive and negative phases of the indices, we present now the composite analysis of Figure 3. During the positive phase of the indices (panel A for NAO and C for MO), lower precipitation is observed (up to -1.2 std anomalies). The NAO influence is more evident in the Western Mediterranean and some areas of the Ionian whereas the MO is associated with a noticeable reduction in precipitation in extensive areas of the whole basin. In the negative phase (panels B for NAO and D for MO), higher precipitation is observed, especially for the MO index, with values up to 1.2 std anomalies in the northern area. NAO influence is not so evident in this state, the Levantine basin being the most sensitive region.

--------------------------------Approximate location of Figure 3--------------------------------

Anti-correlation is expectable for P since the positive NAO phase (stronger dipole) strengthens and modifies the orientation of prevailing westerly winds and associated storm-track activity which cause increased precipitation over the northern Europe and dry anomalies in the Mediterranean region (Hurrell, 1995; Serreze et al., 1997; Dai et al., 1997). Roughly opposite conditions occur during the negative (weaker dipole) NAO phase. The relation with the MO index is highlighted in Figure 4, where sea level pressure anomalies are shown both for its positive (panel C) and negative (panel D) phases. The positive phase is associated with higher than average pressure over the Mediterranean, especially over the northern and eastern areas and hence lower precipitation is expected. In contrast, the negative phase is linked with anomalously low pressure over the whole basin and intense cyclogenesis over the Central/Western

Mediterranean that produces anomalously wet conditions over most of the Mediterranean and, hence, negative correlation with P.

At decadal timescales (Figure 2C-D), the correlation considerably increases up to a mean absolute value close to 0.6 (table 1) with extended regions (especially the Algeric-Balearic and the Aegean and northern Levantine) highly correlated (~ -0.8) and a very similar performance of both NAO and MO indices. This result confirms the importance of the choice of a long period for budget studies in the Mediterranean, since the long time scale effects of the indices must be taken into account because of their direct implication on the climatic variables (Pettenuzzo et. al., 2010). The precipitation anomalies resulting from the regression of precipitation with the NAO index (Figure 2E, results for MO index are rather similar, not shown) indicates that, following positive NAO index anomalies, the Mediterranean experiences a decrease in precipitation up to 150-200 mm/year in some regions, mostly restricted north of 35ºN, a result already mentioned by Mariotti et al. (2002).

--------------------------------Approximate location of Figure 4--------------------------------

Basin wide (Figure 2F), decadal to interdecadal variability of the Mediterranean precipitation appears to be even more closely related to NAO and MO indices with correlations of -0.8 and -0.78, respectively (table 1). In particular, the decrease from mid-60s to late-80s corresponds to a switch from a low to a high state of the indices (notice that –NAO and -MO indices have been plotted). These results are in good agreement with those of Mariotti et al. (2002), who obtained (only for NAO) a correlation of -0.51 and -0.84 for annual and decadal (5-year running means) variability, respectively.

--------------------------------Approximate location of Table 1---------------------------------

Evaporation

On annual basis, evaporation is poorly correlated with winter NAO (Figure 5A) and only the northern Levantine sub-basin seems to be sensitive to large-scale atmospheric forcing. More success is observed for the summer MO index (Figure 5B) that, although with a moderate correlation (between -0.3 and -0.5 in most regions and a mean absolute value of 0.37, see table 1) influences 70% of the Mediterranean. Composite analysis for the positive (panel A) and negative (panel B) phases of the MO index is displayed in Figure 4. During its positive phase, lower than average evaporation is observed, especially in the Western basin with values up to -1 std anomaly in the Tyrrhenian basin but also in the Levantine basin with values between -0.6 to -0.8 std anomalies. During the negative phase, higher than average evaporation is observed elsewhere but especially in the Levantine basin (up to 1.4 std anomalies).

Anti-correlation is again expected since, with negative indices, anomalously low pressure over the whole basin is observed (see Figure 4D) and colder and dryer air masses from continental regions prevail, generating more severe weather conditions over the Northern and Eastern Mediterranean. With this state, an intensification of evaporative losses to the atmosphere is expected. Conversely, positive values of the indices are associated with higher than average pressure over the Mediterranean and

North Africa (Figure 4C) that promote a shift of the wind trajectories toward lower latitudes. Warmer and moister air masses are then conveyed toward the Mediterranean leading to milder winters and a consequent decrease in the evaporative lost (Hurrell, 1995). But in autumn, when higher evaporation is observed (Mariotti et al., 2002; Criado-Aldeanueva et al., 2012), the southern centre of NAO is rather far from the Mediterranean and the regional MO index reflects more successfully local wind trajectories that condition evaporation. It is interesting to notice that summer MO index achieves the maximum correlation (although close values are obtained with the annual MO index) because its positive and negative phases are associated with very different sea level pressure anomaly patterns (Figure 4 C-D) during the year that determine the wind trajectories and hence, evaporation. Since evaporation is higher in autumn and winter, the atmospheric forcing in summer triggers, to a certain extent, its evolution in the following months.

--------------------------------Approximate location of Figure 5--------------------------------

At decadal timescales, the correlation increases up to a mean absolute value about 0.55 (table 1) with higher values (-0.7 to -0.8) in the Levantine (both indices) and Tyrrhenian (MO index) sub-basins (Figure 5C-D), again confirming the long time scale effects of the indices on the climatic variables (Pettenuzzo et. al., 2010). But the difference between NAO and MO influence remains evident (only 55% of the basin in sensitive to NAO and more than 80% to MO). The evaporation anomalies resulting from the regression with the indices (Figure 5E, only results for NAO index are shown) indicates that only the Levantine sub-basin, where higher evaporation is observed (Mariotti et al., 2002; Criado-Aldeanueva et al., 2012), experiences a considerable decrease in evaporation (250-350 mm/year) as a consequence of +1 NAO index anomalies.

Basin wide (Figure 5F), decadal to interdecadal variability of the Mediterranean evaporation is also better correlated to the regional MO index (see table 1). For instance, from mid 70s to early 90s, there is a considerable discrepancy between NAO index and E variability, which seems to be better captured by MO index.

E – P freshwater deficit

The annual freshwater deficit (E-P) is poorly correlated with atmospheric indices (Figure 6A-B). Only a reduced area near Corsica and Sardinia and the Adriatic (for the MO index) are positively correlated whereas the easternmost Levantine sub-basin is negatively correlated. Seasonal correlations are more successful: for instance, winter deficit is positively correlated with winter MO index with a mean value of 0.45 in most of the Northern (above 35ºN) Mediterranean (not shown), but winter only accounts for 20% of annual deficit (Criado-Aldeanueva et al., 2012).

At decadal timescales, a clear bi-modal pattern is observed both for NAO and MO indices (Figure 6C-D): in the North-Central Mediterranean, E-P is positively correlated (0.5-0.6) with the atmospheric forcing whereas in the Levantine sub-basin anti-correlation is observed (close to -0.6). In accordance, regression analysis of NAO (and, similarly MO, not shown) index with E-P also show an increment (decrement) in the freshwater deficit in the Central (Levantine) sub-basins following +1 change (Figure 6E). This bi-modal behaviour can be explained based on the different sensitiveness of E and P to the atmospheric forcing in those regions. In the Central basin, P is dominant (compare Figures 2E and 5E) and changes in E-P follow those of –P (hence, positive correlation is expected). In contrast, the Levantine sub-basin is highly sensitive to E (see Figure 5E) and changes in E-P follow those of E (hence, negative correlation).

--------------------------------Approximate location of Figure 6--------------------------------

Mediterranean-averaged decadal to interdecadal E-P variability (Figure 6F) is not well correlated with the large atmospheric forcing (~0.25), probably due to this bi-modal pattern. The correlation doubles (0.5 and 0.48 for NAO and MO indices, respectively) if only the period from 1970 is considered (when a switch from a low to a high state of the indices seems to be followed by an increase in E-P), in agreement with the results of Mariotti et al. (2002), who report 0.18 from NCEP (1949-98) and 0.55 from ERA (1980-93) data. Longer time series are necessary to elucidate the large scale atmospheric relationship with the water deficit.

Net heat flux

The net heat budget consists of two radiation components (solar shortwave radiation absorbed by the sea and longwave radiation emitted by the sea) and two turbulent contributions (latent and sensible heat fluxes). Annual net heat flux is moderately (mean absolute value close to 0.4) correlated with MO index (Figure 7A) in most parts of the Mediterranean (except the Alboran, Adriatic and north Aegean sub-basins). Similar results are found for NAO index but more extended areas (especially the southern Ionian) are not significantly correlated (Figure 7B). Decadal variations are more successfully correlated with both indices (|corr|~0.6, see table 1) with higher values close to -0.8 in the Levantine sub-basin (for NAO index, Figure 7C) and in the Central Mediterranean (for MO index, Figure 7D). The composite analysis of Figure 8 reveals that, during the positive phase of the indices (panel A for NAO and C for MO), ocean heat losses are lower (especially for the MO index in most of the Western basin with values up to -1 std anomalies). In the negative phase (panels B for NAO and D for MO), ocean heat losses are higher. This anomaly is more evident in the Levantine and Aegean sub-basins (higher than 1.2 std anomalies) under the negative MO phase.

The physical explanation for this is related to the wind trajectories that induce the sea level pressure anomaly pattern in both MO phases: in the positive state (Figure 4C), the dipole of high pressure anomaly over North Africa and Central Europe brings warmer and moister air masses, especially to the Central and Western Mediterranean, that lead to milder winters and a consequent heat loss decrease. In contrast, in the negative state (Figure 4D), the dipole of anomalously low pressure over Central Europe and Turkey brings colder and dryer air masses from continental regions towards the Mediterranean, that merge in the Levantine and Aegean sub-basins, generating more severe weather conditions and higher heat losses, especially in these areas.

--------------------------------Approximate location of Figure 7--------------------------------

As shown by Criado-Aldeanueva et al. (2012), fluctuations in the net heat flux closely follow those of the latent heat, this contribution becoming the main source of interannual variability. Since latent heat losses are directly related to evaporation, similarity between Figure 5 and Figure 7 (and also between Figure 4A-B and Figure

8C-D) is expectable. However, better correlation is observed for net heat flux (see also table 1) due to the other heat contributions that correlate well with the atmospheric indices (especially the MO index, e.g. |corr| = 0.52 and 0.55 for long and shortwave radiation, respectively, in more than 80% of the basin at annual timescales). Notice that the sign of the correlation is negative because we have selected net heat flux positive toward the atmosphere (the same as evaporation). The net heat flux anomalies resulting from the regression with the indices (Figure 7E for NAO index and very similar for MO index, not shown) reveal that, similarly to evaporation, the Levantine sub-basin is the most sensitive to changes in the large-scale atmospheric forcing.

Basin wide (Figure 7F), decadal to interdecadal variability of the Mediterranean net heat flux is better correlated to the regional MO index (table 1). As previously said, from mid 70s to early 90s, there is a considerable discrepancy between NAO index and E (and hence, net heat) variability, which seems to be better captured by MO index.

--------------------------------Approximate location of Figure 8--------------------------------

4.- SUMMARY AND CONCLUDING REMARKS

We have correlated interannual to interdecadal precipitation, evaporation, water deficit (E-P) and total heat flux with climatic NAO and MO indices to explore the influence of atmospheric forcing in the Mediterranean water and heat budgets variability. The effectiveness of NAO and MO indices is rather similar for P and E-P but the regional MO index has turned out to be a more successful indicator of interdecadal evaporation and net heat flux (see table 1, in bold).

The indices exhibit considerable interannual and multi-decadal variability and prolonged periods of both positive and negative phases of the pattern are common. The positive phase of the indices is associated with higher than average pressure over the Mediterranean and hence lower precipitation whereas the negative phase is linked with anomalously low pressure over the whole basin that produces anomalously wet conditions over most of the Mediterranean. Evaporation and net heat flux is related to the wind trajectories that induce the sea level pressure anomaly pattern in both MO phases (Figure 4 C-D): in the positive state, the dipole of high pressure anomaly over North Africa and Central Europe brings warmer and moister air masses, especially to the Central and Western Mediterranean, that lead to milder winters and a consequent heat loss (and evaporation) decrease. In contrast, in the negative state, the dipole of anomalously low pressure over Central Europe and Turkey brings colder and dryer air masses from continental regions towards the Mediterranean, that merge in the Levantine and Aegean sub-basins, generating more severe weather conditions and higher heat (and evaporative) losses, especially in these areas.

The annual time series of NAO and MO indices are highly correlated (~0.6), this indicating a close relationship between the indices due to the forcing of Atlantic low systems on Mediterranean cyclogenesis (Trigo et al., 2002). The MO can be seen as an oscillation of sea level pressure anomalies in the Central and Western Mediterranean, a significant source of cyclogenesis. Since the occurrence of these cyclones is partially linked with the activity of North Atlantic fronts governed by NAO, a high correlation is expectable. In winter, the southern centre of the NAO is located closer to the Mediterranean and, for this reason, the best correlation for all variables is always observed for winter NAO index. But in summer and spring, the southern centre of the NAO moves westward (Hurrell, 1995) and lower correlation is observed. In contrast, the MO centre remains rather steady and it influences the Mediterranean all year round (hence annual indices are preferred). Additionally, due to its effect in the Mediterranean pressure field, the MO index captures to a certain extent the influence of other independent modes of low-frequency atmospheric variability, especially the East Atlantic (EA, r = 0.43 on annual basis) but also the East Atlantic-West Russia (EA-WR) or the Scandinavian (SCAND) patterns during the cold part of the year (Papadopoulos et al., 2012), and provides a valuable measure of the atmospheric impact on the basin, then becoming, more suitable for monitoring long term water and (especially) heat budgets variability.

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REFERENCES

Angelucci, M. G., N. Pinardi, and S. Castellari, 1998. Air–sea fluxes from operational analyses fields: Intercomparison between ECMWF and NCEP analyses over the Mediterranean area. Phys. Chem. Earth, 23, 569–574.

Artale, V., Calmanti, S., Malanotte-Rizzoli, P., Pisacane, G., Rupolo, W. and Tsimplis, M. (2005). Mediterranean climate variablity. In: Lionello, P., Malanotte-Rizzoli, P., Boscolo, R. (eds). Elsevier, pp 282-323.

Barnston, A.G. and Livezey, R.E., 1987. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Mon. Weather Rev. 115, 1083-1126.

Bethoux, J.P, 1979. Budgets of the Mediterranean Sea: their dependence on the local climate and on the characteristics of Atlantic waters. Ocean. Acta 2, 157-163.

Bethoux, J.P. and Gentili B., 1999. Functioning of the Mediterranean Sea: Past and Present Changes realed to freshwater input and climatic changes. J. Mar. Syst. (20), 33-47.

Bethoux, J.P., Gentili, B. and Taillez, D. (1999). Warming and freshwater budget change in the Mediterranean since the 1940s, their possible relation to the greenhouse effect. Geophys. Res. Lett 25, 1023-1026.

Boukthir, M., and B. Barnier, 2000. Seasonal and inter-annual variations in the surface freshwater flux in the Mediterranean Sea from the ECMWF re-analysis project. J. Mar. Syst., (24), 343–354.

Bryden, H. L., and T. H. Kinder, 1991b. Steady two-layer exchange through the Strait of Gibraltar. Deep-Sea Res., 38S, 445–463.

Bunker, A.F., Charnock, H., Goldsmith, R.A., 1982. A note on the heat balance of the Mediterranean and Red Seas. J. Mar. Res. 40, 73-84, Suppl.

Castellari, S., Pinardi, N., Leaman K., 1998. A model study of air-sea interactions in the Mediterranean Sea. J. Mar. Sys. 18, 89-114.

Conte, M., Giuffrida, A. and Tedesco, S., 1989. The Mediterranean Oscillation, impact on precipitation and hydrology in Italy. Conference on Climate Water. Pub. of the Academy of Finland, Helsinki, 121-137.

Criado-Aldeanueva, F., Soto-Navarro, J., García-Lafuente, J., 2012. Seasonal and interannual variability of surface heat and freshwater fluxes in the Mediterranean Sea: budgets and exchange through the Strait of Gibraltar. International Journal of Climatology, 32, 286-302 doi: 10.1002/joc.2268.

Dai, A., Fung, I.Y., del Genio, A.D., 1997. Surface observed global land precipitation variations during 1900-88. J. Clim 10, 2943-2962.

Garrett, C., Outerbridge, R., Thompson, K., 1993. Interannual variability in Mediterranean heat and buoyancy fluxes. J. Climate 6, 900-910.

Gilman, C., Garrett, C., 1994. Heat flux parameterization for the Mediterranean Sea: the role of atmospheric aerosols and constraints from the water budget. J. Geophys. Res. 99 (C3), 5119-5134.

Gomis, D., Tsimplis, M.N., Martín-Míguez, B., Ratsimandresy, A.W., García-Lafuente, J. and Josey, S.A., 2006. Mediterranean sea level and barotropic flow through the Strait of Gibraltar for the period 1958-2001 and reconstructed since 1659. J. Geophys. Res. 111, C11005 doi: 10.1029/2005JC003186.

Harzallah, A., D. L. Cadet, and M. Crepon, 1993. Possible forcing effects of net evaporation, atmospheric pressure and transients on water transports in the Mediterranean Sea. J. Geophys. Res., 98 (C7), 12 341–12 350.

Hurrell, J.W., 1995. Decadal trends in the North Atlantic Oscillation – regional temperatures and precipitation. Science 269(5224), 676-679.

Hurrell, J.W. and van Loon, H., 1997. Decadal variations in climate associated with the North Atlantic Oscillation. Clim. Change 36, 301-326.

Hurrell, J.W., Kushnir, Y., Ottersen, G. and Visbeck, M., 2003. The North Atlantic Oscillation: climate significance and environmental impact. Geophys. Monogr. Ser 134, 279pp.

Hurrell, J.W. and Deser, C., 2010. North Atlantic climate variability: the role of the North Atlantic Oscillation. J. Mar. Sys. 79, 231-244.

Jones, P.D., Jonsson, T. and Wheeler, D., 1997. Extension to the North Atlantic Oscillation using early instrument pressure observations from Gibraltar and south-west Iceland. Int. J. Climatol. 17, 1433-1450.

Jones, P.D., Osborn, T.J. and Briffa, K.R., 2003. Pressure-based measures of the North Atlantic Oscillation (NAO), a comparison and assessment of changes in the strength of the NAO and its influence on surface climate parameters. In The North Atlantic Oscillation: Climatic Significance and Environmental Impact, Geophys. Monogr. Ser., vol. 134, edited by J. W. Hurrell et al., pp. 51–62, AGU, Washington, D. C., doi:10.1029/134GM03.

Kalnay, E and co-authors (1996). The NCEP/NCAR 40-year reanalysis project. Bull. Amer. Meteor. Soc., 77:437-471.

Kutiel, H., Maheras, P. and Guika, S., 1996. Circulation indices over the Mediterranean and Europe and their relationship with rainfall conditions across the Mediterranean. Theor. Appl. Climatol. 54, 125-138.

van Loon, H. and Rogers, J.C., 1978. The see-saw of winter temperatures between Greenland and northern Europe. Part I: general descriptions. Mon. Weather Rev 106, 296-310.

Maheras, P., Xoplaki, E. and Kutiel, H., 1999. Wet and dry monthly anomalies across the Mediterranean basin and their relationship with circulation 1860-1990. Theor. Appl. Climatol 64, 189-199.

Mariotti, A., Struglia, M.V., Zeng, N., Lau, K.-M., 2002. The hydrological cycle in the Mediterranean region and implications for the water budget of the Mediterranean Sea. Journal of Climate 15, 1674–1690.

Mariotti, A. and Arkin, P., 2007. The North Atlantic Oscillation and oceanic precipitation variability. Clim. Dyn 28, 35-51.

Mariotti A, 2010. Recent Changes in the Mediterranean Water Cycle: A Pathway toward Long-Term Regional Hydroclimatic Change? Journal of Climate 23 (6), 1513-1525.

Matsoukas, C., Banks, A. C., Hatzianastassiou, N., Pavlakis, K. G., Hatzidimitriou, D., Drakakis, E., Stackhouse, P. W., Vardavas, I., 2005. Seasonal heat budget of the Mediterranean Sea. J. Geophys. Res., 110, C12008, doi:10.1029/2004JC002566.

May, P.W., 1986. A brief explanation of Mediterranean heat and momentum flux calculations. NORDA code 322, NSTL, MS 39529.

Millot, C., Candela, J., Fuda, J.L. and Tber, Y. (2006). Large warming and salinification of the Mediterranean outflow due to changes in its composition. Deep-Sea Res. 53, 656-666.

Papadopoulos, V., Josey, S.A., Bartzokas, A., Somot, S., Ruiz, S. and Drakopoulou, P. (2012). Large-scale atmospheric circulation favoring deep -and intermediate- water formation in the Mediterranean Sea. J. Climate 25, 6079-6091.

Peixoto, J. P., M. De Almeida, R. D. Rosen, and D. A. Salstein, 1982. Atmospheric moisture transport and the water balance of the Mediterranean Sea. Water Resour. Res., 18, 83–90.

Pettenuzzo, D., Large, W.G. and Pinardi, N. (2010). On the corrections of ERA-40 surface flux products consistent with the Mediterranean heat and water budgets and the connection between basin surface total heat flux and NAO. J. Geophys. Res. 115, C06022, doi: 10.1029/2009JC005631.

Potter, R. and Lozier, S. (2004). On the warming and salinification of the Mediterranean outflow waters in the North Atlantic. Geophys. Res. Lett 31, L01202. doi: 10.1029/2003GL018161.

Rogers, J.C. and van Loon, H., 1979. The see-saw of winter temperatures between Greenland and northern Europe. Part II: some oceanic and atmospheric effects in middle and high latitudes. Mon. Weather Rev 107, 509-519.

Rogers, J.C., 1984. The association between the North Atlantic Oscillation and the Southern Oscillation in the northern hemisphere. Mon. Weather Rev. 112 1999-2015.

Ruiz S., Gomis D., Sotillo M. G., Josey S. A., 2008. Characterization of surface heat fluxes in the Mediterranean Sea from a 44-year high-resolution atmospheric data set. Global and Planetary change, (63), 256-274.

Sanchez-Gomez, E., Somot, S., Josey, S.A., Dubois, C., Elguindi, N. and Déqué, M. (2011). Evaluation of Mediterranean Sea water and heat budgets simulated by an ensemble of high resolution regional climate models. Clim. Dyn. 37, 2067-2086.

Serreze, M.C., Carse, F., Barry, R.G. and Rogers, J.C., 1997. Icelandic low cyclone activity: climatological features, linkages with the NAO and relationships with recent changes in the northern hemisphere circulation. J. Clim 10(3), 453-464.

Slonosky, V.C. and Yiou, P., 2001. Secular changes in the North Atlantic Oscillation and its influence on 20th century warming. Geophys. Res. Lett. 28, 807-810.

Supic, N., Grbec, B., Vilibic, I. and Ivancic, I., 2004. Long-term changes in hydrograpic conditions in northern Adriatic and its relationship to hydrological and atmospheric processes. Annales Geophysicae 22, 733-745.

Suselj, K. and Bergant, K., 2006. Mediterranean Oscillation Index. Geophys. Res. Abstr. 8, 02145 European Geosciences Union.

Trenberth, K.E., 1984. Signal versus noise in the Southern Oscillation. Mon. Weather Rev. 112, 326-332.

Trigo, I.F., Bigg, G.R. and Davies, T.D. (2002). Climatology of cyclogenesis mechanisms in the Mediterranean. Monthly Weather Review 130 (3), 549-569.

Tsimplis, M., Zervakis, V., Josey, S. A., Peneva, E.L., Struglia, M.V., Stanev, E., Teocharis, A., Lionello, P., Malanotte-Rizzoli, P., Artale, V., Tragou, E. and Orguz, T. (2006). Changes in the oceanography of the Mediterranean Sea and their link to climate variability. In: Lionello, P., Malanotte-Rizzoli, P., Boscolo, R. (eds). Elsevier, pp 226-281.

Walker, G.T. and Bliss, W.E., 1932. World Weather V. Memories of the Royal Meteorological Society 44, 53-84.

FIGURE CAPTIONS

Table 1: Mean absolute correlation, |corr|, at 95% significance level between annual and decadal (5-years running means) NAO and MO indices and P, E, E-P and net heat flux (Q). The fraction of points significantly correlated is shown in brackets. The last two columns display the correlation between the indices and the Mediterranean-averaged variables at decadal (5-years running means) timescales (time series of panel F of Figures 2, 5-7). The best correlated seasonal index is indicated (w: winter, s: summer, a: annual). Better results of MO index compared to NAO are highlighted in bold.

Figure 1: Map of the Mediterranean Sea. The main basins and sub-basins are indicated. The MO pattern (contours) has been computed as the first PC of normalised sea level pressure anomalies across the extended Mediterranean region (30ºW-40ºE, 30ºN-60ºN).

Figure 2: Correlation (95% significance) between precipitation (P) and large-atmospheric indices for the period 1948-2008. A) Annual P and winter NAO index; B) Annual P and MO index; C) 5-year running means of P and winter NAO index; D) 5-year running means of P and MO index. E) Regression of P with winter NAO index at decadal (5-year running means) timescales; F) Time series of 5-year running means of winter -NAO (upper, green) and annual -MO (lower, red) indices and Mediterranean-averaged P.

Figure 3: Composites of precipitation standard anomalies associated to the positive (upper quartile) and negative (lower quartile) phases of winter NAO and MO indices for the 60-year 1948-2008 period. A) Positive winter NAO; B) Negative winter NAO; C)

Positive MO; D) Negative MO. Only the points where the results are statistically different from zero (according to a *t*-Student test at 95% significance) have been represented.

Figure 4: Composites of evaporation standard anomalies (panels A-B) and sea level pressure anomalies (hPa, panels C-D) associated to the positive (upper quartile, left panels) and negative (lower quartile, right panels) phases of summer MO index for the 60-year 1948-2008 period. For evaporation, only the points where the results are statistically different from zero (according to a *t*-Student test at 95% significance) have been represented.

Figure 5: The same as Figure 2 for evaporation. The best correlated summer MO index has been selected for correlations with this variable.

Figure 6: The same as Figure 2 for freshwater deficit E-P. Notice that positive NAO and MO indices have been plotted in panel F.

Figure 7: The same as Figure 2 for net heat flux Q. The best correlated summer MO index has been selected for correlations with this variable.

Figure 8: Composites of net heat flux standard anomalies associated to the positive (upper quartile) and negative (lower quartile) phases of winter NAO and summer MO indices for the 60-year 1948-2008 period. A) Positive winter NAO; B) Negative winter NAO; C) Positive summer MO; D) Negative summer MO. Only the points where the

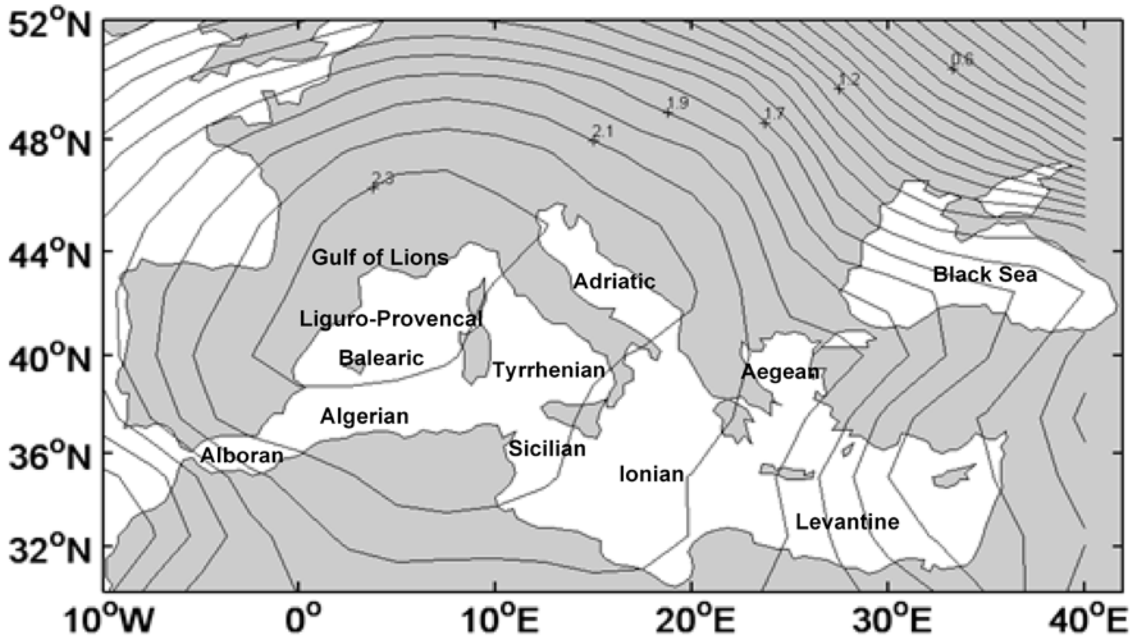
results are statistically different from zero (according to a *t*-Student test at 95% significance) have been represented.

TABLES

	Annual means		5-years means		5-years Med-averaged	
	NAO index	MO index	NAO index	MO index	NAO index	MO index
P	0.40 (54%)	0.45 (56%)	0.58 (82%)	0.56 (80%)	w -0.8	a -0.78
E	0.37 (36%)	0.37 (**68%**)	0.53 (55%)	0.55 (**83%**)	w -0.48	s **-0.63**
E-P	0.38 (38%)	0.39 (38%)	0.50 (60%)	0.48 (59%)	w 0.25	a 0.22
Q	0.39 (55%)	0.37 (**74%**)	0.56 (83%)	0.59 (**93%**)	w -0.63	s **-0.70**

Table 1: Mean absolute correlation, |corr|, at 95% significance level between annual and decadal (5-years running means) NAO and MO indices and P, E, E-P and net heat flux (Q). The fraction of points significantly correlated is shown in brackets. The last two columns display the correlation between the indices and the Mediterranean-averaged variables at decadal (5-years running means) timescales (time series of panel F of Figures 2, 5-7). The best correlated seasonal index is indicated (w: winter, s: summer, a: annual). Better results of MO index compared to NAO are highlighted in bold.

FIGURES



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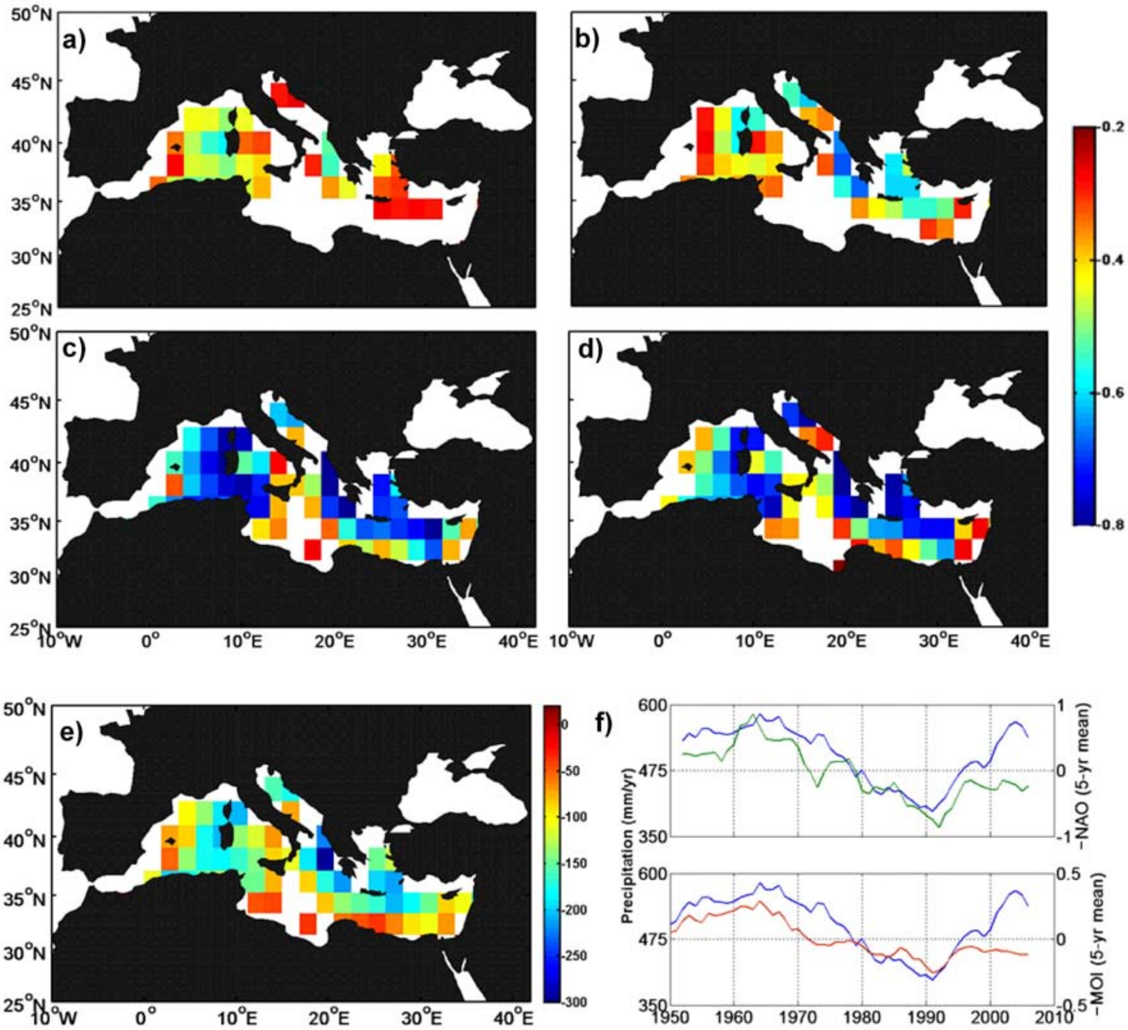

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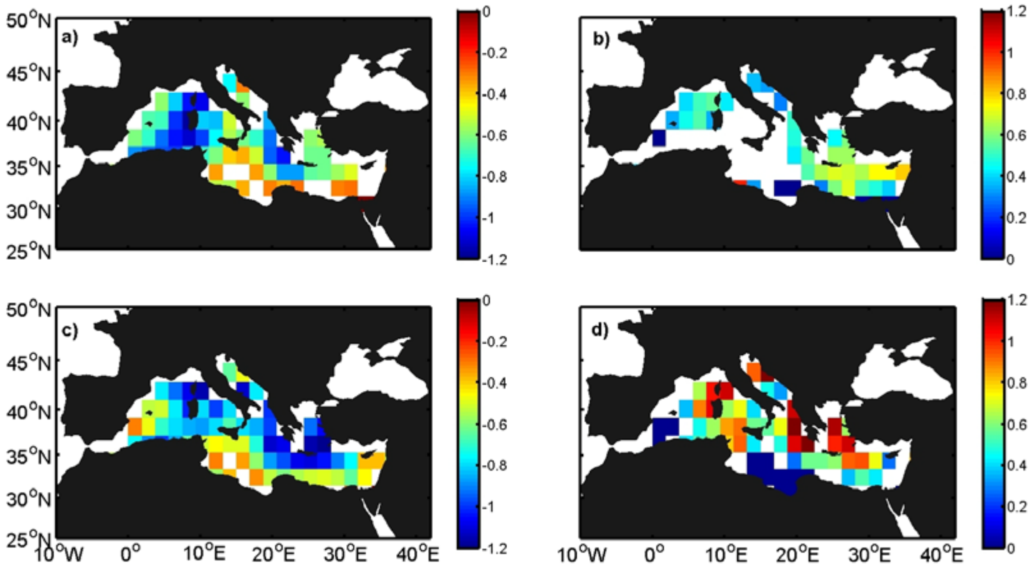
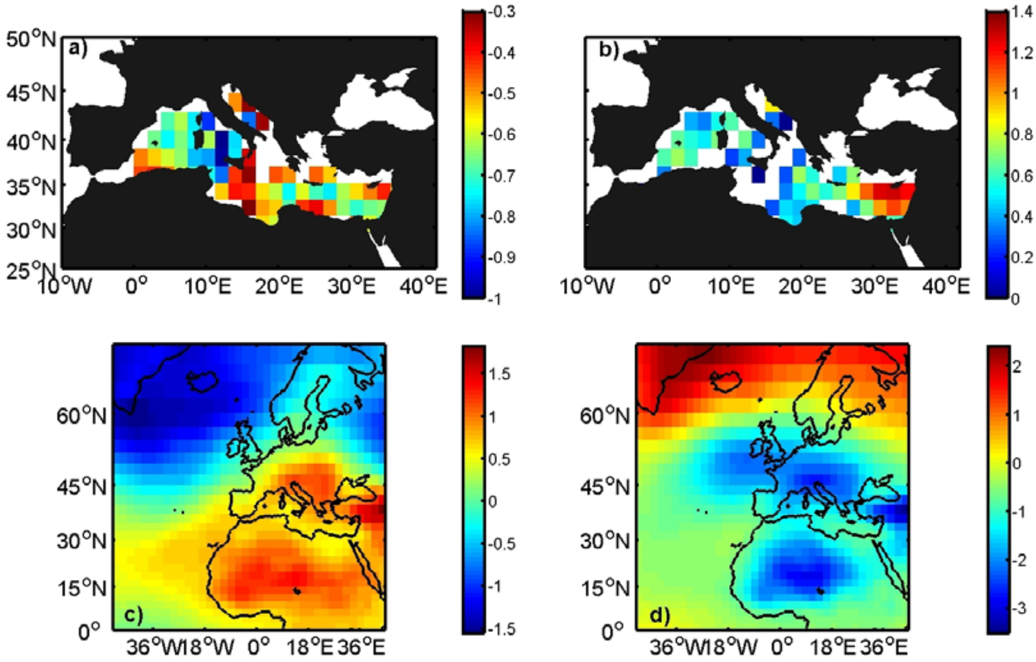


Figure 3: Composites of precipitation standard anomalies associated to the positive (upper quartile) and negative (lower quartile) phases of winter NAO and MO indices for the 60-year 1948-2008 period. A) Positive winter NAO; B) Negative winter NAO; C) Positive MO; D) Negative MO. Only the points where the results are statistically different from zero (according to a *t*-Student test at 95% significance) have been represented.



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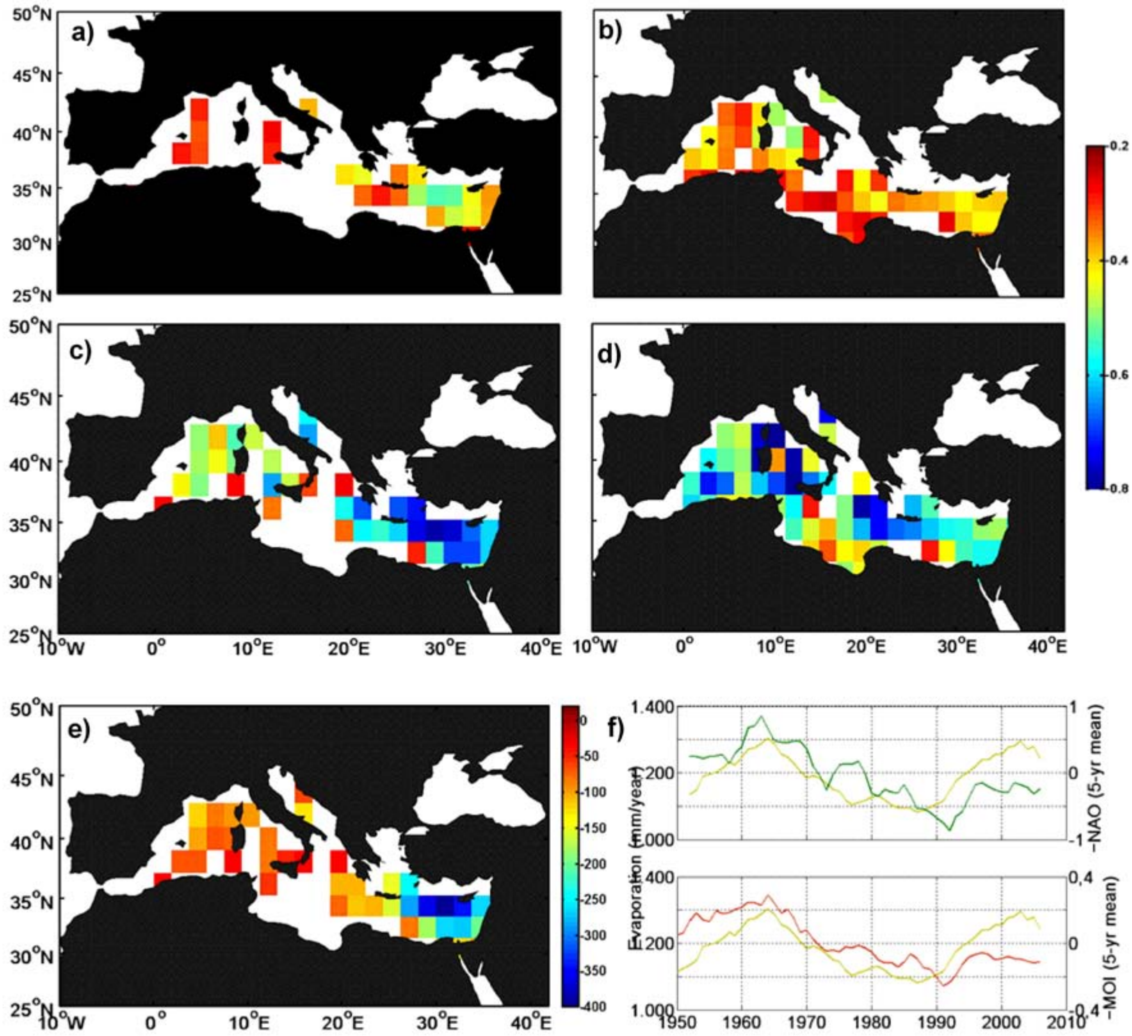

Figure 5: The same as Figure 2 for evaporation. The best correlated summer MO index has been selected for correlations with this variable.

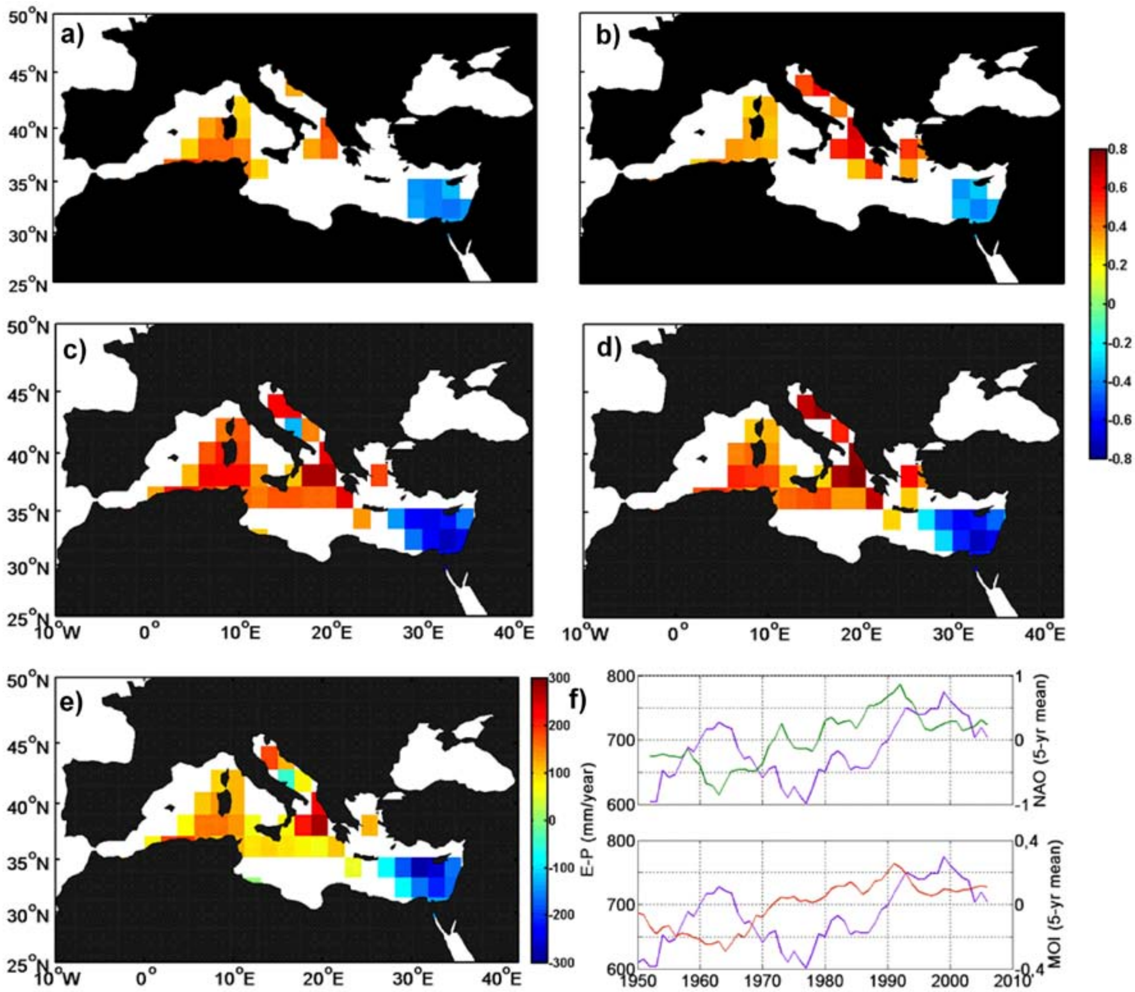

Figure 6: The same as Figure 2 for freshwater deficit E-P. Notice that positive NAO and MO indices have been plotted in panel F.

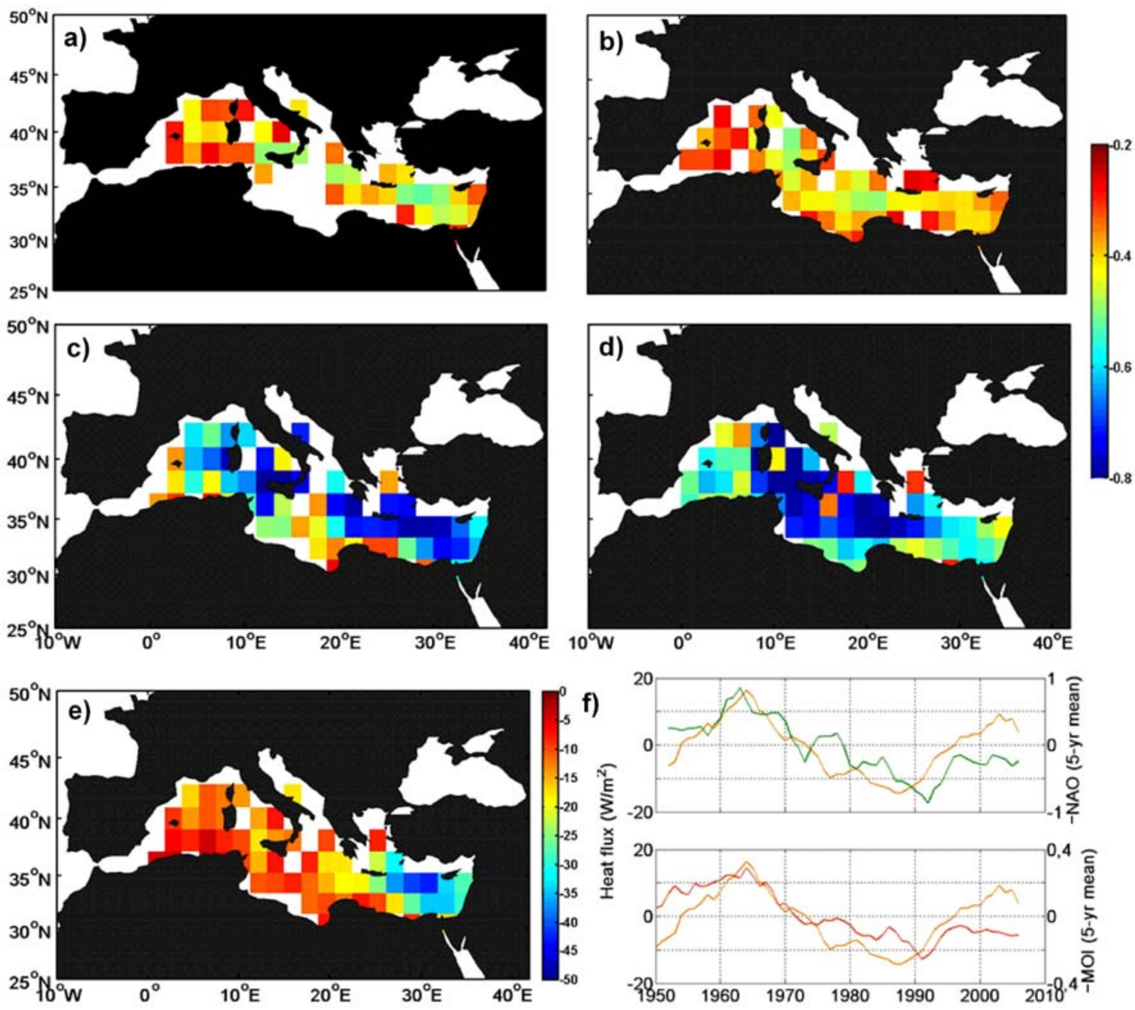

Figure 7: The same as Figure 2 for net heat flux Q. The best correlated summer MO index has been selected for correlations with this variable.

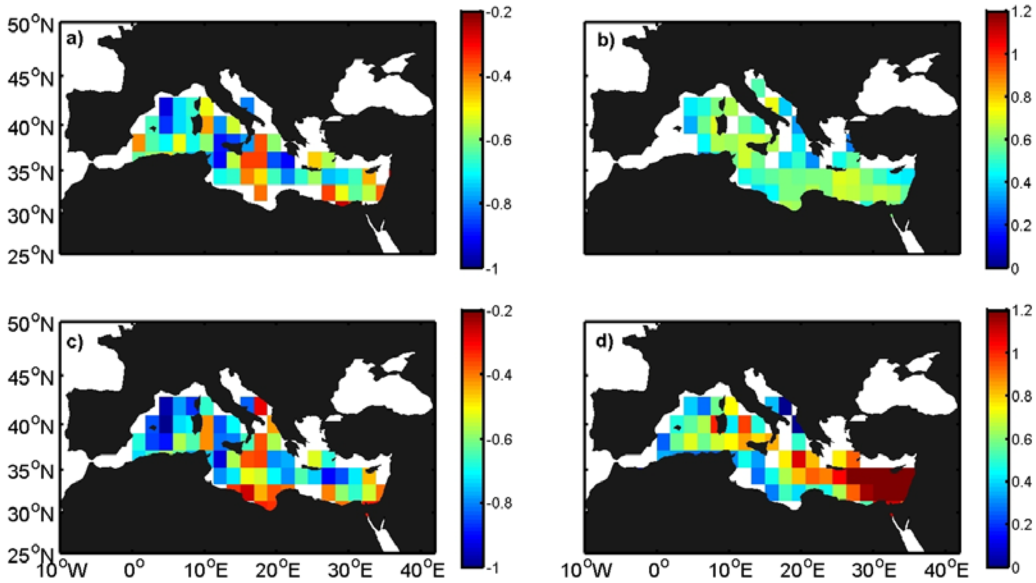

Figure 8: Composites of net heat flux standard anomalies associated to the positive (upper quartile) and negative (lower quartile) phases of winter NAO and summer MO indices for the 60-year 1948-2008 period. A) Positive winter NAO; B) Negative winter NAO; C) Positive summer MO; D) Negative summer MO. Only the points where the results are statistically different from zero (according to a *t*-Student test at 95% significance) have been represented.