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FISH HABITAT MAPPING

Atmospheric forcing on chlorophyll concentration in the Mediterranean

Isidora Katara · Janine Illian · Graham J. Pierce · Beth Scott · Jianjun Wang

Abstract Recent research suggests the coupling of climatic fluctuations and changes in biological indices that describe species richness, abundance and spatio-temporal distribution. In this study, large-scale modes of atmospheric variability over the northern hemisphere are associated with chlorophyll-a concentration in the Mediterranean. Sea level atmospheric pressure, air temperature, wind speed and precipitation are used to account for climatic and local weather effects, whereas sea surface temperature, sea surface height and salinity are employed to describe oceanic variation. Canonical Correlation Analysis was applied to relate chlorophyll concentration to the above-mentioned environmental variables, while correlation maps were also built to distinguish between localized and distant effects. Spectral analysis was used to identify common temporal cycles between chlorophyll concentration and each environmental variable. These cycles could be interpreted as mechanistic links between chlorophyll and large-scale atmospheric variability. Known teleconnection patterns such as the East Atlantic/Western Russian pattern, the North Atlantic Oscillation, the Polar/Eurasian pattern, the East Pacific/North Pacific, the East Atlantic jet and the Mediterranean Oscillation are found to be the most important modes of atmospheric variability related to chlorophyll-a concentration and distribution. The areas that are mostly affected are near the coasts and areas of upwelling and gyre formation. The results also suggest that this influence may arise either through local effects of teleconnection patterns on oceanic features or large-scale changes superimposed onto the general circulation in the Mediterranean.

Keywords Teleconnection pattern · Canonical correlation analysis · Productivity

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Essential Fish Habitat Mapping in the Mediterranean

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Introduction

The distribution of phytoplankton biomass is defined by the availability of light and nutrients. These growth-limiting factors are in turn regulated by physical processes of ocean circulation, mixed layer dynamics, atmospheric dust deposition and the solar cycle. A common factor driving these processes is climate. A description of trends in primary production on a global scale is provided by Behrenfeld et al. (2006). In their study, satellite chlorophyll concentration records are linked to the Multivariate El Niño-Southern Oscillation (ENSO) index, a climatic index based on variables such as sea level pressure, surface wind, sea surface temperature, surface air temperature; and cloudiness fraction over the tropical Pacific, sea surface temperature (SST) and stratification intensity. The leading role of climate variability in determining primary productivity is illustrated.

On a less extensive scale, the most profound and best-studied large-scale, oceanic-atmospheric phenomenon, affecting phytoplankton concentration, is El Niño. The mechanisms proposed to link changes in the atmosphere to primary productivity during these events include the presence of upwelling favourable winds, the presence of macronutrients, CO_2 flux (Chavez et al., 1999) and the turning off/recommencement of the iron-rich Equatorial Undercurrent (Murtugudde et al., 1999; Murakami et al., 2000; Wilson & Adamec, 2001).

Focusing on the northern hemisphere one of the prominent and therefore best-studied patterns of atmospheric variability is the North Atlantic Oscillation (NAO). NAO has been linked to changes in phytoplankton biomass (Lindhal et al., 1998; Reid et al., 1998; Barton et al., 2003; Pingree, 2005), species composition (Irigoien et al., 2000) and toxic algal blooms (Belgrano et al., 1999). However, in a review of the ecological effects of NAO, Ottersen et al. (2001) comment on the lack of evidence supporting the hypothesis on the causal mechanisms of the NAO-phytoplankton relationships, pointing out the need for mechanism-oriented studies.

Here, we focus on surface chlorophyll-a concentration in the Mediterranean, in an effort to disentangle its relationship with climatic patterns and describe possible mechanisms. The general hypothesis is that large scale atmospheric phenomena affect chlorophyll concentration, by inducing changes in local weather patterns and oceanic features. Therefore, the hypothesis is tested and the subsequent variable selection is based on known links between chlorophyll concentration and oceanic/local weather patterns and between oceanic/local weather patterns and large-scale atmospheric patterns. The Mediterranean appears to be the perfect candidate for the study of the effect of large-scale atmospheric patterns on the spatiotemporal distribution of chlorophyll. Despite its prevailing oligotrophy, the Mediterranean supports a large biomass of marine organisms, due to oceanographic features that locally maintain high levels of primary productivity. Therefore, it is expected that a large proportion of the spatial and temporal variability of primary production will depend on changes in oceanic conditions rather than on biological interactions. Trophic conditions vary, from oligotrophic to mesotrophic. The known oligotrophy in the area and the prominent seasonal cycle in the forcing concur in creating a dynamical environment where physical processes play a crucial role in conditioning the ecosystem functions. Oceanic circulation is in turn dependent to a great extent on climate.

A climatological synopsis of the trophic response to physical forcing in the Mediterranean Sea is provided by Crise et al. (1998, 1999). Permanent cyclonic features located at the north-western Mediterranean and the Levantine, unstable coastal fronts and gyres along the Algerian current and coastal effects such as upwelling and coastal boundary currents are considered to be the prevailing processes, importing nutrients into the euphotic zone.

A number of mechanisms for how weather and oceanic variability might affect productivity in the Mediterranean have been suggested in the literature. At the same time, atmospheric patterns of a global or hemispheric scale have been associated with weather patterns and oceanic variability. Combinations of meteorological, oceanographic and biological studies can evoke interesting hypothesis about how teleconnection patterns could drive phytoplankton abundance and distribution in the Mediterranean. For example, winds influence primary productivity in the Mediterranean especially through wind-induced upwelling (Bakun & Agostini, 2001), while wind patterns and Mediterranean cyclone tracks are associated with the East Atlantic Jet (Barnston & Livezey, 1987), the Asian monsoon region (Raicich et al., 2003; Rodwell & Hoskins, 1996) and the North Atlantic Oscillation. These findings lead to the hypothesis that wind could be the link between large-scale atmospheric patterns and primary production.

Precipitation is also a candidate for explaining the influence of atmospheric patterns on primary production. Freshwater input has an overriding effect on the dynamics of the Mediterranean ecosystem; it affects mesoscale circulation, deep-water formation, exchanges with the Atlantic, atmospheric deposition and the input of materials from land (Paerl, 1985; Paerl et al., 1990; Rohling & Bryden, 1992; Béthoux & Gentili, 1996; Roether et al., 1996; Martin & Milliman, 1997; Özsoy & Saydam, 2000; Arhonditsis et al., 2002), which in turn determine primary production. Duarte et al. (1999) commented on the importance of rainfall and the occurrence of storms as factors influencing the ecosystem and proposed the association of storms with high discharge of suspended material, which leads to a deterioration in conditions for phytoplankton growth, as a possible mechanism. Precipitation is also one of the best-studied variables in relation to teleconnection patterns. For the Mediterranean, precipitation has been linked to the East Atlantic pattern (Rodriguez-Puebla et al., 1998; Wibig, 1999), the East Atlantic/Western Russian (EA/WR) pattern, the East Atlantic (EA) jet (Dünkeloh & Jacobeit, 2003) and the NAO (Hurrell, 1995; Moulin et al., 1997).

Variables describing oceanic status, such as SST and Sea Surface Height (SSH), have also been associated with primary productivity. SST has been employed numerous times in efforts to identify areas of elevated primary production such as fronts, gyres and upwelling (e.g. Su & Sheng, 1999; Demarcq & Faure, 2000; Shaw & Vennell, 2000; Somayajulu et al., 2003; Valavanis et al., 2004; Sokolov et al., 2006), because of the cold water signature of these features. SSH can be seen either as an indication of the thermocline depth or can be used to identify tidally-induced and large-scale ocean circulation features (currents, eddies) (Fu & Cazenave, 2000). Furthermore, wave intensity is considered to be important for the development of blooms (Marchetti, 1992; Cacciamani et al., 1992; Cebrian et al., 1996). The link between planktonic variation and that of sea level and wave action does not result from a direct cause-effect relationship, but rather through the influence of these climatic factors on the proximal factors, such as nutrient inputs and water column stability, influencing planktonic organisms (Duarte et al., 1999). Both SST and SSH are highly dependent on atmospheric variability. The EA/WR pattern exerts its influence on wave height in the western Mediterranean in winter (Galati & Lionello, 2007). EA is also strongly and negatively correlated with wave height. Teleconnections with the Indian monsoon have been reported to affect the meridional circulation over the Mediterranean, winds and wave height (Lionello & Sanna, 2005). Raicich et al. (2003) found a negative correlation between sea-level anomalies at coastal stations in the eastern Mediterranean and the Indian monsoon index, due to changes in the wind structure.

The aim of this study is to reveal which large-scale atmospheric patterns over the northern hemisphere drive chlorophyll-a distribution in the Mediterranean. Furthermore, the role of regional weather/oceanic circulation patterns is described and possible mechanistic links between climatic indices and chlorophyll-a concentration are tested.

Materials and methods

Monthly data on sea level atmospheric pressure (SLP), air temperature, wind speed, precipitation, sea surface temperature (SST), sea surface height (SSH), salinity and chlorophyll-a concentration were analysed. Their temporal extent and sources are listed in Table 1. The spatial extent for all the datasets is the Mediterranean with the exception of sea level pressure data that extend over the northern hemisphere. All datasets were processed and organized in a GIS database, using Arc Info routines (ESRI, 1994), as monthly grid maps. The average for each map point for each month was computed and subtracted from the equivalent monthly maps, in order to remove seasonality from the data. The resulting anomalies were organized in a matrix, for each variable, with each column representing a month and each row a map point, and the matrices were introduced into MATLAB. All the analyses described below are applied to the anomaly datasets.

In a first exploratory approach, maps of correlations between chlorophyll and each of the explanatory variables were produced by calculating the Pearson correlation coefficient, and corresponding *P*-values, between the time series of the anomalies at each map point. Maps of statistically significant correlation coefficients were produced. A more sophisticated method, namely Canonical Correlation Analysis (CCA), was employed to analyse the joint variability, pair-wise, between chlorophyll concentration and the explanatory variables. The analysis was applied to Empirical Orthogonal Functions (EOF) space as

Table 1 Datasets used, their units, resolution and sources

Parameter	Sensor/model	Units	Resolution	Source
Sea surface chlorophyll-a (CHLO)	SeaWiFS	mg/m^3	9 km	www.oceancolor.gsfc.nasa.gov
Sea level pressure (SLP)	NCEP/NCAR Reanalysis	Millibars	2.5°	http://www.cdc.noaa.gov/ http://www.cdc/data.ncep.reanalysis
Air temperature (AIR)	NCEP/NCAR Reanalysis	°C	2.5°	http://www.cdc.noaa.gov/ cdc/data.ncep.reanalysis
Precipitation (PRE)	CPC Merged Analysis of Precipitation (CMAP)	mm/day	2.5°	http://www.iridl.ldeo.columbia.edu
Sea surface temperature (SST)	AVHRR	°C	1.1 km	http://www.eoweb.dlr.de:8080
Sea surface wind speed (WS)	QSCAT	m/sec and degree from N	0.25°	http://www.ssmi.com
Mean sea level anomaly (MSLA)	Merged Jason-1, Envisat, ERS-2, GFO, T/P	cm	0.25°	http://www.jason.oceanobs.com
Sea surface salinity	CARTON-GIESE SODA and CMA BCC GODAS models	psu	0.5°	http://www.iridl.ldeo.columbia.edu

proposed by Barnett & Preisendorfer (1987). The Barnett Preisendorfer (BP-CCA) type CCA involves the application of an EOF analysis to the data prior to a classical CCA, and retaining only a few leading EOFs. The EOF analysis is in essence a type of filter that removes much of the small-scale noise. CCA is a long-standing multivariate statistical technique that finds linear combinations of two datasets of random variables, whose correlations are maximal (von Storch & Zwiers, 1999; Wikle, 2004). The aim of CCA is to identify and quantify the relationships between a p-dimensional variable X and a q-dimensional random variable Y. The tables of each variable were produced by sampling the grid cells of each map so that each table will be organized in space (columns) and time (rows). We look for linear combinations aT X and bT Y of the original variables, having maximal correlation. Expressed in mathematical terms, CCA seeks vectors *a* and *b* such that:

$$(a,b) = \arg\max_{a,b} |Corr(a^T X, b^T Y)|$$

The resulting univariate variables $U = aT$ X and V $= bT$ Y are then called canonical variates. Higher order canonical variates and correlations are defined as in the above equation, but now under the additional restriction that a canonical variate of order k, with $1 < k \leq \min(p; q)$, should be uncorrelated with all canonical variates of lower order.

Therefore, CCA results for each pair of variables comprise a number of canonical variates that explain a large percentage of the coupled variability of the two datasets analysed. Each pair of canonical variates is a spatial (visualized in a map) and a temporal (time series) pattern for each variable that is maximally correlated. In this analysis, one of the matrices is always chlorophyll-a concentration and the other is one of the atmospheric/oceanic variables listed in Table 1. Therefore a time series of chlorophyll-a concentration index associated with an environmental parameter is produced from each CCA, and time-series of chlorophyll-a concentration indices that explain a proportion of chlorophyll variability are produced from EOF analysis. Due to the different resolution of the data, the spatial patterns are more (finer resolution) or less (coarser resolution) detailed.

Cross correlation analysis (or Cross Correlation Functions—CCF) was applied to northern hemisphere teleconnection indices sourced from the NOAA/Climate Prediction Centre and the leading chlorophyll-a time series derived from the EOF analysis, in order to verify the CCA results. CCF is in essence the estimation of correlation coefficients between two time series at different time lags. The teleconnection indices were also correlated to chlorophyll-index time series derived through CCA. This analysis provided an insight into the relationship between atmospheric patterns and coupled modes of

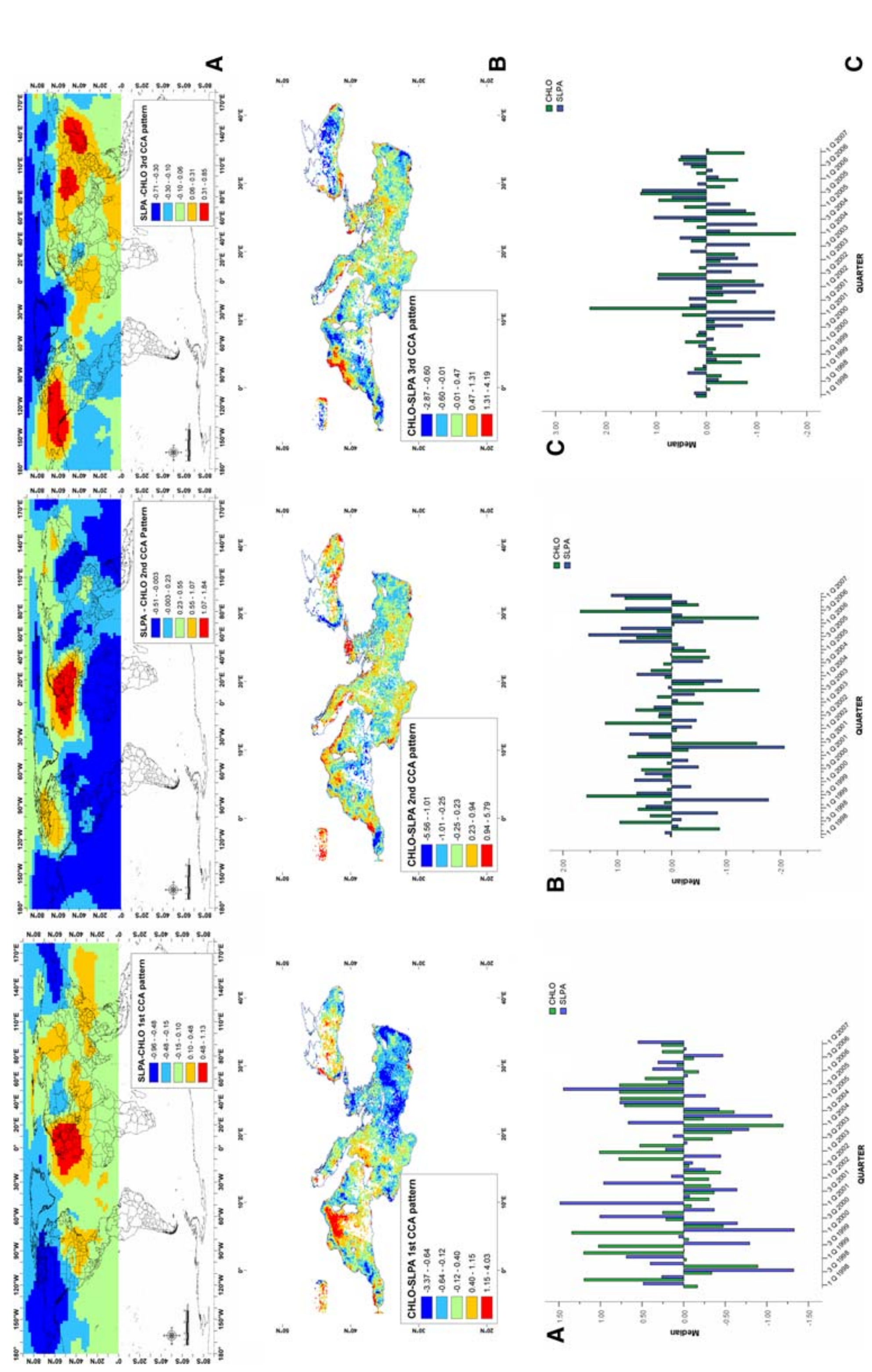


Fig. 1 Sea level pressure spatial patterns over the northern hemisphere, correlated to chlorophyll distribution in the Mediterranean (SLPA-CHLO) and Chlorophyll distribution patterns in the Mediterranean correlated to Sea Level Pressure spatial patterns over the northern hemisphere (CHLO-SLPA). Patterns were derived through Canonical Correlation analysis

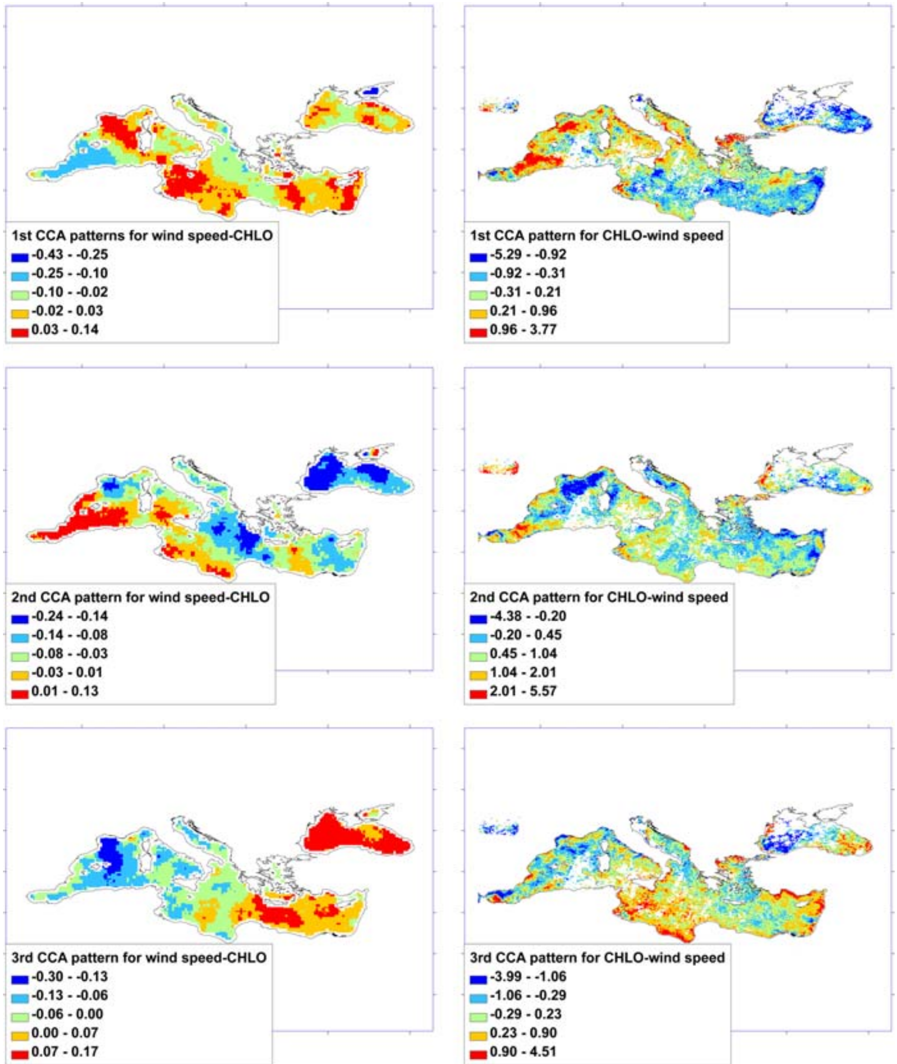


Fig. 2 Canonical pairs for wind speed and chlorophyll in the Mediterranean

variability for chlorophyll and led to the suggestion of various mechanisms that could potentially explain how large-scale atmospheric patterns influence chlorophyll distribution.

Climatic variations may take place at various spatial and temporal scales. Sometimes, the variations are due to oscillations which recur in periodic fashions. Cyclical patterns in the atmosphere might lead to cyclical variations in the ocean and vice versa. The analysis of such dependencies between two time series is the role of bivariate spectral analysis. Cross Spectral Analysis (CSA) was applied to detect common cycles between the chlorophyll-index time series derived from CCA and the northern hemisphere teleconnection indices. The purpose of CSA is to find out how the variability of the two time series is interrelated in the spectral domain; to determine the time scale at which the variability is related, as well as the characteristics of this co-variation. Thus, from cross spectral analysis, it is possible to obtain not only the coherence, which is the measure of correlation between two processes at each frequency, but also the phase spectrum, which measures the phase difference at each frequency.

Results

Correlation maps

Wind speed and precipitation present a positive correlation with chlorophyll-a while air temperature

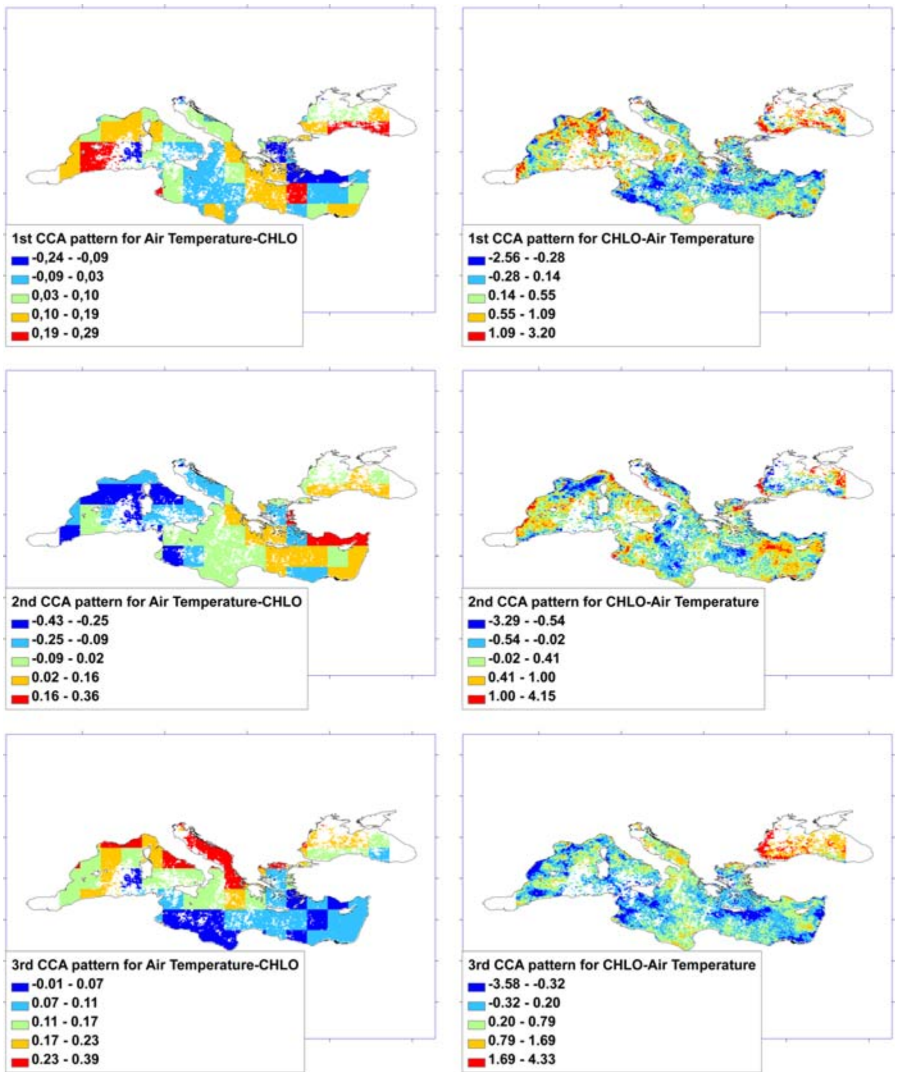


Fig. 3 Canonical pairs for air temperature and chlorophyll in the Mediterranean

presents a negative one. The relationship with SST is straightforward as well, with all statistically significant correlations being negative. However, the relationships become more complicated as we move to variables, such as SSH and salinity, that describe complex oceanic phenomena and features.

Canonical correlation analysis

Chlorophyll-a and sea level pressure over the northern hemisphere

For the first pair of canonical variates for SLP and chlorophyll, the SLP pattern for the northern hemisphere consists of a combination of the East Atlantic pattern (EA) and remnants of the East Atlantic/Western Russian pattern (EA/WR), both in their positive phases. The pattern dominating the Pacific sector probably represents the negative phase of the East Pacific/North Pacific pattern. The corresponding pattern for chlorophyll-a concentration in the Mediterranean reveals higher than average values for the western and central parts of the Mediterranean and lower for the eastern part. This pattern accounts for 12% of the variability of chlorophyll concentration in the Mediterranean. The second CCA SLP pattern for the northern hemisphere explains 9% of the variability of chlorophyll-a concentration and the major feature identified corresponds to the East Atlantic Jet, the third primary mode of low frequency variability

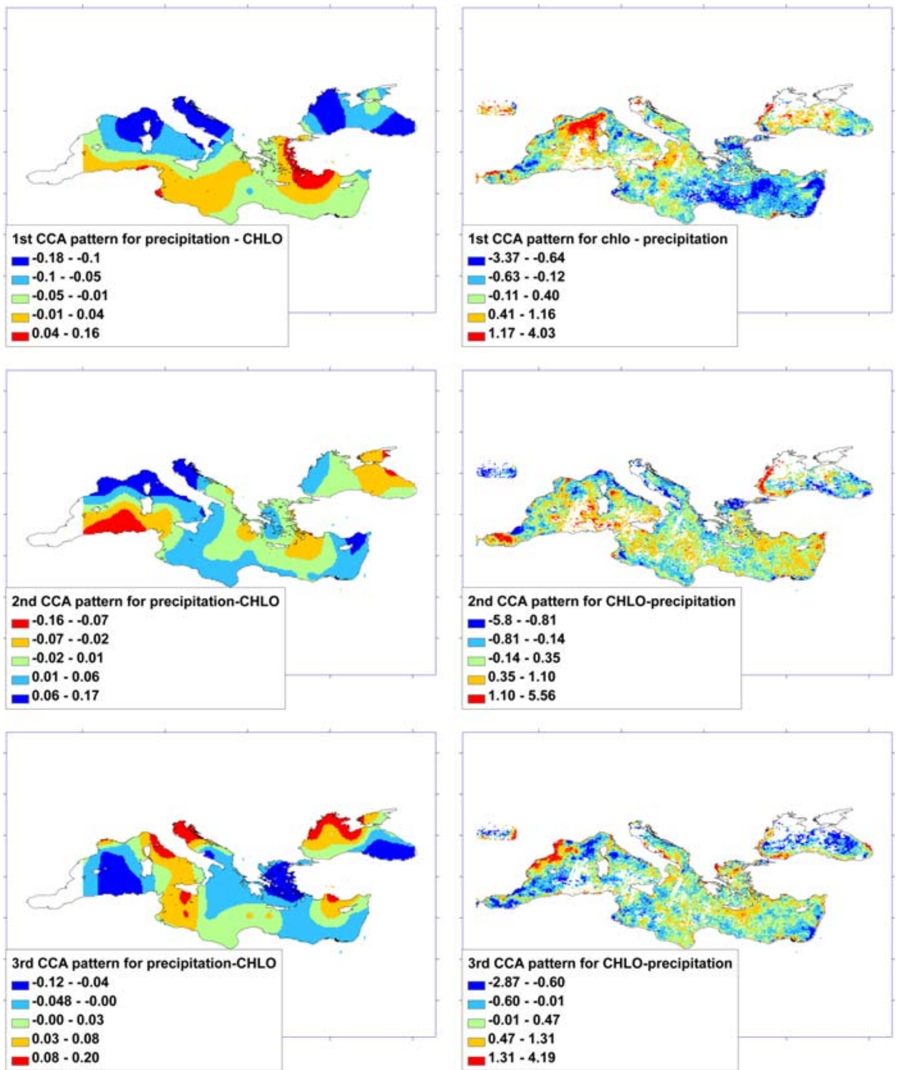


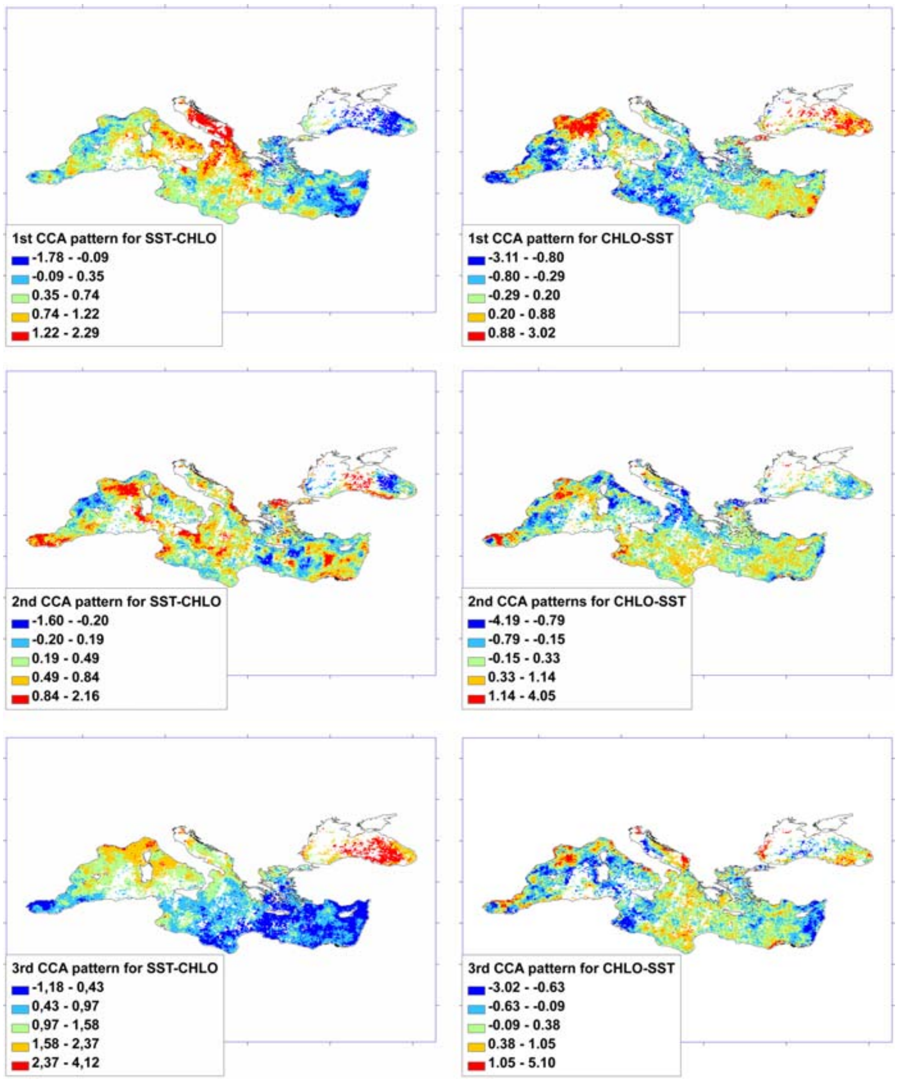
Fig. 4 Canonical pairs for precipitation and chlorophyll in the Mediterranean

found over the North Atlantic, in its negative phase. This pattern seems to positively influence chlorophyll in coastal areas of the Mediterranean; equivalently strong negative effects are observed near the strait of Gibraltar, the Balearic Sea and the Levantine. The third CCA spatial component for chlorophyll concentration (7.3% of variation explained) reveals localized correlations. The corresponding SLP CCA component can be interpreted as remnants of the North Atlantic Oscillation (NAO; positive phase) and the Mediterranean Oscillation (MO), which is related to the larger pattern of the NAO. Remnants of what could be interpreted as the Polar/Eurasian (POL) and the East Pacific/North Pacific (EP/NP) patterns can also be identified (Fig. 1).

Chlorophyll-a and wind speed

A see-saw between the western part of the basin (positive values) and the central-eastern part (negative values) shapes the first CCA component for wind speed. The corresponding pattern for chlorophyll shows enhanced concentrations in most areas. The second pair of canonical variates shows a 'wave' form, i.e. an alternation of positive and negative centres with an east-west direction, for wind speed, inducing higher than average chlorophyll concentrations in the west and lower in the east. Two areas of opposite signs are identified for the third CCA mode for wind speed, with the negative values over the western part and the positive ones over the eastern

Fig. 5 Canonical pairs for sea surface temperature and chlorophyll in the Mediterranean



part of the basin. This pattern seems to have a negative effect on chlorophyll concentrations for the north-western Mediterranean and positive for the south-central and eastern parts of the basin (Fig. 2).

Chlorophyll-a and air temperature

For the first pair of canonical variables a ‘wave’ form dominates the air temperature spatial pattern, while the corresponding chlorophyll pattern shows mostly negative anomaly values for the central and eastern Mediterranean (Fig. 3). The second CCA component for air temperature is a dipole between west (negative) and east (positive) that induces local influences on chlorophyll-a concentration. A dipole between north (positive values) and southwest (negative values) constitutes the air temperature pattern of the third pair of canonical variables and is associated with large areas of negative values for chlorophyll.

Chlorophyll-a and precipitation

The CCA results for chlorophyll and precipitation show higher than average values of chlorophyll in the western Mediterranean and lower than average values in the eastern part for the first pair of variates. The corresponding precipitation pattern reveals two major poles, a negative one over the central-north Mediterranean and a positive one over the eastern-north Mediterranean (Fig. 4). The second CCA spatial

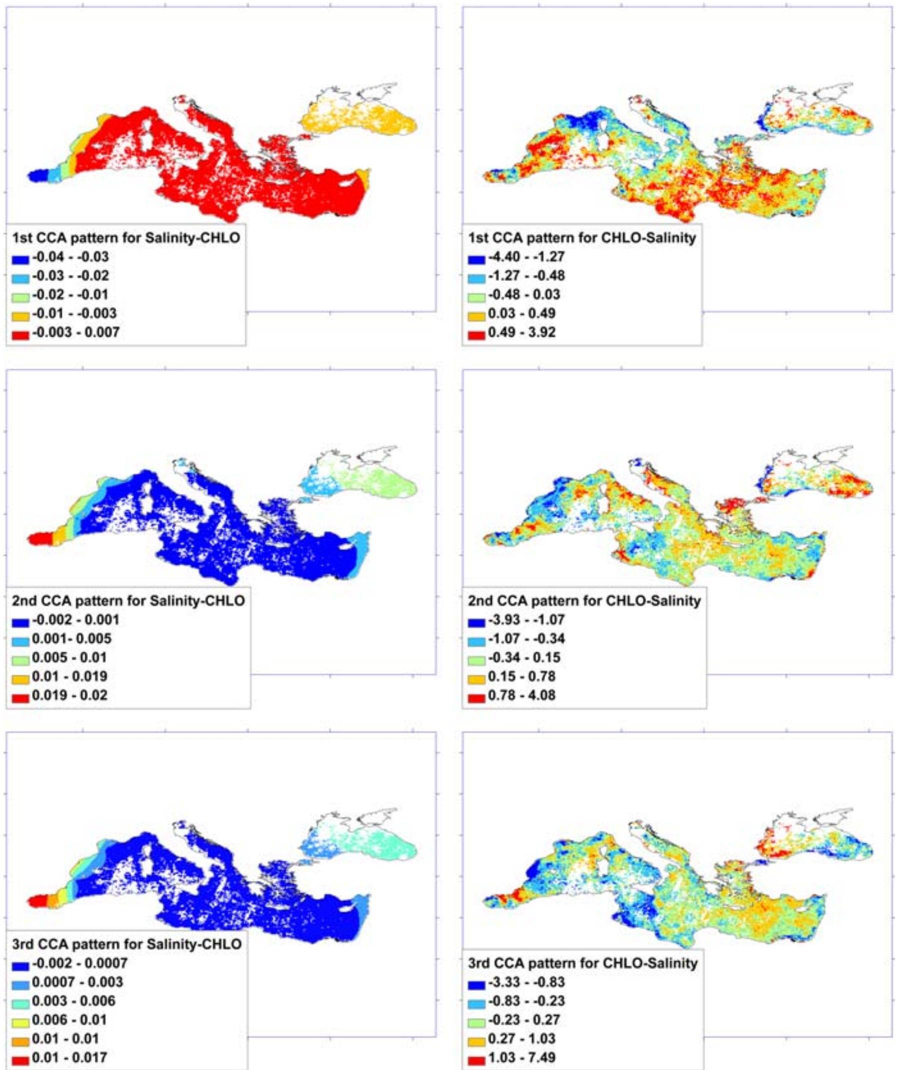


Fig. 6 Canonical pairs for salinity and chlorophyll in the Mediterranean

pattern reveals a positive precipitation pole over north-west Mediterranean and a negative one for the south-western part. This pattern is correlated with lower than average chlorophyll concentration in northern regions and positive anomaly values in southern regions. The third spatial pattern for precipitation has a ‘wave’ form with an east-west direction and affects chlorophyll mostly in the western part of the Mediterranean.

Chlorophyll-a and sea surface temperature

Higher than average temperatures for the central part of the Mediterranean and lower values for the eastern comprise the first CCA mode for SST (Fig. 5). This pattern seems to affect mostly the western part of the basin as well as some small areas in the Levantine with higher than average chlorophyll concentrations. Low chlorophyll values are observed in the western part of the Alboran Sea, around the Balearic Islands and in the Sea of Sicily. In the second CCA component, SST represents mesoscale patterns. Negative chlorophyll concentration values are observed in the Adriatic, the northern Aegean and the western Mediterranean. A dipole between the northwest (positive) and southeast parts of the Mediterranean basin characterizes the third spatial pattern for SST and has diverse effects on chlorophyll in different areas.

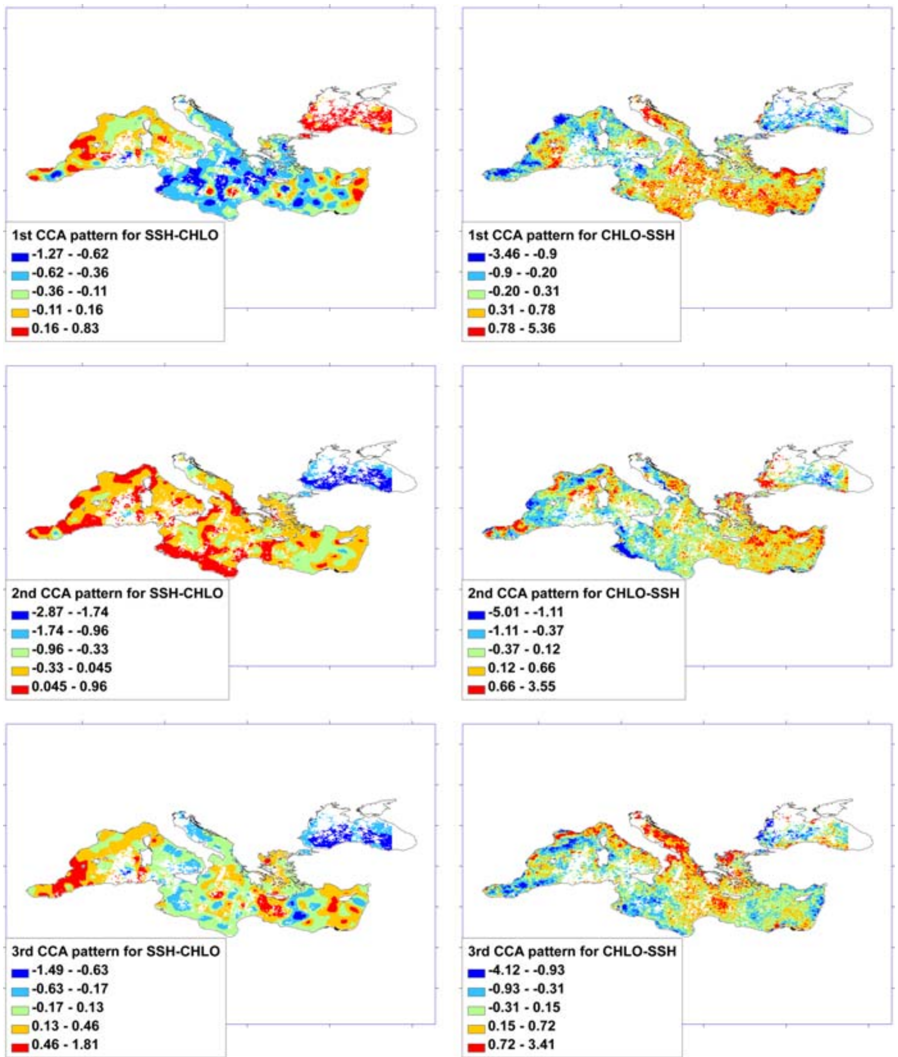


Fig. 7 Canonical pairs for sea surface height and chlorophyll in the Mediterranean

Chlorophyll-a and salinity

A positive anomaly value centre, stretching from the Balearic Islands to the Libyan sea, and a negative gradient of salinity stemming from the Atlantic are the dominant patterns in the first salinity CCA pattern (Fig. 6). A similar salinity pattern, but with opposite signs, appears in the second CCA component. The third CCA component shows a similar pattern of salinity to the second, with the negative centre displaced to the north. The effect on chlorophyll is local.

Chlorophyll-a and sea surface height

Higher than average SSH values are observed, in the first SSH CCA component, for the western Mediterranean and in particular for the path taken by the northern current (Fig. 7). However, negative values are also observed for the central-south and eastern Mediterranean with the exceptions of two cyclonic features offshore Libya and another meso-scale feature located near the eastern Levantine coasts, probably the Shikmona gyre. Negative chlorophyll anomalies are located in the western part of the basin and positive values in the central and eastern parts. For the second pair of canonical variables, higher than the average SSH values are observed mainly along the south coasts of the basin and at the western edge of Crete. The western sub-basin and the eastern part of the mid-Mediterranean jet present lower than average SSH values. Positive values in the Alboran Sea and for locations characterized by cyclonic circulation in the Levantine, and negative anomalies for areas of anticyclonic circulation in the Levantine comprise the second spatial pattern for chlorophyll. The pattern of the third pair of variates for chlorophyll shows higher than average values for the central Mediterranean and the coasts of the Greek mainland. The opposite sign is observed for the western part of the basin. The corresponding SSH pattern reveals mesoscale eddies.

Time series analysis

Cross correlation functions

Statistically significant correlations between chlorophyll indices, derived from the CCAs, and the teleconnection indices for the northern hemisphere are estimated with CCF. SST-related chlorophyll indices appear to have the highest number of significant correlations followed by SSH-related chlorophyll indices. The most frequent time lags at which the correlations are statistically significant are 0 months for EA, PNA and POL, 2 for SCA and WP and 8 for NAO and EA/WR. Only PNA presents time lags of more than 2 years and only SCA does not present time lags of more than one year. Among the chlorophyll indices, precipitation-related ones appear mostly in correlations at lag 4, air temperature- and salinity-related at lag 2, and SSH-, SST- and WS-related at 0 lag.

The EA pattern is correlated with WS- and SST-related chlorophyll indices, at different time lags, 0 and 20 months, respectively. The WP and POL patterns are associated with SST-related chlorophyll indices at lag 2, while correlations with the NAO and PNA are estimated for almost all the CCA-derived chlorophyll indices at varying time lags, the most frequent ones being from 0 to 8 months.

Spectral analysis

The spectral analysis showed statistically significant correlations between chlorophyll-a EOF patterns and the EA, EA/WR, NAO and POL teleconnection indices as well as PNA and WP, from the Pacific sector. The periods of the common cycles extend from 2 months to more than a decade and their time intervals from 0 to 13 years. As for the correlation with the CCA-derived chlorophyll indices, the EA pattern has common cycles with WS-related chlorophyll, the EA/WR with precipitation-related chlorophyll, and the NAO with salinity- and SSH-related chlorophyll indices. PNA, SCA and WP also correlate with SSH-related chlorophyll indices. Tables 2 and 3 present the statistically significant correlations, the frequency/period of the common cycles and the phase/time interval between them.

Discussion

The East Atlantic pattern, the East Atlantic/Western Russian pattern, the North Atlantic Oscillation and the East Atlantic Jet and the Mediterranean oscillation, appear to be the most important climatic patterns of the northern hemisphere driving chlorophyll-a variability in the Mediterranean.

The first pair of CCA patterns between chlorophyll and sea level pressure over the northern hemisphere reveals a dipole for chlorophyll, which could be interpreted either as an opposite/delayed effect of an external forcing on the western and eastern sub-basins or as an interaction between the two sub-basins. It could thus be hypothesized that chlorophyll-a distribution is linked to a phenomenon that ‘moves’ from west to east (or vice versa). Storm/precipitation tracks that move from the Atlantic to eastern Mediterranean are such a phenomenon and, what is more, they are known to be regulated by the East Atlantic and the EA/WR patterns, the two dominant patterns seen in the SLP map of this first CCA pair of variates. Both patterns have been related to the transport of air masses from the Atlantic to the Eastern Mediterranean with a positive effect on precipitation of the EA in the western Mediterranean and a negative effect of the EA/WR on the eastern part of the basin. This hypothesis is further supported by the results of spectral analysis that suggest wind speed as the link between EA and chlorophyll and precipitation as the link between EA/WR and chlorophyll. A see-saw between east and west and what was described as a ‘wave’ in the results, namely alternation of positive and negative centres, also appear in wind speed, air temperature and precipitation CCA patterns, which further supports the above-mentioned hypothesis.

The third CCA pattern of chlorophyll associated with SLP is related to the North Atlantic Oscillation.

Table 2 Spectral analysis results between teleconnection indices (1st column) and chlorophyll indices derived from CCA for chlorophyll and wind speed (WS), precipitation (PRE), surface air temperature (AIR), sea surface temperature (SST), surface salinity (SAL) and sea surface height (SSH) (2nd column). Numbers in parenthesis indicate the rank of the CCA pattern

Teleconnection index	CCA of CHLO with:	Coherency	Frequency	Phase	Period	Time interval
EA	WS(1)	0.81	0.39	1.20	2.56	0.49
EA	WS(3)	0.80	0.05	0.00	20.00	0.00
EA/WR	PRE(1)	0.80	0.00	0.00	10,000	0.00
EA/WR	PRE(3)	0.82	0.50	3.00	2.00	0.95
EP/NP	AIR(3)	0.83	0.40	0.80	2.50	0.32
EP/NP	SST(1)	0.80	0.00	3.00	0.00	0.00
NAO	SAL(2)	0.90	0.27	0.03	3.70	0.02
NAO	SSH(1)	0.88	0.02	1.00	50	7.96
PNA	SSH(1)	0.90	0.45	2.50	2.22	0.88
PNA	SSH(2)	0.90	0.18	1.50	5.56	1.33
POL	AIR(2)	0.83	0.48	2.70	2.08	0.90
POL	SSH(3)	0.85	0.00	3.00	10,000	4774.65
POL	SST(2)	0.82	0.05	0.20	20	0.64
POL	WS(2)	0.80	0.40	2.80	2.50	1.11
SCA	SSH(1)	0.80	0.01	0.00	100	0.00
WP	SSH(1)	0.80	0.13	2.00	7.69	2.45

Table 3 Spectral analysis results between teleconnection indices (1st column) and chlorophyll indices derived from EOF analysis (2nd column)

Teleconnection index	Chlorophyll EOF index	Coherency	Frequency	Phase	Period	Time interval
EA	7	0.79	0.30	0.00	3.33	0.00
EA/WR	9	0.78	0.20	2.00	5.00	1.59
NAO	3	0.79	0.35	3.00	2.86	1.36
NAO	8	0.79	0.16	1.50	6.25	1.49
PNA	10	0.78	0.20	0.00	5.00	0.00
PNA	3	0.81	0.00	1.00	1,000	159.15
POL	10	0.80	0.23	3.00	4.35	2.08
POL	6	0.77	0.49	3.00	2.04	0.97
POL	8	0.80	0.36	0.00	2.78	0.00
POL	9	0.80	0.38	2.80	2.63	1.17
SCA	6	0.80	0.36	2.80	2.78	1.24
WP	10	0.77	0.05	0.20	20.00	0.64

NAO seems to be affecting areas of wind-induced upwelling and gyre formation. Chlorophyll patterns suggest that upwelling, probably induced by the westerlies along the northern coasts of the Mediterranean, are favoured during the positive NAO phase, leading to higher chlorophyll values. Other studies have shown that the EA/WR pattern often comes hand in hand with the NAO in regulating atmospheric phenomena and oceanic features in the Mediterranean (Rodríguez-Puebla et al., 2001). Below-normal precipitation over most of the Mediterranean region, with lowest values along the western coasts of the peninsulas and highest in the south-eastern part of the basin, correlates with NAO/AO and EA/WR and the northward shifts of storm tracks from the Mediterranean towards western and northern Europe that produce the dryness over the Mediterranean (Xoplaki et al., 2004). It is therefore probable that abrupt changes in wind and precipitation intensity are mechanisms through which large-scale atmospheric patterns disturb the mean status of chlorophyll concentration in the basin. The spectral analysis results also show EA and EA/WR patterns influencing chlorophyll through wind speed and precipitation at small time lags.

The second chlorophyll CCA pattern associated with SLP is a north—south dipole. This can be ascribed to changes in the inflow of Atlantic water through the strait of Gibraltar, which affect the southern part of the basin, or to the presence of strong westerlies that could affect both the currents carrying the Atlantic water and the upwelling forming along the northern coasts. The East Atlantic jet is the teleconnection pattern correlated with chlorophyll in this case. Its positive phase is associated with strong westerlies over Europe, and the negative phase with long-lived blocking anticyclones in the vicinity of Greenland and Great Britain. It is related to Mediterranean cyclone tracks in summer, which are mostly arranged from the western basin towards the Black Sea (Alpert et al., 1990; Trigo et al., 1999) and has been linked to summer precipitation in the northern Mediterranean (Dunkeloh & Jacobeit, 2003). It can therefore be concluded that the East Atlantic jet affects chlorophyll concentration through changes in wind and wind-induced circulation patterns.

Considering weather patterns, in general the CCA results reveal a combination of local and large-scale events influencing chlorophyll-a concentration. Local effects tend to produce positive correlations and can be attributed to the supply of nutrients through rainfall. On the other hand, negative correlations occur due to large scale weather and climatic patterns. The results also suggest that strong winds and rainfall might have a direct negative effect to phytoplankton growth, due to causing turbulence in the water column, but they favour chlorophyll concentration in the long run by importing nutrients into the euphotic zone.

The areas that are most affected by the atmospheric and oceanic regime are either coastal or areas of known upwellings such as the northwest coasts, the Alboran Sea, regions characterized by the influences of the inflow of water from the Atlantic and the southern coasts of Turkey, where the system is dominated by changes in the mid-Mediterranean jet and the Levantine Intermediate Water. The north Aegean, one of the most productive parts of the Mediterranean, also appears to be affected by the atmosphere mainly due to changes in the inflow of water from the Black Sea and from rivers.

The time series analysis on the other hand stresses the importance of sea surface temperature and sea surface height, as links between atmospheric patterns and chlorophyll. When SST is the intermediate link between chlorophyll and the atmosphere, the significant time lags are more than a year which could imply changes in the circulation regime. The inflow of water from the Atlantic, currents such as the Algerian current and the Asia Minor Current, and gyres located mainly in the Levantine, appear in the leading CCA patterns for the pairs Sea Surface Temperature—Chlorophyll and Sea Surface Height—Chlorophyll.

Patterns from the Pacific sector also produce significant correlations with chlorophyll, probably because they are related to other atmospheric patterns over Europe and the Atlantic or to ENSO-monsoon teleconnections that affect the eastern Mediterranean.

These analyses provide a reasonable means to generate hypotheses linking phytoplankton and climate-dependent physical factors. Nevertheless, conclusions based on relatively short time series are speculative and must be interpreted cautiously (Barton et al., 2003).

When CCA is applied on EOF space the amount of variability explained by the correlation between the variables depends on the amount of variability explained by the EOF. The small portion of chlorophyll variability captured by the EOF analysis, along with the patchiness of the spatial patterns derived for chlorophyll, depicts the unique characteristics of each area and the importance of local features. However, the results of this study suggest that some of the major features affecting chlorophyll concentration and distribution in the Mediterranean are driven by large-scale atmospheric patterns, and provide a basis to speculate on possible mechanisms. The role of precipitation and wind as links between large-scale atmospheric phenomena and mesoscale changes in chlorophyll concentration is pointed out, whereas oceanic variables such as SST and SSH seem to be influencing chlorophyll in different ways and according to each area's specific features. At the same time the complex nature of this system is inferred; more than one parameter affects chlorophyll simultaneously with a very diverse pattern as a result. In addition, relationships between biological indices and environmental factors tend to be non-linear, an aspect that was not considered in this analysis but is a subject for future studies. Lastly, much information can be derived from the seasonal component of the datasets. Seasonality is of utmost importance for the Mediterranean and incorporating it in the analysis would result in higher percentages of the variability being explained. However, the aim of this study was not to describe seasonal fluctuations but to see how the regime of chlorophyll is disturbed due to atmospheric forcing.

A number of known teleconnection patterns have been suggested to play some role in changes of the spatiotemporal patterns of chlorophyll-a in the Mediterranean. The prominent mechanism pertains to large-scale patterns causing air mass movements from the Atlantic to the Eastern Mediterranean that in turn affect oceanic features related to higher primary production.

Future work will focus on different spatial scales, in order to acquire information on how local characteristics interact with large-scale features, and on non-linear relationships between chlorophyll and atmospheric patterns. The complexity of the data suggests that different mechanisms of atmospheric forcing act on different areas at different temporal and spatial scales.

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