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Long-term variability of the South Adriatic circulation and phytoplankton biomass in relation to large-scale climatic pattern

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Abstract

The interannual variability of the South Adriatic Gyre and its relation to the wind vorticity and the large-scale climatic pattern (North Atlantic Oscillation – NAO), was studied using the time-series of satellite altimetry data and ocean surface wind products. The cyclonic circulation observed in the South Adriatic area was mainly sustained by the local wind forcing, as suggested by the positive correlation between the rate of change of the current vorticity and the wind-stress vorticity. Nevertheless, the influence of vorticity advection from the adjacent area (North Ionian Sea) cannot be ignored and it is more significant during the anticyclonic phase of Adriatic–Ionian Bimodal Oscillation System. The geostrophic current vorticities of the South Adriatic and North Ionian Seas are correlated with a time lag of 15 months, which corresponds to an advection speed of $\sim 1\,\mathrm{cm\,s^{-1}}$. The different wind patterns observed during the two NAO phases revealed a stronger positive vorticity during the negative NAO phase. Conversely, during the positive NAO phase the wind vorticity is characterized by lower positive values. Subsequently, the calculated positive linear correlation between the NAO index and the frequency of the cold and dry northerly wind suggests the strengthening of the winter convection, and of the consecutive deep water formation, during the positive NAO phases. As a consequence of the winter deep convection, Southern Adriatic area is characterized by the late winter/early spring algal blooms. Relationship between the spatially averaged surface chlorophyll concentrations and the northerly wind frequencies revealed that the two biological productivity regimes likely exist: the subtropical one and the subpolar one depending on the frequency of windy days. We also showed that the bloom timing is a linear function of the wind frequency and can vary within the range of almost two months. This study thus contributes to our understanding of the possible impact of climate change on the SAG circulation and its ecosystem.

OSD
12, 203–226, 2015

1 Introduction

The Adriatic Sea is a source of the Adriatic Dense Water (ADW), the main component of the Eastern Mediterranean Dense Water (EMDW). The dense water formation in the Adriatic Sea takes place both in the North Adriatic shelf area (Hendershott and Rizzoli, 1976) and in the South Adriatic Pit (SAP), in the center of the permanent topographically trapped South Adriatic Gyre (SAG), through two different processes. In the North Adriatic, the dense water is formed over the large northern shelf area through winter cooling and mixing, while in the South Adriatic the dense water is formed via open-ocean convection mechanism (Gačić et al., 2002; Manca et al., 2002) which occurs under the action of cold and severe northerly winds, more specifically the ENE or NE bora wind associated with the persistent synoptic condition and orographic configuration (Grisogono and Belušić, 2009). Major contribution to the outflowing AdDW comes from the water formed in the SAP (∼ 90 %) (Vilibić and Orlić, 2001) and it presumably varies on interannual scale (Mihanović et al., 2013). The estimated total average rate of the dense water formation/outflow from the Adriatic is 0.3 Sv (1 Sverdrup (Sv) = 1 000 000 $m^3 s^{-1}$) (Lascaratos, 1993). Obviously, this estimate is an average value and the formation rate is subject to pronounced interannual and decadal variability. Decadal variability is presumably linked to the buoyancy variations related to the import of intermediate and surface waters of varying salinity from the Ionian as associated to Adriatic–Ionian Bimodal Oscillating System (BiOS) (Gačić et al., 2011). On the other hand, interannual variability in the dense water formation rate is due to the combination of two factors: winter air–sea heat flux and the intensity of the SAG. Variations in the strength of the SAG result in changes of the vertical distribution of isopycnals and in general in changes of the doming shape of the physical and biogeochemical interfaces.

Winter convective mixing in south Adriatic was shown to be the main triggering factor for spring phytoplankton bloom and its interannual variability (Gačić et al., 2002). While vertical mixing in the upper layer can increase productivity through enhanced nutrient supply from deep layer, it can also decrease or retard the productivity when stronger and more persistent wind events induce a phytoplankton mixing over a larger depth range, i.e. below Sverdrup's critical depth (Moline and Preìzelin, 1996; Dutkiewicz et al., 2001). Indeed, mixing related to stratification and de-stratification is a key physical process which can control the timing and magnitude of blooms (Sverdrup, 1953; Xu et al., 2012). Gačić et al. (2002) showed that the primary production and phytoplankton biomass were strongly reduced in years with mild winter climatic conditions. Santoleri et al. (2003) on the basis of three years of data (1998, 1999 and 2000), presented evidences that the interannual variability of phytoplankton bloom could be reproduced taking into considerations not only the convective penetration depth but also the extent of the mixing rate. Convection depth and mixing rate modulated the nutrients supply in the euphotic layer. The authors conclude that in South Adriatic two biological productivity regimes exist, subtropical and subpolar, in function of the intensity and rates of the vertical mixing.

The aim of this paper is to study the interannual variability of the SAG intensity, i.e. the vorticity of the flow field in the South Adriatic, to relate it to the vorticity inputs (from wind and advection), and then to large-scale climatic regime (NAO index will be considered). Subsequently, the dependence of the northerly winds responsible for the winter convection, on the NAO will also be studied. Finally, a possible relationships between climatic forcing and the phytoplankton biomass, as well as with the timing of bloom onset will be analysed.

2 Data and methods

The wind products used in this study were the Cross-Calibrated, Multi-Platform (CCMP) ocean surface wind velocity, downloaded from the NASA Physical Oceanography DAAC for the period July 1987–December 2011 (Atlas et al., 2009). These products were created using a variational analysis method to combine wind measurements derived from several satellite scatterometers and micro-wave radiometers. The CCMP six-hourly gridded analyses (level 3.0, first-look version 1.1, resolution of 25 km), were used to quantify the vertical component of the wind-stress curl $[\mathrm{curl}\tau]_z$ over the Mediterranean Sea:

$$[\mathrm{curl}\tau]_z = \frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}; (\tau_y, \tau_x) = \rho C_\mathrm{D}(u_w, v_w) U_{10} \tag{1}$$

where (τ_x, τ_y) are the wind-stress components, ρ ($1.22\,\mathrm{kg\,m^{-3}}$) is the density of air, (u_w, v_w) and U_{10} are the components and the magnitude of the wind speed at 10 m, respectively, and C_D is the drag coefficient which has been obtained according to Yelland and Taylor (1996).

$$\begin{aligned}
C_\mathrm{D} &= 10^{-3} && |U_{10}| \leq 3\frac{m}{s} \\
C_\mathrm{D} &= \left(0.29 + \frac{3.1}{U_{10}} + \frac{7.7}{U_{10}^2}\right) \times 10^{-3} && 3\frac{m}{s} \leq |U_{10}| \leq 6\frac{m}{s} \\
C_\mathrm{D} &= (0.6 + 0.07 U_{10}) \times 10^{-3} && 6\frac{m}{s} \leq |U_{10}| \leq 26\frac{m}{s}
\end{aligned} \tag{2}$$

The vorticity associated with the surface geostrophic circulation in the SAG and in the northern Ionian was estimated using the gridded (1/8° Mercator projection grid) Ssalto/Duacs weekly, multi-mission, delayed time (quality controlled) products from AVISO (SSALTO/DUACS users handbook 2014). Absolute geostrophic velocity (AGV) data, derived from the satellite absolute dynamic topography (ADT) through geostrophic balance equations, were downloaded for the 1992–2014 period. The ADT is the sum of sea level anomaly and synthetic mean dynamic topography, estimated by Rio et al. (2014), over the 1993–2012 period. The delayed time product used in this work was based on two satellites (Jason-2/Altika or Jason-2/Cryosat or Jason-2/Envisat or Jason-1/Envisat or Topex-Poseidon/ERS) with the same ground track. This data series was homogeneous all along the available time period, thanks to a stable sampling. The relative vorticity (ζ) of the AGV data was evaluated as the vertical com-

OSD
12, 203–226, 2015

L. Shabrang et al.

ponent of the velocity field curl (Pedlosky, 1987):

$$\zeta = \frac{\partial v_g}{\partial x} - \frac{\partial u_g}{\partial y} \tag{3}$$

Where (u_g, v_g) are the components of the AGV.

The monthly NAO index used in this work was obtained from the National Weather service, Climate Prediction Center of NOAA (National Oceanic and Atmospheric Administration). The procedures used to identify the NAO index was the Rotated Principal Component Analysis (RPCA) (Barnston and Livezey, 1987). The RPCA procedure is superior to grid-point-based analyses, typically determined from one-point correlation maps, in that the teleconnection patterns in the RPCA approach are identified based on the entire flow field, and not just from height anomalies at selected locations (http://www.cpc.ncep.noaa.gov/data/teledoc/nao.shtml).

Monthly means of the wind-stress curl and of the geostrophic current vorticity fields were spatially averaged in the region of the SAG and in the northern Ionian (areas of averaging are shown in Fig. 1). Time series of these spatially averaged parameters were filtered using a 13 months moving average, in order to remove the seasonal and intra-annual variations and focus on the interannual fluctuations.

In order to assess the influence of the NAO phases on the wind-stress vorticity in the SAG, the spatial distributions of wind velocities field over the winter months, from January to March (hereafter we refer to this time period as JFM), and of the relative wind-stress curl were estimated separately for the years characterised by the positive and negative phases of the JFM NAO index (NAO+ and NAO−, respectively). Then, the speed and direction of the wind and the strength of the vorticity in two wintertime NAO phases were studied and compared.

Since the northerly cold and dry continental air outbreaks are the essential factor in the vertical mixing in the South Adriatic Sea, its correlation with the NAO index can represent a connection between the large-scale atmospheric pattern and the deep water formation (and the primary production) in the SAG. Spatial distribution of the

OSD
12, 203–226, 2015

correlation coefficient between NAO index and the frequency of the northerly winds (2nd and 3rd quadrants) in winter months (January to March) was thus estimated. Only northerly winds with speed larger than 1 m s^{-1} were taken into consideration.

Daily chlorophyll concentration products delivered by the Ocean Colour Climate Change Initiative (OC_CCI) project version 1.0 (http://www.esa-oceancolour-cci.org/) were used to obtain a consistent time-series of surface chlorophyll concentration in the South Adriatic for the period from January 1998 to May 2012. All the available data were spatially averaged over the area delimited by latitude of 41.15 and 42.24° N and longitude of 17.27 to 18.44° E (Fig. 1). A visual control allowed to ensure that this spatial domain encompasses all the South-Adriatic biomass patches which slightly move from year to year. Then, for each year, the starting date of the first bloom was determined using a threshold method (Siegel et al., 2002; Racault et al., 2012), as follows. First, annual time-series were filtered using a moving average with a 9 day window. Then, we have looked for the last date, before annual maxima, when chlorophyll concentration was lower than a defined threshold. The date of this event was considered as the starting date of the bloom. The threshold was defined as the 0.7 quantile of the annual chlorophyll distribution. This algorithm succeeded in identifying the starting date for the bloom in 11 cases out of 14. Failures in years 2000, 2001 and 2011, were explained by the absence of clear spring chlorophyll peak in the annual time-series, and they were excluded from subsequent analyses. Correlation between phenological parameters and the northerly wind frequencies was done comparing the average phytoplankton biomass for February, March and April with the average wind frequency for January, February and March. We thus implicitly assumed that the wind contributes to the mixing and the phytoplankton bloom in a period preceding and partially overlapping the bloom onset period. In addition, for this purpose we considered the 5 m s^{-1} wind speed threshold assuming that wind speeds lower than the threshold are weakly efficient in generating the vertical mixing.

OSD
12, 203–226, 2015

3 Results and discussion

The different terms of the vorticity equation were analysed in order to evaluate the various sources of current vorticity. Following Ezer and Mellor (1994) and Schwab and Beletsky (2003) current vorticity equation can be written as:

$$\frac{\partial \zeta}{\partial t} = -\mathrm{curl}\left(\frac{A}{D}\right) - \mathrm{div}(fv) - \frac{1}{\rho_0}\mathrm{curl}\left(\frac{1}{D}\nabla\Phi\right) + \mathrm{curl}\left(\frac{\tau_s}{\rho_0 D}\right) - \mathrm{curl}\left(\frac{\tau_b}{\rho_0 D}\right) \tag{4}$$

where ζ is current vorticity, A is advection and diffusion, D is total water depth, ρ_0 is the reference density, Φ is the potential energy, f is Coriolis parameter, v is current velocity, and τ_s and τ_b are wind-stress and bottom stress, respectively. Since we assume the barotropic flow, the internal pressure gradient (the third term on the right) can be negligible. We also ignore the bottom stress.

If we separate the current velocity into geostrophic and ageostrophic parts and consider the non-divergence of the geostrophic current, we will have:

$$V = V_g + V_a; \quad \zeta = \zeta_g + \zeta_a \tag{5}$$

$$\mathrm{div}(fV) = f\left(\frac{\partial u_a}{\partial x} + \frac{\partial v_a}{\partial y}\right) = \frac{f}{D}\left(\frac{\mathrm{d}h}{\mathrm{d}t}\right) \tag{6}$$

Replacing the Eqs. (5) and (6) in Eq. (4) and neglecting the diffusion A as well as bottom stress and divergence ($\frac{f}{D}(\frac{\mathrm{d}h}{\mathrm{d}t})$ which is two orders of magnitude smaller than rate of change of the vorticity) implies:

$$\frac{\partial(\zeta_g + \zeta_a)}{\partial t} = -(V_g + V_a)\cdot\nabla(\zeta_g + \zeta_a) + \frac{1}{\rho D}\mathrm{curl}(\tau_s) \tag{7}$$

Since $\frac{|V_a|}{|V_g|} = \frac{|\zeta_a|}{|\zeta_g|} \sim O(Ro) = O(\frac{U}{fL}) = 10^{-2}$ $(U \sim 10^{-1}\,\frac{m}{s},\ L \sim 10^5\,m,\ f \sim 10^{-4}\,s^{-1})$, the ageostrophic parts vanish and finally we obtain the current vorticity equation:

$$\frac{\partial \zeta_g}{\partial t} = -V_g \cdot \nabla(\zeta_g) + \frac{1}{\rho D}\mathrm{curl}(\tau_s) \tag{8}$$

OSD
12, 203–226, 2015

Calculations of the spatially averaged current vorticity (Fig. 2b) show that the South Adriatic was characterized, as expected, by a permanent positive vorticity since the SAG is a cyclonic circulation feature. Nevertheless, prominent interannual or decadal variability was present in the time-series (Fig. 2). The interannual variability prevailed in both wind-stress curl and current vorticity in the South Adriatic (Fig. 2a and b), while decadal variability was prevalent in the vorticity field of the northern Ionian (Fig. 2c). In fact, the vorticity field in the northern Ionian is mainly subject to decadal variability due to BiOS (Gačić et al., 2010) as opposed to the Adriatic current vorticity and the wind-stress curl. This latter one was positive for the major part of the record with only short periods of negative values. Therefore, considering the current vorticity Eq. (8), interannual variability of the intensity of the geostrophic cyclonic circulation in the South Adriatic can only partly be explained in terms of the local wind vorticity input. Thus in addition to the local wind curl effect, the vorticity advection from adjacent area should be taken into consideration. The vorticity in the northern Ionian was analysed in order to estimate the vorticity advection through the Strait of Otranto.

First we compared the low passed (seasonal signal filtered out) time-series of the time-derivative of current vorticity with the curl of the wind-stress calculating the linear correlation coefficient in each data point of the study domain. The spatial distribution of the correlation coefficient over the study area shows that the maximum positive correlation coincided rather well with the center of the SAG, i.e. with the minimum of the sea level height (Fig. 3). This suggests that the Ekman suction controls the strength of the SAG determining the valley in the center of the gyre. Therefore, in accordance with the quasi-geostrophic equation of the vorticity conservation, the most important mechanism responsible for the variations of the current vorticity is the wind-stress curl.

In order to study whether possibly the vorticity advection from the Ionian plays a role in controlling the curl of the flow in the South Adriatic, we calculated the lagged correlation between the spatially averaged vorticity in the northern Ionian and South Adriatic (see Fig. 1 for the averaging areas). The correlation between the Adriatic and Ionian flow vorticities reached maximum for the Adriatic vorticity lagging the Ionian one by about 15 months, which corresponds to the advection speed of $1\,\mathrm{cm\,s^{-1}}$, rather reasonable values (Fig. 4). We thus conclude that, apart from the wind curl input, the vorticity advection from the Ionian may contribute to variations of the intensity of the SAG. It is interesting to note that the correlation between the wind-stress curl, i.e. the local vorticity input, and the current vorticity was apparently stronger in the period 1997–2006 than in the rest of the studied period. This can be explained by the fact that the period 1997–2006 was characterized by the cyclonic phase of BiOS in the Ionian and in that case the vorticity advection term was proportional to the differences between absolute values of the Adriatic and Ionian vorticities. Before 1997 and after 2006 the Ionian was characterized by the anticyclonic circulation mode and the vorticity advection term was proportional to the vorticity sum. Therefore, in the Ionian cyclonic circulation phase the local input, i.e. the wind-stress curl, has a prevailing effect on the current vorticity and thus the correlation between the two is stronger. On the other hand, in the BiOS anticyclonic phase the vorticity advection term may become significant and probably of comparable importance as the wind-stress curl. Consequently, the correlation between the flow vorticity tendency and wind-stress curl is weaker.

In order to relate the interannual variability of the wind-stress curl to the large climatic system we compared time-series of the low-passed NAO index (13 month moving average) with the wind-stress curl, calculating the correlation coefficient between the two time-series in each point of the study area for the period 1988–2011 (Fig. 5a). Previous research showed that the correlation between the wind speed and NAO in the Adriatic was practically null (Pirazzoli and Tomasin, 2003). Considering however the wind-stress curl, the results revealed negative correlation between the wind-stress curl and NAO for the major portion of the open Adriatic Sea: NAO index negative values were concomitant with maximum wind-stress curl, and conversely minima of the wind-stress curl were associated with NAO maximum values. Spatially, the area of the maximum absolute value of the correlation between the wind-stress curl and NAO coincided with the area where we observed the highest correlation between the current vorticity tendency and the wind-curl (compare Figs. 3 and 5a).

OSD
12, 203–226, 2015

South Adriatic Gyre and phytoplankton variations

L. Shabrang et al.

During the positive NAO phase, north-westerlies are dominant in southern Europe and Mediterranean Sea as the result of the enhancement of the Icelandic Low as well as of the Azores High. Conversely, in the negative phase, the intensification of the westerlies is observed in these regions (Jerez et al., 2013). More specifically, depending on the phase of NAO, the pressure gradient over the North Atlantic changes in the magnitude and orientation which causes the differences in the speed and direction of winds in mid latitudes (Lamb and Peppler, 1987). In agreement with Trigo et al. (2002), the local maximum of the wind vorticity were present in the southern Adriatic Sea during both positive and negative NAO phases. The positive winter NAO indices were followed by strong northwesterly winds over the Mediterranean, which is the consequence of the intensification of the high pressure over the Mediterranean region (Fig. 6a). This configuration resulted in a rather weak low over the southern Adriatic and a weakening of the cyclonic vorticity. On the contrary, during the negative NAO periods rather strong northward atmospheric flow along the eastern coast of the southern Adriatic was observed, reinforcing the wind-stress curl (Fig. 6b).

Therefore, we can say that the large-scale climatic conditions associated with a positive NAO phase weaken the positive wind-stress curl, while the low or negative wind-stress curl is related to the high or positive NAO index. The wind-stress curl, on its turn, prevailed in determining the current vorticity tendency in the central part of the southern Adriatic. The correlation between the NAO index and the frequency of the northerly wind clearly divides the Adriatic Sea into two parts with opposite behaviour: positive correlations occurred in the South Adriatic, whereas negative correlation were observed north of 43° N (Fig. 5b). Assuming that the winter convection is dictated mainly by the northerly winds, we can conclude that in the period of high and/or positive NAO values the winter convection is at its maximum and vice versa. This is opposite to what happens in the Northern Adriatic.

Convection and mixing are the most important drivers for bloom's developments. In a stratified ocean, nutrients are mainly concentrated below the surface euphotic zone. Therefore, phytoplankton growth occurs only if vertical exchanges are sufficiently strong to inject nutrients in the surface layer. Nutrient availability in surface layer is then primarily driven by the vertical mixing (William and Follows, 2003). Since the northerly cold and dry continental air outbreaks are the essential factor in the vertical mixing in the SAP, possible correlation of the spring phytoplankton biomass with the climatic conditions in the SAP were considered.

Frequency of days with northerly wind having an average speed higher than 5 m s^{-1} in the period January–March, and the average chlorophyll concentration in the period February–April for the SAG area (Fig. 1) were calculated. Their dispersion diagram (Fig. 7a) shows that for relatively low northerly wind frequencies (up to 20 %) the phytoplankton biomass increased almost linearly with the wind frequency. For higher wind frequencies, the diagram appears more dispersed, however suggesting a decreasing trend of biomass with the wind frequency. The high dispersion of data points for wind frequencies up to 20 % stresses the complexity of the bloom which is impacted in this case by numerous factors like the light and nutrient availability or the zooplankton grazing pressure whereas one can assume that for wind frequencies lower than 20 % the main factor limiting phytoplankton bloom is the nutrient availability. That could explain the lower dispersion of data points. Nevertheless, the negative trend for high frequencies of northerly wind events, may be an indication that in the SAG, as suggested by Santoleri et al. (2003) two regimes for phytoplankton bloom exist as a function of the wind frequency and of the mixed layer depth; i.e. the subtropical and the subpolar regime. More detailed analysis which will include the mixed layer depth is necessary in order to check this hypothesis. So far, we have only shown that there is no univocal relationship between the wind and the surface phytoplankton biomass. In addition to the relationship between the average chlorophyll data and the northerly wind frequency, we have looked for the dependence of the timing of the bloom and the percentage of windy days. Several papers showed for various parts of the ocean that the wind plays an important role in determining the timing of the spring bloom (Yamada and Ishizaka, 2006; Collins et al., 2009). Moreover, it was shown that other physical forcing like the solar irradiance through cloud cover are of a secondary importance for the spring bloom timing. Our results for the southern Adriatic (Fig. 7b) indeed show that there was a linear increase of the bloom timing with the frequency of the northerly winds. The bloom initiation is retarded by about two months for an increase of the northerly wind frequencies of about 20 %. This means that contrary to the biomass, the timing of the spring bloom can be considered a univocal function of the climatic conditions giving some elements for further studies of the impact of climate change on the SAG ecosystem.

4 Conclusions

Intensity of the SAG shows prominent intra-annual and interannual variability. In this paper its interannual variability was analyzed using the surface geostrophic current vorticity. Possible local forcing is sought considering the wind-stress curl in the area of the South Adriatic, while advective contributions were looked for in the vorticity from the adjacent area, i.e. the northern Ionian. The large-scale climatic conditions were presented by the NAO index and the wind curl variations were related to them. Correlation between the wind-stress curl and the geostrophic vorticity tendency (low-pass monthly data, seasonal signal removed) shows that the correlation reaches maximum in the centre of the SAG coinciding with the sea level minimum. We thus conclude that the current vorticity was partially induced by the local wind vorticity input. The fact that direct forcing from the wind-stress curl is the dominant mechanism determining the vorticity of the mean circulation pattern was evidenced for a number of large lakes (Schwab and Beletsky, 2003). Subsequently, the moving correlation between the current vorticity in the northern Ionian, possible source area, and in the South Adriatic shows that the vorticity variations in the Adriatic lag those in the Ionian by about 15 months. This suggests that the advection speed is about 1 $\mathrm{cm\,s^{-1}}$. The importance of the advective term in the vorticity equation depends on the BiOS circulation mode. It was evidenced that in the BiOS cyclonic phase the main vorticity input into the SAG comes from the wind-stress curl although we cannot exclude completely the advection term. In the anticyclonic phase the advective vorticity inputs from the Ionian become

OSD
12, 203–226, 2015

more important. Comparison between the NAO and the wind-stress curl shows that in both positive and negative NAO phases cyclonic atmospheric circulation is dominant, but higher vorticity in the wind field coincides with low NAO, and conversely smaller values of the wind-stress curl are concomitant with positive NAO values. This was explained in terms of the prevailing atmospheric flows over the larger Mediterranean area suggesting that the interannual variations of the strength of the SAG are associated with the large-scale climatic variations via the wind-stress curl forcing. The frequency of the northerly wind during the winter is positively correlated with the NAO index in the South Adriatic Sea, while it is out of phase in the North Adriatic. More frequent southerlies during the negative phase of NAO over the South Adriatic Sea results in the lower frequency of the bora wind. In contrary, the positive NAO phase is associated with the intensification of the northerly winds bringing dry and cold air from the Balkan peninsula and consequently stronger winter convection which implies the reinforcement of the deep water formation. Phytoplankton biomass as a function of wind does reveal the existence of the two regimes in the SAG, while the timing of the bloom is a linear function of the wind frequency. Due to the increased wind frequencies the bloom can retard up to two months. These results thus show that the timing is a function of the northerly winds and probably of the large-scale climatic systems.

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OSD
12, 203–226, 2015

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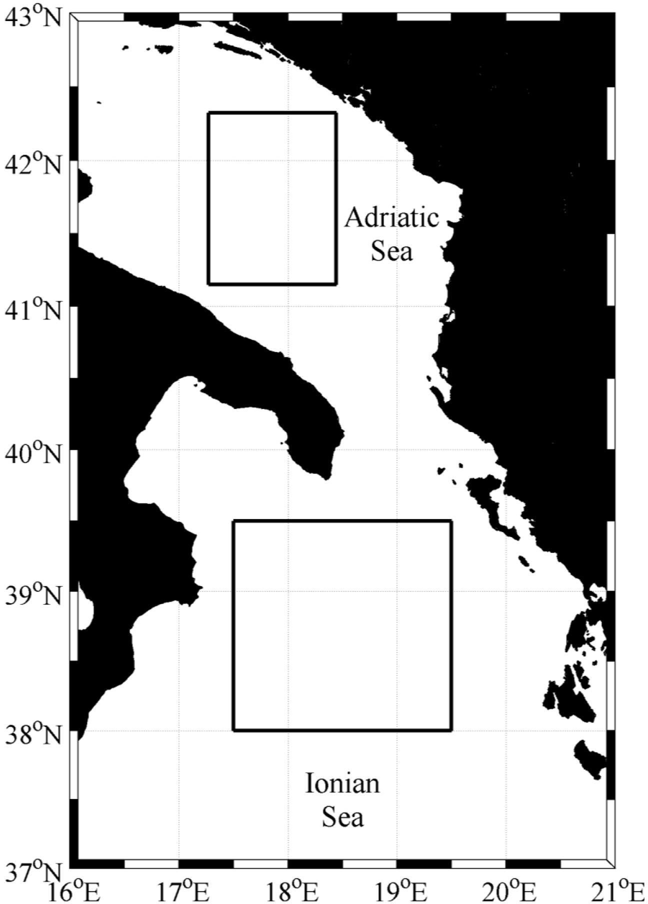

Figure 1. Geography of the South Adriatic and North Ionian Seas. The black squares show the areas used to estimate the time-series in Fig. 2. Also, the annual average chlorophyll values for the Adriatic were obtained from the same domain.

OSD
12, 203–226, 2015

South Adriatic Gyre and phytoplankton variations

L. Shabrang et al.

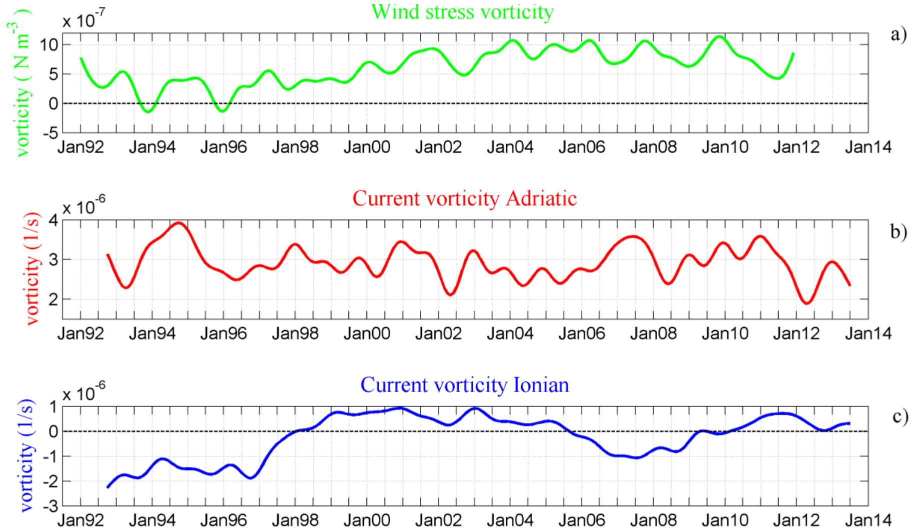

Figure 2. Time-series of the spatially averaged, low pass filtered (thirteen months), wind-stress vorticity **(a)** and current vorticity **(b)** in the Adriatic Sea, computed over the domain denoted in Fig. 1. Time-series of the low pass filtered current vorticity in the Ionian Sea **(c)** spatially averaged over the domain presented in Fig. 1.

OSD
12, 203–226, 2015

South Adriatic Gyre and phytoplankton variations

L. Shabrang et al.

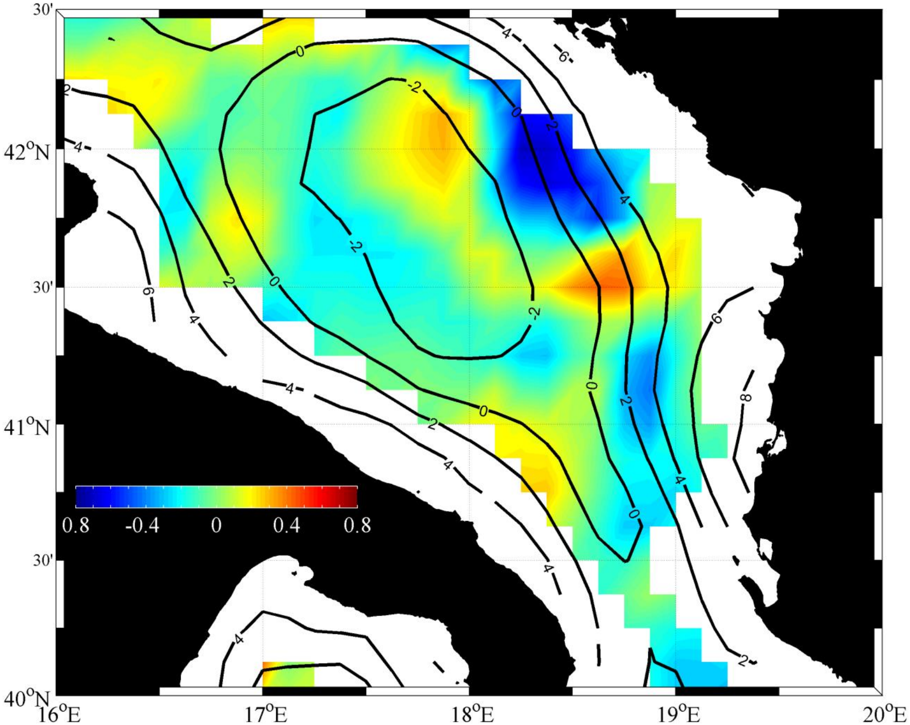

Figure 3. Spatial distribution of the correlation coefficient between the time derivative of the low-passed flow vorticity and the wind-stress curl for the period 1993–2011 (colours); black contours outline the 20 years average of the sea level height (cm).

OSD
12, 203–226, 2015
South Adriatic Gyre and phytoplankton variations
L. Shabrang et al.

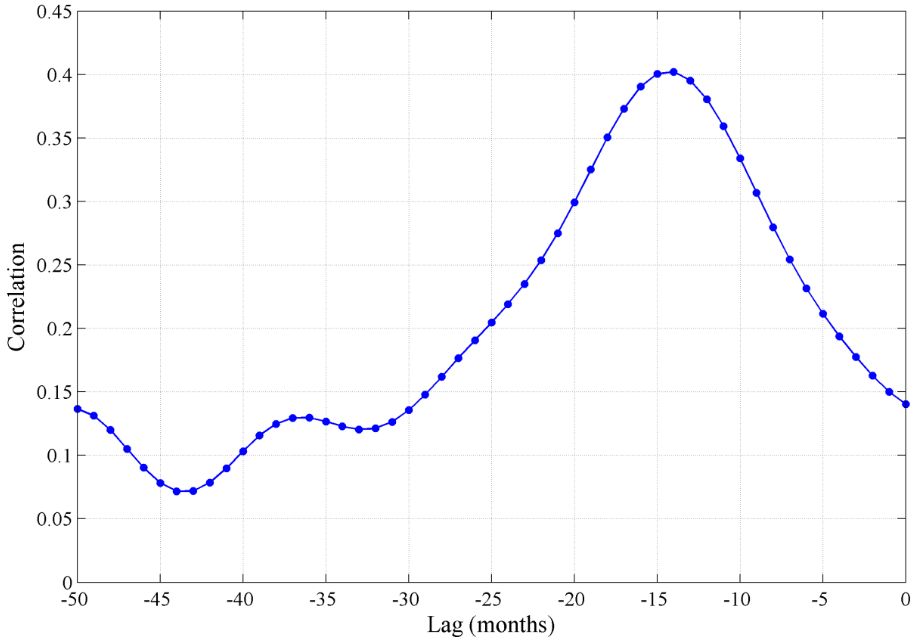

Figure 4. Correlation between the time-series of the low passed current vorticity in the Adriatic (Fig. 2b) and Ionian Sea (Fig. 2c).

OSD
12, 203–226, 2015

South Adriatic Gyre and phytoplankton variations

L. Shabrang et al.

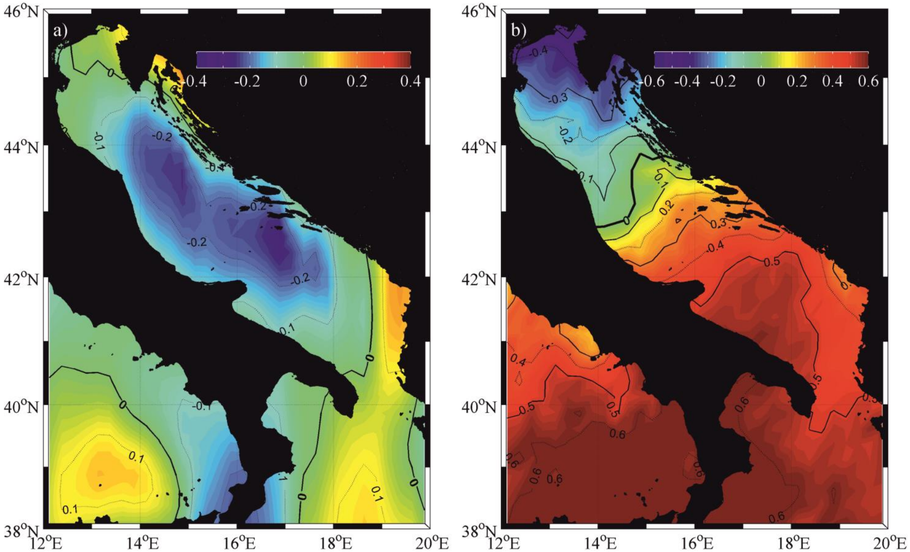

Figure 5. Spatial distribution of the correlation coefficient of **(a)** the low passed filtered NAO index and wind-stress vorticity, and **(b)** JFM NAO index and the frequency of northerly winds, 1988–2011. The black solid line indicates the 0 correlation.

OSD
12, 203–226, 2015

South Adriatic Gyre and phytoplankton variations

L. Shabrang et al.

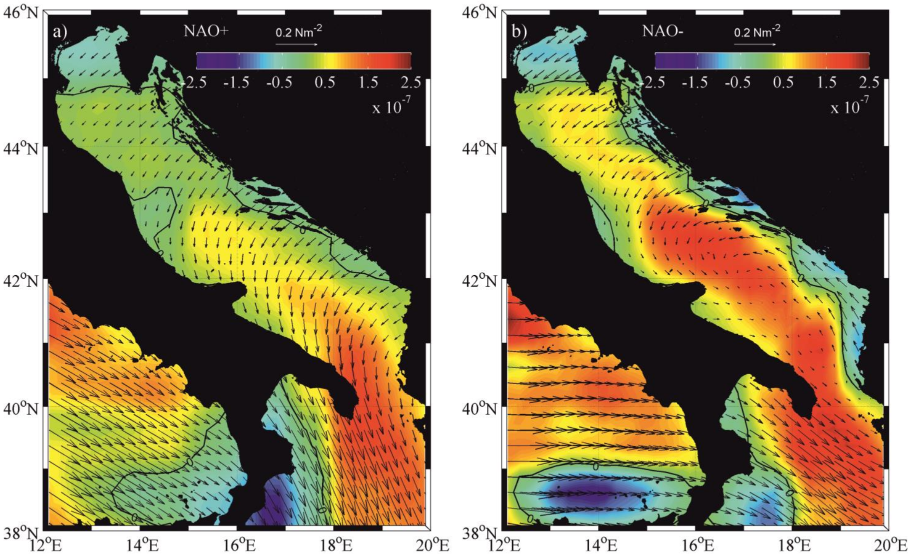

Figure 6. Spatial distribution of the mean JFM wind-stress vorticity (colours; Nm^{-3}) and wind-stress vectors (arrows; Nm^{-2}) in the positive NAO phase **(a)** and negative NAO phase **(b)**, 1988–2011.

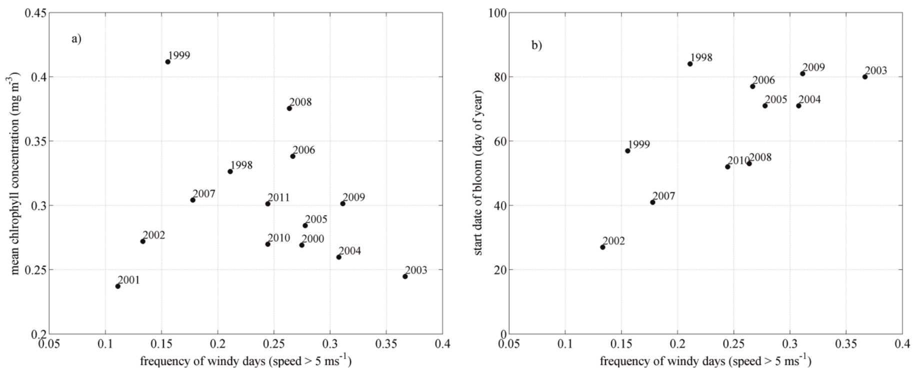

Figure 7. (a) Mean chlorophyll concentration during the February-March-April period against frequency of winter days (January-February-March) with a northerly wind speed exceeding $5\,\mathrm{m\,s^{-1}}$. **(b)** Start date of the bloom (day of year) against frequency of winter days with a northerly wind speed exceeding $5\,\mathrm{m\,s^{-1}}$. Chlorophyll and wind speed data were spatially averaged over the South Adriatic domain displayed in Fig. 1. The methodology used to determine the start date of the bloom is described in Sect. 2.

OSD
12, 203–226, 2015

South Adriatic Gyre and phytoplankton variations

L. Shabrang et al.