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Can internal processes sustain reversals of the ocean upper circulation? The Ionian Sea example

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[1] In 1997 an inversion in the Ionian upper-layer circulation was documented and ascribed to a massive inflow of Aegean dense waters associated with the Eastern Mediterranean Transient (EMT) and not to the wind-stress (Borzelli et al., 2009). Here we generalize the concept hypothesizing that such inversions are possible even in the absence of the Aegean influence. Indeed, salinity and density data collected in the Southern Adriatic, the main source of the Eastern Mediterranean deep water, show decadal variations coherent with changes in the sea level height in the northern Ionian. Scaling considerations suggest that the redistribution of Ionian water masses, resulting from changes in the thermohaline properties of waters entering the basin, can sustain inversions of the upper-layer circulation. Therefore, we propose a feedback mechanism (named the Adriatic-Ionian Bimodal Oscillating System – BiOS) between variations in the thermohaline properties of waters formed in the Southern Adriatic and the Ionian circulation. **Citation:** Gačić, M., G. L. E. Borzelli, G. Civitarese, V. Cardin, and S. Yari (2010), Can internal processes sustain reversals of the ocean upper circulation? The Ionian Sea example, *Geophys. Res. Lett.*, *37*, L09608, doi:10.1029/2010GL043216.

1. Introduction

[2] The contribution of internal oceanic processes (baroclinic sources and column stretching due to vertical movements of interfaces) in modifying the upper-layer vorticity of the oceans is often neglected in favor of the wind effect. However, in semi-enclosed, stratified basins, like the Mediterranean, these effects can be as important as, or even more important than, the wind stress in determining the circulation [i.e., *Strub and Powell*, 1986; *Malanotte-Rizzoli and Bergamasco*, 1991].

[3] The Ionian Sea (Figure 1), the deepest regional sea of the Mediterranean, plays an important role in the intermediate and deep thermohaline cell of the Eastern Mediterranean (EMed) conveyor belt. Dense and oxygenated waters, mainly of Adriatic origin, spread into the Ionian bottom layer, whilst the intermediate layer is influenced by salty and warm waters coming from the Levantine and Aegean basins. Through the Sicily Strait, the relatively fresh water of Atlantic origin (Modified Atlantic Water - MAW) enters the Ionian, propagates toward the Levantine basin and, occasionally, bifurcates northward. Therefore, the Ionian circulation plays an important role in the redistribution of the different water masses to adjacent seas.

[4] From the first basin-wide oceanographic cruise in the Ionian Sea performed in 1987, *Malanotte-Rizzoli et al.* [1997] traced the intrusion of MAW from the Sicily Strait that formed a broad anticyclonic meander influencing the entire basin. The primary Levantine Intermediate Water (LIW) pathway was westwards, while a secondary one followed the eastern flank toward the Otranto Strait. In 1991, experimental data show that the entire northwestern Ionian was occupied by an anticyclone, broader and stronger than in 1987, with MAW influence being felt over the basin interior. The flow along the eastern coastline towards the Otranto Strait was completely absent [*Malanotte-Rizzoli et al.*, 1999]. In 1997 the Northern Ionian upper-layer circulation reversed from anticyclonic to cyclonic and *Vigo et al.* [2005] hypothesized that this circulation reversal could be associated with variations in the deep and intermediate water mass distributions.

[5] During the 1990s, the area of the Mediterranean deep water formation switched from the Southern Adriatic to the Cretan Sea. This change is known as the Eastern Mediterranean Transient (EMT). Massive outflow of Cretan Sea Outflow Water (CSOW) from the Aegean at an average rate of 1.0 Sv caused changes to occur not only in the deep layers but over the entire water column [*Roether et al.*, 2007]. *Borzelli et al.* [2009] showed that the reversal of the Ionian upper-layer circulation in 1997 was not sustained by wind stress as it took place in the presence of an anticyclonic wind field. The authors proposed that it was associated with the filling up of the Ionian bottom layer with the CSOW following the EMT.

[6] In the second half of the 20th century, from long-term oceanographic time-series, several high-salinity events in the Adriatic Sea were documented and explained in terms of the intensification of the water exchange between the Ionian and the Adriatic [*Vilibić and Orlić*, 2001, and references therein].

[7] Here we present salinity and density data, collected in the Southern Adriatic in the period 1986–2008, evidencing decadal high-salinity events. Concurrently, by means of remotely sensed Sea Level Anomaly (SLA) data spanning the period 1993–2008, we document inversions of the Ionian basin-scale surface circulation taking place over the same time scale. Comparing the rate of change of the vorticity and the source of vorticity due to the wind stress we show that variations in the Ionian circulation are effectively driven by internal oceanic processes, which can outweigh wind stress. These processes are proposed to be the result of a feedback mechanism between the redistribution of water masses, related to variations in the thermohaline properties

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Figure 1. The Mediterranean Sea. The area in the Southern Adriatic where the mean temperature and salinity over the 200–800 m layer were calculated is represented with a red rectangle. The continuous red line in the Ionian delimits the area where the average rate of change of geostrophic vorticity and the vertical component of the wind-stress curl were calculated. Black squares represent areas used for calculations of meridional geostrophic current components.

of the Southern Adriatic, and inversions of the Ionian circulation. Associated with the Ionian cyclonic or anticyclonic circulation, the alternate advection into the Adriatic of saltier water from the Aegean/Levantine basin or fresher water of Atlantic origin modifies the thermohaline properties of the Adriatic. These modifications are hypothesized to induce redistribution of water masses in the Ionian capable of sustaining the reversals of the upper-layer circulation. The described mechanism is hereinafter referred to as the Adriatic-Ionian Bimodal Oscillating System (BiOS).

2. Data and Methods

[8] We used CTD data from 39 cruises carried out between 1985 and 2008 in an area of 1°lat × 1°long centered on 41.75°N, 17.75°E in the Southern Adriatic Pit (Figure 1, red rectangle). We took into account all stations deeper than 1000 m. From all the profiles available, an average value together with its standard deviation was calculated for the layer between 200 m and 800 m.

[9] Remotely sensed data consisted of weekly SLA objective maps over the region 33–42°N, 15–24°E in the period January 1993–December 2008, extracted from the merged altimetric delayed-time Mediterranean data set [*Ducet et al.*, 2000].

[10] The wind speed data at 10 m above the mean sea level for the period Jan. 1985–Dec. 2008, sampled with a spatial resolution of 0.25° × 0.25°, were obtained from the European Centre for Medium Range Weather Forecast (ECMWF) operational reanalysis data set. An area covering the EMed (10E–37E and 30N–47N) was extracted from the data set. The wind stress components were calculated from the average monthly wind data as $(\tau_x, \tau_y) = \rho \cdot C_D \cdot (u,v) \cdot \sqrt{u^2 + v^2}$ where ρ is the air density, $C_D = 1.25 \times 10^{-3}$ the drag coefficient and u and v are zonal and meridional wind velocity components.

3. Results and Discussion

[11] The occurrence of the upper-layer cyclonic or anticyclonic circulation in the Ionian very likely has an important impact on the water masses that enter the Adriatic and thus on the thermohaline properties of water masses formed in the Southern Adriatic (Figure 1). In this area in winter, vertical mixing takes place and thus the average water column thermohaline properties represent an integrated response to the advected signal. In agreement with previous studies [*Vilibić and Orlić*, 2001], salinity and density in the Southern Adriatic show decadal variations (Figure 2a). The question to be addressed here is to what extent such changes can be associated with variations in the upper-layer Ionian circulation. To characterize the sense and the intensity of the circulation pattern in the Ionian, we discuss the average SLA distributions. As in fall the water exchange between the Ionian and Adriatic reaches its maximum [*Gačić et al.*, 2001], and thus the advected signal from the Ionian should be the most prominent, we chose the interval October, November and December to calculate the average SLA patterns. In addition, the meridional surface geostrophic current component in the northwestern Ionian for each autumn was calculated from the SLA differences between the two 3 × 3 pixel areas (1 pixel = 0.125 degrees) as shown in Figure 1.

[12] In Figure 2a, we show that surface flow in the northwestern Ionian co-varies with the density of water masses formed in the Southern Adriatic. High density of the Southern Adriatic water masses corresponds with the positive meridional current component in the northwestern Ionian reflecting anticyclonic upper-layer circulation. Vice-versa, the low Adriatic water density coincided with the negative meridional surface geostrophic current in the northwestern Ionian suggesting the cyclonic circulation.

[13] Now we will interpret salinity and density variations in the Adriatic in terms of the reversals in the Ionian upper-layer circulation. In 1994, the anticyclonic gyre was well apparent being extended over a major portion of the northern Ionian (Figure 2b). The anticyclonic circulation advected low salinity water (MAW) into the Adriatic, as it is evident from the salinity decrease showed in Figure 2a. The anticyclonic circulation started to weaken in 1995 (Figure 2c), and in 1998 a fully developed basin-wide cyclonic circulation was evident (Figure 2e). Concurrently, the salinity in the Adriatic started to increase. The large cyclonic structure persisted until 2006, when again the Ionian Sea appeared populated by a large number of sub-basin-scale cyclones and anticyclones (Figure 2f). In the

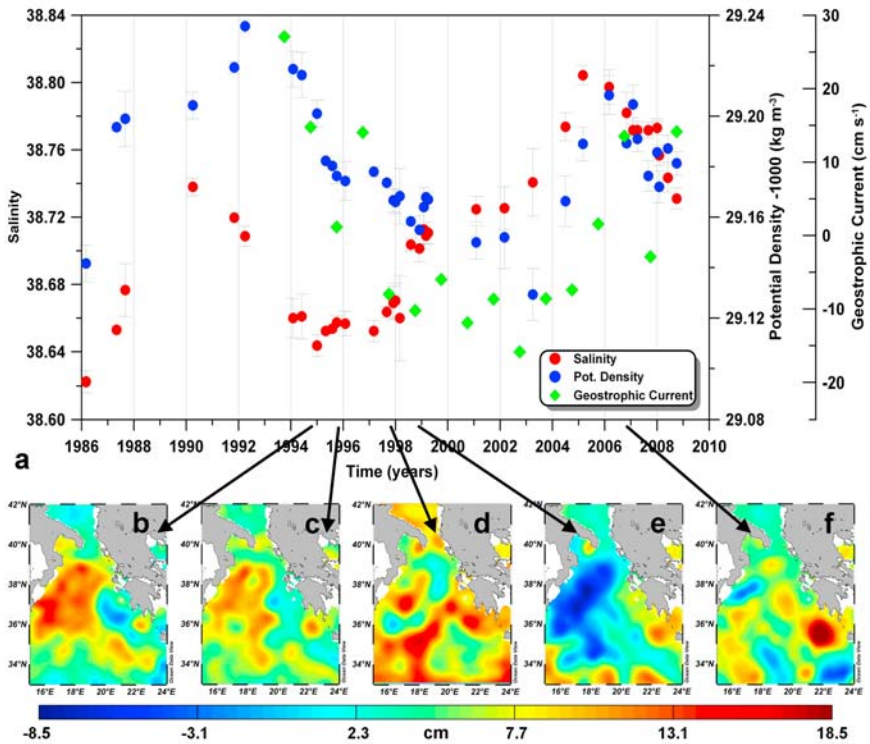

Figure 2. (a) Time-series of the average salinity (red dots) and potential density (blue dots) calculated for the 200–800 m layer in the Southern Adriatic. Vertical bars denote standard deviations around the mean. Green dots represent the meridional geostrophic surface current component in the northwestern Ionian. Average horizontal SLA maps for the fall period (October, through December) in the Ionian are shown for 1994 (b), 1995 (c), 1997 (d), 1998 (e) and 2006 (f).

case of the cyclonic circulation, the water that possibly enters the Adriatic Sea propagates along a pathway that is no longer along the western coast of the Ionian, as it was the case during the anticyclonic phase. Instead, it extends northward along the eastern coast, suggesting that salty LIW and/or Cretan Intermediate Water are mainly advected into the Adriatic and the contribution from MAW is reduced. In fact, during the entire period of the cyclonic circulation the salinity in the Southern Adriatic showed a clear trend of increase.

[14] In order to analyze circulation variations in the Ionian, ocean vorticity was computed by assuming geostrophic and hydrostatic dynamics from SLA maps (i.e. $\zeta = (g/f) \cdot \nabla^2 SLA$). In Figure 3, time-series of the rate of change of the geostrophic vorticity and the vorticity source due to wind stress, averaged over the area depicted in Figure 1, are presented. In agreement with the results presented by *Borzelli et al.* [2009], Figure 3 shows that, prior to 1999, the spatial average of the geostrophic vorticity rate of change and of the vorticity source due to the wind stress were, for

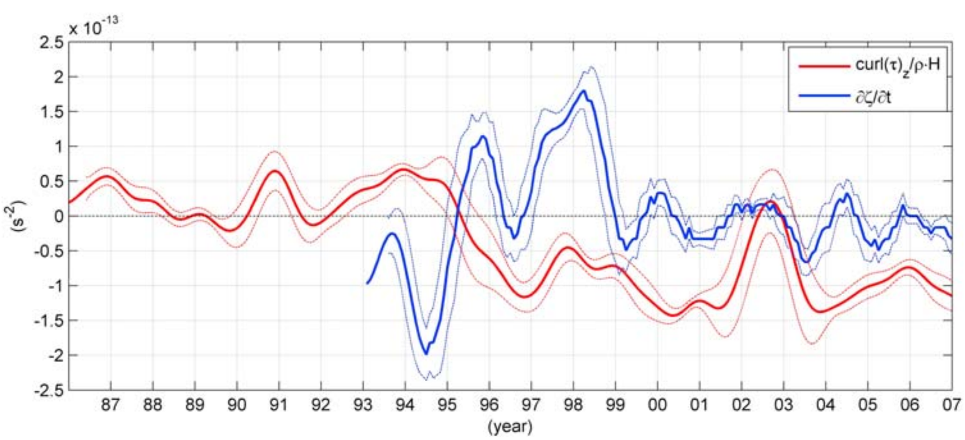

Figure 3. Low-pass time-series of the spatially averaged rate of change of geostrophic vorticity (blue line) and the spatially averaged vertical component of the wind-stress curl (red line). The dashed lines represent the interval of one standard deviation over moving three-months windows.

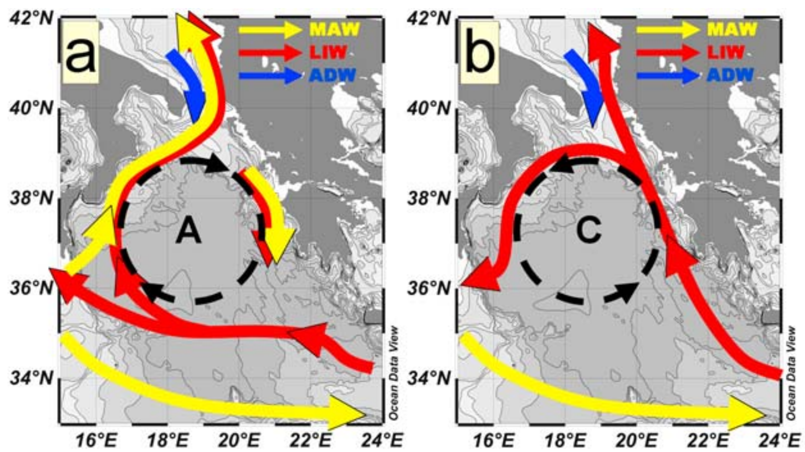

Figure 4. Schematic representation of the Adriatic-Ionian bimodal oscillating system: (a) anticyclonic mode and (b) cyclonic mode. For water mass acronyms please see the text.

most of the time, of the opposite sign, suggesting the predominant role of interior oceanic processes in determining vorticity variations. Between 1999 and 2003, the spatial average of the vorticity rate of change was rather small and oscillated around zero. After 2003 the vorticity rate of change became predominantly negative, as did the vorticity source due to the wind stress. To analyze the relative importance of the wind stress and internal oceanic processes on the vorticity balance of the Ionian between 1999 and the end of the study period we assumed a two layer, linear ocean, in which the vorticity balance of the upper layer is governed by the equation [see, e.g., *Pedlosky*, 1986]

$$\frac{\partial \zeta}{\partial t} = \frac{(\nabla p \times \nabla \rho)_z}{\rho^2} + f\left(\frac{\partial w}{\partial z}\right) + \frac{1}{\rho H}[curl\tau]_z \quad (1)$$

where $\zeta = (\partial v/\partial x) - (\partial u/\partial y)$ is the vertically averaged flow vorticity, w the vertical component of the velocity, H the thickness of the upper layer, ρ and p density and pressure respectively, while $\boldsymbol{\tau}$ is the wind stress. The order of magnitude of the first term (the baroclinic term) can be evaluated using the geostrophic equation (i.e. $\mathbf{u_g} = (1/\rho f) \cdot \hat{\mathbf{z}} \times \nabla p$ where $\mathbf{u}_g$ is the geostrophic velocity and $\hat{\mathbf{z}}$ the vertical unit vector) and the thermal wind equation (i.e. $\partial \mathbf{u_g}/\partial z = -(g/\rho f) \cdot \hat{\mathbf{z}} \times \nabla \rho$). According to the geostrophic equation, the horizontal pressure gradient is of the order of $\rho f u_g$, while from the thermal wind equation we obtain the magnitude for the horizontal density gradient $(f\rho/g) \cdot (\partial u_g/\partial z)$. Therefore, the estimate of the order of magnitude of the baroclinic contribution to the vorticity balance is $O\left(\frac{f^2 u_g^2}{gH}\right)$ (J. Pedlosky, personal communication, 2009). Taking $u_g \approx 0.1$ m/s, $f \approx 10^{-4}$ s^{-1} and $H \approx 500$ m we get, for the baroclinic contribution to the vorticity balance in equation (1), $0.2 \cdot 10^{-13}$ s^{-2}. To estimate the contribution to the vorticity balance of the second term (tube stretching), following *Borzelli et al.* [2009], the interface changed the depth by 150 m over two years. This gives the vertical velocity $w \approx 2.4 \cdot 10^{-6}$ m/s. Taking the average depth of the upper layer as $H = 500$ m, we get for the tube stretching term $f(\partial w/\partial z) \approx f(w/H) \approx 5 \cdot 10^{-13}$ s^{-2}. The vertical velocity estimate is subject to uncertainties due to two main reasons. One relates to the fact that it is difficult to determine, on the basis of available data, the time interval in which isopycnals welled up. The second relates to the way we determine the isopycnal depth. It can be either obtained as an average over the basin or over the gyre center. In spite of the different ways the vertical velocity is estimated, the tube stretching term may vary within an order of magnitude (i.e. between 10^{-13} and 10^{-12} s^{-2}). Finally, Figure 3 shows that the contribution of the wind stress curl term to the vorticity balance of the Ionian is 10^{-13} s^{-2}. These considerations show that internal oceanic processes, mainly through the tube stretching term, are as efficient as, or even more efficient than the wind in determining the upper-layer circulation.

[15] The fact that internal oceanic processes may prevail on wind stress in determining vorticity variations in the Ionian allows us to conjecture an interesting feedback mechanism between the Ionian and the Adriatic, which underlies the vorticity balance of the Ionian. According to this hypothesis, the Adriatic-Ionian area behaves as a bimodal system oscillating between two regimes represented by the cyclonic and anticyclonic Ionian upper-layer circulation (Figures 4a and 4b). In this scenario the background effect constituted by local winds, is not the primary forcing of the surface circulation. The functioning of the Adriatic-Ionian BiOS may be summarized as follows: in the late 1980s, the Ionian upper-layer circulation was characterized by a series of anticyclonic gyres that in the early 1990s merged into one basin-wide gyre [*Malanotte-Rizzoli et al.*, 1997]. During this phase, the interior of the Ionian was replenished by the fresher MAW advected northward by the anticyclonic circulation entering the Adriatic. This caused a density decrease in the Adriatic (Figure 2a) which produced and exported Adriatic Deep Water (ADW) with progressively lower density, spreading along the Ionian flanks. This resulted in the deepening of isopycnal surfaces along the ADW pathway and in the upper-layer column stretching. Consequently, the sea level along the ADW pathway at the flanks of the Ionian increased, gradually weakening the anticyclonic upper-layer circulation and finally inverting the surface pressure gradient and the circulation from anticyclonic to cyclonic. This phenomenon was acting in concomitance with the mechanism discussed

by *Borzelli et al.* [2009]. Indeed, the filling up of the Ionian central abyss with the CSOW following the EMT relaxation, produced an upward motion of the isopycnal surfaces in the center of the Ionian [*Roether et al.*, 2007] and induced a decrease in the sea level, contributing further to the circulation reversal. The reversal took place in 1997, as it is evident from the fact that no clear basin-wide anticyclone appeared in the Ionian (Figure 2d). From 1998 until 2005, a rather strong cyclonic basin-wide circulation was established (Figure 2e). The cyclonic circulation favored the ingression of salty water of Cretan and/or Levantine origin in the intermediate layer, inverting the salinity trend in the Adriatic (Figure 2a) and facilitating the production of ADW with increasing density [*Civitarese et al.*, 2005]. In fact our data show that the period 2003–2006 was characterized by a prominent density increase in the center of the Southern Adriatic (Figure 2a). This was associated with the inflow of salty waters as consequence of the Ionian cyclonic upper-layer circulation. In this situation, the lowering of the sea level along the flanks of the Ionian resulted in the weakening of the upper-layer cyclonic circulation. The inversion from the cyclonic to the anticyclonic regime seems to have already been started in 2006, given the absence of the basin-scale circulation pattern (Figure 2f). It is interesting to note that, using numerical simulations of the Mediterranean wind-driven general circulation for the period 1987–1994, *Molcard et al.* [2002] showed that the Ionian climatological circulation pattern was cyclonic, in contrast to what was obtained from experimental data [*Malanotte-Rizzoli et al.*, 1999; *Vigo et al.*, 2005]. This suggests that the wind forcing cannot explain the prevailing upper-layer circulation pattern. However, the role of remote forcing by the wind needs further studies.

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