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On the continuous functioning of an internal mechanism that drives the Eastern Mediterranean thermohaline circulation: The recent activation of the Aegean Sea as a dense water source area

George Krokos *, Dimitris Velaoras, Gerasimos Korres, Leonidas Perivoliotis, Alexander Theocharis

Hellenic Centre for Marine Research, Institute of Oceanography, 46.7 km Athens — Sounio Avenue, 190 13 Anavyssos, Greece

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ABSTRACT

The scientific interest in Eastern Mediterranean (EMed) processes of major importance has been revived in recent years due to the predominance of internal variability manifested in a decadal time scale leading to the alternating activation of the two dense water sources (i.e. the Adriatic and Aegean Seas). Analysis of available hydrographic data during the 2003–2012 period reveals an anticorrelated almost decadal oscillation in the thermohaline properties of the upper and intermediate water masses in both the Ionian and the Levantine/Aegean Seas. This event is the manifestation of an ongoing internal mechanism initially introduced by Theocharis et al. (in press) which periodically disturbs the upper thermohaline EMed conveyor belt and changes the respective water mass pathways, thus driving the alternating activation of the two dense water sources through salinity preconditioning. Since 2004–2005, the salinity of the upper/intermediate layer in the eastern part of the EMed gradually increased up to 2010, while at the same time it decreased in the North Ionian Sea. During the same period we observed the activation of the Aegean Sea as a Dense Water Formation area even though the atmospheric forcing conditions were not favorable. After 2010 the salinity trend reversed in both regions. This suggests that in the near future the salinity preconditioning of the Adriatic Sea will be favored again following the respective water mass pathway changes.

1. Introduction

The Mediterranean is a semi-enclosed sea, in which all major oceanographic processes occur, but on much smaller spatial and temporal scales compared to the world ocean. This makes the Mediterranean Sea an ideal test basin for the study of climate variability and air–sea interactions. Its upper unified thermohaline cell consists of the eastward flow of the less saline Atlantic Water (AW) that enters at the surface layer through the Gibraltar Strait and the return westward flow of the more saline Intermediate Water that mainly originates in the Eastern Mediterranean (EMed) Basin. Deep thermohaline cells also exist in both the Western Mediterranean (WMed) and EMed Basins, which presented important variability in the last decades. This fact revealed that the Mediterranean thermohaline circulation is not in an almost steady state as believed in the past. The most significant thermohaline event that occurred during the 20th century in the EMed was the 1980–1990s abrupt shift of the Deep Water source from the Adriatic to the Aegean Sea referred to in the literature as the Eastern Mediterranean Transient (EMT) (Roether et al., 1996). It had a profound impact on both physical and biochemical processes on the EMed but in the long term affected the WMed Basin as well (Malanotte-Rizzoli, 2003; Schroeder et al., 2006).

Different causes or synergetic actions have been proposed as responsible for the EMT event. Some arguments are inclined towards the atmospheric forcing that dominated upon the Aegean and Levantine Basins (e.g. Josey, 2003), whilst others on the combined effect of atmospheric factors along with the redistribution of water properties due to changes of the main water mass pathways in the upper and intermediate layers of the EMed (e.g. Malanotte-Rizzoli et al., 1999).

Studies concerning the post EMT period (i.e. after the mid 1990s) (Borzelli et al., 2009; Gačić et al., 2010, 2011) have shown that changes in the Ionian upper layer circulation pattern is a recurrent phenomenon occurring on an almost decadal time scale. According to these studies, the Ionian upper layer circulation undergoes reversals which correspond to varying rotation modes of a gyre covering the North Ionian Basin, named North Ionian Gyre (NIG). They have proposed a feedback mechanism, named the Adriatic–Ionian Bimodal Oscillating System (BiOS), between the observed NIG reversals and the water mass redistributions of the Ionian Sea which relate to variations of the thermohaline properties of the Southern Adriatic and the Aegean Seas.

Theocharis et al. (in press) using numerical simulations and in-situ observations have shown that the Aegean and Adriatic Seas during the 1960–2000 period present alternating cycles of intense Dense Water

* Corresponding author.
E-mail address: gkrokos@hcmr.gr (G. Krokos).

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Formation (DWF) which are followed by intervals of less intense activity creating an anti-correlated, competitive oscillating pattern between them. These authors proposed a different mechanism that drives the alternation of the two DW sources of the EMed, at quasi regular, almost decadal, time intervals. This mechanism is based on the antagonistic functioning of the two DWF sites in controlling the EMed deep thermohaline cell. The massive outflow of dense water through the deepest layers of these two marginal seas during their active phases is balanced by intense inflow from the upper layers. This process creates the conditions of a thermohaline pump that advects available upper layer water masses towards the active area and gradually modifies the main water mass pathways.

According to this theory, the competitive functioning of the two source areas leads to the disturbance of the upper thermohaline cell of the EMed which is portrayed by two modes: 1) the deflection of the basin-wide Atlantic–Ionian Stream (AIS) pathway towards the North Ionian with limited eastward flow, resulting in the recirculation of the Levantine Intermediate Water (LIW) in the Levantine Basin, and 2) the re-establishment of the AIS eastward flow and the consequent restoration of the LIW westward return flow. The first mode is caused by the activation of the Adriatic and the latter of the Aegean. Therefore, the NIG/BiOS and the associated reversals of the circulation in the Northern Ionian reflect the disturbance of the upper thermohaline cell in the western part of the EMed. The abovementioned thermohaline cell variability changes the thermal and salt contents of the DWF source areas respectively and sustains the quasi decadal oscillations observed in the thermohaline properties and DWF processes in both the Adriatic and Aegean Seas. The time scale of the oscillations may vary depending on the intensity and magnitude of the DWF events.

In this paper we intend to show that during the last decade (2003–2012) the mechanism proposed in Theocharis et al. (in press) is an ongoing process, manifested by salinity and temperature variations, anticorrelated between the Levantine/Aegean and the North Ionian Seas. This mechanism is responsible for the activation of the Aegean as dense water source by 2007.

2. Data set

In order to describe the thermohaline evolution of the EMed during the decade 2003–2012, we analyze hydrological data sets, along with the atmospheric forcing that prevailed during this period.

The in-situ hydrological data used herein originate from two different data sources: i) The Hellenic National Oceanographic Data Center (HNODC) which provided 57 CTD profiles in the Cretan Sea during 2003–2012 and ii) data provided by the MyOcean near real-time in-situ temperature and salinity observations in the Mediterranean Sea. From the latter dataset (available through www.myocean.eu) only profiling data from ARGO floats and Gliders have been used. This kind of platforms has already grown to be a major component of the global ocean observing system and can provide the scientific community with reliable, high-quality in-situ data. ARGO float deployments are globally active since 2000 and data from 2003 onwards can be retrieved for the EMed through the MyOcean portal. From the ARGO/Glider profilers data only those that had successfully passed the MyOcean quality checks have been accepted in this study. Hereafter we refer to the ARGO/Glider data as ARGO data for simplicity. In total we used 78 (21 ARGO + 57 CTD) T, S profiles for the Central Cretan Sea (2003–12), 1579 for the Levantine Basin (2003–12) and 555 for the North Ionian Sea (2004–12). Table 1 presents the number of profiles used per year in every region.

Data used to evaluate atmospheric conditions in the associated areas of the EMed originate from the ERA-Interim latest ECMWF global atmospheric reanalysis of the period 1979 to the present (Dee et al., 2011). Heat and freshwater fluxes are analyzed using the available monthly means of daily accumulation fields based on forecast for each day, extracted at the resolution of the data assimilation and forecast system used by ERA Interim, N128, interpolated to a 0.75° x 0.75° Gaussian grid.

Table 1
Number of profiles per year and per EMed region.

Years	EMed Region					
	Levantine Basin				North Ionian Sea	Central Cretan Sea
	L1	L2	L3	L1 + L3		
2003	71	6	57	128	0	1
2004	51	46	100	151	20	0
2005	101	89	161	262	92	24
2006	49	140	168	217	21	13
2007	42	80	70	112	0	3
2008	24	116	119	143	22	11
2009	116	21	102	218	37	1
2010	5	20	221	226	14	10
2011	13	48	9	22	48	12
2012	58	102	42	100	301	3
Total	530	668	1049	1579	555	78

3. Results and discussion

Annual means of integrated salinity in the 30–300 dbar layer were calculated for the Levantine Basin at first. This layer includes surface/subsurface but also intermediate water masses in this basin, as the LIW core here is found at depths less than 300 dbar. As many ARGO floats end their profiling below ~20 dbar, the 30 dbar depth has been used as the standard upper integration limit.

The basin was initially divided into 3 regions (Fig. 1). Regions 1 and 3 correspond to the easternmost part of the Levantine which is less affected by the direct influence of the AW eastward flow. Moreover, region 1 feeds the Cretan Sea with highly saline surface/intermediate water masses through the Asia Minor Current flowing eastwards in the periphery of the Rhodes Gyre close to the Asia Minor coast (Özsoy et al., 1993; Theocharis et al., 1993, 1999). Region 2 on the other hand lies directly within the AW path, making results produced by data originating from this region more dependent on spatial distribution of the profiles. Data for the northwest Levantine were not taken into consideration as this region is dominated by the presence of the Rhodes Gyre large permanent cyclone which could greatly bias the results. ARGO floats which constitute the only observing platforms for this region tend to drift in the periphery of the gyre which presents very different hydrological conditions compared to the center of the gyre.

Fig. 2 shows the annual means of integrated salinity in the 30–300 dbar layer for each of the three Levantine regions (Fig. 1) during the period 2003–2012. Regions 1 and 3 show an almost identical behavior. After 2005 there is a clear salinity rise in the upper 300 dbar layer of the easternmost part of the Levantine, which peaks in 2010. The increase between 2005 and 2010 is almost 0.3 psu while the salinity relaxes during 2011 and 2012. It is worth mentioning that the fitted polynomial curve shows an oscillation pattern with a clear quasi decadal period. Region 2 also shows a salinity increase after 2004, but this drops after 2007, especially in 2009–10. In fact as already mentioned, region 2 lies on the AW path and thus the spatial distribution of the profiles is crucial in determining the results. This is the case for 2009 and 2010, when the lower salinity values found in the profiles are due to their spatial distribution being restricted close to the African coast, i.e. directly on the AW eastward path. Overall, the salinities in region 2 are lower than in regions 1 and 3 because of the region's vicinity to the AW main flow.

Data from Levantine regions 1 and 3 were merged and the new annual means of integrated salinity in the upper 300 dbar layer were compared to the upper 400 dbar layer for the North Ionian Sea (north of latitude 37°N) and the 10–1000 dbar layer for the Central Cretan Basin (latitude limits: 35.4–36.2°N, longitude limits: 23.7–26.3°E). The integration depth was extended to 400 dbar for the North Ionian Sea