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Effects of the Eastern Mediterranean Sea circulation on the thermohaline properties as recorded by fixed deep-ocean observatories

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ABSTRACT

Temperature and salinity time-series from three fixed observatories in the Eastern Mediterranean Sea (EMed) are investigated using multi-annual (2006–2014), high-frequency (up to 3 h sampling rate) data. Two observatories are deployed in the two dense water formation (DWF) areas of the EMed (Southern Adriatic Sea, E2-M3A; Cretan Sea, E1-M3A) and the third one (Southeast Ionian Sea, PYLOS) lays directly on the intermediate water masses pathway that connects the DWF sources. The long-term variations of the hydrological characteristics at the observatories reflect the oscillating large-scale circulation modes of the basin (i.e. BiOS-Bimodal Oscillating System and internal thermohaline pump theories). In particular, between 2006 and 2014 an anti-correlated behaviour of the intermediate layer (200–600 m) salinity between the Adriatic and Cretan Sea observatories is verified. This behaviour is directly linked to reversals of the North Ionian Gyre, which appeared cyclonic during 2006–2011 and turned anticyclonic after 2011. Statistical analysis suggests that the travel time of the intermediate salinity maximum signal between the Cretan and Adriatic Sea is roughly 1.5 years, in good agreement with the analysis of additionally presented ARGO data as well as previous literature references. We argue that the understanding of such oscillations provides important foresight on future DWF events, as increased salinity may act as a crucial preconditioning factor for DWF processes. Additionally, energy spectrum analysis of the time-series revealed interesting short-term variability connected to mesoscale activity at the observatories. Hence, the sustain of permanent observatories able to monitor oceanic parameters at high sampling rates may play a key role in understanding both climatic and oceanic processes and trends.

1. Introduction

The Mediterranean Sea is a semi-secluded oceanic basin of “concentration” type, since evaporation exceeds precipitation and river run off. The surface/subsurface (roughly 0–150 m) inflow of Atlantic Water (AW) that enters the Mediterranean through the Gibraltar Strait in order to compensate the water deficit of the basin, reaches the Eastern Mediterranean (EMed). There, in its easternmost part, AW is converted through winter open-sea convection into a dense and saline intermediate water mass known as Levantine Intermediate Water (LIW, Özturgut, 1976; POEM Group, 1992). Apart from the LIW, an additional intermediate water mass similar to the former in hydrological characteristics, namely the Cretan Intermediate Water (CIW), is formed inside the Cretan Sea through winter convection that locally reaches roughly 300 m depth (Georgopoulos et al., 1989; Cardin et al., 2003; Velaoras et al., 2013). The CIW is considered slightly colder, saltier and denser than the LIW (Astraldi et al., 1999; Theocharis et al., 1999). It flows out from the Cretan Sea through a complex strait system of successive islands that separate Crete from the adjacent landmasses, such as the Antikythira Straits west of Crete (700 m deep) and the Kassos and Karpathos straits east of Crete (900 m and 850 m deep respectively, see Fig. 1). The LIW/CIW formation in the EMed drives a westward return flow at intermediate depths (roughly 150–500 m) carrying saline water masses into the Central and Western Mediterranean (WMed) seas. This surface eastward inflow-intermediate westward outflow system constitutes the upper thermohaline conveyor belt of the Mediterranean Sea. The Ionian Sea, due to its central position linking the WMed and the EMed, is a key region for the exchange of water masses (AW and LIW/CIW) between these two major Mediterranean sub-basins.

The role of the saline intermediate masses (i.e. LIW, CIW) is of great importance for the dense water formation (DWF) processes

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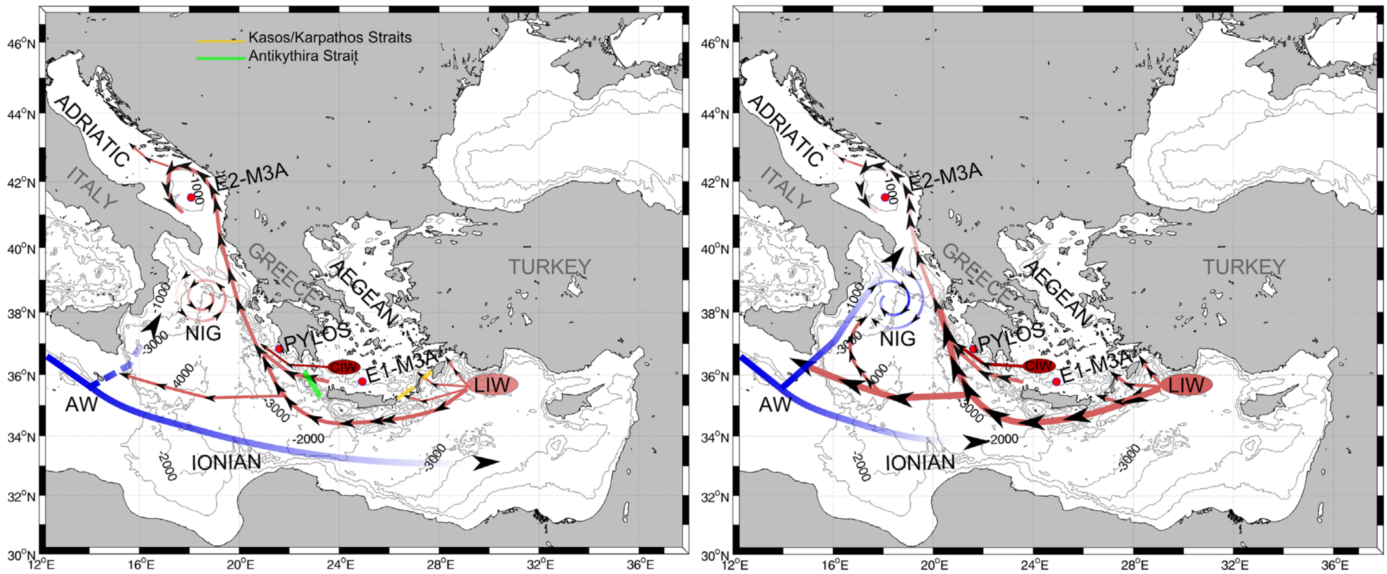

Fig. 1. General circulation of the EMed (LIW/CIW=Levantine/Cretan Intermediate Water; AW=Atlantic Water) associated with the NIG (North Ionian Gyre) during the cyclonic (left panel) and anticyclonic phases (right panel). Red dots show the three fixed observatories part of the FixO^3 network (E1-M3A, E2-M3A, and PYLOS). The color shading indicates the strength of the S signal associated with the water masses' flow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

taking place in the Mediterranean Sea. They provide the DWF areas with the necessary salt amount that acts as a preconditioning factor favouring local winter convection. Two such DWF formation areas exist in the EMed, namely the Adriatic and the Aegean Seas (Zervakis et al., 2000; Gačić et al., 2002; Manca et al., 2002; Vilibić, 2003; Nittis et al., 2003a; Supić and Vilibić, 2006). It is in these DWF areas where the strong cold and dry winds, blowing during the winter period, provoke significant surface buoyancy loss. This last causes the sinking of surface water and the formation of dense waters that contribute to the Eastern Mediterranean Deep Water (EMDW, Hainbucher et al., 2006).

Water masses dense enough to reach deep/bottom layers of the EMed are formed during winter mainly in the Adriatic Sea, but occasional very dense waters (able to reach the Ionian abyssal plain) have also been formed in the Aegean Sea. In the latter case, the most important episode was reported between 1987 and 1995, when a massive dense water outflow from the Cretan Sea altered the characteristics of the deep thermohaline cell of the EMed, making the EMDW saltier and warmer than in the past. This event was called Eastern Mediterranean Transient (EMT, Roether et al., 1996; Theocharis et al., 1999). Amongst the various synergetic causes that led to the EMT event and to the change of the main DWF sources in the EMed, there is the alternation of the AW and LIW water mass pathways in the Ionian interior as reported by Malanotte-Rizzoli et al. (1999). This alteration took place between 1987 and 1991 and resulted in the advection of AW masses towards the Northern Ionian while saline LIW was at the same time confined in the eastern part of the EMed. Consequently, there was a freshening of the Ionian basin accompanied by a respective salinity increase in the Aegean Sea that favoured DWF in that basin. By 1999, the AW pathway had re-established its eastward flow towards the Levantine (Theocharis et al., 2002), and the EMed has gradually been returning to its previous state with the Adriatic Sea as the main DWF source (Rubino and Hainbucher, 2007; Bensi et al., 2013; Cardin et al., 2015; Meccia et al., 2015).

More recently, newly emerged theories have shown that the upper thermohaline cell of the EMed is subjected to periodical (quasi decadal) oscillations of circulation modes. In particular, Gačić et al. (2010, 2011, 2013) have proposed a feedback mechanism induced by the Adriatic dense water production, named the Adriatic–Ionian Bimodal Oscillating System (BiOS), which can influence the salt distribution in the whole EMed. Additionally, Theocharis et al. (2014) and Velaoras et al. (2014) have suggested the existence of an internal thermohaline pumping mechanism that takes into account the whole upper thermohaline cell of the EMed, which regulates the salinity distribution and the DWF processes in the respective formation areas of the EMed. Both aforementioned theories attribute the circulation oscillations to internal thermohaline mechanisms. Other studies (e.g. Cessi et al., 2014; Pinardi et al., 2015) point out the effect of the wind stress as the main driving factor for the circulation changes. They argue that the wind works together with the buoyancy fluxes, both contributing in comparable portion, to the support of the mechanical energy of the circulation in the whole Mediterranean Sea. The upper thermohaline cell oscillations are manifested by reversals of the Ionian upper circulation. The latter are expressed in different phases of the North Ionian Gyre (NIG), which presents alternations between cyclonic and anticyclonic rotation schemes (Fig. 1). These reversals affect the salt distribution within the EMed by modifying the AW pathways towards the Levantine or Northern Ionian Sea thus producing out-of-phase variations between the salt content in the Adriatic or in the Aegean (Cretan) Seas. In turn, these salinity oscillations favour DWF in each of these marginal seas in an anti-correlated, competitive way. Hereafter, we will refer generally to the NIG in cyclonic or anticyclonic phase, to understand the effects induced by different circulation modes on the thermohaline properties of the Adriatic and Aegean (Cretan) Seas. Observations during the last two decades have indeed shown that the NIG experiences periodical reversals that consequently govern the salt content changes in the Adriatic and Cretan Seas. Borzelli et al. (2009), Bessières et al. (2013), Gačić et al. (2011, 2014), Poulain et al. (2012) have confirmed that in 1997, 2006, and 2011 the Ionian Sea upper circulation demonstrated reversals (1997–2006 cyclonic NIG, 2006–2011 anticyclonic NIG, and again cyclonic after 2011). Additionally, both Gačić et al. (2014) and Mihanović et al. (2015) showed how these reversals could be rapid or slow, depending on the governing basin-scale processes that drive them.

Results from time-series, often retrieved from repeated cruise stations, have been very helpful to understand long-term ocean processes at different temporal scales (Schroeder et al., 2013). For