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# Interannual thermohaline (1979–2014) and nutrient (2002–2014) dynamics in the Levantine surface and intermediate water masses, SE Mediterranean Sea

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ABSTRACT

In this study a >30 years dataset of 1382 CTD casts in the Levantine Basin (LB) was analyzed to examine the thermohaline trends of the Surface (~0–50 m) and Intermediate (~150–350 m) Water masses (LSW, LIW). In addition, a 13 years (2002–2014) dataset of 3 deep water stations (>1000 m) in the eastern Levantine Basin (Haifa Section cruises) that were visited 2–3 times annually was used to explore the relations between the physical and nutrient properties in the LIW. Over the past 30 years the LSW and LIW masses displayed positive long-term trends in salinity of $+0.008 \pm 0.006$ and $+0.005 \pm 0.003$ year$^{-1}$, respectively, and temperature of $+0.12 \pm 0.07$ and $+0.03 \pm 0.02$ °C year$^{-1}$, respectively. Decadal variations in salinity and temperature were superimposed on all long-term trends. Throughout the period 2002–2014 nutrient levels in the LIW core and corresponding integrated values of chlorophyll *a* also varied in nearly opposite phase with temperature and salinity. Furthermore, these variations occurred with a similar decadal periodicity, but with shifted phase with those observed in the Southern Adriatic and North Ionian Seas in the same water mass. The latter were considered to be caused by decadal reversals in the North Ionian Gyre, i.e. Bimodal Oscillation System (BiOS). These results indicate that the thermohaline flux variations attributed to the BiOS mechanism have a significant impact in magnitude on the available nutrients and the dynamics of the eastern basin primary productivity. These results should be taken into consideration in assessing the relative contribution of external nutrient loads in comparison to those attributed to variations in thermohaline fluxes and in the assessment of long-term and interannual primary productivity (chlorophyll *a* and nutrients) trends in the LB.



## 1. Introduction

The Mediterranean Sea (MS) is the largest semi-enclosed water body on Earth and is characterized by limited water exchange with the Atlantic Ocean through the Gibraltar Strait. Surface water from the Atlantic flows eastward and undergoes continuous transformation due to air–sea heat and moisture fluxes resulting in the highest salinities in the Levantine Basin (LB) at the extreme eastern end of the Eastern Mediterranean (POEM group, 1992; Hamad et al., 2005; Gerin et al., 2009; Malanotte-Rizzoli et al., 2014). The Levantine Surface Water (LSW) originates from Modified Atlantic Water (MAW) that first passes through the Ionian Basin (IB) and into the LB. In the course of their eastward propagation these waters are subject to further transformation through deep winter mixing, eddy formation and decay, evaporation and heating (Hecht et al., 1988). Levantine Intermediate Water (LIW) formation occurs when LSW cools down and sinks along isopycnals to intermediate depths (ca. 130 m < z < 350 m). This usually occurs as LSW reaches the Rhodes Gyre area (Lascaratos et al., 1999). In addition, observations show that LIW formation may also occur along the continental margins of the LB (Ozsoy et al., 1989). The LIW mass flows westward across the entire basin in the opposite direction below the MAW, spreading from the LB into the IB and through the Sicily Straits into the western Mediterranean, eventually exiting the MS through the Strait of Gibraltar at mid-depth (Tanhua et al., 2013; Malanotte-Rizzoli et al., 2014). This LIW circulation of relatively high salinity and nutrient levels plays an important role in the deep-water formation in both the eastern and western basins (Robinson et al., 2001; Schneider et al., 2014) and in the biogeochemistry of the MS (Malanotte-Rizzoli et al., 2014; Powley et al., 2014; Kress et al., 2014).

The LB is significantly influenced by the water exchange with the IB via the Cretan passage, which isolates it from the rest of the MS. The Bimodal Oscillating system (BiOS), thoroughly described in Gacic et al. (2010, 2011) controls the trajectory of the MAW flow after passing through the Sicily Straits to both the Southern Adriatic (SA) and the LB that correspond to decadal reversals in the North Ionian Gyre (NIG). The BiOS mechanism has been shown to have a crucial effect

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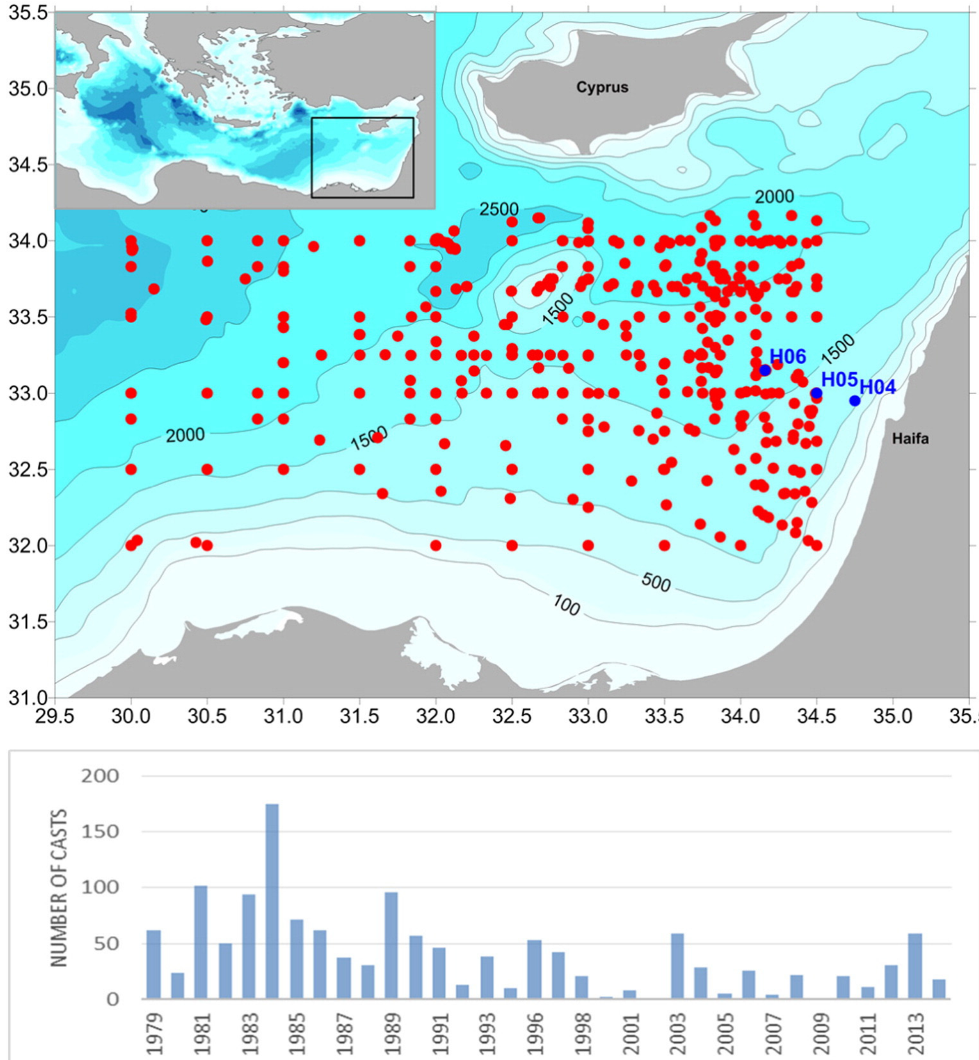


**Fig. 1.** The spatio-temporal distribution of hydrographic casts in the investigated region of the South-East Mediterranean Sea. CTD stations from 1979 to 2014 used to determine the thermohaline structure of the south eastern Mediterranean extracted from SESAME and PERSEUS data bases (red) and Haifa Section deep-water stations used for LIW analysis from 2002 to 2014 (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

on the physical and chemical dynamics in the Southern Adriatic (Civitarese et al., 2010; Gacic et al., 2010). These studies proposed that the BiOS mechanism is a feedback mechanism between changes in the thermohaline structure of SA waters and the IB and further linked it to the Eastern Mediterranean Transient (EMT) event that occurred during the 1990s (Roether et al., 1996, 2007; Gertman et al., 2006). In periods of cyclonic NIG, high salinity LIW is injected into the SA while the transport of MAW is diverted to the LB. This results in buoyancy loss in the SA, which is thought to be a preconditioning factor for the formation of Adriatic Dense Water (Gacic et al., 2010, 2011). During the anticyclonic NIG, MAW intrusion into the Ionian and Adriatic Basins increases at the expense of the LB and the creation of Adriatic Dense water is minimized. In accordance with these variations, Gacic et al. (2011) showed that during cyclonic NIG surface salinity in the SA and IB increase and in the LB decreases and vise-versa for anticyclonic NIG. Furthermore, these salinity variations associated with the BiOS mechanism were shown to co-vary with nitrate levels in both the SA and IB in opposite phase (Civitarese et al., 2010).

We hypothesize that long-term changes in the volume of MAW transported to the LB, or in their thermohaline properties due to a prolonged residence time in the IB and LB, should affect the thermohaline and nutrient properties in the LB upper water masses as well, similar yet in shifted phase to the variations in the SA and IB that have been associated with the BiOS. This effect should probably be most apparent in the LIW layer, which is less sensitive to the seasonal cycle, but is yet shallow enough to reflect surface layer dynamics.

Here we describe the magnitude of the long-term and superimposed thermohaline interannual variations and corresponding changes in nutrient and chlorophyll *a* levels in the upper water masses of the LB (LSW and LIW). We discuss the potential mechanism controlling these variations and long-term trends, and assess the impact of the hydrological variability on nutrient dynamics. For this purpose a >30 years dataset of 1382 CTD casts in the LB was analyzed to examine the thermohaline trends of LSW and LIW. In addition, a 13 years (2002–2014) dataset of 3

**Table 1**
List of Haifa Section deep-water stations used for examining the relationships between physical and chemical tendencies in the Levantine Intermediate Water (LIW).

| Station name | Longitude E [deg] | Latitude N [deg] | Water depth [m] |
|---|---|---|---|
| H04 | 34.75 | 32.95 | 1100 |
| H05 | 34.50 | 33.00 | 1400 |
| H06 | 34.15 | 33.15 | 1700 |