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Mediterranean waters along and across the Strait of Gibraltar, characterization and zonal modification

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ABSTRACT

Hydrological data collected in the Strait of Gibraltar have been used to examine the distribution and spatial–temporal evolution of the water masses in the area. The spatial variability has been addressed by means of a clustering method that determines the affinity of a collection of temperature–salinity samples to one of the water masses involved in the exchange. The method, which has been applied to a nearly-synoptic data set, highlights the clear evolution of the Mediterranean Waters as they flow westward through the Strait. While up to four different Mediterranean Waters are spatially distinguishable east of the main sill of Camarinal in the Strait, most of their differentiating characteristics are eroded after flowing over this restrictive topography due to mixing. West of the sill, therefore, speaking of a unique Mediterranean Water seems more appropriate. The same applies to the North Atlantic Central Water flowing in the opposite direction, which is noticeably modified along its path to the Mediterranean Sea, most of its transformation taking place in the Camarinal sill surroundings. A series of repeated transects carried out in the eastern and western sides of the Strait, provided a temporal analysis of the water masses evolution: the temporal variability manifests seasonality in the surface waters, while interannual signal is mainly detected in the deeper water masses. It is worth remarking the statistically significant positive trend of Western Mediterranean Deep Water (0.009 °C/year) and Winter Intermediate Water (0.03 °C/year), with the latter showing also intermittent occurrence in the Strait.

1. Introduction

In the Mediterranean Sea (MedS, hereinafter) the Atlantic Water (AW) that flows in through the Strait of Gibraltar (SoG) is modified by evaporation and transformed into Mediterranean water, saltier and denser, which ends up flowing out through the SoG to the Atlantic Ocean. A simplified Mediterranean basin is schematized by an eastern and a western basins connected by the Strait of Sicily. In the eastern basin, Levantine Intermediate Water (LIW) is formed through open-sea convection. In the western basin, more specifically in the Gulf of Lion, Western Mediterranean Deep Water (WMDW) is formed by deep convection. It was known since long ago that the LIW was a permanent contributor to the outflow. However, the possibility that the WMDW was participating significantly in the outflow was first presented by Stommel et al. (1973), who attributed its presence to the Bernouilli aspiration of this water from great depth in the MedS over the main sill of Camarinal in the SoG. Subsequently, other authors have revisited the topic and stressed this thought (Bryden and Stommel, 1982; Gascard and Richez, 1985; Whitehead, 1985; Kinder and Parrilla, 1987; Kinder and Bryden, 1990; Millot and Taupier-Letage, 2005; García Lafuente et al., 2007; Naranjo et al., 2012; Naranjo et al., 2014) At present, it is accepted that this deep water is a permanent part of the outflow.

Studies dealing with the outflow within and nearby the SoG used to focus on the two main Mediterranean Waters (MWs hereinafter), the LIW and the WMDW (Pettigrew, 1989; Bray et al., 1995; García Lafuente et al., 2007), which are easily identified by the maximum and minimum potential temperature, respectively, in the densest part of the θ–S diagram (Gascard and Richez, 1985). Recent efforts made to clarify the hydrological characteristics of the water masses leaving the MedS through the SoG have suggested the presence of other Mediterranean water masses, more specifically, the Tyrrhenian Dense Water (TDW) and the Winter Intermediate Water (WIW) (Rhein et al., 1999; Millot et al., 2006; Millot, 2009, 2014a,b). The first is formed by the mixing of old

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WMDW residing in the Tyrrhenian Sea with newly entered LIW flowing into the western MedS through the Strait of Sicily (Rhein et al., 1999; Millot et al., 2006). The WIW is seasonally formed by convection of cooled modified Atlantic Water under severe winter condition along the continental shelf of the Liguro-Provençal subbasin and Catalan Sea (Conan and Millot, 1995; Vargas-Yáñez et al., 2012). At its source, it is the coolest water in the Western MedS (Salat and Font, 1987; Lopez Jurado et al., 1995; Millot, 1999) and it is easily detected in any θ–S diagram by a minimum of potential temperature between potential density anomaly σ_θ=28.0 and σ_θ=29.0 (Millot, 2014a). The volume of formed WIW has been reported to show marked interannual fluctuations (Pinot et al., 2002; Monserrat et al., 2008), the case of no formation being non-discardable (Pinot et al., 2002; Ribó et al., 2015).

These MWs are rather well differentiated (when present) at the eastern side of the SoG (Fuda et al., 2000; Millot, 2009), but the question remains as whether or not they are still distinguishable at the western part of the SoG once the Mediterranean outflow has crossed the Camarinal sill. The reason behind this noticeably different spatial distribution of the water masses in both halfs of the SoG (East–West) is the outstanding tidal dynamics in the area (Candela et al., 1990; Bryden et al., 1994; García-Lafuente et al., 2000; García Lafuente et al., 2007), which is strongly enhanced in the surroundings of Camarinal sill and westwards of it (Wesson and Gregg, 1994; Sánchez Garrido et al., 2008; Sánchez Garrido et al., 2011).The barotropic tidal currents interact with the SoG's topography, mainly with Camarinal sill, to produce a remarkable internal tide (Candela et al., 1990; Bryden et al., 1994; García-Lafuente et al., 2000) that in turn gives rise to dissipation rates that are amongst the highest found in the world ocean (Wesson and Gregg, 1994). The supercritical-to-subcritical flow transitions at the different critical (in hydraulic sense) sections, that happen not only in Camarinal sill but also oceanwards of it at specific times of the tidal cycle, drive that enhanced mixing (Sánchez Garrido et al., 2011; García Lafuente et al., 2013), which is the responsible for the fading out of the water masses identities in the western half of the SoG.

On the other hand, Millot (2014a), using schematic mixing lines in the Mediterranean zone of a θ–S diagram, has proposed that the four MWs can be still detected as far as at 6º15′ W to the West of the main sill and, even, traced along the Gulf of Cadiz in the Atlantic Ocean. This stand point differs from the widespread view of a Mediterranean Water that exits the SoG as a rather well mixed plume with typical properties of $\theta \sim 13$ °C and $S \sim 38.4$ (Baringer, 1993; Baringer and Price, 1997) in which the different MWs water masses are not discernable.

With the aim of provide a clear and standardized method to classify the water masses in the SoG, this work proposes a statistical method to automatically classify every water mass involved in the exchange. Two sets of data, described in Section 2, were specifically collected in the SoG area to address the topic. The first dataset was acquired during the Gibraltar International Campaign (GIC, Section 2.1) and the second one throughout the lifespan of the INGRES projects (Section 2.2) funded by the Spanish Government. Section 3 describes the data processing, paying special attention to the description of the proposed method of analysis (Section 3.2). The hydrological information contained in these two sets of data has been exploited in different ways in this study. GIC data were collected during a very short period and allow us to make a quasi-synoptic description of the water masses distribution in the SoG. On the contrary, INGRES data gather samples spanning a rather long period of time and have the potential of addressing the time variability and evolution of the water masses. Section 4 discusses both topics in Sections 4.1 (GIC) and 4.2 (INGRES) respectively. Finally, Section 5 summarizes the findings and conclusions of the study.

2. Data

2.1. CTD and MVP data from Gibraltar International Campaign

In the framework of the international Hydrochanges programme sponsored by the Commission Internationale pour l'Exploration Scientifique de la Méditerranée (Mediterranean Science Commission, CIESM) and supported by the HyMeX programme, the French *Mediterranean Institute of Oceanography* carried out the *Gibraltar International Campaign* on board the R/V Tethys II from the 4th to the 6th July 2012. The cruise was aimed at obtaining high resolution Conductivity–Temperature–Depth (CTD) profiles along the transects as shown in Fig. 1 in order to give an accurate water mass characterization and distribution of Mediterranean waters within the SoG. Except for section R5, a Moving Vessel Profiler (MVP) was employed; this instrument allows semi-autonomous sampling of the water column with very high spatial resolution (horizontal averaged resolution is 500 m while vertically resolution is 1 m). A drawback of the MVP is its limited range depth (∼350 m). Transect R5 and a repetition of transect R2 were sampled with a CTD probe (SBE 911plus CTD, sampling frequency of 24 Hz) that reached the seafloor. The CTD vertical profiles in these transects, however, are substantially further apart than MVP profiles (typical distance between casts ranging from 1 to 3 Km).

2.2. Historical CTD data from INGRES project

The INGRES projects were initiated in 2004 with the objective of monitoring the Mediterranean outflow and its variability in response to subinertial and longer-term forcing as well as the hydrological properties of the densest and, hence, deepest Mediterranean water leaving the MedS. At the time of this study the monitoring, which is planned to be kept on position *sine die*, is still in progress. Whenever the station was serviced (every 4 or 6 months) and weather permitting, CTD transects were accomplished. Among them, transects labeled TES and TAC in Fig. 1 have been repeatedly sampled during the lifespan of INGRES projects. They make up an unevenly distributed time series since the meteorological conditions often prevented the accomplishment of one or both transects. Overall, TES was sampled 15 times and TAC 12 times (details about the dates when these transects were collected are shown in Table 1).

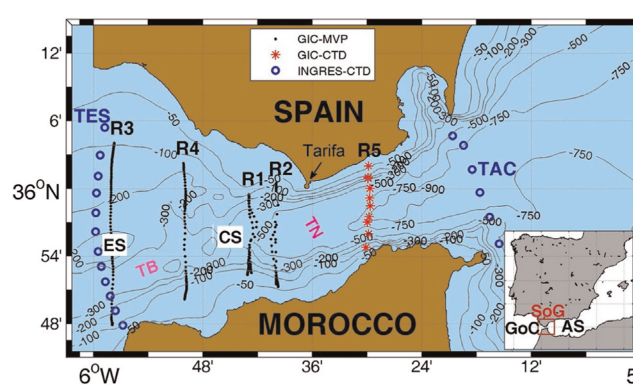

Fig. 1. Map of the Strait of Gibraltar showing bathymetric contours, in meters. The black dots and red asterisks indicate the location of the vertical profiles along the 5 sampled sections for MVP and CTD data in GIC campaign (R1–R5), respectively. Blue circles represent the two CTD sections regularly repeated in the INGRES project (TAC and TES). The main sills of Espartel (ES) and Camarinal (CS), the small Tangier Basin (TB) between them and the Tarifa Narrows (TN) are also indicated. The inset shows the location of the Strait (SoG) between the Alboran Sea (AS), the westernmost basin of the Mediterranean Sea, and the Gulf of Cadiz (GoC) in the Atlantic Ocean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)