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Tracking the Mediterranean outflow in the Gulf of Cadiz

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ABSTRACT

The Mediterranean Water leaves the western end of the Strait of Gibraltar as a bottom wedge of salty and warm waters flowing down the continental slope. The salinity of the onset Mediterranean Outflow Water (MOW) is so high that leads to water much denser (initially in excess of 1.5 kg m^{-3}) than the overlying central waters. During much of its initial descent, the MOW retains large salinity anomalies – causing density anomalies that induce its gravity current character – and relatively high westward speeds – causing a substantial Coriolis force over long portions of its course. We use hydrographic data from six cruises (a total of 1176 stations) plus velocity data from two cruises, together with high-resolution bathymetric data, to track the preferential MOW pathways from the Strait of Gibraltar into the western Gulf of Cadiz and to examine the relation of these pathways to the bottom topography. A methodology for tributary systems in drainage basins, modified to account for the Coriolis force, emphasizes the good agreement between the observed trajectories and those expected from a topographically-constrained flow. Both contour avenues and cross-slope channels are important and have complementary roles steering the MOW along the upper and middle continental slope before discharging as a neutrally buoyant flow into the western Gulf of Cadiz. Our results show that the interaction between bottom flow and topography sets the path and final equilibrium depths of the modern MOW. Furthermore, they support the hypothesis that, as a result of the high erosive power of the bottom flow and changes in bottom-water speed, the MOW pathways and mixing rates have changed in the geological past.

1. Introduction

The dense Mediterranean Water (MW) flows at depth along the Strait of Gibraltar with salinities in excess of 38.5 g kg^{-1}, underlying North Atlantic Central Water (NACW) with salinities ranging between 36.0 and 36.2 g kg^{-1}. After the MW overcomes the western sills of the Strait of Gibraltar, it plunges into the Atlantic Ocean as the Mediterranean Outflow Water (MOW). The most restrictive sill is Camarinal (35°55′N, 5°46′W; 290 m) although, further west (35°50′N, 5°58′W; 360 m), Espartel Sill has also great dynamic importance as it imposes permanent hydraulic control on the MOW (García Lafuente et al., 2002); at this longitude, the Majuan Ridge (35°53′N, 6°W; 60 m depth) divides the outflow into a main channel, where Espartel is found, and a northern channel with a minimum depth of 150 m (Luján et al., 2011; Hernández-Molina et al., 2014a). A third and deeper topographic constriction is West Espartel Sill (32°47′N, 6°20′W; 420 m), located some 22 km downstream of Espartel Sill (Armi and Farmer, 1988; Gasser et al., 2011; Nash et al., 2012). As the MOW overpasses this last sill, it undergoes a substantial increase in water depth, from 420 to 500 m in about 1 km, which accelerates the flow and causes instability and vertical mixing (Gasser et al., 2011; Nash et al., 2012).

The MOW progresses through the eastern/northern margins and the eastern middle slope of the Gulf of Cadiz, first through the ambient NACW and later into the North Atlantic Deep Waters (NADW). The salinity of the NACW decreases nearly linearly with depth, from about 36.6 g kg^{-1} at the sea surface to 35.5 g kg^{-1} at depths of about 600 m. Within the Gulf of Cadiz and the entire eastern subtropical North Atlantic Ocean, the transition from NACW to NADW takes place in an intermediate water stratum, between about 600 and 1400 m, with contributions of both

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Mediterranean and Antarctic waters. The MOW is the predominant water mass in the Gulf of Cadiz, introduced through the shedding of Mediterranean eddies (meddies) and the posterior diffusion from these lens-type pulses (Richardson et al., 2000) and as a result of lateral diffusion of salt and heat (Iorga and Lozier, 1999; Mauritzen et al., 2001). The slope waters off NW Africa, north of the Canary Islands and into the Gulf of Cadiz, are also influenced by a diluted form of Antarctic Intermediate Water, located immediately on top of the level of maximum MOW influence (Machín and Pelegrí, 2009, 2016; Louarn and Morin, 2011).

Beyond Camarinal Sill, the principal pathway for the MOW is towards the W-SW, along a valley that arises as an extension of the Strait of Gibraltar. In this valley, the MOW becomes a salty wedge about 5 km wide and 150 m thick with time-averaged speeds near 1.5 m s^{-1} (Ambar and Howe, 1979) and instantaneous values as large as 3 m s^{-1} (Mulder et al., 2003). During its initial descent, the westward MOW is driven by pressure gradients arising from its excess density relative to the ambient NACW, and its path is constrained by the bottom topography. Eventually the MOW reaches the continental slope and propagates into the Gulf of Cadiz in approximate geostrophic equilibrium, splitting into at least two main branches or cores centered at depths of about 600 m and 1000 m, respectively (Madelain, 1970; Zenk, 1975; Ambar and Howe, 1979; Ochoa and Bray, 1991; Price et al., 1993; Baringer and Price, 1997a, 1999; Ambar et al., 2002; Borenäs et al., 2002). The upper branch flows along the base of the upper slope (depths between 500 and 800 m) until Cape São Vicente, with average speed about 0.5 m s^{-1}, temperature 13.7 °C and salinity 37.1 g kg^{-1} (Madelain, 1970; Zenk, 1975; Ambar and Howe, 1979; Ambar et al., 1999; García et al., 2009). The lower branches are located further south – at depths 800–1200 m, with average speed about 0.25 m s^{-1}, temperature 13.6 °C and salinity 37.4 g kg^{-1} (Madelain, 1970; Zenk, 1975; Zenk and Armi, 1990; Bower et al., 2002). These lower branches detach from the seafloor in the western Gulf of Cadiz, constituting the main path for MOW transport into the open ocean (Iorga and Lozier, 1999; Mauritzen et al., 2001).

Numerical models have also depicted the MOW as an along-bottom plume, widening with multiple velocity streams that eventually settle at two principal depths (Borenäs et al., 2002; Serra et al., 2005; Peliz et al., 2007, 2009, 2013; Dietrich et al., 2008; Xu et al., 2007). Papadakis et al. (2003) and Legg et al. (2009) endorsed that environment NACW is entrained by the turbulent MOW, therefore creating a layer of intermediate properties that leads to a second MOW core. However, Jungclaus and Mellor (2000) emphasized the relevance of the bathymetry for splitting the flow, pointing at relatively small canyons (widths less than 5 km) as the plausible responsible for routing the bottom waters. Peliz et al. (2013) and Barbosa Aguiar et al. (2015) used a 2-km horizontal-resolution model (though substantially smoothed) and observed two velocity cores but one single salinity core along 8.5°W, all them at different latitudes; however, these results depend largely on the intensity of vertical mixing.

It seems likely that the different cores arise from both topography and mixing acting together, with diapycnal mixing changing the vertical structure of density and speed in such a way that leads to differential topographic steering of the bottom and intermediate layers. Independently of the exact mechanism, in order to position these cores, models require a high resolution of the short-scale bottom topography, as either local intense mixing or the flow diversion through narrow canyons depend on structures of the order of 1 km or less (Gasser et al., 2011; Nash et al., 2012). This is substantially less than the grid size for all of the above models, with typical resolution of 10 km or even less after horizontal numerical smoothing.

The Iberia-Biscay-Irish (IBI) operational model of Sotillo et al. (2015, 2016) deserves special mention. It has 50 vertical levels and a horizontal resolution of 1/36°, or about 2–3 km for the region under consideration, which implies some substantial smoothing of its 30-s resolution GEBCO08 seafloor topography (Becker et al., 2009). The IBI model is forced with 3-h atmospheric fields, includes tides and river discharges, and assimilates several datasets (altimetry, sea surface temperature and data from the Argo program). A data subset from 1 June to 31 August 2016 (downloaded from the Copernicus Environment Monitoring Service) has been used to produce the near-bottom distribution of temperature, salinity, density and velocity fields (Fig. S1, supplementary materials). Near the Strait of Gibraltar, the model displays one single salinity-velocity core that, as it enters the Gulf of Cadiz, diverges into two cores, one along the continental slope and one single core in the open waters of the Gulf of Cadiz.

Several of the above oceanographic studies have indeed pointed at the relevance of the eastern and central Gulf of Cadiz bathymetry in driving the path and branching of the MOW (Madelain, 1970; Zenk, 1975; Baringer and Price, 1997a, 1999). The strong interaction between bottom flow and seafloor has also been progressively recognized by bathymetric and stratigraphic studies of the Gulf of Cadiz. Nelson et al. (1993, 1999) pointed out the relevance of diapiric ridges blocking the propagation of the MOW, and thus forcing the current to run along the ridges generating erosive moats and accumulating contourite deposits on their side. Hernández-Molina et al. (2003, 2006) produced a morpho-sedimentary map of the contourite depositional system of the Gulf of Cadiz, and Llave et al. (2006, 2007, 2011) examined the relation of this depositional system with both erosional and tectonic processes during the Quaternary. García et al. (2009) placed the emphasis on the erosive features, proposing a bottom flow scheme that combines along-slope excavation of contourite moats and channels with down-slope erosion of valleys and furrows. Hernández-Molina et al. (2014a,b), using high-resolution bathymetry, described contouritic channels in the eastern Gulf of Cadiz that suggest an early partition of the MOW into two branches. These authors also stressed the relevance of both erosional and depositional processes in the contourite systems and the abundance of erosive scours downslope, located at different depths and distances from the western end of the Strait of Gibraltar. All these studies, using sedimentary and chronostratigraphic data, support the idea that the different valleys and scours in the slope of the SW Iberian margin respond to current and/or previous MOW paths (Nelson et al., 1993, 1999; Llave et al., 2006, 2007, 2011; Rogerson et al., 2005; Hernández-Molina et al., 2014a,b).

Despite these numerous studies, we still lack a detailed understanding of the main MOW pathways in the Gulf of Cadiz: its early plunging and partition into different streams in the eastern Gulf, the steering of these streams through a complex network of channels over the middle slope in the eastern and central Gulf, the way these streams lead to several cores of distinct water properties, and the MOW final departure from the seafloor as neutrally-buoyant veins in the western Gulf. The available schemes are either based on detailed descriptions of depositional-erosional features together with a limited analysis of hydrographic data (Nelson et al., 1993, 1999; Maestro et al., 2007; García et al., 2009; Hernández-Molina et al., 2006, 2014a; Hernández-Molina et al., 2014b), or on more comprehensive hydrographic and velocity data accompanied by a restricted characterization of the subjacent bathymetry (Madelain, 1970; Zenk, 1975; Ambar and Howe, 1979; Price et al., 1993; Baringer and Price, 1997a; Ambar et al., 2002; Borenäs et al., 2002; Bower et al., 2002; Serra et al., 2005). A step forward has been recently done by Hernández-Molina et al. (2014a), combining geomorphological and stratigraphic data with hydrographic data to propose current and past