New insights on bottom water flows crossing a marine sill under periodic or impulsive perturbations: an application to the Sicily Channel sill (Central Mediterranean Sea)

M. Di Paolantonio, F. Falcini (federico.falcini@cnr.it), E. Salusti

CNR-ISMAR, 00133 Rome, Italy

Abstract. Here we discuss the eventual role of non-steady, impulsive phenomena occurring at surface layer (e.g., storm events) on the remarkable uplift of the Eastern Mediterranean bottom waters that flow westward, over the Malta Escarpment, and cross the sill of the Channel of Sicily (Astarldi et al., 2001; Iudicone et al., 2003; Falcini & Salusti 2015). This dynamics is rather similar to the one occurring at the Strait of Gibraltar (Mediterranean Sea) and at the Bab el Mandab, Red Sea (Siddall et al., 2002). The classic, steady uplift, which usually occurs for a three-layer system dynamics, is mostly explained by the Bernoulli suction effect (Lane-Serff et al., 2000). However, real filed analyses suggest that this dynamics can be significantly perturbed by large scale storms and, in general, wind-induced processes (Smeed et al., 2004). We therefore consider a novel, theoretical approach to obtain a rather realistic view of natural perturbations that affect these deep flow dynamics. In addition, our insights on uplift processes may give a contribution to the general understanding of the Mediterranean Sea deep water circulation and its heat storage dynamics. We finally remark that similar phenomena happens in several marine straits and/or in semi-enclosed, peripheral basins of particular importance for local and large-scale processes.

Introduction

The Mediterranean Sea is a remarkably stratified, “thermodynamic” system. In its central sector and, in particular, in the Strait of Sicily (Box 1), the whole water column was characterized as follow (Astraldi et al., 2001):

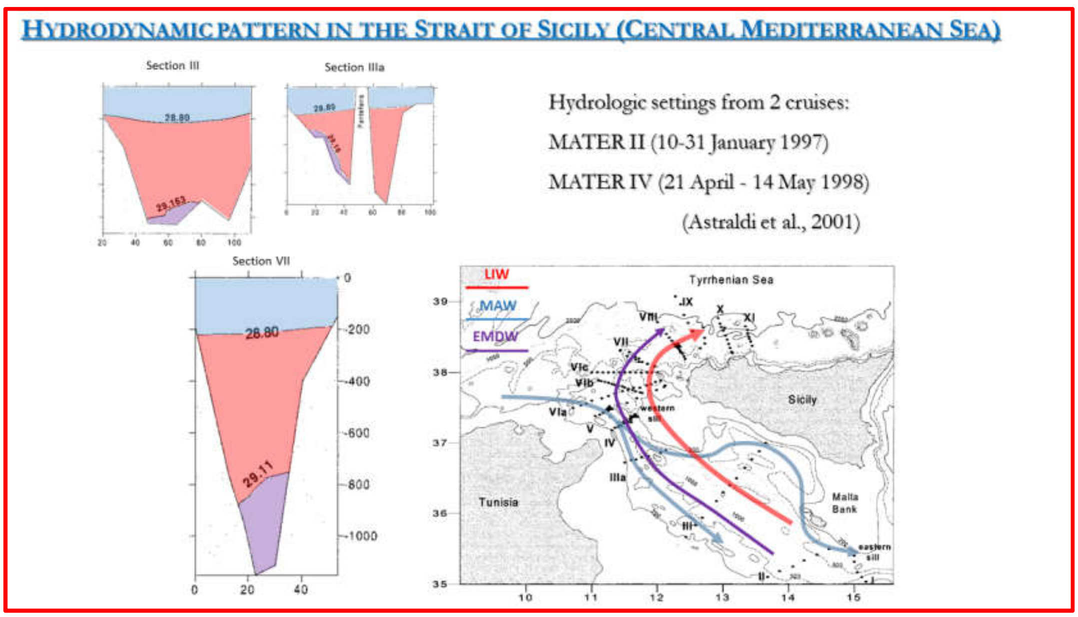
a) the rather fresh Atlantic Modified Water (MAW) of Atlantic origin, in a ~200 *m* thick surface layer, moving eastwards through different branches and stream. In many cases its characteristics can be perturbed by meteorological events as winds and storms. Its climtologic potential density is about $\sigma_{MAW} \approx 28.80$.

b) the salty Levantine Water, flowing westward roughly between ~200 and 800 *m* depth. This water mass is mainly due to the strong air-sea interactions near the island of Rhodes in winter; its average density approximately is $\sigma_{LIW} \approx 29.05$.

c) the Eastern Mediterranean Deep Waters, EMDW, originated in the eastern sub-basins, such as the Adriatic or in the northern Aegean Sea (Bellacicco et al., 2016; Bensi et al., 2016;

Artale et al., 2019) and climatologically flowing westward over the sea bottom, with pathway and velocity somehow similar to those of the LIW; its σ_{EMDW} reaches about 29.15.

The Strait of Sicily is a ≈ 600*km* long, rather linear channel connecting the two main basins of the Mediterranean Sea. Over its sill, in the narrowest section between Sicily and Tunisia, the Channel is $W \approx 150$ *km* wide (Box 1).The sill bottom depth is at ≈ 300*m* while the deepest points with EMDW in the Western Mediterranean basin can reach more than ≈ 2000 *m* depth. Ove rthe sill, the EMDW has a surprising uplift from ≈ 700 *m* depth in the Eastern basin towards the sill at ≈300 *m* depth over the sill (Iudicone et al., 2003). At the western exit of the channel this vein reaches a depth of about 1000 *m* in the southern Tyrrhenian Sea (Sparnocchia), along the Sicilian slope (Box 1).



Box 1. *Hydrodunamic patter of the Strait of Sicily during the period 1993-1998 (from Astraldi et al., 2001)*

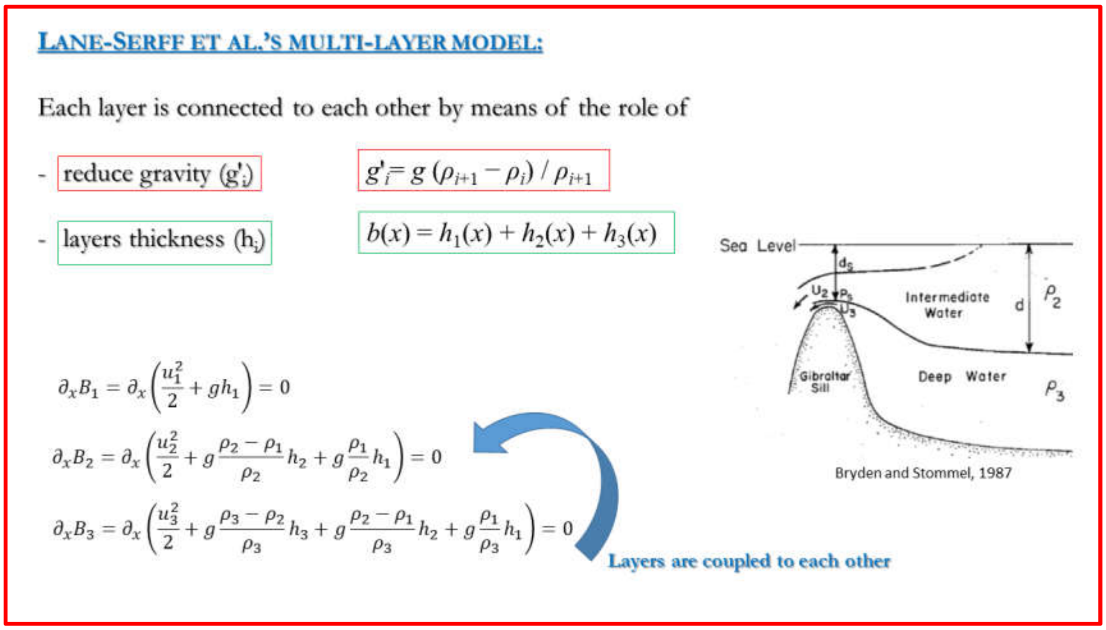
Here we focus on a remarkable, surprising uplift of bottom Mediterranean water (i.e., the EMDW), flowing westward from the base of the Malta canyons (~ 800 m depth) and crossing the sill of the Channel of Sicily (50-100 m depth).

The novelty that we introduce is the inclusion of realistic perturbations occurring at the sea surface layer, such as large-scale meteorological effects, that generalize the classic Bernoulli suction effect (Siddall et al., 2002; Smeed et al., 2004), already applied to Central

Mediterranean Sea water mass exchanges (Astraldi et al., 2001; Falcini and Salusti, 2015; See Box 2).

A multi-layer model for hydraulic exchange including storm-induced perturbation.

To analyze the uplift of a bottom current crossing a channel as a theoretical model for dynamics of multi-layers flowing over a sill (Box 2) we considered the *1D* dynamics along the channel direction*x*, i.e., the eastward along-strait coordinate for the Strait of Sicily (or other Mediterranean straits).



Box 2. *The multi-, coupled-layer Bernoulli model (from Lane-Serff et al., 2000)*

We then consider three immiscible layers of different uniform density ρ_i,for i= 1,2,3.The layer vertical thicknesses are h_i and velocities in each layer are u_i. These velocities and layer thickness are inherited bounded by the total flux water conditions at the domain boundaries, i.e., $Q_i = u_i\,(h_i - h_{i+1})$.

The total depth, i.e., the sea bottom depth, of the channel is (Box 2)

$$b(x) = h_1(x) + h_2(x) + h_3(x). \qquad (1)$$

In presence of a large-scale storm, with strong horizontal winds schematized as a simple $T(t)$, and considering $p_0/\rho^* \approx const$, the model equation for the surface layer (Lane-Sherf et al., 2000;) is

$$\partial u_1/\partial t + \partial (u_1{}^2/2 + p_0/\rho^*)/\partial x = T(t), \tag{2}$$

which can be analytically solved and gives

$$u_1 = x^2/t + \int^t{}_0 T(t')dt' + const = x^2/t + \Phi(t) \tag{3}$$

where $\Phi(t)$ plays the role of a forcing that contributes to the upper layer velocity evolution. For the second layer, in turn, one has (Box 2):

$$\partial u_2/\partial t + \partial (u_2{}^2/2 + p_0/\rho^* - g_1'h_1)/\partial x = 0 \quad , \tag{4}$$

where the effect of an eventual storm appears in the term $g_1' h_1$, which also contributes to the LIW velocity (u_2).

Finally, for the lowest layer, one has (Box 2):

$$\partial u_3/\partial t + \partial [u_3^2/2 - g_1'h_1 - g'_2(h_1+h_2)]\partial x = 0 \tag{5}$$

where the effect of the storm appears in the forcing $g_1'h_1 + g'_2(h_1+h_2)$.

The inherited link between the layer thickness h_1 and its velocity u_1 for a constant water flux (i.e., $u_1 (h_1 - h_2) = Q_1$) gives that the storm-induced velocity perturbation $u_1 \rightarrow u_1 + \int T(t')dt'$ affects the bottom layer dynamics, increasing its momentum (Box 3).

Conclusions

Starting from the classic multi-layer Bernoulli equations for hydraulic exchange flows, here we introduce an additional forcing acting on the sea surface layer, that represents non steady perturbations such as storm or wind-induced phenomena. From the coupling of different layers that is due to the pressure distribution along the water column, and by explicitly solving the perturbed upper layer velocity, we include the upper layer perturbation within the bottom layer Bernoulli equation. Our mathematical approach, therefore, can describe the ability of a sea surface non-steady perturbation to propagate to the bottom layer, providing additional momentum to uplift of the bottom current. Our discussion can be generally applied for similar hydraulic system, such as the sill of Gibraltar, outflowing westward towards the Atlantic Ocean (Artale et al., 2006).

The mechanistic understanding of uplifting phenomena may improve knowledge on the thermodynamic processes (e.g., heat storage) occurring at the bottom layers for the Mediterranean system (Artale et al., 2019).

IMPULSIVE EFFECTS ON BOTTOM CURRENT UPLIFT

The storm affects the deep currents in terms of surface forcing

Perturbing effect of a large scale storms

large-scale storm with strong horizontal winds schematized as $T(t)$:

$$\partial u_1/\partial t + \partial (u_1^2/2 + p_0/\rho)/\partial x = T(t) > 0$$

Upper layer

$$u_1 = x^2/t + \int_0^t T(t')dt' + const = x^2/t + \Phi(t)$$

where $\Phi(t)$ is the forcing that increases the upper layer velocity

$$\partial u_3/\partial t + \partial [\, u_3^2/2 - g_1'h_1 - g'_2(h_1+h2)\,]\, \partial x = 0$$

Lowest layer

For a conserved flux Q_i, layer velocity u_i and thickness h_i are strictly connected:

$$u_1(h_1 - h_2) = Q_1 = cost$$

the storm appears in the forcing $g_1'h_1 + g'_2(h_1+h2)$.

Box 3.*A storm-induced perturbation in the Bernoulli upper layer equation propagates to the bottom layer momentum*

References

Artale, V., Calmanti, S., Malanotte-Rizzoli, P., Pisacane, G., Rupolo, V., &Tsimplis, M. (2006). The Atlantic and Mediterranean Sea as connected systems. In Developments in Earth and Environmental Sciences (Vol. 4, pp. 283-323). Elsevier.

Astraldi, M., Gasparini, G. P., Gervasio, L., &Salusti, E. (2001). Dense water dynamics along the Strait of Sicily (Mediterranean Sea). Journal of physical oceanography, 31(12), 3457-3475.

Bellacicco, M., Anagnostou, C., Falcini, F., Rinaldi, E., Tripsanas, K., &Salusti, E. (2016). The 1987 Aegean dense water formation: A streamtube investigation by comparing theoretical model results, satellite, field, and numerical data with contourite distribution. Marine Geology, 375, 120-133.

Bensi, M., Velaoras, D., Meccia, V. L., & Cardin, V. (2016). Effects of the Eastern Mediterranean Sea circulation on the thermohaline properties as recorded by fixed deep-ocean observatories. Deep Sea Research Part I: Oceanographic Research Papers, 112, 1-13.

Iudicone, D., BuongiornoNardelli, B., Santoleri, R., &Marullo, S. (2003). Distribution and mixing of intermediate water masses in the Channel of Sicily (Mediterranean Sea). Journal of Geophysical Research: Oceans, 108(C9).

Lane-Serff, G. F., Smeed, D. A., &Postlethwaite, C. R. (2000). Multi-layer hydraulic exchange flows. Journal of Fluid Mechanics, 416, 269-296.

Sparnocchia, S., Gasparini, G. P., Astraldi, M., Borghini, M., &Pistek, P. (1999). Dynamics and mixing of the Eastern Mediterranean outflow in the Tyrrhenian basin. Journal of Marine Systems, 20(1-4), 301-317.

Falcini, F., &Salusti, E. (2015). Friction and mixing effects on potential vorticity for bottom current crossing a marine strait: an application to the Sicily Channel (central Mediterranean Sea). Ocean Science, 11(3).

Siddall, M., Smeed, D. A., Matthiesen, S., &Rohling, E. J. (2002). Modelling the seasonal cycle of the exchange flow in Bab el Mandab (Red Sea). Deep Sea Research Part I: Oceanographic Research Papers, 49(9), 1551-1569.

Smeed, D. A. (2004). Exchange through the Bab el Mandab. Deep Sea Research Part II: Topical Studies in Oceanography, 51(4-5), 455-474.