THE INFLUENCE OF TIDES ON THE EXCHANGE THROUGH THE STRAIT OF GIBRALTAR AND ON PROPERTIES OF THE MEDITERRANEAN SEA

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INTRODUCTION.

The baroclinic nature of the exchange through the Strait of Gibraltar (SoG) is ultimately forced by the buoyancy losses within the Mediterranean Sea (MS) that drives the anti-estuarine thermohaline circulation of this sea. It is an open convective cell that starts and ends in the SoG with the inflow of Atlantic water (AW) and the outflow of Mediterranean water (MW), respectively. As the latter is formed within the sea, the SoG and the MS form an indivisible system. If the only force acting were a steady buoyancy flux to the atmosphere, the MS would tend to the overmixing limit (Bryden and Stommel, 1984), where the density difference between AW and MW reaches the minimum, and the inflow and outflow the maximum value (maximal exchange) consistent with the internal hydraulic of the strait. The average properties of the MS will be determined by the size of the buoyancy losses and the geometry and internal hydraulics of the SoG. Farmer and Armi (1986) and Armi and Farmer (1986) showed that, for the SoG bathymetry, the maximal exchange implies the presence of hydraulic control in two notable topographic sections: minimum width (Tarifa Narrows, TN, Fig. 1) and minimum cross-area and depth (Camarinal sill, CS). Using a maximal exchange two-layer model, a realistic configuration of SoG and taking the density difference as $\Delta\rho = \rho_0 \beta \Delta S$ (ΔS the salinity difference and β the haline contraction of sea water) Bryden and Kinder (1991) fully resolved the exchange, giving the inflow, outflow and ΔS in terms of the net evaporation over the MS uniquely, which becomes the proper reservoir condition to be imposed on the steady, two-layer maximal exchange problem. If ΔS is small compared with S_A, (the Atlantic salinity, assumed given), then $\Delta S \approx 2.7\ E^{2/3}$, E being the evaporation over the MS in $m\ yr^{-1}$.

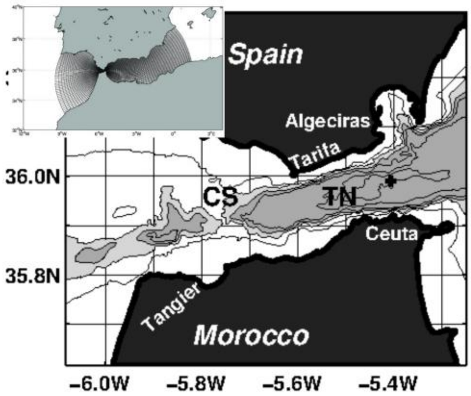

Figure 1.- Map of the Strait of Gibraltar. The inset in the top shows the spatial extension of the numerical model

THE EFFECT OF TIDES ON THE EXCHANGE.

The simple analysis by Bryden and Kinder neglects effects such as the thermal contraction to $\Delta\rho$ that may be 20% the effect of ΔS, and also tides, on which this study focus on. Theoretical (Farmer and Armi, 1986; Helfrich, 1995), laboratory (Helfrich, 1995) and numerical (Sannino et al., 2004) works show that tides interact with and modify the long-term exchange, the most remarkable result being the increase of the mean exchange. As far as the MS and the SoG are coupled parts of a unique system, the modification must affect other long-term properties or processes of the MS whose identification is the objective of this study. We use the numerical model of the exchange used in Sanchez-Garrido et al (2011) that was run with and without tidal forcing (TIDE and NOTIDE runs, respectively). Both simulations include meteorological forcing, the models were run to simulate year 2011 and the outputs compared to infer the effects of tides in different processes (see oceano.uma.es/sampa-gofima for the performance of the model). Next we present the main results.

Tides increase the mean exchange:

Figure 2 shows the Mediterranean transport estimated as a function of the isohaline used to separate AW and MW. The isohaline that maximizes the transport is the most suitable interface and this maximum transport is considered as the outflow. The procedure

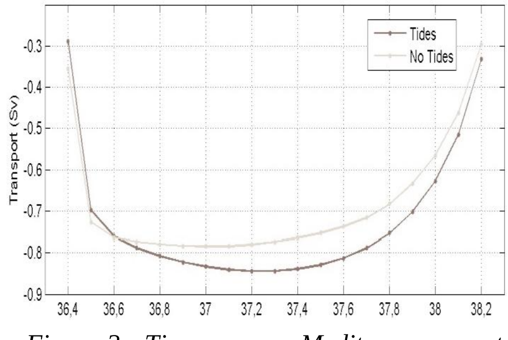

Figure 2.- Time-average Mediterranean outflow at CS computed using different isohalines as interface. Tides (dark line) increase the outflow by ~10%.

avoids *a-priori* assumptions about which isohaline is the interface and has been used in previous works (Garcia Lafuente et al., 2000; Baschek et al, 2001). Tides increase the value of the salinity that acts as interface with regards to the NOTIDE run, a result of enhanced mixing. More importantly, TIDE run increases the outflow by around a 10% (see also Table 1). The inflow (not shown) is a mirror image. The last physical mechanism behind this increase is the positive correlation between tidal currents and interface oscillations (eddy-fluxes), a mechanism that is enhanced during spring-tide periods.

Tides help ventilate the Western Mediterranean Deep Water (WMDW)

Several papers have addressed the question of the aspiration of deep MW from the MS over CS and then to the Atlantic Ocean (Stommel et al., 1973; Bryden and Stommel, 1982; Whitehead, 1985; Naranjo et al., 2012). The invoked mechanism is Bernoulli aspiration due to the spatial acceleration underwent by the MW undercurrent as it goes through the SoG. As far as tidal forcing increases the intensity of the total current, it should also increase the amount of WMDW ventilated, since Bernoulli suction allows now for WMDW aspiration from deeper levels. Table 1 shows that TIDE run fulfills the expectations. The flow of WMDW with potential temperature ϑ<13ºC increases by ~20%, not only in the very strait (second row) but also in the Alboran Sea (AS) in the MS. The increase is noticeably higher if we consider ϑ<12.9ºC, an isotherm often used to identify WMDW. In both cases it, is much higher than the increase of 8.2% estimated for the outflow, which is interpreted in terms that tides favors the deep ventilation.

Location	Q_{TIDE} (Sv)	Q_{NOTIDE} (Sv)	$\lvert\Delta Q\rvert$ (Sv)	ΔQ (%)
Outflow CS (total outflow)	*-0,85*	*-0,78*	*0,07*	*8,2%*
Eastern SoG (5.3ºW, ϑ<13ºC)	*-0,233*	*-0183*	*0,050*	*21,5%*
Western AS (3ºW, ϑ<13ºC)	*-0,253*	*-0,204*	*0,049*	*19,4%*
Eastern SoG (5.3ºW, ϑ<12.9ºC)	*-0,067*	*-0,038*	*0,029*	*43,3%*
Western AS (3ºW, ϑ<12.9ºC)	*-0,070*	*-0,047*	*0,023*	*32,9%*

Table 1.- Outflow computed from TIDE and NOTIDE runs. First row is the total outflow, second and third rows are the outflow of MW cooler than 13ºC (potential temperature) slightly eastward of TN (Fig.1) and at 3ºW in the MS. Fourth and fifth rows repeat the results for ϑ<12.9ºC.

Tides thicken the interface layer within the SoG

Although strongly stratified, the SoG is far from being a two-layer system. A realistic model must include a transitional interface layer originated in the mixing of both water masses. This layer is relevant for marine biology as it facilitates the nutrient availability in the photic layer, particularly in the eastern part of the Strait where the interface layer shallows, an issue addressed in some detail in Garcia Lafuente et al. (2013). Figure 3 shows the interface thickness and depth (both parameters estimated from the fitting of a hyperbolic tangent function to vertical salinity profiles as described in Sannino et al, 2007) for NOTIDE/TIDE runs. The influence of tides is particularly clear in the eastern SoG where the interface is brought to the surface and thickened. A consequence of these features is that the volume of water carried within the interface layer, which flows towards the MS east of CS (Bray et al., 1995), is largely increased at the eastern part of the SoG (+0.09Sv in NOTIDE *versus* +0.32Sv in TIDE runs) which partially compensates the increase of WMDW in the opposite direction in the case of TIDE run indicated in Table 1.

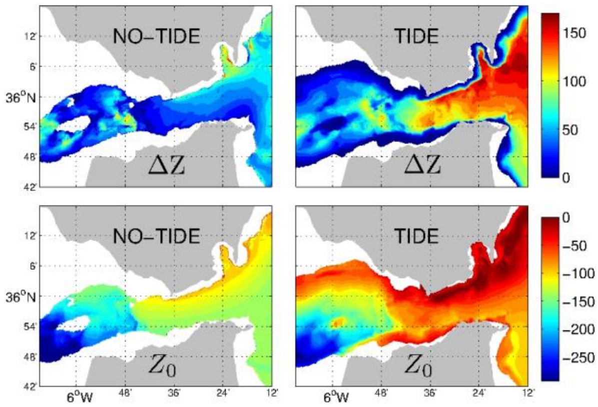

Figure 3.- Interface thickness (upper panels) and depth (lower panels) for NOTIDE and TIDE runs. Color bar on the right is m. Depth coincides roughly with the vertical position of the mid-interface.

Tides make the inflow of AW be colder and saltier

Figure 4 is the sea surface temperature (SST) difference between TIDE and NOTIDE runs (TIDE minus NOTIDE) in the AS. Modeled data correspond to September-December of year 2011 and the map shows the time averaged difference. The region under the direct influence of the AW inflow in the vicinity of the SoG is clearly cooler in the TIDE run, with differences as high as -4ºC. The differences fade out to the east but are still detectable (around -0.5ºC) in the easternmost part of the map along the African shore, where the Algerian current carries AW to the interior of the MS. Although not showed, salinity distribution resembles SST, the water being saltier in the TIDE simulation. It is timely to point out that Mikolajewicz (2011), in a paleoclimate study of the Mediterranean Sea, found that the SST hindcast by his model, which was not forced by tides, was greater than the observations, a fact that he ascribed to the absence of tidal forcing.

The fact that AW moving to the interior of the MS is cooler and saltier (i.e., denser) may have profound implications in other large scale processes occurring in the MS, such as the amount and sinking depth of the WMDW formed in winter in the Gulf of Lions. Actually, the higher density predicted by TIDE run represents an effective pre-conditioning of the AW that now requires less buoyancy losses to reach the density needed for deep convection. The issue is further addressed in Sannino et al. (2013, in preparation) who shows that the area of deep convection, the volume of WMDW formed and the maximum convection depth, all them are sensitive to the inclusion of tides.

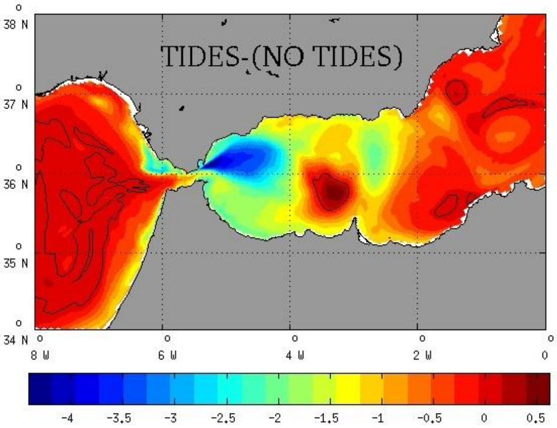

Figure 4.- SST difference between TIDE and NOTIDE runs in the AS

ACKNOWLEDGMENTS

Financial support from the Spanish Government Project CTM2010-21229 is acknowledged. We are grateful to G. Sannino for their help and useful comments in the development of the numerical models used in this work.

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