J. Black Sea/Mediterranean Environment
Special Issue: 110-116 (2015)

Recent advancements on modelling the exchange flow dynamics through the Turkish Straits System

Gianmaria Sannino[1*], **Adil Sözer**[2], **Emin Özsoy**[2]

[1] ENEA, via Anguillarese 301, 00123, Rome, ITALY
[2] Institute of Marine Sciences, Middle East Technical University (IMS-METU), Erdemli, Mersin, TURKEY

[*]**Corresponding author:** gianmaria.sannino@enea.it

Abstract

The system composed by the two narrow Straits, Dardanelles and Bosphorus, and the Marmara Sea is known as the Turkish Straits System (TSS). The scientific questions on the role of the TSS in coupling the adjacent basins of the Mediterranean and Black Seas with highly contrasting properties and in a region of high climatic variability can only be answered by model predictions of the processes that determine the integral properties of the coupled sub-systems. This can only be achieved if the entire TSS is modeled as a finely resolved integral system that appropriately accounts for the high contrasts in seawater properties, steep topography, hydraulic controls, fine and meso-scale turbulence, nonlinear and non-hydrostatic effects, thermodynamic states and an active free-surface in the fullest extent, based on well represented fluid dynamical principles. In this study the MITgcm (MIT General Circulation Model) is used at very high resolution to study this extreme environment that needs to be represented as a whole and with the full details of its highly contrasting properties. The capability of MITgcm to represent the two-layer exchange dynamics both in the straits and in the Marmara Sea is examined. The non-uniform grid and the vertical resolution implemented have demonstrated to be suitable to capture the fine scales within the two Straits and also to well represent mesoscale in the Marmara Sea. The response of the currents and density structure over the water column to different net flow is also examined through the setup of experiment with varying net barotropic volume fluxes.

Keywords: numerical ocean modelling, Turkish Straits System, Bosphorus, Marmara Sea, Dardanelles

Introduction

The Turkish Straits System (TSS) consists of the Sea of Marmara connecting to the Aegean and Black Seas respectively through the Dardanelles (length 75 km, min. width 1.3 km) and Bosphorus (length 35 km, min. width 0.7 km) Straits. The Marmara Sea has three elongated depressions (max. depth ~1350 m) interconnected by sills (depth ~600 m) and adjoining continental shelves. The nonlinear, turbulent, strongly stratified hydrodynamics of the flow through the narrow straits has made the modeling of the TSS a grand challenge. The coupling of the adjacent basins of highly contrasting properties, in a region of extreme hydro-climatic variability can only be achieved if the entire TSS is modelled as a finely resolved integral system, accounting for steep topography, nonlinear hydraulic controls and turbulent mixing processes, as well as an active free-surface. The nonlinear, turbulent, strongly stratified hydrodynamics of the flow through the narrow straits has made the modeling of the TSS a grand challenge. Here, thanks to a PRACE (Partnership for Advanced Computing in Europe) infrastructure this grand challenge has been achieved. In the following we describe and validate the TSS model together with a discussion on some preliminary results.

Data and Methods

In this work the MITgcm model (http://mitgcm.org) is used to study TSS with full details of its contrasting properties. The model domain chosen extends over the entire TSS, including also parts of the north-east Aegean Sea and the Black Sea at its two ends (Figure 1). A non-uniform curvilinear orthogonal grid covers the domain at variable resolution: from less than 50 m in the two Straits up to about 1 km in the Marmara Sea. To adequately resolve the complex hydraulic dynamics of the TSS, the model grid is made by 100 inhomogeneous distributed vertical z-levels. The thickness exponentially ranges from 1.2 m at the surface to 80 m at the bottom with most of the levels concentrated in the first 100 m.

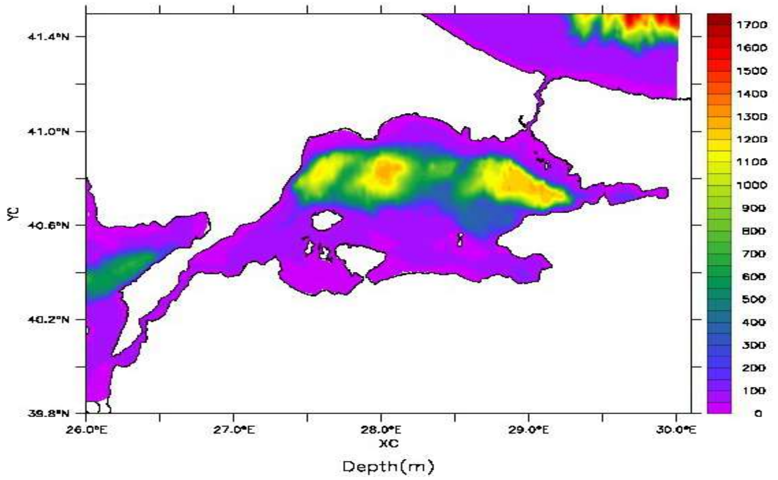

Figure 1. Model bathymetry (colorbar: depth in m)

The very high horizontal resolution adopted in MITgcm, together with the partial cell formulation result in a very detailed description of the bathymetry. The model has been initialized with three different water masses filling the western part of the domain, the Marmara Sea and the eastern side of the domain respectively, with vertical profiles selected from CTD casts obtained during the cruise of the R/V BILIM of the Institute of Marine Sciences in June-July 2013. With the initial condition specified as lock-exchanges at the two straits, the model is left free to adjust to the expected two-way exchange. No-slip conditions were imposed at the bottom and lateral solid boundaries.

Results

The non-uniform curvilinear orthogonal grid and the vertical resolution implemented have demonstrated to be sufficient to capture the fine scales within the two Straits and also to well represent mesoscale in the Marmara Sea. The response of the currents and density structure over the water column to different net flow is also examined through the setup of experiments with varying net barotropic volume flux values (Q=-9600, 0, 5600, 9600, 18000 and 50000 m^3/s respectively). The expected range of fluxes for testing the TSS behavior with respect to barotropic net flows were guided by our earlier experience based on frequent sampling by past field experiments using in-situ ADCP and CTD measurements of the strait hydrography and currents, covering the TSS under normal and extreme climatic conditions (Beşiktepe *et al.* 1994; Özsoy *et al.* 1998; Gregg *et al.* 2002). Positive values of Q represent flow from the Black Sea towards the Mediterranean, while negative values represent net flow in the opposite direction. The free surface variations in the Marmara Sea, corresponding to configurations initialized with vertical profiles representative of the three basins selected from CTD casts in June-July 2013 and variable values of net barotopic flow values are shown in Figure 2.

Discussion

For the studied flows, characterized to be driven exclusively by the imposition of net flux, an S-shaped current, first moving south from the Bosporus, later turning northwest and finally exiting from the from the Dardanelles Strait, appears to be the basic character of the circulation. With a negative flux of Q=-9600 m^3/s, such that the net flow is towards the Black Sea, the upper layer flow from the Bosphorus into the Marmara Sea is still positive, and sufficient to generate an anticyclonic net circulation in the midst of the Marmara Sea, as shown in Figure 2. For zero net flux, the same structure is preserved and as the positive values of the barotropic flux is increased further the size of the central gyre is reduced and the flow becomes increasingly more attached to the northern coast of the Marmara Sea. As the flux is increased to 9600 m^3/s, the central anticyclonic circulation cell takes an elongated form. For the extreme flux values of Q=18000 m^3/s and Q=50000 m^3/s, the lower layer flow in the Bosphorus becomes blocked, and qualitative changes occur in the circulation of the Marmara Sea, with a smaller anticyclone near the Bosphorus exit, a jet attached to the northern coast, and a secondary anticyclone further west, and a cyclonic circulation emerging in the south. For these cases, the circulation pattern looks more like the buoyancy driven flow along the coast adjacent to the mouth of a river. The generation of a basic anticyclonic circulation in the Marmara Sea for lower net fluxes, evolving towards a more balanced circulation of cyclonic-anticyclonic eddies appears to be a result of the vorticity balance of the basin.

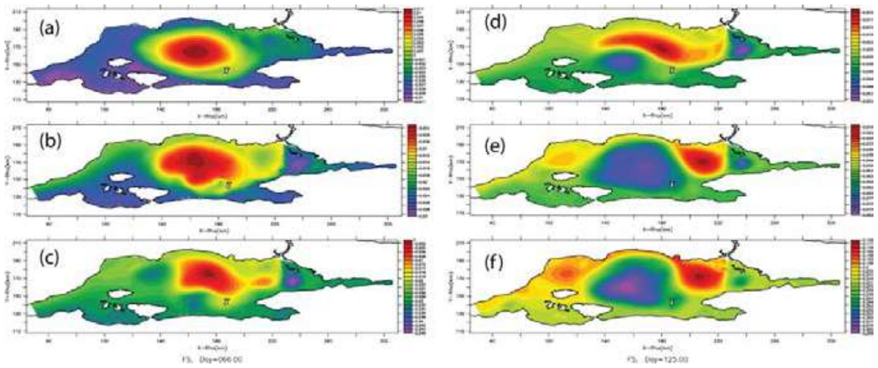

Figure 2. The free surface variations in the Marmara Sea for varying net barotropic volume flux values of:

(a) Q = -9600 m^3/s, day=67, range=2.2 cm
(b) Q = 0 m^3/s, day=100, range=2.7cm
(c) Q = 5600 m^3/s, day=66, range=4.5 cm
(d) Q = 9600 m^3/s, day=22, range=4.8 cm
(e) Q = 18000 m^3/s, day=65, range=6.4 cm
(f) Q = 50000 m^3/s, day=125, range=12.0 cm

As shown by Spall and Price (1998), and studied by Morrison (2011), the net basin circulation is sensitively determined by the potential vorticity (PV) imports and exports of the basin. From this point of view, the reduction of interface depth (or upper layer thickness) from the Black Sea to the Marmara Sea implies a decrease in fluid vorticity, or anticyclonic circulation assuming the input to have zero vorticity. The behaviour of the buoyant plume entering the Marmara Sea, initially shooting south and hitting the opposite coast is displayed in all cases in Figures 2, although the later turning of the flow to the west is typical of buoyant plumes at this scale. Buoyant flows entering the sea are typically attached to the right hand coast (looking out from the exit in the northern hemisphere), especially for initial vorticity zero below a critical limit (e.g. Nof 1978; Stern *et al.* 1982). Often a bulge of the buoyant fluid is formed, as the flow turns right to follow the coast, as often observed at river mouths (e.g. Huq 2013). In a two-layer system with variable bottom topography and dynamically active layers, the circulation may develop differently, with topography influencing the lower layer flow, and the resultant interface topography influencing the upper layer flow (Beardsley *et al.* 1978). As the net flux is increased in Figure 2, the changes in the circulation pattern may be a result of this kind of interactive adjustment of the flow layers to bottom and interface topography. The qualitative change in the circulation towards a series of anticyclonic and cyclonic eddies following the meander of the currents, when the flux is increased to 18000 m^3/s and 50000 m^3/s is reminiscent of the Alboran

Sea, where similar gyres filling the basin develop under high fluxes (Spall and Price 1998).

Table 1. Sea level difference at both edges of the two straits as a function of net flux

Net flux Q (m^3/s)	Bosphorus (TSS) sea level difference $\Delta\eta$ (cm)	Dardanelles (TSS) sea level difference $\Delta\eta$ (cm)	Bosphorus (ROMS) sea level difference $\Delta\eta$ (cm)
-9600	2	1.5	-
0	8	5	14
5600	10	7	18
9600	14	11	22
18000	22	16	30
50000	85	32	-

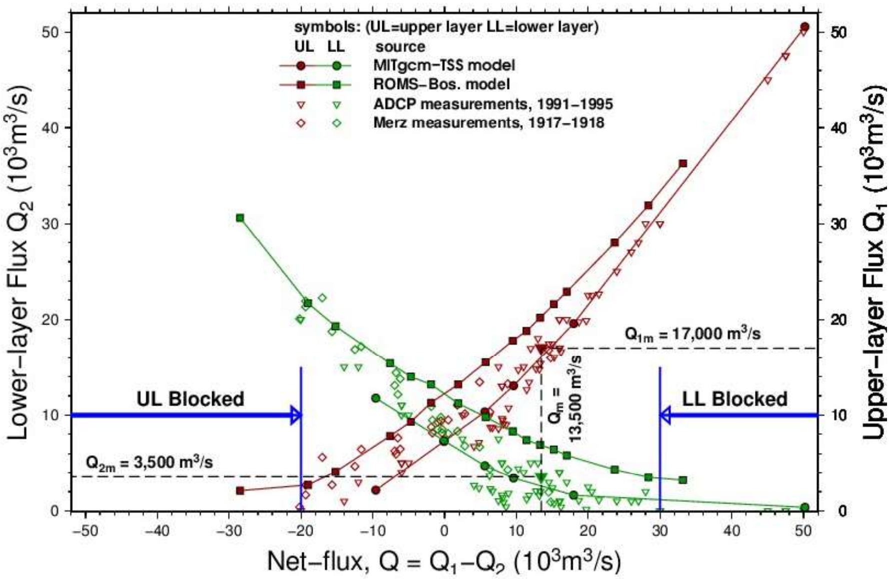

Figure 3. Upper-layer (Q_1) and lower-layer (Q_2) volume fluxes through the Bosphorus as a function of the net flux ($Q=Q_1-Q_2$), based on observational data and compared with the results from the Bosphorus model (ROMS) of Sözer (2013) and the TSS (MITgcm) models

The sea level differences that develop at the two straits, Bosphorus and Dardanelles are given in Table 1, in relation to the net barotropic fluxes and the values obtained from the TSS model are compared with the ROMS model results for the Bosphorus (Sözer 2013). While the total range of sea level in the Marmara Sea between cyclonic and anticyclonic areas varies between 2-12 cm (Figure 1), the net sea level differences across straits are much larger, varying between 2-85 cm in the Bosphorus and 1-32 cm in the Dardanelles, while the results for the Bosphorus compare well between the two models. These results would imply sea level differences of about 0-120 cm between the Black Sea and the Aegean Sea, for the range of net transport tested. Finally a comparison is made of the upper-layer (Q_1) and lower-layer (Q_2) volume fluxes through the Boshorus (Figure 3), based on observational data and the results from the Bosphorus model (ROMS) of Sözer (2013) and the TSS (MITgcm) models. Although the Bosphorus model is more specific to the Strait and has better resolution, the TSS model results perform even better in comparison with observations.

References

Beardsley, R.C., Hart, J. (1978) A simple theoretical model for the flow of an estuary on to a continental shelf. *J. Geophys. Res.* 83:873-883.

Beşiktepe, Ş., Sur, H.İ., Özsoy, E., Latif, M.A., Oğuz, T., Ünlüata, Ü. (1994) The circulation and hydrography of the Marmara Sea *Prog. Oceanogr.* 34: 285-334.

Gregg, M.C., Özsoy, E. (2002) Flow, water mass changes and hydraulics in the Bosphorus. *J. Geophys. Res.* 107(C3): doi:10.1029/2000JC000485.

Huq, P. (2013) Buoyant outflows to the coastal ocean. In: Handbook of Environmental Fluid Dynamics, Volume One, (ed. H. J. S. Fernando). CRC Press / Taylor & Francis Group, LLC, 1, pp. 207-215.

Morrison, A. (2011) Upstream Basin Circulation of Rotating, Hydraulically Controlled Flows, 2011 Summer Program in Geophysical Fluid Dynamics, WHOI, 429 pp.

Nof, D. (1978) On geostrophic adjustment in sea straits and wide estuaries: theory and laboratory experiments. part ii – two-layer system. *J. Phys. Ocean.* 8: 861-872.

Özsoy, E., Latif, M.A., Beşiktepe, S., Çetin, N., Gregg, N. Belokopytov, V., Goryachkin, Y., Diaconu, V. (1998) The Bosphorus Strait: exchange fluxes, currents and sea-level changes. In: Ecosystem Modeling as a Management Tool for the Black Sea, NATO Science Series 2 (eds., L. Ivanov, T. Oğuz): Environmental Security 47, Kluwer Academic Publishers, Dordrecht, pp. 1-26

Sözer, A. (2013) Numerical Modeling of the Bosphorus Exchange Flow Dynamics, Ph.D. thesis, Institute of Marine Sciences, Middle East Technical University, Erdemli, Mersin, Turkey.

Spall, M., Price, J.F. (1998). Mesoscale variabilty in Denmark Strait: the PV outflow hypothesis. *J. Phys. Ocean.* 28:1598-1623.

Stern, M., Whitehead, J., Hua, B. (1982) The intrusion of a density current along the coast of a rotating fluid. *J. Fluid Mech*. 123:237-265.