ON WATER TRANSPORT VARIABILITY OF THE BOSPHORUS STRAIT

Murat GÜNDÜZ [1,*] and Emin ÖZSOY [2, 3]

[1]Institute of Marine Sciences and Technology, Dokuz Eylül University, İzmir, Turkey
[2]Eurasia Institute of Earth Sciences, İstanbul Technical University, İstanbul, Turkey
[3]Institute of Marine Sciences, Middle East Technical University, Mersin, Turkey
[*]murat.gunduz@deu.edu.tr

1. Introduction

The exchange of water between the Black Sea and the Aegean Sea occurs through the Turkish Straits System (TSS) (Figure 1). The properties and volume of the transported water crucially depend on the circulation and mixing processes throughout the system, as well as the water, heat and salt fluxes and mixing in the adjacent basins (Yüce 1993; Özsoy 1993; Özsoy *et al.* 1995, 1996, 1998; Jarosz *et al.* 2011a, 2011b, 2012).

Fast counter-flowing currents as a function of depth develop especially in the narrow Bosphorus and Dardanelles Straits and their exit regions. The exchanges in the two straits are stratified turbulent flows creating entrainment and mixing between the oppositely directed currents (Gregg and Özsoy 1999, 2002; Özsoy *et al.* 1996, 1998, 2001). Surface buoyant jets and bottom gravity currents develop in the exit regions of straits joining the adjacent basins (Oğuz 1990; Latif *et al.* 1991; Beşiktepe *et al.* 1993; 1994; Özsoy *et al.* 2001). All these studies show that the greatest modifications in seawater properties occur inside the straits and in their exit regions, as a result of turbulence, buoyant spreading and mixing processes.

Since dynamical processes and mixing at the two straits influence the interior circulation and material transports in the coupled basins of the Aegean, Marmara and Black Seas (e.g. Beşiktepe *et al.* 1993, 1994; Özsoy *et al.* 1993; Özsoy and Ünlüata 1997, 1998; Rank *et al.* 1998; Özsoy *et al.* 2002; Androulidakis *et al.* 2012a; Delfanti *et al.* 2013), they also imply how open boundary conditions should be applied in individual models of the Mediterranean and Black Seas. The understanding and accurate estimation of the volume and properties of the water transport through the Bosphorus and Dardanelles Straits are therefore essential for proper modeling of the adjacent seas, and the same is even more true for the particular case of the Marmara Sea. Further critical applications can be in relation to influences on the Mediterranean, such as in the case of the Eastern Mediterranean Transient (EMT) (Roether *et al.* 1996). One of the possible mechanisms leading to the EMT has been claimed to be the decrease in the amount of the BSW entering the Aegean Sea during the EMT period (Zervakis *et al.*

2000; Androulidakis *et al.* 2012b). Understanding the variability of the BSW outflow to the North Aegean Sea is therefore essential for understanding of the regional hydro-climatic processes.

The inflow-outflow at the two Straits are shown to be the primary drivers of the quasi-permanent surface circulation in the Marmara Sea, based upon a model simulation integrated for 18 years (Demyshev *et al.* 2012). Because the surface circulation is confined within the upper layer of 25 m depth throughout the year, the response to wind-stress forcing tends to be rapid, resulting in smaller scale eddies with short-term variations, as shown by the observations (Beşiktepe *et al.* 1994) and modeling (Chiggiato *et al.* 2011). The latter authors implemented a three-dimensional ocean model (ROMS), which indicated excessive diapycnal mixing as compared to the sharp interface often observed at the halocline of the TSS.

The Black Sea Water (BSW) entering from the Black Sea to the Bosphorus Strait at the surface has salinity of 16-18, while the Mediterranean Water (MW) entering from the Aegean Sea at the Dardanelles Strait in the lower layer flow has salinity of about 38-39, reaching the Bosphorus lower layer flow with a salinity of about 38.5. Mass conservation at the Bosphorus implies a ratio of about 2 between the upper and lower layer volume fluxes, reflecting the excess of fresh water inputs (runoff and precipitation) into the Black Sea as compared to evaporation losses (Ünlüata *et al.* 1990). Similar to Bosphorous Strait, the properties of the water entering to the Dardanelles Strait experience strong physical modification during its course. The Nara passage is the only hydrolic control on the water in this Strait. The upper and lower layer waters are mixed strongly in this narrow passage.

The circulation of the Marmara Sea is strongly coupled to the flow dynamics at the two Straits, where buoyancy and pressure forces are dominant. In addition to the simplified models individually applied to the Bosphorus (Oğuz *et al.* 1990; Ilıcak *et al.* 2009) and Dardanelles Straits (Oğuz and Sur 1989; Staschuk and Hutter 2001), modern three-dimensional primitive equation models have recently been developed for the Straits of Bosphorus (Sözer and Özsoy 2002; Oğuz 2005; Sözer 2013) and Dardanelles (Kanarska and Maderich 2008). Only a few of the model studies performed so far have attempted to realistically resolve either the complicated physics of the flow in the Straits, or its fine details as influenced by the steep topography; until the recent work of Sözer (2013), who used a high resolution 3-D model (The Regional Ocean Modelling System (ROMS)) for the Bosphorus, including a free surface and turbulent mixing parameterization. Observations of mixing along the Bosphorus Strait and reduced gravity modeling of the Mediterranean water outflow into the Black Sea by Özsoy *et al.* (2001) showed the importance of the hydraulic controls in the Strait and the narrow canyon (the 'pre-Bosphorus channel') leading up from the Black Sea entrance.

During exceptional conditions especially in winter time, the upper layer flow may be blocked (locally known as “Orkoz”) (Latif *et al.* 1991). Although there is modeling effort to create the blocking conditions by Sözer 2013, there is no clear understanding of the required forcing to generate the blocking events and mechanism behind the blocking conditions.

Modeling the TSS and its influence on the adjacent seas is a grand challenge for modelers (Chiggiato *et al.* 2013, Sözer 2013) because of the ultimate need to better resolve the coupled dynamics of the two large marine basins, the smaller Marmara Sea and narrow straits between them, subject to highly contrasting hydrological properties, complicated physics, extremes of climatic variability and the influences of the major hydro-meteorological drivers acting on the system. The modeling efforts concerning the TSS have so far only been able to surmount some of the initial aims of this potentially immense undertaking, through process oriented studies trying the limits of applicability of present ocean models. These studies consistently show the dynamical complexity of the exchange flows of the TSS.

Yet, there has been few attempts if any, to model the entire TSS as a coupled system with open boundary conditions specified at the adjacent Aegean and Black Seas, while keeping account of all the fine details of the narrow channels and topographic features at full resolution, the hydraulic controls, shallow shelf regions versus deep basins, at the same time adequately representing the turbulent mixing in the entire system. One of the difficulties inevitably to arise in the model is the ability to control of the sharply stratified density interface against excessive diapycnal mixing that would result from the possible inadequate representation of turbulence in the highly stratified environment.

In the present study we use the HYbrid Coordinate Ocean Model (HYCOM) as the model of choice, utilizing its simplified near-isopycnal dynamics and powerful vertical coordinate system most easily adapted to the existing conditions of the TSS. Making use of the unique features applicable to the highly stratified Marmara Sea, the high-resolution ocean model is configured for the entire TSS including the two Straits and its adjacent domains. By conducting model experiments, water transport and upper layer blocking dynamics at the Bosphorous Strait will be investigated.

2. Model Features and Set-up

2.1. Numerical Model

The HYCOM (Bleck 2002) is a three dimensional, isopycnal ocean model solving five prognostic equations: two for the horizontal velocity components, a mass continuity or layer thickness tendency equation and two conservation equations for a pair of thermodynamic variables, such as salt and potential temperature or salt and potential density. The HYCOM uses a generalized (hybrid isopycnal/terrain-following (sigma/z-level) coordinate system, so that it behaves like a conventional sigma coordinate (terrain-following) model in shallow regions, like a z-level (fixed-depth) coordinate model in the mixed layer or other unstratified regions, and like an isopycnic-coordinate model in stratified regions (e.g., Bleck 2006). The model uses the layer continuity equations to make a dynamically smooth transition to z-levels in the unstratified surface mixed layer and sigma levels in shallow water (Kara *et al.* 2010). The optimal coordinate is chosen at every time step, using a hybrid coordinate generator. The thickness of the model layers is adjusted according to target densities and the type of vertical coordinate. Figure 2 shows an example for the adaptation of the model layers. The model layer thickness changes in every model time step, as in the two cases shown in the figure for October 15 and November 10. The top four layers are based on z-levels following the topography near the coast, and in the deeper regions they approach isopycnal layers. The preservation of the stratification is evident in this figure. A time series of salinity in a station in the Marmara Sea (not shown) prove that the stratification conserved during the model integration.

The HYCOM model has been used in a wide range of applications varying from global oceans to regional seas. Among the recent studies using HYCOM, we can cite Chassignet *et al.* (2009) implementing a global system; Mehra and Rivin (2010), setting up a model of the North Atlantic Ocean; and Kara *et al.* (2005), who set up a regional version of HYCOM in the Black Sea. Gündüz and Özsoy (2014) studied the climatological Caspian Sea circulations by using HYCOM.

2.2 Application of HYCOM to the Marmara Sea

The model domain in Figure 1 a includes the TSS (Marmara Sea, Bosphorus Strait, Dardanelles Strait) accompanied by the western Black Sea and North Aegean Sea domains partially included to represent the influences of the neighboring seas. The model bathymetry is the combination of various sources, in which the GEBCO topography (Becker *et al.* 2009) has been blended with the available local data sets of high resolution. Detailed explanation for the processing of the bathymetric data can be found in Özsoy *et al.* (2001). Figure 1 b shows the detailed bathymetry of the Bosphorus Strait, where a good representation has been obtained of the contraction and sills of the Bosphorus Strait. It should be noted that the model bathymetry was smoothed by averaging the four neighboring points around the selected grid.

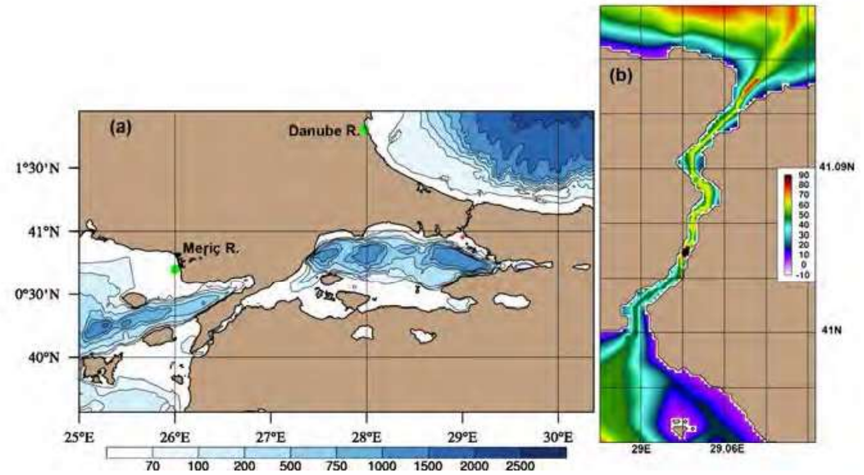

Figure 1. Geographical settings of TSS with (a) HYCOM-Marmara model domain and bathymetry (m), the green dots show the location of the river mouths used in the model and the red star at the Marmara Sea exit of the Bosphorus Strait is the station to generate the Figure 6. (b) detailed bathymetry of the Bosphorus Strait.

The model has 1/225° horizontal resolution, which nominally corresponds to about 400 m at the latitude of interest. The HYCOM TSS model has 10 vertical layers; four of which are at z-levels (mostly at the surface), while the rest are isopyncal layers. The model uses spatially varying isopycnal target densities, set between 11 to 28.6 in the Marmara Sea. The minimum thickness of the z-levels was set to 1.5 m, and the maximum was set to 15 m. Vertical mixing is parameterized by the Price-Weller-Pinkel Dynamical Instability Model (Price *et al.* 1986), with the critical Richardson number set to a value of 0.25. This parameterization performed better (not shown) than the other available parameterizations available in HYCOM (such as the K-Profile parameterization mixed layer model (KPP) and the NASA Goddard Institute for Space Studies (GISS) model). The baroclinic and barotropic time steps were set to 30 s and 1 s respectively.

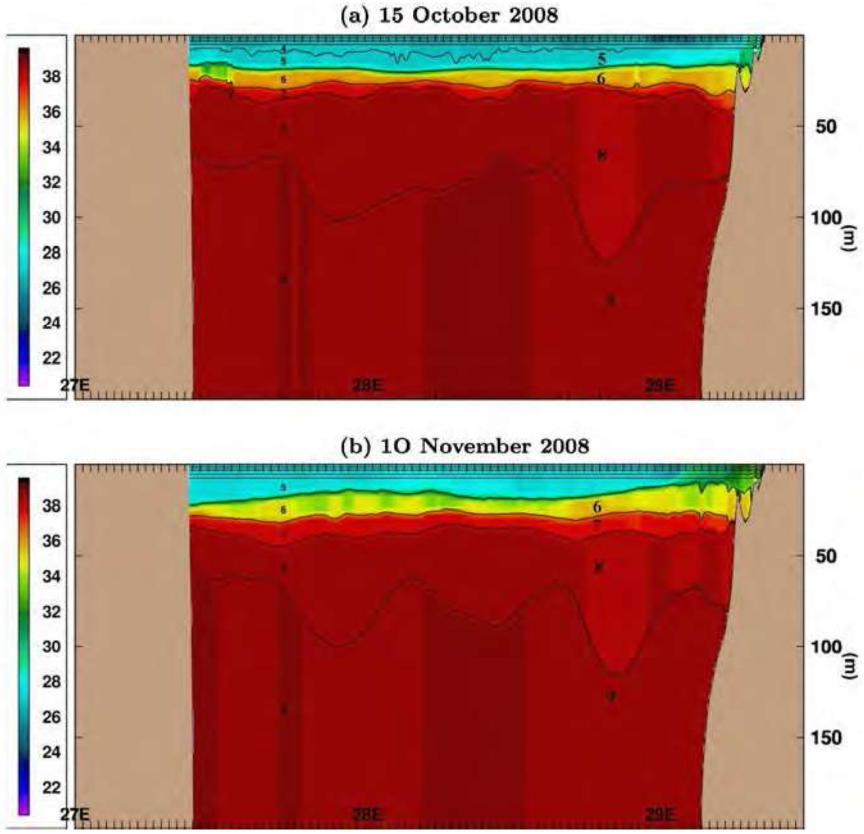

Figure 2. Zonal cross-section of salinity at 40.8° N (Northern Marmara Sea) for (a) 15 October 2008 (b) 10 November 2008. The layer numbers of the HYCOM–Marmara model were also shown.

The model was initialized with the in-situ CTD observations obtained during the September 2008 cruise (in the framework of the NATO TSS project, "Exchange Process in Ocean Straits", Book *et al.* 2014). The distinct properties of the adjacent basins of the Aegean, Marmara and Black Seas were represented by three profiles selected and applied uniformly in each of these seas. Figure 3 shows the temperature and salinity (T/S) profiles used to initialize the model. The salinity profiles indicate a strong pycnocline at a depth of ~20 m in the Marmara Sea (top), and a weaker one in the Black Sea (middle), while the Aegean Sea (bottom) has high salinity water with milder stratification.

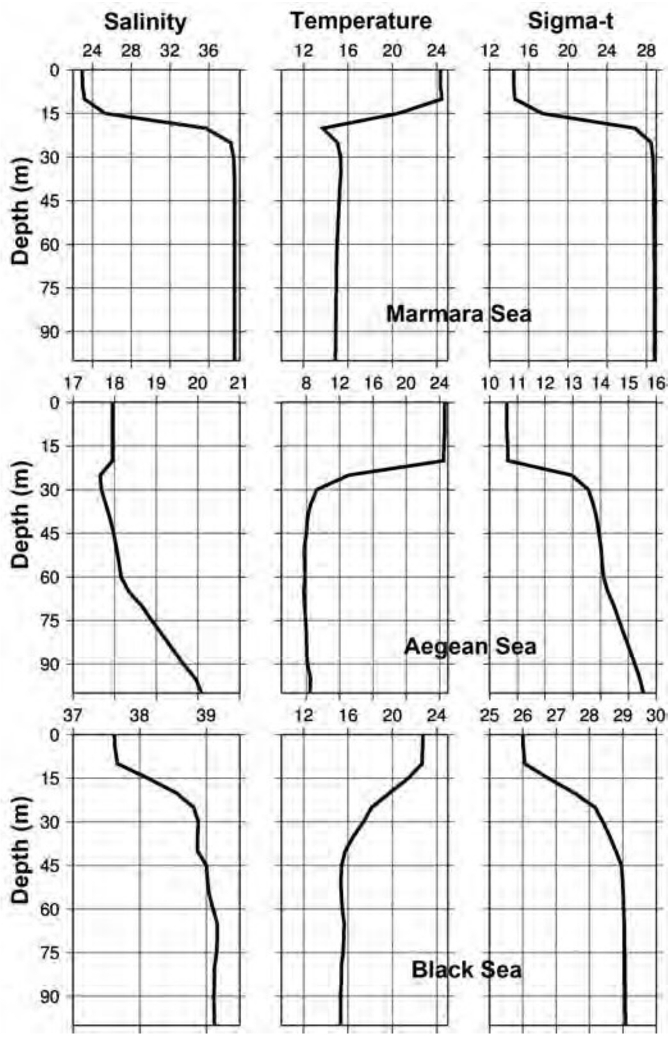

Figure 3. Temperature, salinity (used to initialize the model) and density (sigma-t) profiles. Upper: Marmara Sea, middle: Black Sea, lower: Aegean Sea. The profiles were selected from TSS September-2008 field experiment (NATO TSS project, "Exchange Process in Ocean Straits").

The World Ocean Atlas 2005 (WOA05 Antonov *et al.* 2005, Locarnini *et al.* 2005) gridded climatology data set (78 depth levels and 0.25^{o} horizontal resolution) was used to specify temperature and salinity at the open boundaries in the Black and Aegean Seas, where the model variables were relaxed over the twenty rows of grid points along the boundaries with e-folding time varying from 3 days to 30 days in the different runs. Since there is no available data for sea surface elevation, zonal and meridional velocities to force the model at the open boundaries, the model relax only temperature and salinity at the OBs.

The Danube River was included in the model, and treated as a precipitation source on the western Black Sea coast. The river discharge has been divided among the three branches of its delta and the river mouths have been extended up to 10 grid points for each branch. Considering the fact that the Danube river mouth is located out of model domain, half of the real climatological discharge was used. The climatological discharge rates were obtained from the RivDAS data (Vorosmarty *et al.* 1998).

The atmospheric forcing was specified based on the ECMWF Interim Re-Analysis (ERA-Interim, Dee *et al.* 2011) product, which has 1.125^{o} horizontal resolution at 3 hours time interval. The HYCOM only needs wind stress, precipitation, net heat flux and short-wave radiation to be specified for the calculation of air-sea bulk fluxes according to the methods explained in Kara *et al.* (2005).

Each model experiments integrated for five months starting from September 2008 until end of January 2009 which coincides with the available observations made by Jarosz *et al.* (2011).

Table 1. Calculated mean water transport (km^3/yr) in the Bosphorus Strait based on mass budget and long term salinity measurements estimation. Özsoy (1998) and Jarosz *et al.* (2011a) used ADCP observations to calculated the transport. Observation periods are shown in parenthesis.

	Upper Layer	**Lower layer**	**Net**
Ünlüata, 1990	612	312	300
Beşiktepe *et al.* 1994	603	303	300
Tugrul *et al.* 2002	639	318	321
Özsoy 1998 (six month)	540	115	425
Jarosz *et al.* 2011a (Sept. to Jan.)	375	253	122

3. Results

Past studies using different techniques have shown significant variations in transport in response to time-dependent hydro-meteorological events. Based on water balances of the Black and Marmara Seas and long term salinity measurements Ünlüata *et al.* (1990); Beşiktepe *et al.* (1994) and Tugrul *et al.* (2002) performed calculations of average water fluxes at exit sections of the straits. The fluxes at the Bosphorus Strait based on these studies are summarized in Table 1, indicating roughly about 600 km^3/yr for the upper layer flux, and about 300 km^3/yr for the lower layer flux. However, calculations based on various current measurements and modeling results show smaller values of transports. For example, ship-borne ADCP measurements (Özsoy *et al.* 1998) have found average fluxes of 540 km^3/yr for the upper layer and 115 km^3/yr for the lower layer. Based on six months of ADCP measurements, Jarosz *et al.* (2011) found an average upper layer flux of 375 km^3/yr and lower layer flux 253 km^3/yr. We note however, that ADCP measurements usually suffer from a loss of data near the bottom and the surface, which influences the accuracy of the flux estimates.

In general, the model generated volume fluxes are smaller than the average values obtained from measurements. There may be couple of explanations for this. First of all, the model integration periods coincide with the summer and autumn periods when the Black Sea outflow flux is at its lowest level (Beşiktepe *et al.* 1994), while the other values reported in Table 1 are based on annual averages. It should also be noted that the offset between the model and the observations may be related to the model, which underestimates the transport as a result of the artificially confined nature of the adjacent basins. Another important constrain of the model is that the model is non free surface which could influence the water transport significantly.

Figure 4 showing the model daily time series of Bosphorus fluxes display high levels of variability (negative values indicate flows in the direction from the Black Sea to the Marmara Sea). Time dependence of the flows in the Bosphorus may often result in short-term blocking events, resulting in the flow being stopped in either the upper or the lower layers, as shown by Latif *et al.* (1991) and Özsoy *et al.* (1998).

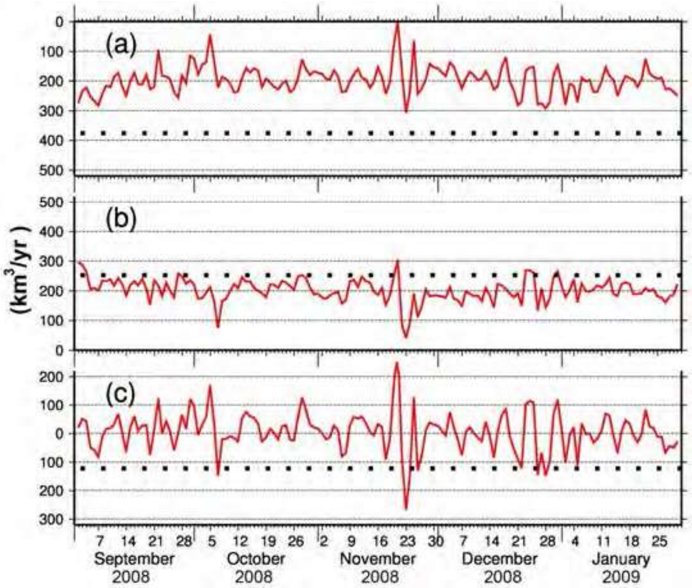

Figure 4. (a) Upper-layer (b) lower-layer (c) net daily water transport (km^3/yr) in the southern Bosphorus Strait from September 2008 to January 2009. The mean water fluxes calculated from the ADCP observation (Jarosz *et al.* 2011a) is shown as dotted line.

The salinity transect along the main axis of the Bosphorus Strait in Figure 5 a corresponds to the case of upper layer blocking in response to a storm with leading southwesterly winds. In Figure 5 b an example is given for the normal, two-layer flow regime in which both layers are active. Figure 5 c shows the salinity transect during a lower layer blocking period.

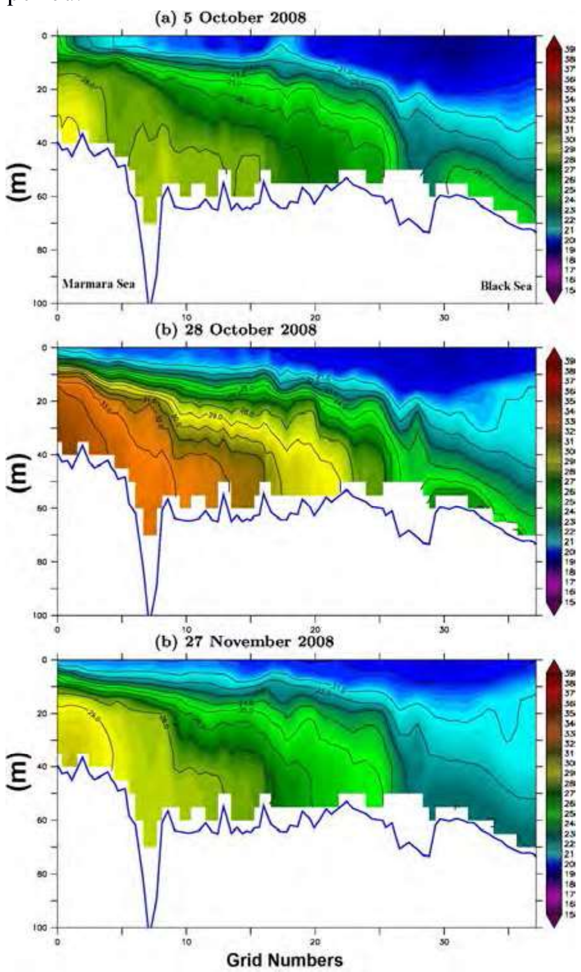

Figure 5. Salinity transect along the main axis of the Bosphorus Strait (a) Upper layer blocked (b) Normal conditions (c) Lower layer blocked. Left side is the Marmara Sea and the right side is the Black Sea.

The upper layer blocking events are evident in the model time-series of meridional velocity near the southern exit of the Bosphorus in Figure 6, when the upper layer currents are reversed (positive) and later followed by increased southward (negative) currents with increased depth for the next couple of days. Comparison of the model generated water transport with ADCP observations (Figure 2 in Jarosz *et al.*

2011) seems to indicate similarities in terms of the time dependence of events. For example, two cases of upper layer blocking events as shown in Figure 5a were also observed by Jarosz *et al.* (2011).

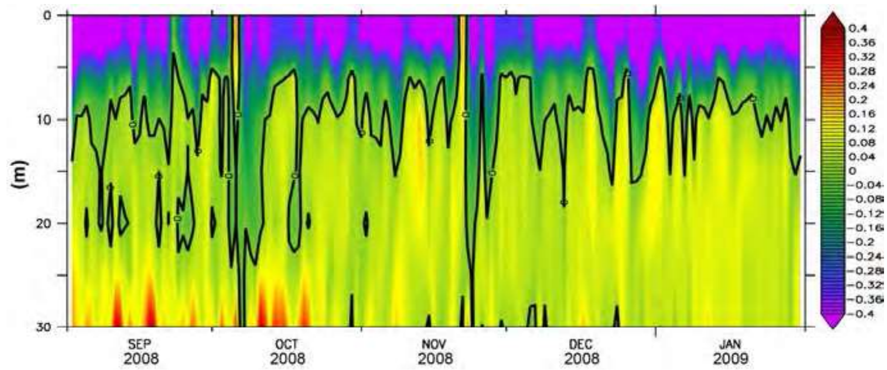

Figure 6. Along strait velocity (m/s) at the station located at the southern exit of the Bosphorus Strait. The black line is zero contours. The two upper layer blocking events happened; one in beginning of October and the other at 19-23 November 2008.

The atmospheric influence on the blocking events is further evaluated by analyzing the time series of the P+R-E (precipitation plus river inflow minus evaporation), wind speed, mean sea level pressure averaged over the Black Sea, and the sea level difference between the two ends of the Bosphorus Strait shown in Figure 7 a,b,c,d. During the blocking events (shaded), the drops in the barometric pressure indicate passing storms, the latter one in November being extensively studied by Book *et al.* (2014). The dominant wind directions (not shown) during the blocking events are southwesterly. Since the HYCOM does not incorporate the effects of the atmospheric pressure, we conjecture that the strong winds reflect these effects. It is less straightforward to establish direct correspondence of upper layer blocking with P+R-E (Figure 7 a). The sea level difference between the two ends of the Strait appears negatively correlated with the water transport (Figure 7 d).

Model experiments (EXP1 to EXP4) have been run in addition to the control experiment, doubling the river inflow in EXP1, doubling the wind stress in EXP2 in comparison to the control run, relaxing the mass conservation option of HYCOM in EXP3. In this set-up surface water fluxes are not required to conserve mass in the model anymore. This option allows the model lose or gain volume during the model integration period at the open boundaries. In EXP4, the river inflow was doubled relative to EXP3. By doubling the wind stress over whole model surface grid points and river discharge in the Black Sea, it is expected that the Strait will response to the changes in forcing fields.

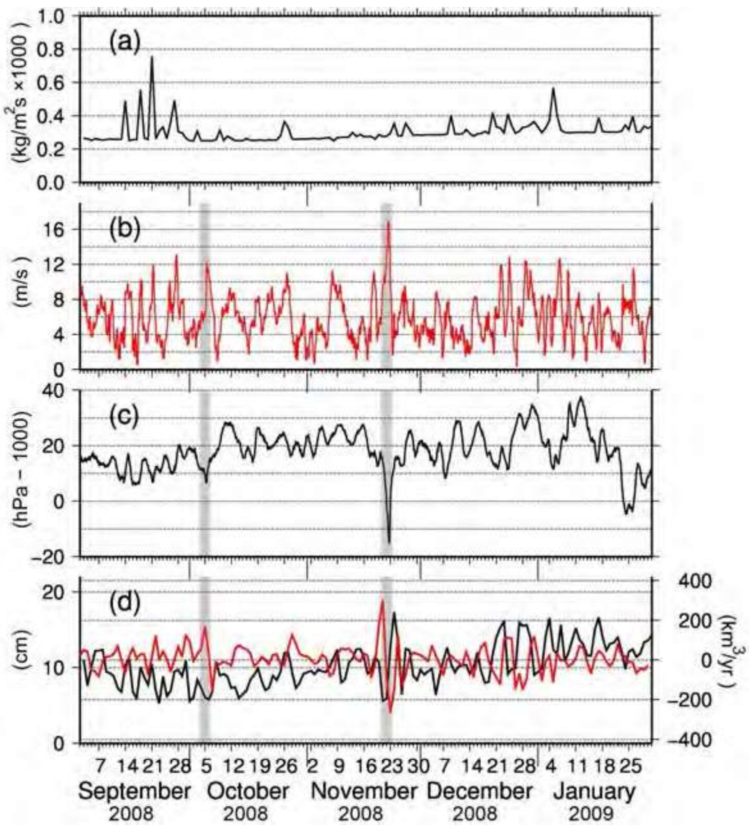

Figure 7. Time series of daily averaged over the Black Sea (a) precipitation minus evaporation (kg/m^{2}s ×1000) (b) wind speed (m/s) (c) mean sea level pressure (hPa − 1000) (d) sea level difference (cm) (black line, left axis) between the southern and nothern ends of the Bosphorus Strait and the net water transport (km^3/yr) (red line, right axis) from the control experiment.

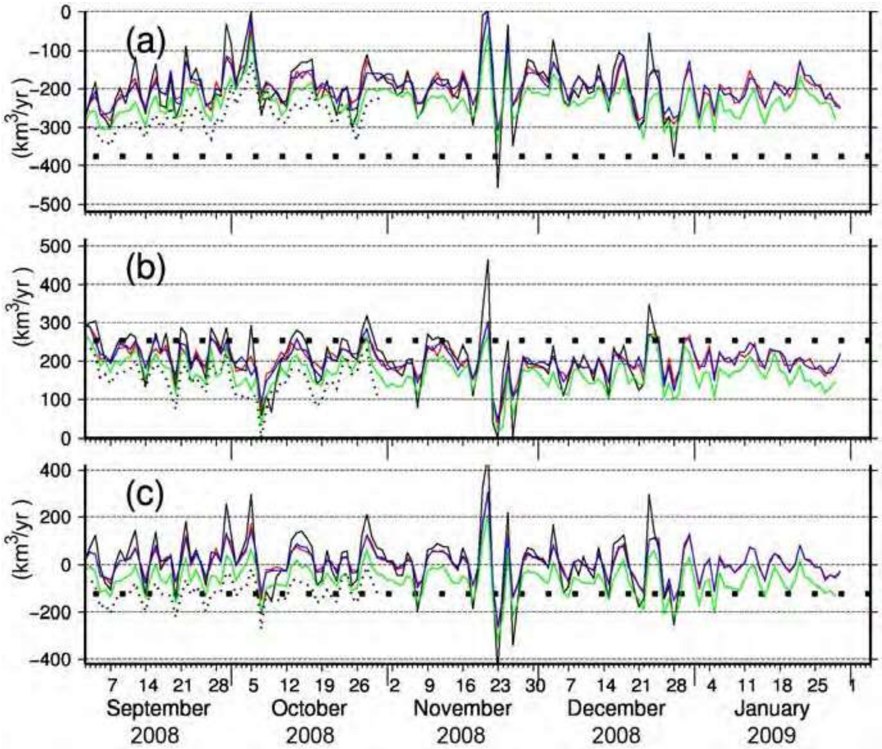

Figure 8. Time series of daily water transport (km^3/yr) at the Bosphorus Strait. Red line is control run, blue line is EXP1, black line is EXP2, green line is EXP3 and the dotted line is EXP4. (a) Upper layer (b) Lower layer (c) Net Flux. The bold dot line shows the averaged transport calculated by Jarosz *et al.* (2011a). EXP4 could not be integrated until the end of the experiment time due to the instability of the model.

The experiments investigated sensitivity with respect to forcing, displaying the time series of water transport in Figure 8. With doubled river influx (EXP1, blue line), or wind stress (EXP2, black line) the results are very similar to the control experiment, since the requirement of mass conservation essentially results in weak or zero net barotropic flux across the TSS in all three experiments. In EXP3 when the mass conservation is relaxed in the model, the upper layer transport is increased due to increased net flux, while the highest increase occurs when river inflow is doubled in combination with the relaxed mass conservation (EXP4). EXP4 could not be integrated until end of the integration period due to the instability of the model generating strong currents along the OBs. Increasing the sponge layer or nudging factor did not work to stabilize the model at the open boundaries. In a further study, the model boundaries would be forced by the real-time temperature, salinity and SSH fields to better represent the open boundaries. Since the model responds quickly (in a couple of days) to the changing forcing fields, the relatively short model integration is enough to see the effects of the relaxation on the water transport.

In summary, a numerical simulation of the Marmara Sea was conducted with a new set-up of the HYCOM. The water transport through the Bosphorus Strait predicted by the model is in agreement with the available observations. The numerical model experiments reveal the importance of the wind stress and rivers on the transport and circulation in the TSS. Upper layer blocking occurs during southwesterly winds of approaching storms indicated by depressions in barometric pressure. Increase in river inflow results in increased transport only when mass conservation is relaxed in the model, while doubling of the river inflow or the wind stress results increased fluctuated response in water transport.

The current model, although of a moderate horizontal resolution of about 400 m, produces encouraging results for investigating the exchange flow and circulation dynamics of the TSS. The relatively coarse resolution 1.125^o of atmospheric forcing utilized does not allow surface fluxes to be represented at sufficient resolution. However, due to the optimal vertical coordinate choice of the model, it is a rather important quality of the model that the pycnocline could be preserved against excessive diffusive effects during the model integration.

References

Androulidakis, Y., Kourafalou, V., Krestenitis, Y. and V. Zervakis 2012a. Variability of deep water mass characteristics in the north Aegean Sea: The role of lateral inputs and atmospheric conditions. *Deep-Sea Res* 67: 55-72.

Androulidakis, Y., Krestenitis, Y. and V. Kourafalou 2012b. Connectivity of North Aegean circulation to the Black sea water budget. *Cont Shelf Res* 48: 8-26.

Antonov, J.I., Locarnini, R.A., Boyer, T.P., Mishonov, A.V. and H.E. Garcia 2006. World Ocean Atlas 2005, Volume 2: Salinity. In: S. Levitus (Ed) NOAA Atlas NESDIS 62, U.S. Government Printing Office, Washington, D.C., 182 pp.

Becker, J.J., Sandwell, D.T., Smith, W.H.F., Braud, J., Binder, B., Depner, J., Fabre, D., Factor, J., Ingalls, S., Kim, S.H., Ladner, *et al.* 2009. Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS. *Marine Geodesy* 32(4): 355-371.

Beşiktepe, Ş., Özsoy, E. and Ü. Ünlüata 1993. Filling of the Marmara Sea by the Dardanelles lower layer inflow. *Deep-Sea Res* 40: 1815-1838.

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

Bleck, R. 2002. An oceanic general circulation model framed in hybrid isopycnic-cartesian coordinates. *Ocean Model* 4: 55-88.

Bleck, R. 2006. On the use of hybrid vertical coordinates in ocean circulation modeling. In: E. Chassignet, J. Verron (Eds) Ocean Weather Forecasting. Springer Netherlands, 109-126 pp.

Book, J., Jarosz, W.E., Chiggiato, J. and Ş. Beşiktepe 2014. The oceanic response of the Turkish Straits System to an extreme drop in atmospheric pressure. *J. Geophys. Res. Oceans* 119: 3629-3664.

Chassignet, E.P., Hurlburt, H.E., Metzger, E.J., Smedstad, O.M., Cummings, J.A., Halliwell, G.R., Bleck, R., Baraille, R., Wallcraft, A.J., Lozano, C. *et al.* 2009. US GODAE global ocean prediction with the hybrid coordinate ocean model (HYCOM). *Oceanography* 22: 64-75.

Chiggiato, J., Jarosz, E., Book, J., Dykes, J., Torrisi, L., Poulain, P., Gerin, R., Horstmann, J. and Ş. Beşiktepe 2011. Dynamics of the circulation in the Sea of Marmara: Numerical modeling experiments and observations from the Turkish Straits System experiment. *Ocean Dynam.* 62: 139-159.

Dee, D.P., Uppala, S.M., Simmons. A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P. *et al.* 2011. The era-interim reanalysis: configuration and performance of the data assimilation system. *Q J Roy Meteor Soc* 137: 553-362.

Delfanti, R., Özsoy, E., Kaberi, H., Schirone, A., Salvi, S., Conte, F., Tsabaris, C. and C. Papucci 2013. Evolution and fluxes of 137cs in the Black Sea/Turkish Straits System/North Aegean Sea. *J Marine Syst* 135: 117-123.

Demyshev, S.G., Dovgaya, S.V. and V.A. Ivanov 2012. Numerical modeling of the influence of exchange through the Bosporus and Dardanelles Straits on the hydrophysical fields of the Marmara Sea. *Izv Atmos Ocean Phy* 48: 418-426.

Gregg, M.C. and E. Özsoy 1999. Mixing on the black sea shelf north of the Bosphorus. *Geophys Res Lett* 26: 1869-1872.

Gregg, M.C. and E. Özsoy 2002. Flow, water mass changes, and hydraulics in the bosphorus. *J Geophys Res-Oceans* 107: 2-1-2-23.

Gündüz, M. and E. Özsoy 2014. Modelling seasonal circulation and thermohaline structure of the Caspian Sea. *Ocean Science* 10: 459-471.

Ilıcak, M., Özgokmen, T., Özsoy, E. and P. Fischer 2009. Non-hydrostatic modeling of exchange flows across complex geometries. *Ocean Model* 29: 159-175.

Jarosz, E., Teague, W., Book, J. and Ş. Beşiktepe 2011a. Observed volume fluxes in the Bosphorus Strait. *Geophys Res Lett* 38.

Jarosz, E., Teague, W., Book, J. and Ş. Beşiktepe 2011b. On flow variability in the Bosphorus strait. *J Geophys Res-Oceans* 116.

Jarosz, E., Teague, W., Book, J. and Ş. Beşiktepe 2012. Observations on the characteristics of the exchange flow in the Dardanelles strait. *J Geophys Res-Oceans* 117.

Kanarska, Y. and V. Maderich 2008. Modelling of seasonal exchange flows through the Dardanelles strait. *Estuar Coast Shelf* 79: 449-458.

Kara, A.B., Hurlburt, H., Wallcraft, A. and M. Bourassa 2005. Black sea mixed layer sensitivity to various wind and thermal forcing products on climatological time scales. *J Climate* 18: 5266-5293.

Kara, A.B., Wallcraft, A., Metzger, E.J. and M. Gündüz 2010. Impacts of freshwater on the seasonal variations of surface salinity and circulation in the Caspian Sea. *Cont. Shelf Research* 30(10-11): 1211-1225.

Latif, M.A., Özsoy, E., Oğuz, T. and Ü. Ünlüata 1991. Observations of the Mediterranean inflow into the Black sea. Black Sea Oceanography: Results from the 1988 Black Sea Expedition. *Deep-Sea Res* 38 (2): 711-723.

Locarnini, R.A., Mishonov, A.V., Antonov, J.I., Boyer, T.P. and H.E. Garcia 2006. World Ocean Atlas 2005, Volume 1: Temperature. In: S. Levitus (Ed) NOAA Atlas NESDIS 61, U.S. Government Printing Office, Washington, D.C., 182 pp.

Mehra, A. and I. Rivin 2010. A real time ocean forecast system for the North Atlantic Ocean. *Terr Atmos Ocean Sci* 21: 211-228.

Oğuz, T. 2005. Hydraulic adjustments of the Bosphorus exchange flow. *Geophys Res Lett* 32.

Oğuz, T., Özsoy, E., Latif, M.A., Sur, H.İ. and Ü. Ünlüata 1990. Modeling of Hydraulically Controlled Exchange Flow in the Bosphorus Strait. *Journal of Physical Oceanography* 20: 945-965.

Oğuz, T. and H.İ. Sur 1989. A 2-layer model of water exchange through the Dardanelles Strait. *Oceanol Acta* 12: 23-31.

Özsoy, E., Ünlüata, Ü. and Z. Top 1993. The evolution of Mediterranean water in the Black Sea interior mixing and material transport by double diffusive intrusions. *Prog Oceanogr* 31: 275-320.

Özsoy, E., Latif, M.A., Beşiktepe, Ş. and A. Gaines 1995. Fluorescent dye measurements of the mixing and transport of wastewater discharge in the Bosphorus. *Water Sci Technol* 32: 61-68.

Özsoy, E., Latif, M., Sur, H.İ. and Y. Goryachkin 1996. A review of the exchange flow regime and mixing in the Bosphorus Strait. Bulletin de l'Institut oc´eanographique, 187-204 pp.

Özsoy, E. and Ü. Ünlüata 1997. Oceanography of the Black Sea: A review of some recent results. *Earth-Sci Rev* 42: 231-272.

Özsoy, E., Latif, M.A., Beşiktepe, Ş. Çetin, N., Gregg, N.V.B., Goryachkin, Y. and V. Diaconu 1998. The Bosphorus Strait: Exchange fluxes, currents and sea-level changes. In: L. Ivanov, T. Oğuz (Eds) Ecosystem Modeling as a Management Tool for the Black Sea. Kluwer Academic Publishers, Dordrecht. Volume 1 of NATO Science Series 2: Environmental Security 47: 367 pp.

Özsoy, E., Di Iorio, D., Gregg, M. and J. Backhaus 2001. Mixing in the Bosphorus Strait and the Black Sea continental shelf: observations and a model of the dense water outflow. *J Marine Syst* 31: 99-135.

Özsoy, E., Rank, D. and I. Salihoğlu 2002. Pycnocline and deep mixing in the Black Sea: stable isotope and transient tracer measurements. *Estuar Coast Shelf* 54: 621-629.

Polat, S. and S. Tuğrul 1995. Nutrient and organic carbon exchanges between the Black and Marmara Seas through the Bosphorus Strait. *Cont Shelf Res* 15: 1115-1132.

Price, J.F., Weller, R.A. and R. Pinkel 1986. Diurnal cycling: Observations and models of the upper ocean response to diurnal heating, cooling and wind mixing. *J. Geophys. Res.* 91:8411-8427.

Rank, D., Özsoy, E. and I. Salihoğlu 1999. Oxygen-18, deuterium and tritium in the Black sea and the Sea of Marmara. *J. Environ. Radioactiv.* 43: 231-245.

Roether, W., Manca, B.B., Klein, B., Bregant, D., Georgopoulos, D., Beitzel, V., Kovacevic, V. and A. Luchetta 1996. Recent Changes in Eastern Mediterranean *Deep Waters Science* 271: 333-335.

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

Sözer, A. and E. Özsoy 2002. A three-dimensional model of Bosphorus Strait dynamics, In: The 2nd Meeting on the Physical Oceanography of Sea Straits, Villefranche, 15th- 19th, 207-210 pp.

Stashchuk, N. and K. Hutter 2001. Modelling of water exchange through the strait of the Dardanelles. *Cont Shelf Res* 21: 1361-1382.

Tuğrul, S. Beşiktepe, Ş. and İ. Salihoğlu 2002. Nutrient exchange fluxes between the Aegean and Black Seas through the Marmara Sea. *Mediterranean Marine Science* 3(1): 33-42.

Ünlülata, U., Oğuz, T., Latif, M.A. and E. Özsoy 1990. On the physical oceanography of the Turkish straits. In: L. Pratt (Ed) The Physical Oceanography of Sea Straits. Springer Netherlands. Volume 318 of NATO ASI Series, 25-60 pp.

Vorosmarty, C.J., Fekete, B.M. and B.A. Tucker 1998. Global River Discharge, 1807-1991, V. 1.1 (RivDIS). Data set. Available online (http://www.daac.ornl.gov) from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, TN, U.S.A.

Yüce, H. 1993. Water-level Variations in the Sea of Marmara. *Oceanol Acta* 16: 335-340.

Zervakis, V., Georgopoulos, D. and P.G. Drakopoulos 2000. The role of the North Aegean in triggering the recent Eastern Mediterranean climatic changes. *J Geophys Res-Oceans* 105: 26103-26116.