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Seasonal and interannual variability of the water exchange in the Turkish Straits System estimated by modelling

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Abstract

A chain of simple linked models is used to simulate the seasonal and interannual variability of the Turkish Straits System. This chain includes two-layer hydraulic models of the Bosphorus and Dardanelles straits simulating the exchange in terms of level and density difference along each strait, and a one-dimensional area averaged layered model of the Marmara Sea. The chain of models is complemented also by the similar layered model of the Black Sea proper and by a one-layer Azov Sea model with the Kerch Strait. This linked chain of models is used to study the seasonal and interannual variability of the system in the period 1970-2009. The salinity of the Black Sea water flowing into the Aegean Sea increases by approximately 1.7 times through entrainment from the lower layer. The flow entering into the lower layer of the Dardanelles Strait from the Aegean Sea is reduced by nearly 80% when it reaches the Black Sea. In the seasonal scale, a maximal transport in the upper layer and minimal transport in the bottom layer are during winter/spring for the Bosphorus and in spring for the Dardanelles Strait, whereas minimal transport in upper layer and maximal undercurrent are during the summer for the Bosphorus Strait and autumn for the Dardanelles Strait. The increase of freshwater flux into the Black Sea in interannual time scales (41 m^3s^{-1} per year) is accompanied by a more than twofold growth of the Dardanelles outflow to the North Aegean (102 m^3s^{-1} per year).

Keywords: Turkish Straits System, Black Sea, Aegean Sea, Marmara Sea, water exchange, seasonal and interannual variability.

Introduction

The Turkish Straits System (TSS) is comprised of the Straits of Bosphorus and Dardanelles, linked by the Marmara Sea (Fig. 1). Two long, shallow and narrow straits separated by a deep basin connect the Mediterranean Sea and the Black Sea. The brackish water of the Black Sea and salty Mediterranean water flowing in upper and bottom layers of TSS influence buoyancy in the North Aegean Sea and the Black Sea, respectively. The TSS also provides a bio-geochemical link between ecosystems of the Black Sea and Mediterranean (Tuğrul *et al*., 2002). The extremely important role of TSS in the past and present evolution of the Black Sea and the North Aegean Sea is well known (e.g. Oĝuz *et al.*, 2006; Zervakis *et al*., 2004; Tzali *et al*., 2010; Androulidakis *et al*., 2012a,b). However, the dynamics of exchange of water, heat, dissolved and particulated matter is not well understood, despite the fact that the Strait of Bosphorus was one of first subjects of physical oceanography study (Marsigli, 1681). The first systematic field study of the TSS was performed by Merz (Möller, 1928). Since the beginning of the 1980s a series of oceanographic surveys have been carried out in the Strait of Bosphorus, during which the sea level and meteorological factors were also monitored (Ünlüata *et al*., 1990; Alpar & Yüce, 1998; Özsoy *et al*., 1998; Gregg *et al.,* 1999; Gregg & Özsoy, 2002; Altiok *et al*., 2010; Jarosz *et al*., 2011a, b). Note that most of these studies were devoted to the short-term variability of the Bosphorus regime. The field studies revealed the complicated structure of the currents caused by the very complex geometry of the strait and synoptic-scale variations of wind, pressure and sea level at the ends of the strait. However, the observed volume fluxes in the Bosphorus Strait demonstrate a regular relationship between the flow rates in the upper and lower layers (Q_1^B and Q_2^B, respectively) and the net flow rate through the strait Q^B (Fig. 2) which shows data from Möller (1928), Özsoy *et al*. (1998), and includes recent measurement data at the Black Sea entrance (Jarosz *et al*., 2011b) after smoothing by moving average filter with 31 days window length. It also shows the results of simulations for the Black Sea entrance discussed in Section 4. The extreme values of the observed flow rates from Özsoy *et al*. (1998) in Fig. 2A are connected with the short time variability of the level difference along the strait, barometric pressure difference between the Black and Marmara seas, and local winds. The observations (Özsoy *et al*., 1998; Gregg &

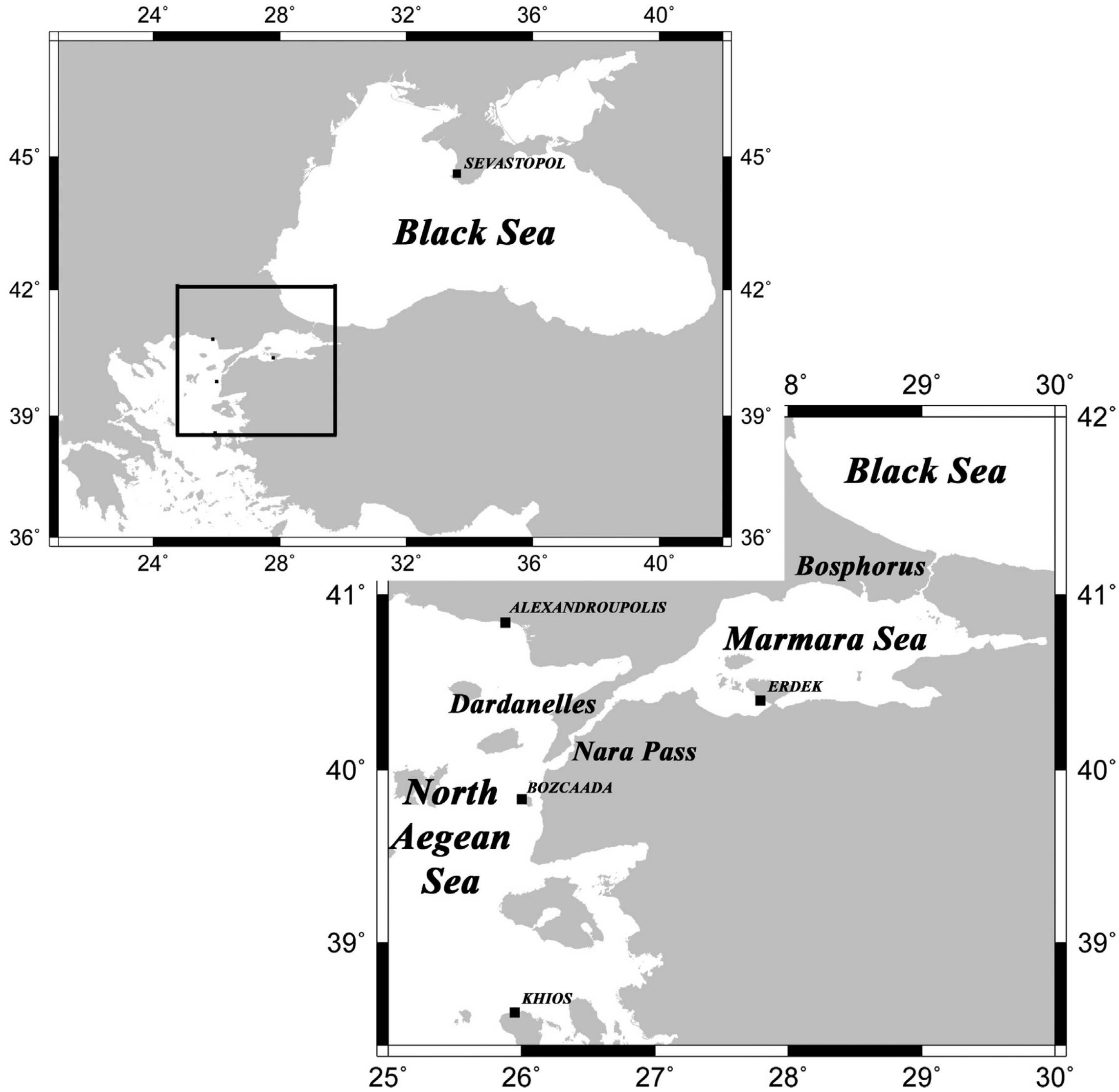


Fig. 1: Geographical position of the Turkish Straits System and location of the gauge stations.

Özsoy, 2002; Altiok *et al*., 2010) suggest that exchange is hydraulically controlled at the sills in the Strait ends and in the constriction inside of the Strait where internal Froude numbers exceed 1. However, hydraulic control is quasi-steady (Gregg *et al*., 1999) and exchange is partly controlled by friction (Gregg & Özsoy, 2002). The observed thermohaline structure and circulation in the Marmara Sea as an intermediary basin filled by water from the Bosphorus and Dardanelles were considered by Beşiktepe (1993), Beşiktepe *et al*. (1993) and Chiggiato *et al*. (2011). Deep layer waters in Marmara Sea are renewed with incoming Dardanelles lower layer flow (Beşiktepe, 1993). Because the flow of water into the Marmara Sea through the Dardanelles lower layer is more than outflow in the upper Bosphorus layer, the excess of water returns to the Aegean Sea (Ünlüata *et al*., 1990) by entrainment into the upper layer of the Marmara Sea. The exchange processes in the Strait of Dardanelles are less studied than that of the Bosphorus Strait (Beşiktepe, 2003; Jarosz *et al*., 2012; 2013). The observed volumetric flow in Fig. 2B show that relationship between the flow rates in the upper and lower layers rates in the Dardanelles Strait (Q_1^D and Q_2^D, respectively) and the net flow rate through the strait Q^D is strongly influenced by seasonal and interannual variations of baroclinic force caused by variations of the temperature and salinity differences along the strait. The recent measurements by Jarosz *et al*. (2013) show that the Dardanelles exchange flows can vary from the intermediate regime between hydraulic control regime and the viscous-advective-diffusion (VAD) regime (Hogg *et al*., 2001) to the two-layer hydraulic control regime at least in the narrow Nara Pass inside of the strait (Fig. 1) where internal Froude numbers exceed 1.

Direct measurements of currents (Gregg & Özsoy, 2002; Jarosz *et al*., 2011b; 2013) and estimates of net water fluxes based on the Knudsen relations expressing steady state water and salt budgets (Ünlüata *et al*., 1990; Beşiktepe *et al*., 1994; Tuğrul *et al*., 2002) show that the entrainment is important in the establishment of the flow

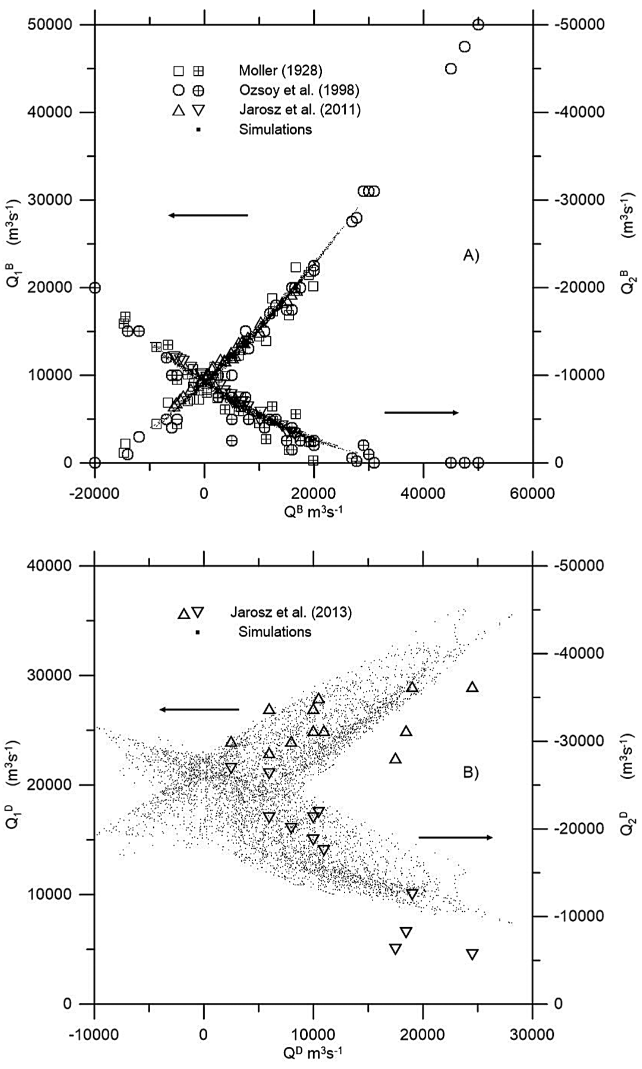


Fig. 2: A) The observed volumetric flow rates in the upper layer Q_1^B (open symbols) and bottom layer Q_2^B (inverted triangles, crossed circles and boxes) of the Bosphorus Strait versus net flow rate Q^B. B) The observed volumetric flow rates in the upper layer Q_1^D (triangles) and bottom layer Q_2^D (inverted triangles) in the northern end of the Dardanelles Strait versus net flow rate Q^D. The simulated flows with 5 day interval from 1970 to 2010 for the northern ends of both straits are shown by dots. Positive numbers in A) and B) correspond to the flow towards the Marmara Sea and Aegean Sea, respectively.

regime in the TSS. In particular, while passing through the Bosphorus Strait the upper layer flow increases by 18% by entraining water from the lower layer as shown by Jarosz *et al*. (2011b) based on direct measurements of currents. The direct measurements in the Dardanelles Strait (Jarosz *et al*., 2013) show that the annual flow rate in the upper layer of the southern Dardanelles (the Aegean Sea entrance) is 40% larger than the flow rate at the northern Dardanelles (the Marmara Sea entrance). Salinity budget estimations (Tuğrul *et al*., 2002) give annual flow rate in the upper layer of the southern Dardanelles 45% larger than the flow rate at the northern Dardanelles. Respectively, only 44% and 59% of the water entering the southern Dardanelles in the lower layer reaches the Marmara Sea, according to estimates by Jarosz *et al*. (2013) and Tuğrul *et al*. (2002). The entrainment in the bottom layer results in freshening of the water travelling from the Aegean to the Black Sea; however, it is less important for the TSS dynamics than entrainment in the upper layer. The salinity of bottom layer decreases along the Dardanelles and the Bosphorus at 0.3 and 1.8, respectively, while salinity of upper layer increases along the Bosphorus and the Dardanelles at 1.7 and 11.3, respectively (Ünlüata *et al*., 1990).

A number of models, ranging from two-layer, semi-analytical models (Maderich & Efroimson, 1986; Oĝuz & Sur, 1989; Ünlüata *et al*., 1990; Maderich, 1998; 1999; Maderich & Konstantinov, 2002; Androulidakis *et al*., 2012b) to three-dimensional, fully numerical models (Oĝuz, 2005; Kanarska & Maderich, 2008; Blain *et al*., 2010; Hüsrevoğlu *et al*., 2010), have been developed for the straits. The Marmara Sea was described by one-dimensional area averaged model (Maderich, 1998; 1999) and by three-dimensional numerical models (Demyshev & Dovgaya, 2007; Chiggiato *et al*., 2011). However, with the exception of the works of Maderich (1998; 1999), Blain *et al*. (2010), and Hüsrevoğlu *et al*. (2010), the Marmara Sea has not yet been modelled as a component of the TSS. The high-resolution 3D models based on the ADvanced CIRCulation Model (ADCIRC) (Luettich & Westerink, 2004) and on the Regional Ocean Modeling System (ROMS) (Shchepetkin & McWilliams, 2005) were implemented for short-term predictions of TSS by Blain *et al*. (2010) and Hüsrevoğlu *et al*. (2010), respectively. The seasonal and long-term variations of the vertical structure of the Mediterranean Sea sub-basins and the Black Sea were simulated by Maderich (1998; 1999) assuming that the volumes of the seas are constant. Nevertheless, the gauge data and recent altimetry measurements showed large level changes in the Black Sea both in the seasonal and decadal scales (Simonov & Altman, 1991; Stanev *et al*., 2000; Stanev & Peneva, 2002; Tsimplis *et al*., 2004). The seasonal variations of the exchange processes in the Bosphorus and Dardanelles were modelled by Maderich & Konstantinov (2002) and Kanarska & Maderich (2008), respectively. To our knowledge, the seasonal and interannual variability in the exchange processes through whole TSS has not been simulated in a framework of 3D models. The reason is that fine resolution 3D models of TSS still are too expensive computationally. Therefore, much simpler two-layer models based on the hydraulic control principle and corrected for entrainment processes can be useful tools for the study of the interannual variability of the TSS.

This work addresses the simulation of the seasonal and interannual variability of the TSS. A modified two-layer hydraulic model (Maderich & Konstantinov, 2002) for the Bosphorus and Dardanelles is coupled with the Marmara Sea model. The simple models of the Black Sea and the Azov Sea are linked with the TSS model. The paper is organized as follows: A simple parameterization of the entrainment in the straits is proposed and validated in Section 2. The chain of models and modelling setup are described in the Section 3. Section 4 discusses results of simulation of seasonal and interannual variations of the system in the period 1970-2009. Section 5 summarizes the findings. The model equations are given in Appendix A.

Parameterization of the entrainment in the straits

To avoid complicating the detailed description of entrainment in the two-layer hydraulic model, a simple two-layer "entrainment box" model is hereby introduced that is applied to the Marmara entrance of the Bosphorus Strait and to the Aegean entrance of Dardanelles (see locations in Fig. 1) in order to emulate effects of interfacial entrainment of water from the bottom layer into the upper layer. To a first approximation, we do not consider less important effects of mixing between layers, thus essentially simplifying the problem and enabling the solution in a closed form. The "entrainment box" volume balance equations for the upper and bottom layers of entrainment box are

$$\begin{aligned} Q_1 + Q_e &= Q_1^* \\ Q_2 + Q_e &= Q_2^* \end{aligned} \tag{1}$$

where Q_1 and Q_2 are net volume flow rates in the upper and lower layers of the straits computed by the model without entrainment; positive values of flow rates correspond to flows directed from the Black Sea to the Aegean Sea; $Q_e \geq 0$ is flux from the bottom to the upper layer due to the turbulent entrainment, Q_1^* and Q_2^* are the upper-layer and bottom-layer flow, respectively, at the Aegean side/Marmara side of the Dardanelles/Bosphorus entrainment box. The net flow through the strait is $Q= Q_1+Q_2 = Q_1^* + Q_2^*$. The salinity and temperature budget equations can be combined in a single budget equation for density using the linearised equation of state

$$(\rho_2 - \rho_1^*)\, Q_e - (\rho_1^* - \rho_1)\, Q_1 = 0, \tag{2}$$

where ρ_1, ρ_2 are densities in the upper and lower layer of the strait, respectively, ρ_1^* is the density in the upper layer of entrainment box. Assuming that the ratio of the density difference between layers at the ends of strait is constant, yields

$$\rho_2 - \rho_1^* = c_e\, (\rho_2 - \rho_1), \tag{3}$$

where $c_e \leq 1$ is an empirical constant that depends on the geometry in the strait. Combining equations (1) - (3) leads to simple formulae for the entrainment flow Q_e and outflow in the upper layer Q_1^* and inflow in the bottom layer Q_2^* of the strait:

$$Q_1^* = \frac{1-c_e}{c_e} Q_1, \tag{4}$$

$$Q_1^* = \frac{1}{c_e} Q_1, \quad Q_2^* = Q - \frac{1}{c_e} Q_1, \tag{5}$$

Using the equations of salinity and temperature budget and equations (4)-(5) with prescribed c_e yields values of salinity and temperature in the upper layer of entrainment box as

$$\begin{aligned} T_1^* &= (1 - c_e)\, T_2 + c_e T_1 \\ S_1^* &= (1 - c_e)\, S_2 + c_e S_1 \end{aligned} \tag{6}$$

Measurements of flow rates in both ends of Bosphorus (Jarosz *et al*., 2011b) and Dardanelles (Jarosz *et al*., 2013) Straits and 3D simulation of seasonal variations in the Strait of Dardanelles (Kanarska & Maderich, 2008) were used to estimate the value of parameter c_e by least squares method. The data from (Jarosz *et al*., 2011b) were smoothed by moving-average filter with 31 days window length. The data from (Jarosz *et al*., 2013) and (Kanarska & Maderich, 2008) are month averaged. The estimated values of c_e are 0.85 and 0.6 for the Bosphorus and Dardanelles Straits, respectively. As seen in Fig. 3, the equations (5) approximate flow rates at these values of c_e and confirm assumption (3). The corresponding coefficients of correlation R and RMSE are R=0.97 and 0.98, RMSE=1205 and 5030 m^3s^{-1}, respectively. However, in modelling the Strait of Bosphorus a higher value c_e=0.90 is used to take into account the deviation of the lower layer in this shallow strait from being homogeneous (Jarosz *et al*., 2011a) and to obtain better agreement with observed temperature and salinity in the upper layer of Marmara exit of the Bosphorus (Ünlüata *et al*., 1990). Besides, observations by Jarosz *et al*. (2011b) for period September 2009 - January 2010 do not represent full annual cycle. Note that estimates based on steady state conservation of mass and salt (Ünlüata *et al*., 1990) yield c_e=0.96 and c_e=0.69 for the Bosphorus Strait and the Dardanelles Strait, respectively.

Model chain and modelling setup

Strait model

To describe exchange flows through the Bosphorus and Dardanelles a quasi-stationary hydraulic two-layer model of long straits is utilised, with bottom and interfacial friction (Maderich & Konstantinov, 2002). The model is based on the so-called "hydraulic control" principle, which requires that the internal composite Froude number G^2 equals 1 at some critical section of the strait. The condition G^2=1 separates regions with sub-critical flows (G^2 <1) and super-critical flows (G^2 >1). Maximal exchange occurs when a region of sub-critical flow links two locations of control (Farmer & Armi, 1986). In a general case, these locations (control points) depend on the geometry, net flow and friction (Armi & Farmer, 1987). The model predicts flow rates in the upper (Q_1) and lower layer (Q_2)respectively, in terms of level and density differences along the strait computed by the sea models. The equations (5)-(6) are used to emulate effects of interfacial entrainment on flow rates and temperature and salinity at the Marmara entrance of the Bosphorus Strait and at the Aegean entrance of Dardanelles. The equations of strait model are given in Appendix A1.

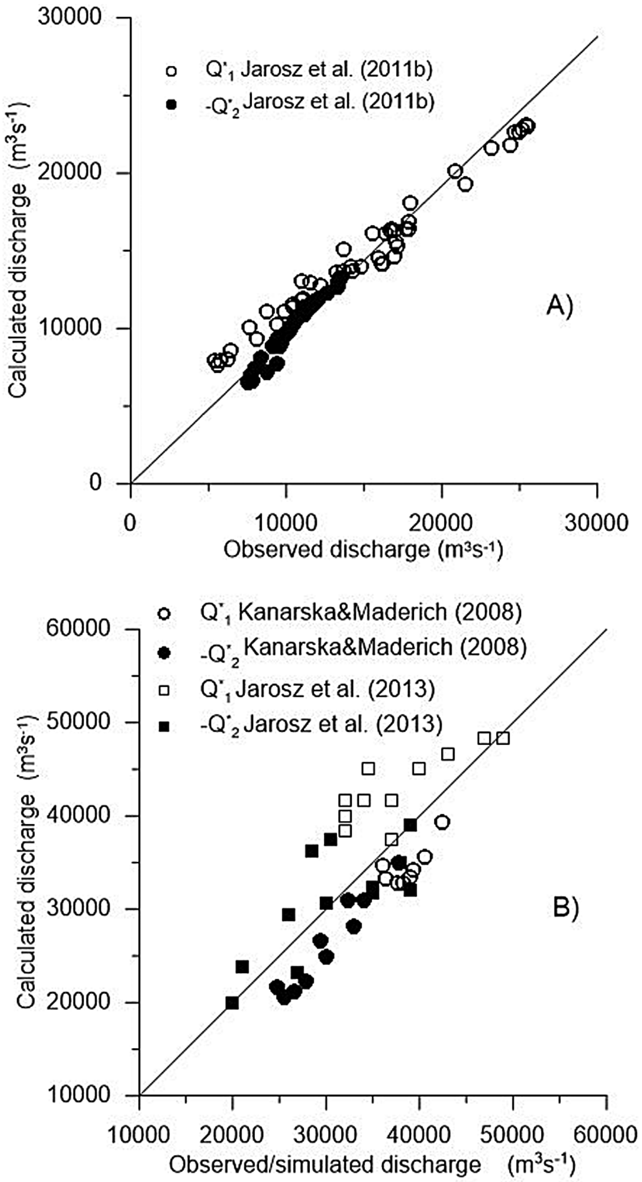


Fig. 3: Calculated from (5) flow rates Q_1^* and $-Q_2^*$ in the upper and bottom layers *vs*. A) observed flow rates in the Bosphorus Strait (Jarosz *et al*., 2011b); B) observed flow rates (Jarosz *et al*., 2013) and simulated by 3D model in the Dardanelles Strait (Kanarska & Maderich, 2008). The data from (Jarosz *et al*., 2011b) were smoothed by moving-average filter with 31 days window length. The values with three day interval are shown. The data from (Jarosz *et al*., 2013) and (Kanarska & Maderich, 2008) are month averaged.

Marmara Sea model

The relatively small and deep Marmara Sea is described by a simple model in which the conservation of mass, heat and salt are considered only in the vertical direction whereas inflow and outflows through straits act as forcing terms for the vertical circulation and feedback for the system. The model includes the mass balance equation to determine sea elevation and multi-layer one-dimensional equations for temperature and salinity evolution. The volume balance equation for the Marmara Sea is

$$\sigma_M \frac{d\varsigma_M}{dt} = -Q^D + Q^B + Q_f^M, \tag{7}$$

where σ_M is area of the Marmara sea, ς_M is the Marmara sea level, Q_f^M is the flux of the fresh water to the upper layer of the Marmara Sea as a sum of the river run-off, precipitation and evaporation,

The vertical density structure of the Marmara Sea is approximated by a set of homogeneous layers (Maderich & Konstantinov, 2002). It is supposed that the horizontally averaged temperature *T* and salinity *S* are constant in the layers. The number of layers and their thickness are varied in time and depend on the history of the process. The horizontal area of each layer is a function of depth. The system of layers includes a surface mixed layer (SML) that is under direct influence of the atmosphere, internal and bottom layers. The SML is under direct influence of the atmosphere heat flux, and wind and salinity flux resulted from freshwater budget of the sea. Two regimes of SML are modelled: “entrainment regime”, when SML grows due to the turbulent entrainment and “detrainment” regime, when turbulence in SML decays and new SML is formed (Turner &Kraus, 1967). The internal layers appear in the detrainment regime, whereas SML absorbs these layers in the entrainment regime. The internal layers can move in the vertical direction, according to the volume balance. The number of these layers varies in seasonal cycle from a few to 30-40 allowing smooth approximation of the stratification. The one dimensional model of the Marmara Sea is linked with the strait models: the upper layer water from the Bosphorus Strait inflows into the SML and lower layer water from the Dardanelles Strait inflows into the bottom layer. The equations of the model are given in Appendix A2.

Black Sea model

In this study, the TSS model is linked with a model of the Black Sea to analyze the evolution of the system in the 1970-2009 periods. The Black Sea model includes sub-models of the Black and Azov seas and the Kerch Strait. The volume balance equation for the Black Sea is

$$\sigma_a + \sigma_B \frac{d\varsigma_B}{dt} = -Q^B + Q^{BP} + Q_f^A, \tag{8}$$

where σ_A, σ_B are areas of the Azov and Black seas, ς_B is the Black Sea level, Q_f^{BP} and Q_f^A are the fluxes of the fresh water to the upper layer of the Black Sea and in the Azov Sea as a sum of the river run-off, precipitation and evaporation. The total freshwater flux in the Black Sea basin is $Q_f^B = Q_f^{BP} + Q_f^A$. The evolution of the vertical structure of the Black Sea is described using the same one dimensional model as for the Marmara Sea. The model is linked with the Bosphorus Strait model: the SML water outflows through the Bosphorus Strait upper layer and lower layer water from the Bosphorus Strait inflows into the bottom layer of the Black Sea. The shallow Azov Sea was modelled solving one layer area averaged equations for temperature and salinity. The sea level in the Azov

Sea was assumed equal to the Black Sea level at seasonal time scale. The horizontally two-way water exchange in the shallow Kerch Strait was parameterized using empirical formulae (Simonov & Altman, 1991) relating exchange with the river run-off in the Azov Sea.

Modelling setup

The surface area of the Azov, Black and Marmara seas are $\sigma_A=3.9\cdot10^{10}$ m^2, $\sigma_B= 4.2\cdot10^{11}$m^2 and $\sigma_M=1.1\cdot10^{10}$ m^2, respectively. The areas of layers in the sea models were interpolated from bathymetric data for the Marmara and Black Seas (Goncharov *et al*., 1965). In the present calculations the complicated topography of the Bosphorus and Dardanelles Straits was replaced by simplified, idealized topography with strait of constant width and depth when control sections are placed at the ends of strait. The parameters of straits were chosen to emulate both straits between the southern entrances and the Narrows inside the straits. This configuration of straits essentially simplifies solution of the equations of hydraulic model (A1)-(A6). The Strait of Bosphorus between the Marmara Sea and the narrow has a length L=12 km, constant width A=750 m and depth H=32 m. The Strait of Dardanelles between the Aegean Sea and the Nara Pass (see Fig. 1) has length L K=25 km, constant width A=1000 m and depth H=55 m. The dynamical parameters of the strait model are: c_b=0.004, c_i=0.0001.

The simulations were carried out for the period 1960-2009. The initial temperature and salinity distributions at 1 January 1960 in the Black and Marmara Seas was two-layer. Ten years of spin-up (1960-1969) resulted in formation of seasonally varying stratification, elevation and exchange flows in TSS. The calculation of the freshwater budget using reanalysis data or regional atmospheric circulation model and runoff model for the Black Sea is a complicated task (Tsimplis *et al*., 2004; Elguindi *et al*., 2011). Here we use monthly freshwater influx time series in the Black and Azov seas (Simonov & Altman, 1991) taken from database of Marine Branch of Ukrainian Hydrometeorological Institute (MBUHMI). The database was established using river runoff data from measurements on stations; the precipitation data originate from coastal and ship observations for the period 1923-1985. It was updated for the period 1986-2009 according to the methodology described by Ilyin *et al*. (2010) for the periods with lack of measurements. The gaps in time series for these periods were filled using regression between datasets; e.g. runoff in the Black Sea was estimated from regression between total runoff and sum of the Danube and Dnieper rivers runoff. The monthly mean time series of the river runoff (R), precipitation (P), evaporation and total freshwater flux into the Black Sea $Q_f^B=R+P-E$ for the period 1970-2009 are shown in Figure 4. The mean values of freshwater budget components for this period are $\bar{R}$ =10360m^{3}s^{-1}≈325 km^{3}year^{-1}, $\bar{P}$=10360 m^{3}s^{-1}≈325 km^3 year^{-1}, $\bar{E}$ =10749 m^{3}s^{-1}≈339 km^3 year^{-1} whereas the total value is $\bar{Q}_f^B$= 8048 m^{3}s^{-1}≈254 km^{3}year^{-1}. The $\bar{Q}_f^B$ is lower than the value 300 km^{3}year^{-1} estimated by Ünlüata *et al*. (1990) using 4 years data on runoff, precipitation and evaporation 352, 300 and 353 km^{3}year^{-1}, respectively. The trends of runoff, precipitation and evaporation for the period 1970-2009 are statistically significant at level 75%. They are 25±10, 27±14 and -39±17 m^{3}s^{-1} per year, respectively, resulting in a trend for freshwater flux of 41±10 m^{3}s^{-1} per year. The significant increase in precipitation and, especially, reduction of evaporation in the period 1970-2009 determine the growth of total freshwater flux even for negative climate trend of runoff.

The air temperature and friction velocity over the seas are necessary for calculation of temperature flux and entrainment rate into the SML (see Appendix A2). They are computed using NCEP and NCEP2 reanalysis data (Kistler *et al*., 2001). The free surface elevation of the North Aegean Sea was prescribed using mean month data of gauge station of Alexandroupolis from Permanent Service for Mean Sea Level (PSMSL) database (Woodworth and Player, 2003). The observation period (1969-2013) for this station is the same as for Khios, but it is closer to Dardanelles. Data for 1960-1968 were substituted by seasonal values calculated from data 1969-1999. The value of time averaged free surface elevation in the North Aegean Sea entrance to the Dardanelles was taken as zero. The salinity and temperature of the flow from the North Aegean Sea were prescribed using MEDATLAS climatological data (MEDAR Group, 2002). Freshwater flux into the Marmara Sea was set to Q_f^M= -100 m^{3}s^{-1} (Ünlüata *et al*., 1990).

Results

Seasonal variations of exchange

The simulated vertical temperature and salinity profiles in the Black and the Marmara seas for typical winter and summer are shown for the period 1970-2009 in Figure 5. They are compared with area-averaged climatic profiles of the temperature and salinity from MEDAR database (MEDAR Group, 2002). The layered model simulates formation of seasonal thermocline and halocline (see Appendix). It is able to describe the vertical structure of temperature and salinity in both seas including the cold intermediate layer (CIL), which plays the crucial role in maintaining the observed vertical profile of temperature in these seas. However, this layered model represents permanent halocline in the Black Sea as two layers with weak internal mixing between them, whereas smooth permanent halocline in this sea is formed due to balance between vertical diffusion and upwelling of deep water.

The calculated seasonal and annual net flows in upper and lower layers at the northern and southern entrances of the Bosphorus and Dardanelles Straits for the period 1970-2009 are given in Table 1. The net flow through TSS (8024 m^{3}s^{-1}≈250 km^3 year^{-1}) is greater than early estimates (205 km^3 year^{-1} (Möller, 1928) and 208 km^3 year^{-1} (Simonov & Altman, 1991)) but less than estimates (Ünlüata *et al*., 1990; Tuğrul *et al*., 2002) based on greater fresh water fluxes (300-321 km^3 year^{-1}). The annual outflow from the Bosphorus Strait to the Marmara Sea (15128m^{3}s^{-1}≈477 km^{3}year^{-1}) also is greater than the value 398 km^3 year^{-1} from early observations (Möller, 1928) but less than more recent estimates of 603-629 km^{3}year^{-1} (Ünlüata *et al*., 1990; Tuğrul *et al*., 2002). The estimates of flow rates in the upper and lower layers for the northern and southern entrances of the Dardanelles agree with results of one-year (2008-2009) direct measurements by Jarosz *et al*. (2013) where the flow rates in the upper and lower layers were 36680 and -31670 m^{3}s^{-1} at the southern entrance and 25660 and -14020 m^{3}s^{-1} at the northern entrance respectively. The simulated annual outflow into the Aegean Sea from the Strait of Dardanelles (39096 m^{3}s^{-1}≈1232 km^3 year^{-1}) is comparable with the estimate of 1331 km^3 year^{-1} (Tuğrul *et al*., 2002). Kanarska & Maderich (2008) estimated flow rates in the upper and lower layers of 38820 and -30000 m^{3}s^{-1} at the southern entrance and 21000 and -12417 m^{3}s^{-1} at the northern entrance, respectively. On seasonal time scales, the maximum transport in the upper layer is observed in winter/spring for the Bosphorus Strait and in spring for the Dardanelles Strait whereas the minimum was observed in summer for the Bosphorus Strait and in autumn for the Dardanelles Strait. The lower layer flows in the Bosphorus and Dardanelles are maximal in summer and autumn, and minimal in winter and spring, respectively. This behaviour of exchange flows in the Strait of Dardanelles was confirmed qualitatively by observations (Jarosz *et al*., 2013) in 2008-2009 and quantitatively by numerical simulations (Fig. 6 in Kanarska & Maderich, 2008). The seasonal variations in the upper layer of the Dardanelles are relatively weaker than in the Bosphorus because of enhancement of the baroclinic component of the flow (caused by the freshening of the upper Marmara Sea layer in summer) that compensates for the summer decrease of the barotropic component. As seen in Table 1 the annual flow rate in the upper layer of Bosphorus between northern and southern entrance increases by 11% whereas the flow rate in the lower layer between the southern and northern entrances decreases by 21% at the cost of entrainment. These results do not contradict estimates based on direct measurements (Jarosz *et al*., 2010b) for the upper and lower layers (18% and 24%, respectively). The influx of water into the Marmara Sea by the lower layer of the Dardanelles Strait exceeds by more than two times the outflow through the lower layer of the Bosphorus Strait. It results in an annual upward flow in the Marmara Sea of 8428 m^{3}s^{-1} (265 km^3 year^{-1}), which is consistent with Tuğrul *et al*. (2002) estimate of 261 km^3 year^{-1}. This flow is entrained in the upper layer of the Marmara Sea and then this water is transported in the upper layer of the Dardanelles Strait. Note that in a simple one-dimensional sea model the water flowing from the lower layers of the Bosphorus and Dardanelles Straits instantaneously mixes with the lowest layer of the Black and Marmara Seas, respectively. Therefore the evolution of a dense plume (Özsoy *et al*., 1993; Beşiktepe *et al*., 1993; 1994) is not considered. The annual flow rate in the upper layer of the Strait of Dardanelles between northern and southern entrances increases by 67%, while the flow rate in the lower layer between the southern and the northern entrance decreases by 50% at the cost of entrainment. Those estimates fall in the range of Tuğrul *et al*. (2002) estimates (44% and 40%, respectively) and Kanarska & Maderich (2008) estimates (84% and 58%, respectively). In total, the flow entering into the lower layer of the Dardanelles Strait in the Aegean end is reduced by nearly 80% when it reaches the Black Sea. Even if we neglect entrainment in the Dardanelles, the corresponding reduction approaches 64%. The salinity of the Black Sea water flowing into the Aegean Sea increases by approximately 1.7 times through the entrainment from the lower layer.

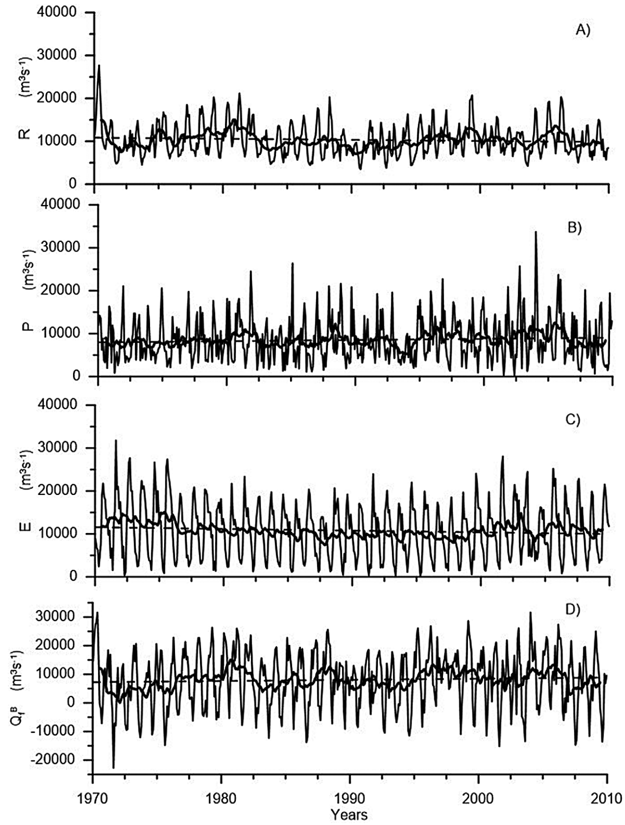


Fig. 4: River run-off A), precipitation B), evaporation C) and total freshwater flux in the Black Sea D). The thick solid line shows interannual variations. The trends are shown by dashed lines.

The model predicts an average level difference between the Black and Aegean seas and Black and Marmara seas of 0.56 m and 0.31 m, respectively, for the period 1970-2009. Based on tide gauge measurements, the sea level difference at the Bosphorus ends is nearly 0.3 m (Ünlüata *et al*., 1990). Figure 6 shows the average

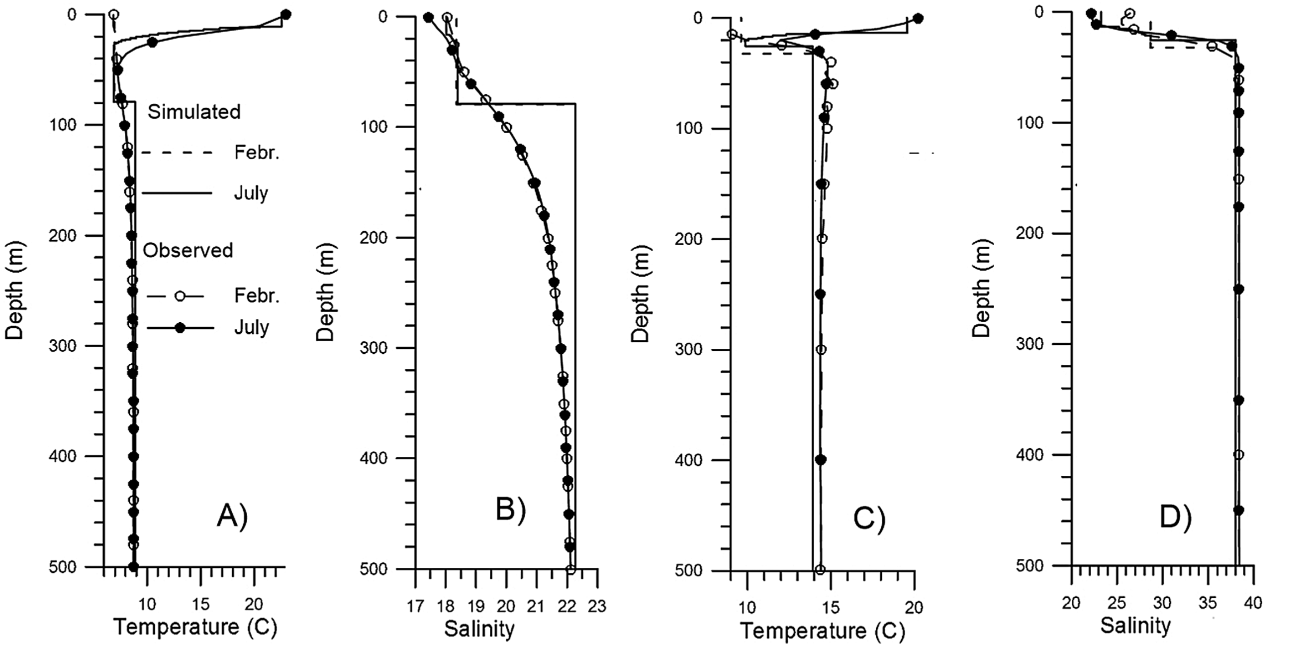


Fig. 5: Simulated *vs*. observed vertical temperature (A) and salinity (B) profiles in the Black Sea and in the Marmara Sea (C and D). The dashed and solid lines are simulations for February and July 1990, respectively. The same lines with open and filled circles represent climatic data (MEDAR Group, 2002) for February and July, respectively.

Table 1. Simulated for period 1970-2009 the seasonal and annual flow rates in upper and lower layers (m^3s^{-1}) at the northern and southern ends of the Bosphorus and Dardanelles Straits.

Season	Northern end		Southern end	
	Upper layer	Lower layer	Upper layer	Lower layer
		Strait of Bosphorus		
Winter	16482	-4013	18314	-5845.
Spring	16672	-3923	18525	-5776
Summer	10276	-7454	11418	-8596
Autumn	11130	-6923	12367	-8160
Annual	13616	-5592	15128	-7104
		Strait of Dardanelles		
Winter	23911	-11505	39852	-27446
Spring	25930	-13375	43218	-30662
Summer	23027	-20288	38378	-35640
Autumn	21004	-16850	35007	-30853
Annual	23456	-15532	39096	-31172

seasonal variability for the period 1970-2009 of the fresh water flux in the Black Sea, the simulated net transport through the Bosphorus Strait Q^B and the elevations in the Black Sea ς_B and the Marmara Sea ς_M, as well as observed elevations in the North Aegean Sea ς_{AE} at gauge stations Alexandroupolis and Khios (see Fig.1). As seen in Fig. 6A, the strong seasonal variability of the freshwater influx in the Black Sea and Aegean sea-level variations results in large variability of the net transport through the Bosphorus Strait Q^B and the levels of the Black and Marmara seas. The Black Sea level variations follow mainly the freshwater influx with a delay of approximately two months whereas delay of the Q^B is around one month. The simulated Q^B in Fig. 6A agrees with the net transport through the Bosphorus estimated by Peneva *et al.* (2001) using mean sea level anomaly (MSLA) data from TOPEX/POSEDON altimetry and fresh water budget from MBUHMI database for the period 1993-1997. Simulation results agree well with Sevastopol gauge data and mean sea level variations (Simonov & Altman, 1991) except in the autumn (Fig. 6B). The Marmara sea level is under the influence of both the Black Sea and Aegean Sea level variations. The simulation results in Fig. 6C also agree with monthly averaged Erdek gauge station data (Marmara Sea) from PSMSL database and with measurements in the North Marmara Sea (Alpar & Yuce, 1998). The observed seasonal variations of sea level in the North Aegean Sea at three close to the Dardanelles gauge stations (Alexandroupolis and Chios from PSMSL database, and Bozcaada (Alpar *et al*., 2000)) are similar (Fig. 6D) that justifies using long Alexandroupolis series of level in computations as North Aegean Sea. We es-

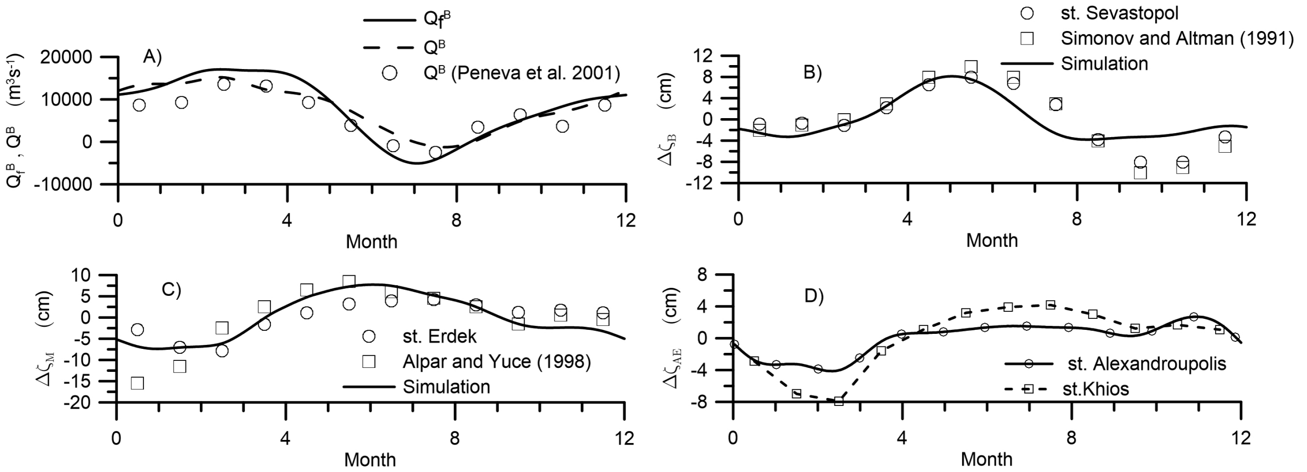


Fig. 6: Seasonal variations of the fresh water budget in the Black Sea and net flow rate in the Bosphorus Q^BA), mean sea level anomalies in the Black Sea $\Delta\varsigma_B$B), Marmara Sea $\Delta\varsigma_M$C), and North Aegean Sea $\Delta\varsigma_{AE}$D) in the period 1970-2009. The seasonal variations of net flow rate obtained by Peneva *et al*. (2002) from TOPEX/POSEDON altimetry and fresh water budget for the period 1993-1997 are shown in A).

timated sensitivity of results to the sea level variations in the North Aegean comparing results of simulations with use of the level data from gauge stations Alexandroupolis and Chios for period 1970-2009. The mean differences between these runs for elevations in the Black and Marmara Seas are less of 1%. The mean differences for flow rates in the TSS are less of 0.1%. The standard deviations for upper layer flow rates in the Bosphorus and Dardanelles straits are 12% and 6%, respectively, due to differences in elevations between the two stations Alexandroupolis and Chios, mainly on intra-annual time scales. The dependence of averaged over period 1970-2009 seasonal variations of flow rates in the upper and bottom layers on the level difference along the Bosphorus and Dardanelles is given in Fig. 7. The level difference in the Bosphorus Strait almost completely governs the flows: the maximums and minimums of upper layer flow rates coincide with maximums and minimums of the level difference (Fig. 7A). As seen in Fig. 2A similar dependence exists between net flow rate and flow rates in layers. The mean year density difference between water entering in the upper and bottom layer for the Bosphorus Strait ($\Delta\bar{\rho}^D$=15.6 kg m^{-3}) is greater than difference for the Dardanelles Strait ($\Delta\bar{\rho}^D$=8.4 kg m^{-3}), whereas amplitude of seasonal variations of density difference in the Dardanelles ($\Delta\bar{\rho}^D$=3.3 kg m^{-3}), is almost three times greater than in the Bosphorus ($\Delta\bar{\rho}^D$=1.3 kg m^{-3}). Therefore, in contrast to the Bosphorus the seasonal variations of flow rates in the Dardanelles Strait essentially depend also on the seasonally varied density difference $\Delta\rho^D$ due to variations of temperature and salinity. It results in a hysteresis caused by baroclinicity for dependence of flow rates on the level difference along the Dardanelles Strait, as in Fig. 7B. This explains the fact that flow rates in the Bosphorus Strait are more sensitive than in the Dardanelles Strait to the level variations in the North Aegean.

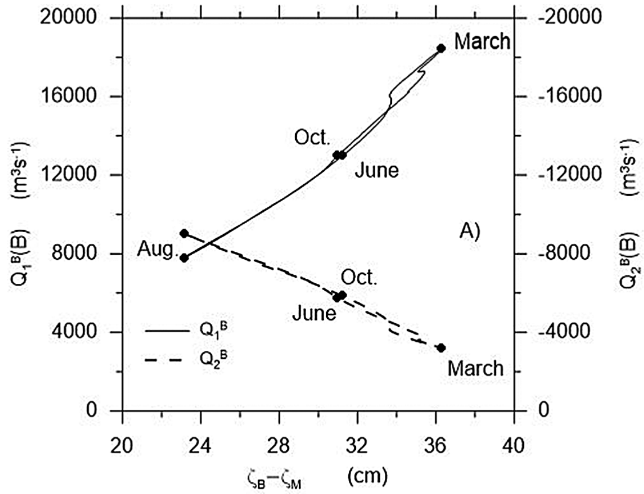
The buoyancy flux through the Dardanelles is an important factor in the buoyancy budget of the North Aegean Sea (Tragou *et al*., 2003; Zervakis *et al*., 2004). It was calculated as

$$F_B = g\,\frac{\Delta\rho^D}{\rho_t}\,Q_1^D \qquad (9)$$

where $\Delta\rho^D$ is the density difference between upper and lower layers in the Dardanelles and Q_l^D is the net transport in the upper layer of the Dardanelles. The simulation results for seasonal variations F_B averaged over the period 1970-2009 are given in Fig. 8A. The buoyancy flux is negative, i.e. it results in a buoyancy inflow into the North Aegean and the establishment and maintenance of a buoyant plume of water in the North Aegean with stable stratification. In winter the buoyancy flux from the Dardanelles to the North Aegean is minimized from December to February. These findings agree well with calculations based on results of 3D modelling (Kanarska & Maderich, 2008).

Interannual variations of exchange

The measurements in the TSS cover relatively short time intervals during the period 1970-2009. The comparison of modelling with the available measurements in this period is given in Fig. 9 and 10. In Fig. 9A the modelled inter-annual MSLA variations with removed annual cycle are compared with basin average in the Black Sea of the mass-induced sea level variations from filtered steric-corrected altimetry (Fenoglio-Marc *et al*., 2012) for the period 2002-2008. The MSLA behaviour is similar for calculations and observations but the interannual variability of sea level obtained from altimetry is higher. Simulated net flow deviations ΔQ^B from the mean value $\bar{Q}^B$ agree with net flow deviations through the Bosphorus inferred by Peneva *et al*. (2001) from Topex/Poseidon altimetry and freshwater budget for the period



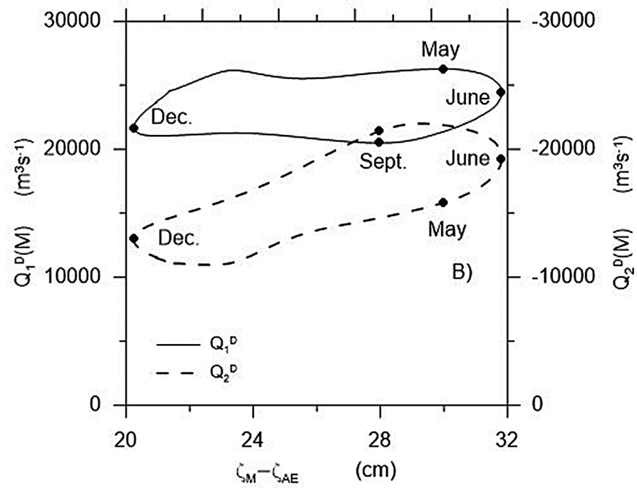


Fig. 7: The dependence of flow rates in the upper and bottom layers on the level difference along the strait for the Bosphorus Strait A) and for the Dardanelles Strait B) seasonally averaged for the period 1970-2009. Here Q_1^B *(B)* and Q_2^B *(B)*, and Q_1^D *(M)* and Q_2^D *(M)*) are corresponding flow rates for the Black Sea entrance of the Bosphorus Strait and for the Marmara Sea entrance of the Dardanelles Strait, respectively; ς_B, ς_M and ς_{AE} are elevations of the Black, Marmara and the Aegean Seas, respectively. The dates of characteristic points in annual cycle are shown.

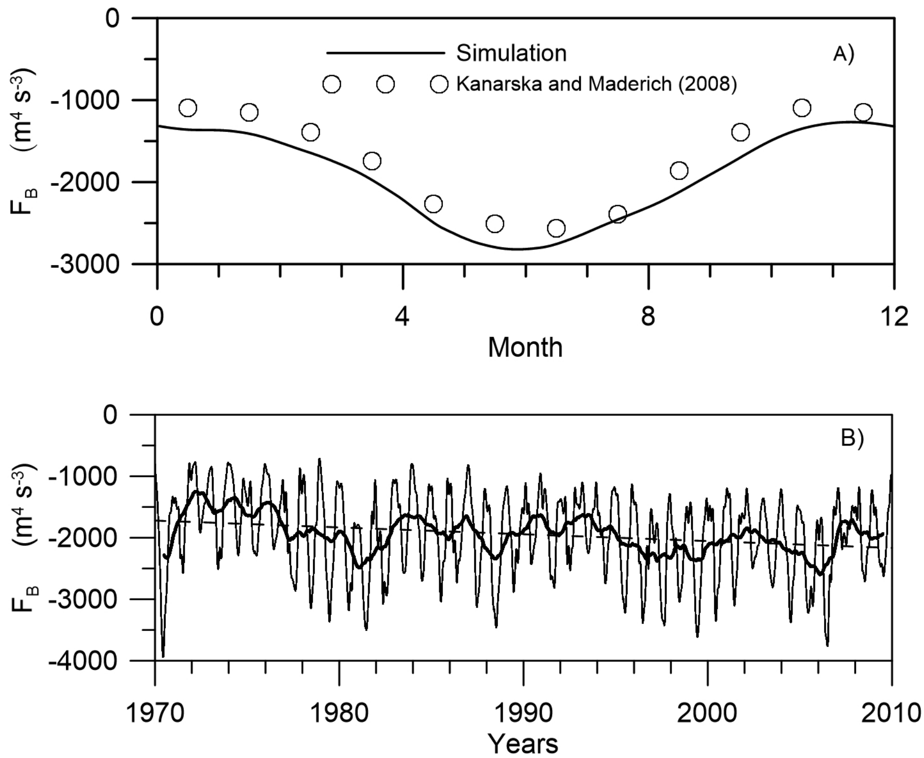


Fig. 8: The seasonal A) and interannual B) variability of the buoyancy flux F_B from the Dardanelles Strait to the North Aegean Sea for the period 1970-2009. The 3D simulation results by Kanarska & Maderich (2008) are shown in A).

1993-1997 (Fig. 9B). In Fig. 10A and 10B the simulated flows in the Bosphorus Strait are compared with observations (Jarosz *et al*., 2011b) for the period September 2008-January 2009. The series of measurements were smoothed by moving-average filter with 31 days window length. The curves are similar, but measured variations are greater. The calculated flows in the Dardanelles Strait are compared with measurements (Jarosz *et al*., 2013) carried out for the period September 2008-August 2009 in Fig. 10C and D. The simulated mean values of transport for this period are 39427 and -26908 m^3s^{-1} at the southern entrance and 23656 and -16145 m^3s^{-1} at the northern entrance, respectively. They agree with the observed by Jarosz *et al.* (2013) values 36680 and -31670 m^3s^{-1} at southern entrance, and 25660 and -14020 m^3s^{-1} at northern entrance, respectively. The strait model qualita-

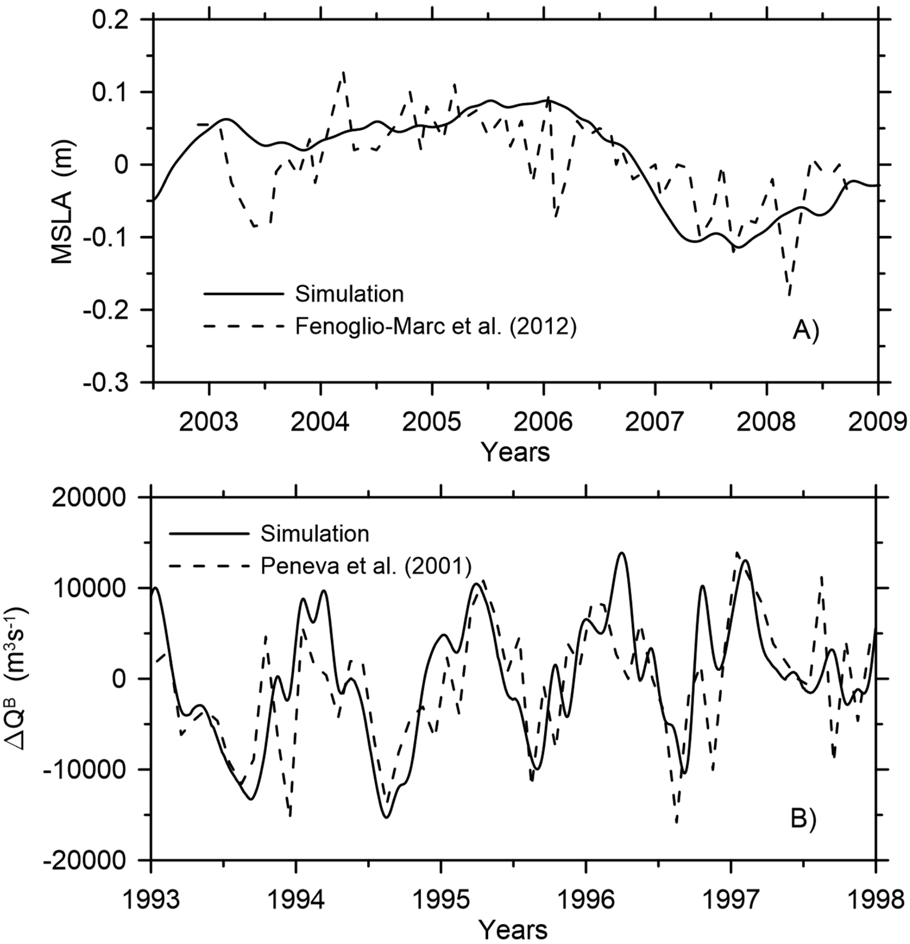


Fig. 9: The comparison of modelling with the measurements: A) Inter-annual MSLA variations with removed annual cycle versus basin average in Black Sea of the mass-induced sea level variations from altimetry (Fenoglio-Marc *et al*. 2012) for the period 2002-2008; B) Simulated net flow deviation ΔQ^B from the mean value $\bar{Q}^B$ versus net flow deviation through the Bosphorus calculated from Topex/Poseidon altimetry and freshwater budget (Peneva *et al*., 2001) for the period 1993-1997.

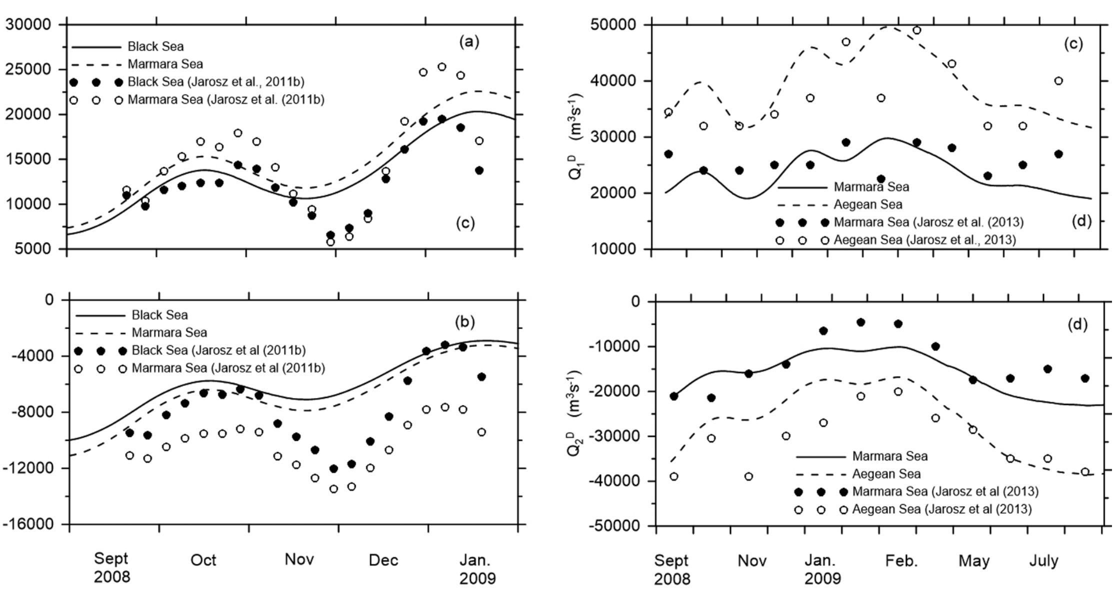


Fig. 10: Simulated flow rates in the Bosphorus versus calculated flow rates from measurements (Jarosz *et al*., 2011b) for the period September 2008-January 2009 in the upper layer A) and the bottom layer B). Simulated flow rates in the Dardanelles versus calculated flow rates from measurements (Jarosz *et al*., 2013) for the period September 2008-August 2009 in the upper layer C) and the bottom layer D). The flow rates from measurements were smoothed by moving-average filter with 31 days window length.

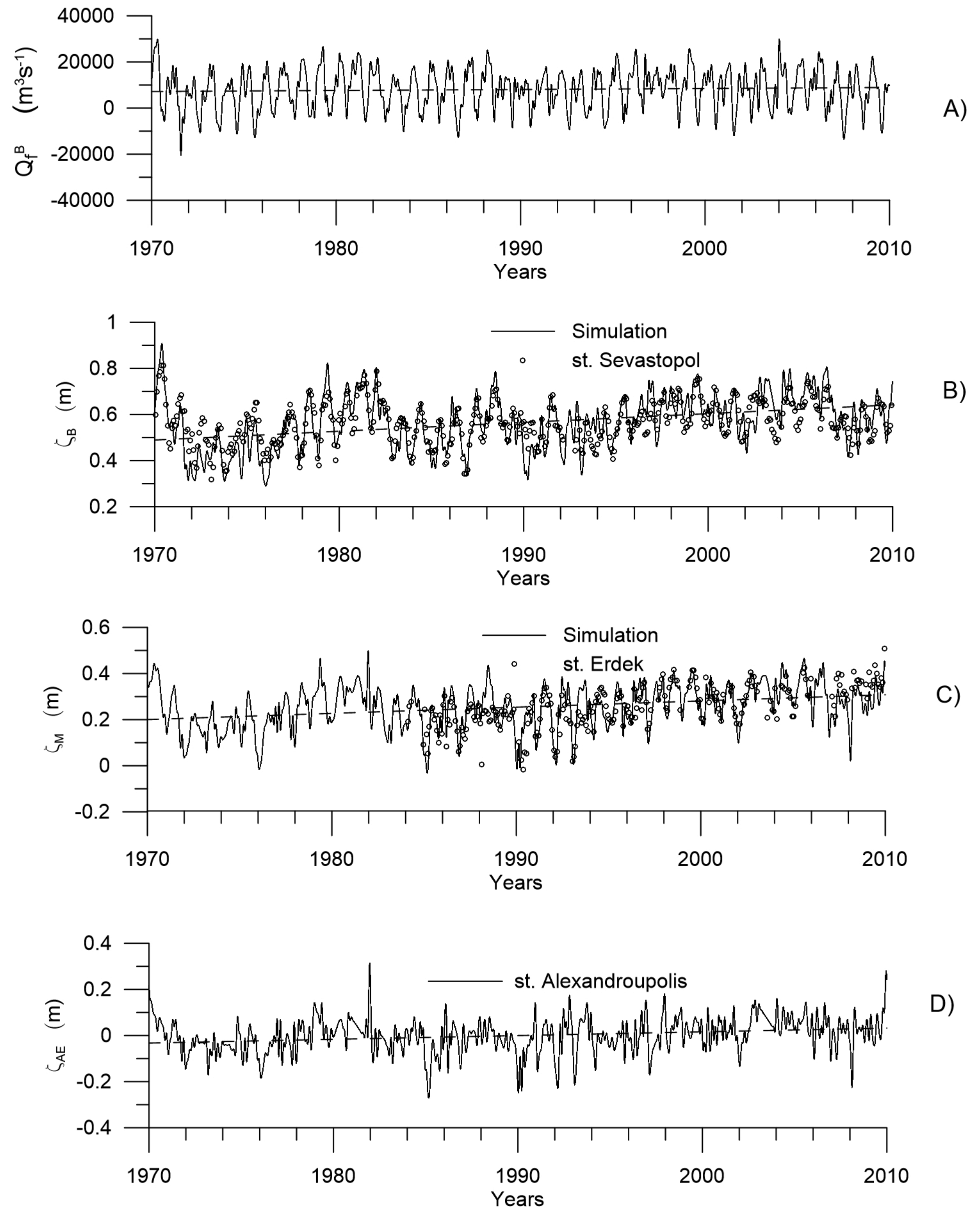


Fig. 11: Time variations of the total freshwater flux in the Black Sea A) and level in the Black Sea B), Marmara Sea C) and North Aegean D). Circles in B) and C) are monthly averaged tide gauge data from Sevastopol and Erdek (PSMSL data base), respectively. The dashed straight lines show trends.

tively and quantitatively predicted exchange rates in TSS despite the idealised geometry, simplified assumptions on the hydraulic control positions and semi-empirical parameterization of the entrainment.

The variations of the elevations in the Black, Marmara and North Aegean seas for the period 1970-2009 are shown in Fig. 11. The interannual variability of the freshwater influx in the Black Sea (Fig. 4D) and Aegean sea-level variations (Fig. 11C) result in large interannual variability of the Black and Marmara sea levels as seen in Fig. 11A and B. The interannual variations are of the order of 20 cm, the same order as seasonal and are much higher than the interannual level variations in the Mediterranean (Tsimplis *et al*., 2004). Simulation results agree with monthly averaged Sevastopol (Black Sea) and Erdek (Marmara Sea) gauge data except for two periods which correspond to the large decrease (1972-1976) and increase (2002-2006) of fresh water flux in Fig. 4D. The coefficients of correlation between observed and simulated elevations are 0.78 and 0.76 for the Black Sea and Marmara Sea, respectively. The RMSE is 7 and 6 cm, respectively, that corresponds to approximately 12% of the elevation range. The interannual variations of the Black sea elevation follow mainly the freshwater influx (Fig. 4D). The observed sea-level trends in the Black Sea (Sevastopol gauge station) for the period 1970-2009 and in the Northern Aegean (Alexandroupolis gauge station) for the same period are 1.9 mm year^{-1}, and 1.6 mm year^{-1}, respectively. The sea-level trend in the Marmara Sea (Erdek gauge station) for the period 1984-2009 is 7.8 mm year^{-1}.

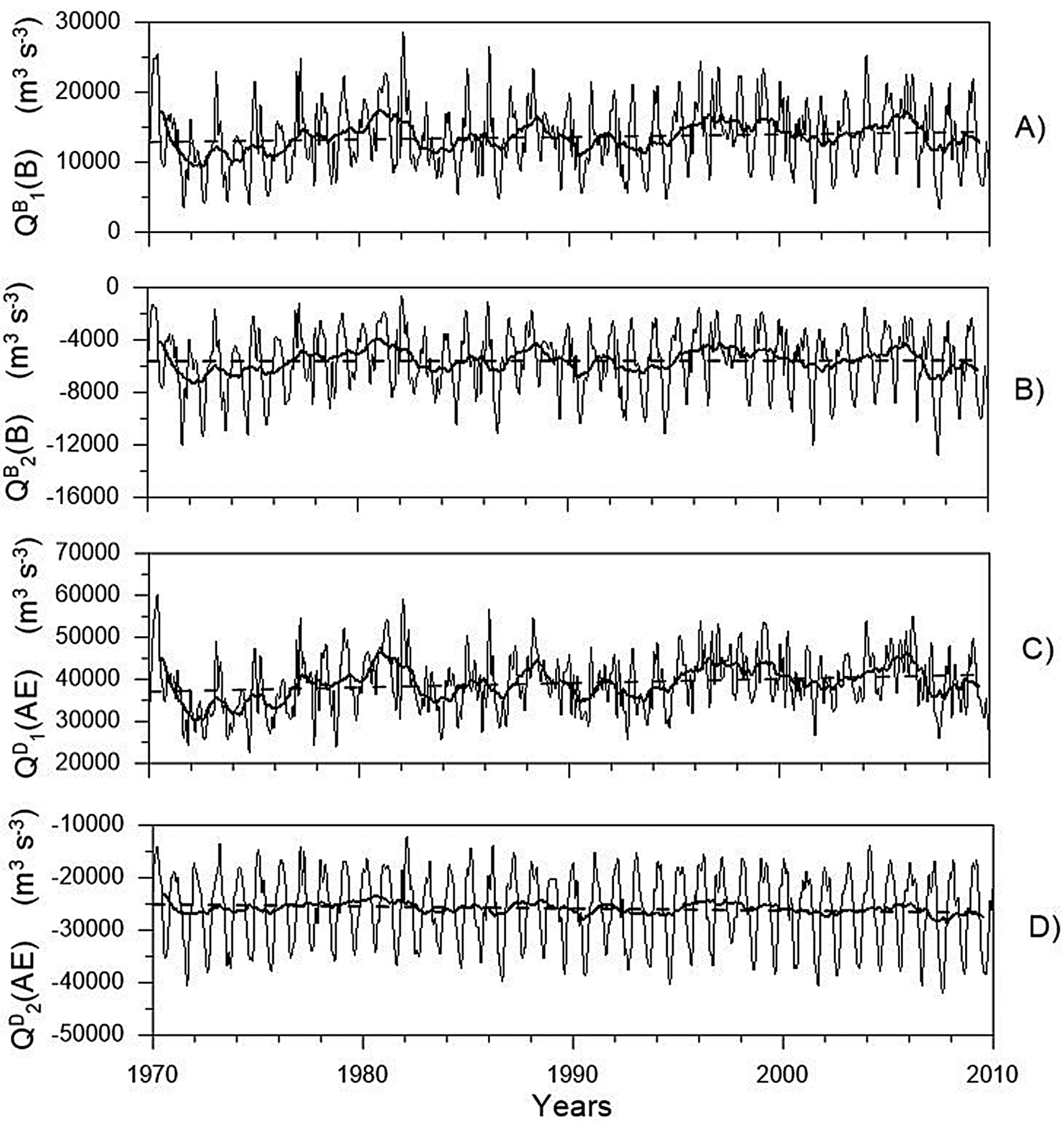


Fig. 12: Time variations of the flow rate in upper layer and bottom layers of the Bosphorus Strait at the Black Sea entrance (A and B) and of the Dardanelles Strait at the Aegean entrance (C and D). The thick lines show interannual variations and dashed straight line shows trend.

The simulated trends are statistically significant at 95% level for the period 1970-2009 and for 1984-2009 trends for elevations in the Black and Marmara seas. They are 3.8±0.9 mm year^{-1} for the Black Sea and 4.6±1 mm year^{-1} for Marmara Sea. The differences in the trend values may be due to inaccuracies in the assessment of the freshwater balance and due to the different lengths of the time series used in trend computations.

The variations of flow rates in upper and bottom layers of the Bosphorus Strait at Black Sea entrance and of the Dardanelles Strait at the Aegean entrance for the period 1970-2009 are given in Figure 12. They reveal a strong seasonal and interannual variability. The corresponding interannual variability is shown by thick curves in Fig. 12, where the seasonal variability has been removed through moving-average filtering with 13 months window length. The figure shows that variations of the interannual flow rates in upper and bottom layers of the straits follow mainly the freshwater flux in the Black Sea (Fig. 4D). The linear trend of the flow rate in upper layer of the Bosphorus Strait is statistically significant at 90% level. It is 36±30 m^3s^{-1} per year whereas trend of inflow in the Black sea from the Bosphorus strait is statistically insignificant. The trend of outflow from the upper layer of the Dardanelles Strait is statistically significant at 95% level. It is 102±52 m^3s^{-1} per year, whereas the flow rate trend in the lower layer is -39±18 m^3s^{-1} per year. It means that growth of freshwater flux in the Black Sea leads to a more than twofold increase of the Dardanelles outflow in the North Aegean and an increase of flow from the Aegean to the Marmara Sea. Note that the average net transport through the Strait of Bosphorus (8024 m^3s^{-1}) is smaller by 24 m^3s^{-1} than the average freshwater flux into the Black Sea. This difference corresponds to the simulated average rise of the Black Sea volume of 0.75 $km^3 year^{-1}$ in 1970-200An important consequence predicted by the model is a decrease in the salinity and the thickness of the upper layer of the Black Sea since 1970. The growing stability suppresses vertical turbulent mixing and ventilation of deep anoxic waters in the sea. The simulated variability of the buoyancy flux through the Dardanelles in 1970-2009 is given in Fig. 8B. The general trend of buoyancy flux is decreasing in 1970-2010 at rate of -15±5 $m^4 s^{-3}$ per year that can contribute to increase of stratification in the North Aegean.

Conclusions

The Turkish Straits System is a very complicated subject of oceanographic studies. The information on seasonal and interannual variability of the TSS still is not complete. Therefore one purpose of this paper was to develop a chain of relatively simple linked models in order to analyse the seasonal and interannual variability of the Turkish Straits System. This chain includes two-layer hydraulic models of the Bosphorus and Dardanelles straits that simulate the exchange in terms of level and density differences along each strait and the one-dimensional layered model of the Marmara Sea. The chain of models for TSS is complemented by similar layered model of the Black Sea proper and by models of the Azov Sea, and Kerch Strait. Several simplified assumptions and semi-empirical parameterizations were used to construct a set of models describing complicated dynamics of TSS. They are justified not only by physical arguments but also by the comparison of results with observational data. This linked chain of models was used to study the variability of the system in the period 1970-2009. To our knowledge the obtained results present the dynamics of the TSS as a whole at seasonal and interannual scales for the first time. The important role of water entrainment into the upper layer of system is revealed: this process has been shown to increase the annual flow rate in the upper layer of the Strait of Bosphorus, Marmara Sea, and the Strait of Dardanelles between northern and southern entrances by 11%, 56%, and 67%, respectively. The salinity of the Black Sea water flowing into the Aegean Sea increases by approximately 1.7 times through the entrainment from the lower layer. In total, the flow entering into the lower layer of the Dardanelles Strait in the Aegean end is reduced by around 80% when it reaches the Black Sea. On a seasonal time scale, the maximum transport in the upper layer was observed in winter/spring for the Bosphorus Strait and in spring for the Dardanelles Strait, whereas the minimum was observed in summer for the Bosphorus Strait and in the autumn for the Dardanelles Strait. The level difference at the ends of the Bosphorus Strait almost completely governs the flows. It allows using empirical relationships for diagnostics of transport through the Bosphorus Strait. However, the seasonal variations of flow rates in the Dardanelles Strait essentially depend also on the seasonally variable temperature and salinity differences along the strait, and therefore the relation with the level difference along the strait exhibits a hysteresis caused by baroclinicity. The variability of flow rates in the upper and bottom layers of the Bosphorus Strait and of the Dardanelles Strait shows strong seasonal and interannual variability for the period 1970-2009. The interannual variability of flow rate in the upper and bottom layers of the straits follows mainly the freshwater flux in the Black Sea. The increase of freshwater flux in the Black Sea at interannual time scales is accompanied by a more than twofold increase of the Dardanelles outflow in the North Aegean and by a corresponding increase of flow from the Aegean to the Marmara Sea. Simplifications in the derivation of the model equations do not allow the description of the synoptic-scale variability of currents in the TSS; however, the presented chain of simple models of the Turkish Straits System shows quite good agreement with available data and demonstrates the ability to describe complicated transport processes in the one of key points of the Mediterranean Sea system and therefore can be used in climate modelling for parameterization of exchange processes.

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References

Altiok, H., Sur, H., Muftuoglu, H., Yüce, H., 2010. Temperature, salinity and flow variations in the Strait of Istanbul (Bosphorus). *Rapport Commission Internationale de la Mer Mediterranee,* 39, 85.

Alpar, B., Dogan, E., Yüce, H., Altiok, H., 2000. Sea level changes along the Turkish coasts of the Black Sea, the Aegean Sea and the Eastern Mediterranean. *Mediterranean Marine Science*, 1, 141-156.

Alpar, B., Yüce, H., 1998. Sea level variations and their interactions between the Black Sea and the Aegean Sea. *Estuarine, Coastal and Shelf Science*, 46, 609-619.

Androulidakis, Y.S., Kourafalou, V.H., Krestenitis, Y.N., Zervakis, V., 2012a. Variability of deep water mass characteristics in the North Aegean Sea: the role of lateral inputs and atmospheric conditions. *Deep Sea Research*, part I, 67, 55-72.

Androulidakis, Y.S., Krestenitis, Y., Kourafalou, V.H., 2012b. Connectivity of North Aegean circulation to the Black Sea water budget. *Continental Shelf Research*, 48, 8-26.

Armi, L., Farmer, D.M., 1987. A generalisation of the concept of maximal exchange in a strait. *Journal of Geophysical Research*, 92, 14679-14680.

Beşiktepe, Ş., 2003. Density currents in the two-layer flow: an example of Dardanelles outflow. *Oceanologica Acta*, 26, 243-253.

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

Beşiktepe, Ş., Sur, H.I., Özsoy, E, Latif, M.A., Oğuz, T. *et al*., 1994. The circulation and hydrography of the Marmara Sea. *Progress in Oceanography,* 34, 285-334.

Blain, C. A., Cambazoglu, M.K., Jarosz E., 2010. Multi-scale model of the Turkish Straits System. *Rapport Commission Internationale de la Mer Mediterranee*, 39, 95.

Chiggiato, J., Jarosz, E., Book, J.W., Dykes, J., Torrisi, L. *et al*., 2011. Dynamics of the circulation in the Sea of Marmara: numerical modeling experiments and observations from the Turkish straits system experiment. *Ocean Dynamics*, DOI 10.1007/s10236-011-0485-5.

Demyshev, S.G., Dovgaya, S.V., 2007. Numerical experiment aimed at modeling the hydrophysical fields in the Sea of Marmara with regard for Bosporus and Dardanelles. *Physical Oceanography,* 17, 141-153.

Elguindi, N., Somot, S., Déqué, M., Ludwig, W., 2011. Climate change evolution of the hydrological balance of the Mediterranean, Black and Caspian Seas: impact of climate model resolution. *Climate Dynamics*, 36, 205-228.

Farmer, D.M. Armi, L., 1986. Maximal two-layer exchange over a sill and through the combination of a sill and contraction with barotropic flow. *Journal of Fluid Mechanics*, 164, 53-76.

Fenoglio-Marc, L., Rietbroek, R., Grayek, S., Becker, M., Kusche, J. *et al*., 2012. Water mass variation in the Mediterranean and Black Seas. *Journal of Geodynamics*, 59–60, 168– 182.

Goncharov, V.P., Emelianova, L.P., Mikhailov, O.V., Tsyplev, Yu. I., 1965. Areas and volumes of the Mediterranean and Black seas. *Oceanology*, 5, 987-992.

Gregg, M.C., Özsoy E., Latif M.A., 1999. Quasi - steady exchange flow in the Bosphorus. *Geophysical Research Letters*, 26 (1), 83-86.

Gregg, M.C., Özsoy, E., 2002. Flow, water mass changes and hydraulics in Bosphorus. *Journal of Geophysical Research*, 107, (C3), 2000JC00485.

Hogg, A.M., Ivey, G.N., Winters, K.B., 2001, Hydraulics and mixing in controlled exchange flows. *Journal of Geophysical Research*, 108, 959-972.

Hüsrevoğlu, S., Özsoy, E., Sözer, A., Gürses, Ö., 2010. Investigation of the Mediterranean-Black Sea coupling using multi-scale models of the Turkish Strait System. *Rapport Commission Internationale de la Mer Mediterranee*, 39, 119.

Ilyin, Y.P., Simov, V.G., Repetin, L.N., 2010. Problems and perspectives of monitoring water balance of the Black and Azov seas. *Ecological safety of coastal and shelf areas and complex use of shelf resources*, 22, 171-181.

Jarosz, E, Teague, W.J., Book, J.W., Beşiktepe, Ş.T., 2011a. On flow variability in the Bosphorus Strait. *Journal of Geophysical Research*, 116, C08038, doi:10.1029/2010JC006861.

Jarosz, E., Teague, W.J., Book, J.W., Beşiktepe, Ş.T., 2011b. Observed volume fluxes in the Bosphorus Strait. *Geophysical Research Letters*, doi:10.1029/2011GL049557.

Jarosz, E., Teague, W.J., Book, J.W., Beşiktepe, Ş.T., 2012. Observations on the characteristics of the exchange flow in the Dardanelles Strait. *Journal of Geophysical Research,* 117, C11012, doi:10.1029/2012JC008348.

Jarosz, E., Teague, W.J., Book, J.W., Beşiktepe, Ş.T., 2013. Observed volume fluxes and mixing in the Dardanelles Strait. *Journal of Geophysical Research,* 118, doi:10.1002/jgrc.20396.

Kanarska, Y., Maderich, V., 2008. Modelling of seasonal exchange flows through the Dardanelles Strait. *Estuarine, Coastal and Shelf Sciences*, 79, 449-458.

Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G. *et al*., 2001. The NCEP-NCAR 50-year reanalysis: monthly means CD-ROM and documentation. *Bulletin of the American Meteorological Society,* 82, 247-267.

Luettich, Jr., R.A., Westerink, J.J., 2004. Formulation and numerical implementation of the 2D/3D ADCIRC finite element model version 44.XX. ADCIRC Theory Rep. www.adcirc.org

Maderich, V., 1998. Modelling of Mediterranean system – changes under climate variations and human impact. *Environmental Modeling and Software*, 13, 405-412.

Maderich, V., 1999. Reconstruction and prediction of the radionuclide transport in the Mediterranean seas chain. *Journal of Environmental Radioactivity*, 43, 205-219.

Maderich, V., Efroimson, V., 1986. A simple model of a sea with the strait. *Oceanology*, 26: 403-408.

Maderich, V., Konstantinov, S., 2002. Seasonal dynamics of the system sea-strait: Black Sea-Bosphorus case study, *Estuarine, Coastal and Shelf Sciences*, 55, 183-196.

Marsigli, L.M., 1681. Osservazioni intorno al Bosforo Tracio o vero Canale di Constantinopli, rappresentate in lettera alia Sacra Real Maesta Cristina Regina di Svezia, Roma. Reprinted in Boll. Pesca, Piscis. *Idrobiologia*, 11, 734-758 (1935).

MEDAR Group, 2002. MEDATLAS 2002. *Mediterranean and Black Sea Database of Temperature, Salinity and Biochemical Parameters and Climatological Atlas [CD-ROM], Eur. Comm. Mar. Sci. and Technol. Programme (MAST), Ifremer, Brest, France*. www.ifremer.fr/sismer/program/medar/. (Accessed 23 May 2014).

Möller, L., 1928. Alfred Merz' hydrographishe untersuchungen in Bosphorus und Dardanellen, *Veroff. Inst. Meerskunde Univ. Berlin. Neue Folge*, A., 18, 284 pp.

Oğuz, T., 2005. Hydraulic adjustments of the Bosphorus exchange flow. *Geophysical Research Letters,* 32, doi:10.1029/2005GL022353.

Oğuz, T., Sur, H., 1989. A two-layer model of water exchange through the Dardanelles Strait. *Oceanologica Acta*, 12, 23-31.

Oğuz, T., Dippner, J.W., Kaymaz, Z., 2006. Climatic regulation of the Black Sea hydro-meteorological and ecological properties at interannual-to-decadal time scales. *Journal of Marine Systems*, 60, 235-254.

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

Özsoy, E., Latif, M.A., Beşiktepe, S., Cetin, N., Gregg, M. *et al*., 1998. The Bosphorus strait: exchange fluxes, currents and sea-level changes. p. 1-27. In: *Ecosystem Modeling as a Management Tool for the Black Sea*. Ivanov, L., Oğuz, T. (Eds.). vol. 2. Kluwer Academic Publishers.

Peneva, E., Stanev, E., Belokopytov, V., Le Traon, P.-Y., 2001. Water transport in the Bosphorus Straits estimated from hydro-meteorological and altimeter data: seasonal and decadal variability. *Journal of Marine-Systems*, 31, 21–33.

Simonov, A.I., Altman, E.N., 1991. *Hydrometeorology and hydrochemistry of seas of USSR. IV, Black Sea, pt.1, Hydrometeorological conditions*. Hydrometeorological Publishers, S. Petersburg.

Shchepetkin, AF., McWilliams, J.C., 2005. The Regional Ocean Modeling System: A split-explicit, free-surface, topography following coordinates ocean model. *Ocean Modelling*, 9: 347– 404.

Stanev, E.V., Le Traon, P.-Y., Peneva, E.L., 2000. Sea level variations and their dependency on meteorological and hydrological forcing. Analysis of altimeter and surface data for the Black Sea. *Journal of Geophysical Research*, 105, 17203-17216.

Stanev, E.V., Peneva, E.L., 2002. Regional sea level response to global climatic change: Black Sea examples. *Global Planetary Change*, 32, 3-47.

Tragou, E., Zervakis V., Papadopoulos, A., Maderich, V.S., Georgopoulos, D. *et al*., 2003. Buoyancy transport through the Aegean Sea. p. 38–46. In: *2nd International Conference on "Oceanography of the Eastern Mediterranean and Black Sea: Similarities and Differences of Two Interconnected Basins*. Yilmaz A. (Ed.), 14–18 October 2002, Tubitak Publishers, Ankara, Turkey.

Tsimplis, M.N., Josey, S.A., Rixen, M., Stanev, E.V., 2004. On the forcing of sea level in the Black Sea. *Journal of Geophysical Research,* 109, C08015. doi:10.1029/2003JC002185.

Tuğrul, S., Beşiktepe T., Salihoğlu, I., 2002. Nutrient exchange fluxes between the Aegean and Black Seas through the Marmara Sea. *Mediterranean Marine Science*, 3, 33-42.

Turner, J.S., Kraus, E.B., 1967. A one-dimensional model of the seasonal thermocline. I. A laboratory experiment and its interpretation. *Tellus*, 19, 88-97.

Tzali, M., Sofianos, S., Mantziafou, A., Skliris, N., 2010. Modelling the impact of Black Sea inflow on the North Aegean hydrodynamics. *Ocean Dynamics*, doi: 10.1007/s10236-010-0277-3.

Ünlüata, U., Oğuz, T., Latif, M.A., Özsoy, E., 1990. On the physical oceanography of the Turkish Straits. p. 25-66. In: *The Physical Oceanography of Sea Straits*. Pratt L.J. (Ed.), Kluwer Academics, Norwell, Massachusetts.

Woodworth, P.L., Player, R., 2003. The permanent service for mean sea level: an update to the 21st century. *Journal of-Coastal Research*, 19, 287-295.

Zervakis, V., Georgopoulos, D., Karageorgis, A.P., Theocharis, A., 2004. On the response of the Aegean Sea to climatic variability. A review. *International Journal of Climatology*, 24, 1845-1858.