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Along-Channel Variation Of The Layer Flow Paths And Fluxes Of The Bosphorus Exchange Based On A Three-Dimensional Model

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Abstract

A three-dimensional numerical ocean model is used to investigate the along-channel variation of the layer flow paths and the layer flux ratios of the Bosphorus exchange. Steady-state realistic solutions utilizing the full topography are obtained under the uniform reservoir conditions for the mean annual net flow rate through the strait. The upper layer and lower layer flow paths based on a two-layer approximation maximizing the respective layers fluxes are found to be different in the northern part of the strait. Ratio of the layer fluxes based on a two-layer separation considering the velocity direction shows considerable variation through the strait without a decreasing or increasing trend in either direction. The results suggest that layer flux estimations utilizing the in-situ data and modeling tools and the expressions related need a delicate considerations.

Keywords: Bosphorus Strait; Modeling; Two-Layer Exchange

İstanbul Boğazi Alt Ve Üst Akimlarinin Kanal Boyunca Değişiminin Ve İzledikleri Patikalarin Sayisal Bir Model Yardimi İle Gösterimi

Özet

Bu çalışmada İstanbul Boğazı değişim akımlarının kanal boyunca izledikleri patikalar üç-boyutlu sayısal bir okyanus modeli uygulamasıyla incelenmiştir. Homojen rezervuar koşulları altında gerçekçi bir topografya kullanılarak boğazın yıllık ortalama net akım değeri için değişmez-durum çözümleri elde edilmiştir. İki tabakalı bir çözümleme ile alt ve üst akımlarn kanal boyunca izledikleri yollar gösterilmiştir ve tabaka akımlarının boğazın kuzeyinde farklı patikalara sahip oldukları belirlenmiştir. Alt ve üst akımlarının oranının kanal boyunca değiştiği ve bu değişimin herhangi bir yönde artma veya azalma eğilimine sahip olmadığı belirlenmiştir. Elde edilen sonuçlar hem doğrudan gözlem veri setleri hem de model sonuçları kullanılarak elde edilen tabaka akımlarının hassas bir yöntemle değerlendirilimesi gerektiğini göstermiştir.

Anahtar Kelimeler: İstanbul Boğazı; Modelleme; İki Tabakalı Değişim

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1. INTRODUCTION

The Turkish Straits System (TSS), located at the junction of the Asian and European continents, provides a restricted connection between the large inland basins of the Mediterranean and Black Seas. The Sea of Marmara connects the Aegean and Black Seas through the Dardanelles and Bosphorus Straits. The two-layer exchange through the TSS is a main driver of environmental changes in the adjacent Black and Mediterranean Seas. Because it is located in a region of climatic contrasts (Özsoy & Ünlüata 1997; Özsoy 1999), the TSS has a strong influence on the long term trends and stability of these basins. Being the most constricted part of the TSS, the Bosphorus strait plays the most crucial role in the exchange between the Black Sea (north) and the Mediterranean Sea (south). The Bosphorus is an elongated passage between the Black and Marmara Seas with a total length of $\sim 35km$. The width of the channel varies between $700m$ and $3500m$ at the surface with an average value of $1.3km$ with quite a distinctive aspect ratio in comparison to other straits of the world. The bathymetry of the strait is highly variable in both the cross-channel and along-channel directions with a maximum depth of $\sim 105m$ occurring at its narrowest section.

The transport through the Bosphorus is realized basically in the form of a two-layer exchange flow with the southward flowing less saline Black Sea waters at the surface and the northward flowing more saline and denser Mediterranean waters beneath it. The driving mechanism of this two-layer exchange is the gravity, producing a hydrostatic pressure difference between the two ends of the strait, favoring a subsurface dense flow towards the Black Sea and compensating less denser surface flow towards the Marmara Sea. The mean excess of fresh water inputs in the water budget of the Black Sea results in higher sea-level on the Black Sea side. Therefore, the direction of the net barotropic flow, based on the climatological balance, is towards the Marmara Sea and the Mediterranean in general.

The first scientific explanation of the existence of an undercurrent in the Bosphorus strait, which was all too well known by the local fisherman throughout history, was made by *Luigi Ferdinando Marsigli (1658-1730)*, who also made the first measurements and presented experimental verification of his discovery (Marsigli 1681). Marsigli's study is the first remarkable contribution to oceanography in history and has been honored three centuries later in the modern age (Soffientino & Pilson 2005; Pinardi 2009).

The two-layer exchange stratification is roughly defined by a sharp pycnocline descending from the surface at the south-exit towards the bottom at the north sill through the strait and displays non-linear and abrupt changes corresponding to hydraulic adjustments occurring mainly at the three topographic or geometric features impacting the flow; the south-exit, the contraction region and the north sill (Özsoy et al 1998). Sharp adjustments observed in the salinity at the north-sill and at the contraction, and the consequent sudden and violent changes observed respectively towards north and south of these sections distinctively illustrate their effects on the flow, as observed by Latif et al (1991), Özsoy et al (2001), Gregg & Özsoy (2002).

The northern sill and the mid-strait contraction serve as the main topographic features responsible for supporting hydraulic controls, and their combined effects. The sill being located on the side of the less dense reservoir and the suitable reservoir conditions make the unique environment in which the Bosphorus is ideally suited to support the 'maximal-exchange' regime of Farmer & Armi (1986) suggesting that the Bosphorus flow can be fully identifiable by its geometry for a specified density difference and a net barotropic flow rate through the strait.

The schematic representation of the upper and lower layer volume fluxes across the compartments of the TSS are given by Ünlüata et al (1990) which is based on the measurements of 1986-1987 (Özsoy et al 1986; 1988) and estimated by the steady-state salt and mass conservation equations utilizing the average salinity values at the junctions of the TSS. The excess fresh water inflow into the Black Sea defined by the Precipitation (P)+River Runoff (R)−Evaporation (E) which is estimated as $300 + 352 - 353 = \sim 300 km^3/yr$ is balanced by the net volume-flux through the Bosphorus into the Marmara Sea resulting in a two-layer exchange with upper and lower layer fluxes roughly and $600km^3/yr$ and $300km^3/yr$ respectively. Tuğrul et al (2002) followed the mass budget technique of Ünlüata et al (1990) but with an improved estimate of fresh water inflow based on the Danube runoff (almost 70% of the total runoff to the Black Sea) and utilizing also the CTD data for the period of 1990-2000 to provide the first time seasonal flux estimation for the Bosphorus which is quite consistent with the previous estimations of Ünlüata et al (1990). Peneva et al (2001) utilized the TOPEX/Poseidon altimeter data for the period of 1993-1997 and the available *P+R-E* data together with the long-term tide-gauge hydro-meteorological data series and showed that the main signal in the net volume-flux through the Bosphorus Strait is the seasonal one with maximum values in March and April and minimum in August.

The exchange through the Bosphorus is always a topic of interest where great effort has been spent for the direct estimation of the fluxes by ADCP transects or continuous records of velocity profiles (Özsoy et al 1996; 1998; Altıok et al 2010; Jarosz 2011). Variation of the net volume-flux though the strait responds to the seasonal and inter-annual changes of the P+R-E and the stratification over the Black Sea, but the instantaneous net barotropic volume transport through the Bosphorus displays quite greater variability than the seasonal variations where direct estimations of the layer fluxes can be three times in magnitude compared to the long-term budget estimations. Apart from the seasonal response, this transient variability in the Bosphorus flow system is mainly provided by the meteorological events within the TSS region with time-scales ranging from a few hours to time scales of the passage of cyclonic systems with periods of 3 to 10 days (Ünlüata et al 1990; Büyükay 1989; Gunnerson & Özturgut 1974).

Temporally scattered observation sets and the differences in the measurement methods certainly prevent us from solid conclusions on the variability of the layer fluxes; but certain aspects such as the seasonal variability of the layer fluxes, with greater variability in the upper layer and estimate for the annual net barotropic flow on the order of 300km^3/yr towards the Marmara Sea are well known. The lack of a multi-purpose real-time monitoring system at the Bosphorus Strait despite the recent efforts reported in Özsoy et al (2009) and Tutsak (2012) creates a serious deficit of critical information in this most important strategic location linking two marine environments.

Two-layer, one or two dimensional models solving either horizontally or vertically integrated hydrodynamic equations have been developed for the Bosphorus (Oğuz et al 1990; Ilıcak et al 2009) and Dardanelles (Oğuz & Sur 1989; Stashchuk & Hutter 2001) Straits. Three-dimensional models solving the full set of primitive equations have also been developed for the simplified hydrography and geometry of the Bosphorus Strait (Sözer & Özsoy 2002; Oğuz 2005). Some observed features, including the blocking and hydraulic transitions of the flow (Latif et al 1991), sharp changes of the free-surface at the contraction (Gregg et al 1999; Gregg & Özsoy 2002) and the separation of the zero-velocity line with the pycnocline (Tolmazin 1985; Gregg & Özsoy 2002) have been demonstrated by some of the above models, however they are still far from being fully representative of the coupled dynamics of the TSS in an integrated way.

Following the increase in computational power, three-dimensional primitive equation high resolution numerical ocean models for stand-alone Bosphorus, Marmara Sea and for the whole TSS utilizing the full topography and the hydrography of the area of interest became accessible in recent years (Öztürk et al 2012; Chiggiato et al 2011; Sannino et al 2015).

A recent PhD study focusing on the modeling of the Bosphorus flow dynamics in detail is performed by Sözer (2013) which is also the source for this article. Here, some of the results of this thesis regarding the along-channel variation of the layer flow paths and layer flux ratios of the Bosphorus flow based on a three-dimensional model are presented.

2. MATERIAL and METHODS

2.1 Numerical Model

The numerical investigation of the Bosphorus flow is performed with a well-known three-dimensional, free-surface, terrain-following primitive equation open source community model, ROMS (www.myroms.org), which is very popular in the scientific community with wide range of applications (Haidvogel et al 2000; Wilkin et al 2005; & Hedström 2009). The model solves the Reynolds averaged Navier-Stokes equations under the hydrostatic and Boussinesq approximations on orthogonal curvilinear/rectilinear coordinates with an Arakawa "C" grid arrangement (Arakawa & Lamb 1977) in the horizontal while utilizing a stretched topography following vertical coordinate system discretized with a staggered vertical stencil in the vertical direction. Together with the availability of boundary fitted curvilinear grids, land/sea masking of the horizontal grid points enables coastal applications with irregular coastlines.

2.2 Model Grid

Full topography is used for the construction of the model grid. Various data sources are utilized, but the main data source is the high resolution data of Gökaşan (2005). The model domain is discretized with a rectilinear variable resolution grid of 163*716 nodes with dx=50−200m (cross-channel), dy=50−325m (along-channel) and 35 s-levels with vertical spacing of 0.7−2.85m. With the aim of providing open boundaries at the two edges of the model domain normal to the mean flow direction and to reduce the pre/post processing work, the model grid is aligned with the average along-channel direction of the strait. Further details of the model grid and the bathymetry can be found in Sözer (2013). The model grid and the bathymetry is demonstrated in Fig. 1.

2.2 Model Setup

Three simulations are performed starting from a lock-exchange (LE) initial by releasing two uniform water bodies meeting at the mid-section of the strait, with contrasting salinity and temperature values of S=38.0, T=13.0^{0}C in the south and S=17.6, T=4.0/14.0/24.1^{0}C in the north (run 1, run 2 and run 3 respectively), the latter representing seasonal variations of surface temperature in the Black Sea. These constant values roughly correspond to typical lower layer properties of the Marmara Sea at the south and the Black Sea surface properties at the north, while excluding the stratification in the Marmara Sea and the cold intermediate water (CIL) of the Black Sea resulting in uniform reservoir conditions.

The model is integrated from an LE initial condition (detailed above) for a total duration ~5.55 days which is started with a very small baroclinic time-step of 1.75s and then restarted after the first day with an increased time-step of 4.0s where a 20 times smaller barotropic time-step is set through the whole simulation. The Generic Length-Scale (GLS) turbulence closure, (Warner et al., 2005) with the k−ε formulation is used in the vertical, while lateral diffusivity and viscosity are parameterized by the Smagorinsky-like formulation (Smagorinsky 1963) on constant geopotential surfaces. Orlanski (1976) radiation conditions are used at the north and south open boundaries for the 2d and 3d flow variables with an exception for the along-channel barotopic (south-north) velocity which is prescribed at the southern edge in order to impose the mean annual volume-flux ($300km^3/yr \approx 9460\ m^3/s$) estimated by Ünlüata et al (1990). No-slip boundary conditions are assumed at the side-walls and a quadratic bottom friction coefficient (RDRG2=0.005) is implemented at the bottom while all surface-fluxes are set to zero. The rotation of the earth is ignored since the internal Rossby Radius of Deformation is significantly larger than the strait width.

3. RESULTS and DISCUSSIONS

For the three simulations, the model is quite robust in terms of energy and volume-flux conservation with achieved steady-state balances less than two days. Along-channel variation of the salinity through the thalweg (shown in Fig.1) for run 2 is demonstrated in Fig. 2, which is also quite similar for the two other simulations. The solutions are representative of many observed features of the Bosphorus flow such as the thin Marmara outflow, apparent transitions at the south-exit, contraction and the north sill followed by a hydraulic jump spreading into the Black Sea shelf, thickness of the interface, the gradual dilution of the layers, evolution of the free-surface through the strait and widely discussed in Sözer (2013); Sözer & Özsoy (2016).

3.1 Along-channel variation of the layer-fluxes

The upper (Q_U) and lower layer (Q_L) flux vectors are in the j−direction of the model grid and computed from the simple cross-channel (i−direction) integration of $\int vdxdz$ where v is the along-channel velocity used in the model (v-velocity). The upper and lower layer estimations are based on the constraints v-velocity<0 and v-velocity>0, respectively.

Evolution of the upper and lower layer fluxes through the strait (Fig. 3) demonstrates that the variation of the layer fluxes through the strait for the three cases, run 1 to run 3, are perfectly similar in characteristic with quantitative differences in response to the change in the density of the Black-Sea. Layer flux estimations based on the velocity direction vary significantly through the strait. Even excluding the exit regions conservatively (from Üsküdar to Garipçe), $|Q_U|$ and Q_L estimations for run 1 vary between 18650m^3/s and 22700m^3/s; 9200m^3/s and 13300m^3/s respectively with $|Q_U|/Q_L$ values from 1.7 to 2.0 without a decreasing or an increasing trend in either direction.

3.1 Upper and lower layer flow paths

A three-layer decomposition (top, interfacial and bottom layers) is also performed by describing an interfacial-layer limited by the depths where 10% change occurs from the surface and the bottom values of salinity. The definition of an interfacial-layer based on the 10% change depths for each model grid point can be quite misleading whenever a fluid column at any grid point is not actually representing a three-layer structure with Black Sea water at the surface separated from the Marmara flow by an interfacial-layer. Therefore the definition of the interfacial-layer is performed by first finding the minimum surface and maximum bottom salinities at each i−section of the model grid and then these values are used for the three-layer decomposition for the respective whole cross-section, this method is found to be quite successful not only in the strait but also in the reservoir sides.

Upper and layer flow paths are constructed for a modified two-layer approximation. This method is based on a computation starting from the usual thalweg and iteratively reaching a flow path maximizing the layer volume-fluxes at each cross-section through the strait for the northward and southward flows separately.

The upper and lower layer flow paths for the simulation run 1 are demonstrated in Fig. 4 together with the total spread width of the top and the bottom layers based on the three-layer decomposition. We see that the upper and lower layer flow paths are in agreement within the southern part of the strait. However, the flow paths are clearly different from İstinye to north-exit, since the northward flowing lower layer is confined within the deep inner-channel whereas the upper layer is confined by the channel width. The difference is quite distinctive within the bend regions through which the more free southward flow selects a shorter path. Upper and lower layer flow paths are bounded with the horizontal limits of the top and the bottom layers respectively, but not always perfectly centered and can be skewed to one side as in the case of lower layer at Beykoz and surface outflow at the Marmara junction.

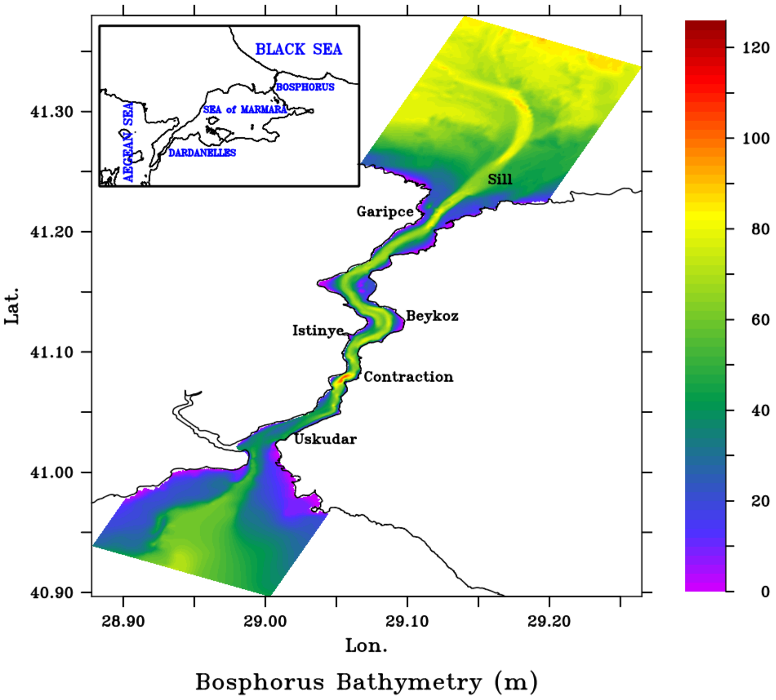

Figure 1. Map of the Turkish Straits System and the raw bathymetry of the Bosphorus Strait demonstrated on the model grid used in the simulations.

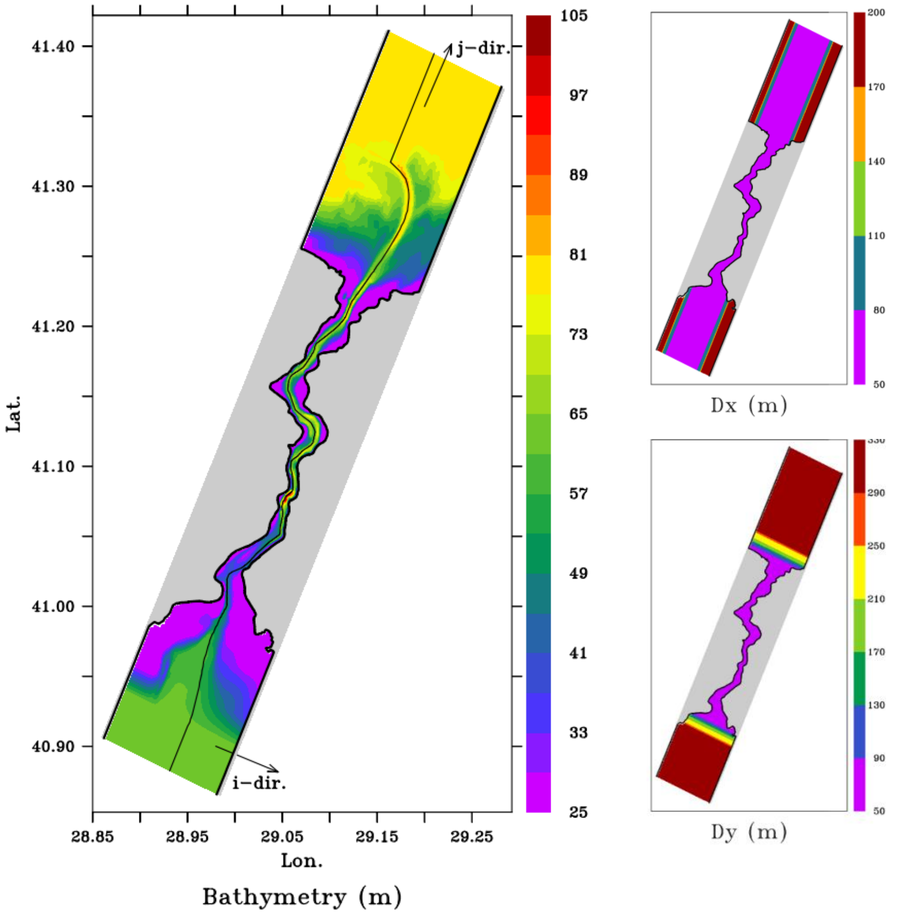

Figure 2. Layout and the bathymetry of the model grid and the position of thalweg points following the deepest path of the strait. Orientation of the rectilinear grid is aligned with the Bosphorus Strait with j-axis of the model pointing towards the northeast direction

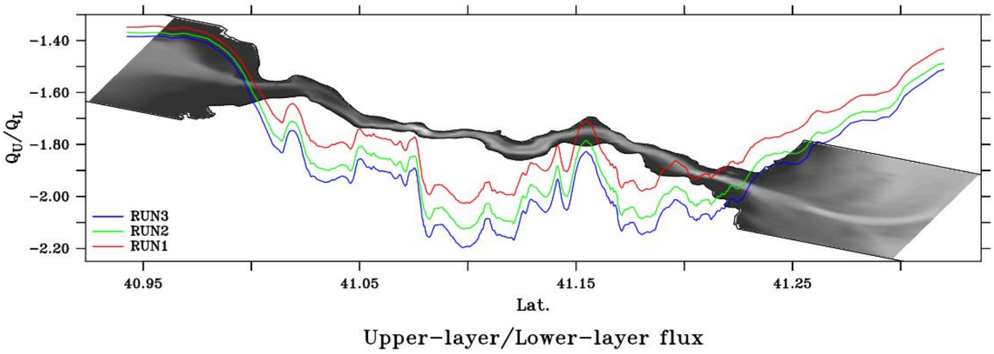

Figure 3. Variation of the ratio of the modeled steady-state layer fluxes ($|Q_U|/Q_L$) through the strait for the cases run 1, run 2 and run 3. The bathymetry of the strait is demonstrated in the background.

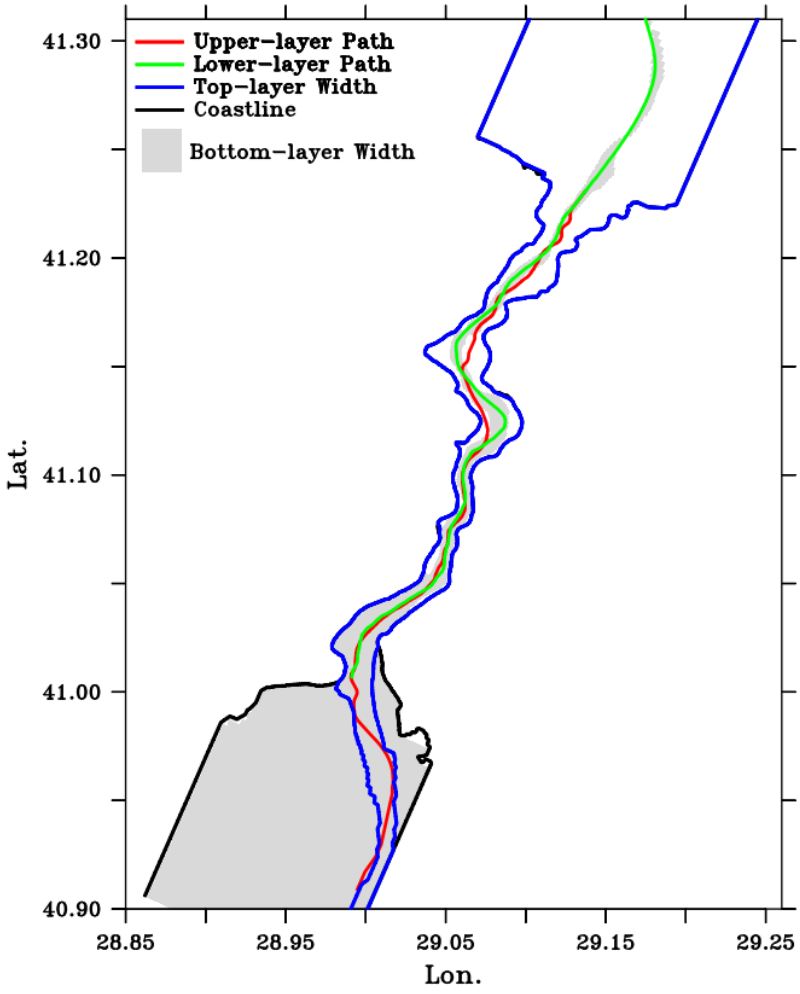

Figure 4. Combined demonstration of the layer paths and widths. Gray shaded area and the region bounded by the blue boundary demonstrates the spread area of the bottom and top layers based on the salinity based three-layer decomposition, respectively. The paths of the upper and lower layers based on the mean flow direction are shown with colored lines.

4. CONCLUSIONS

Being the narrowest part of the TSS, the Bosphorus is a natural observation point to monitor the exchange between the Black Sea and the Mediterranean Sea. There are many scientific studies focusing on the estimations of the layer fluxes through the strait. In addition to the practical difficulties involved in direct measurements of the Bosphorus currents, this study demonstrates that layer flux estimations using a two-layer velocity based layer separation may be misleading due to the recirculated water masses from the opposing layers through the strait. Along-channel variability of the two-layer velocity based layer fluxes should be considered in the evaluation of the layer flux estimations from the concurrent observations at different locations of the strait and also in the comparison of the different data sets.

Another point is the significant difference between the upper and layer flow paths in the northern part of the strait and the deviation of the upper layer flow path from the strait thalweg which complicates the process of extracting an along-channel velocity component from the velocity data. Moreover, the use of a fixed thalweg line for rotating the velocity vector which is the usual way in the literature becomes questionable.

Since, it is often not possible to stream velocity data covering full cross-sections of the strait, simple interpolation and extrapolation of the velocity data for the flux estimations are used to fill the gaps in data. However, even a first order approximation based on a three-dimensional numerical model presented in this paper suggests that the use of model solutions to estimate the layer fluxes would probably be an important element of progress.

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