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A three-dimensional model of Bosphorus Strait dynamics

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Abstract. Bosphorus Strait exchange ows are studied based on SCRUM, a 3-D ocean model with alternative parameterisations of mixing, advection and eddy diffusion, as well as free-surface dynamics. The response of the Strait is investigates with respect to the choices of open boundary conditions and mixing parameters, under idealized geometrical and hydrographical conditions. The selection of open boundary conditions is shown to be crucial, and depends on the direction of net ow. Blocked ow conditions for both ow directions are successfully simulated. The results of sensitivity tests are reported.

Introduction

The exchange flow through the Bosphorus Strait is principally determined by geometry and stratification, and exhibits a complex nonlinear response to forcing by the net water budget, pressure and wind setup effects in adjacent basins [*Ünlüata et al.*, 1990; *Özsoy et al.*, 1998; *Gregg et al.*, 1999; *Gregg and Özsoy*, 2001]. Time-dependent forcing creates daily to interannual variability in the currents and extreme conditions result in temporary blocking of the flows in either direction [*Özsoy et al.*, 1996, 1998].

The development of realistic numerical models of strait exchange flows has to resolve difficulties imposed by parameterization of mixing, as well as the need to implement physically relevant boundary conditions. Reduced order models based on the two-layer approximation have been used by [*Oğuz et al.*, 1990; *Brandt et al.*, 1986]. Recent developments by [*Winters and Seim*, 2000; *Hogg et al.*, 2001] utilize a three-dimensional model with rigid-lid dynamics and parameterized vertical mixing.

The present study aims for a better understanding of the behaviour of Bosphorus Strait flows based on a realistic three-dimensional model of its dynamics. As a first step before considering the application of the model to actual conditions of the Bosphorus Strait, the response of the Strait is investigated with respect to open boundary conditions corresponding to idealized geometrical and hydrographical conditions. As opposed to earlier studies, we use a model with free-surface dynamics. Although the rigid-lid assumption would be appropriate for long-term dynamics, the presence of a free surface is essential to predict short-term changes and relate them to sea-level variability in the Strait and the adjacent basins.

Model description

The free-surface primitive equation model, SCRUM, is used for numerical simulations of the idealized Bosphorus Strait flows. The model has terrain-following coordinates, optional mixing parameterizations and various choices for the bottom, solid or open boundary conditions []. Idealized model geometry of a straight channel with a contraction and a sill, as shown in Figure 1, is considered. A contracting channel, $3.4km$ in width and $30km$ in length, is overlaid on a 17×100 rectilinear grid for numerical simulations.

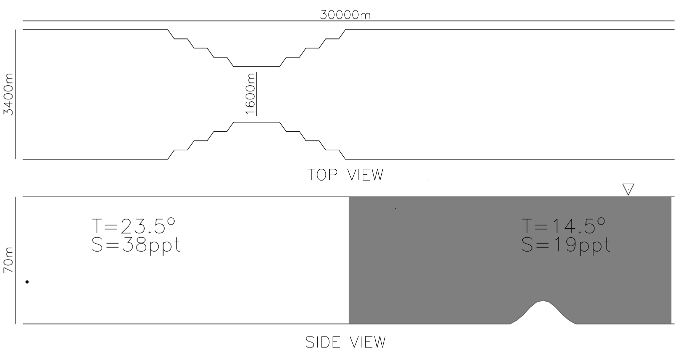

Figure 1. Model geometry: top and side views of the channel

The initial conditions for tracers consist of water masses with contrasting temperature and salinity values (Figure 1) typical of Marmara and Black Sea waters, meeting at mid-channel. In all runs, free slip boundary conditions are used on the side walls and the bottom. The Smolarkiewicz tracer advection scheme is used to escape the overshooting effect of centred advection, while dealing with sharp gradients. Laplacian diffusion is assumed in the horizontal and vertical directions, with typical diffusion coefficients in ranges of $K_h = 150 - 350m^2/s$ and $K_v = 10^{-6} - 10^{-3}m^2/s$ respectively, for tracers and momentum. To ensure stable integrations, a time step of 5 seconds for the baroclinic modes have been used in all model runs, with a barotropic time step that is 20 times smaller.

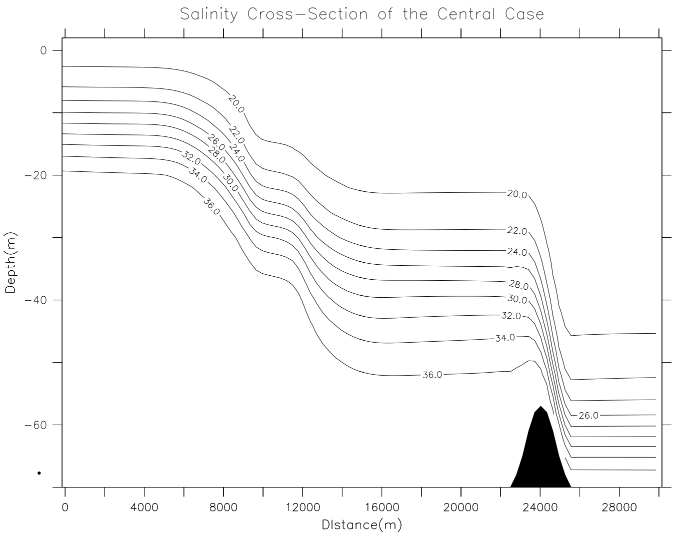

Figure 2. Salinity cross-section for the central run

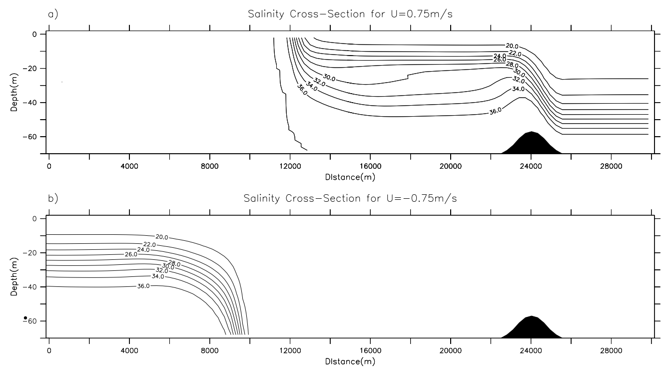

Figure 3. Salinity cross-sections for cases in which (a) the upper layer or (b) the lower layer is blocked

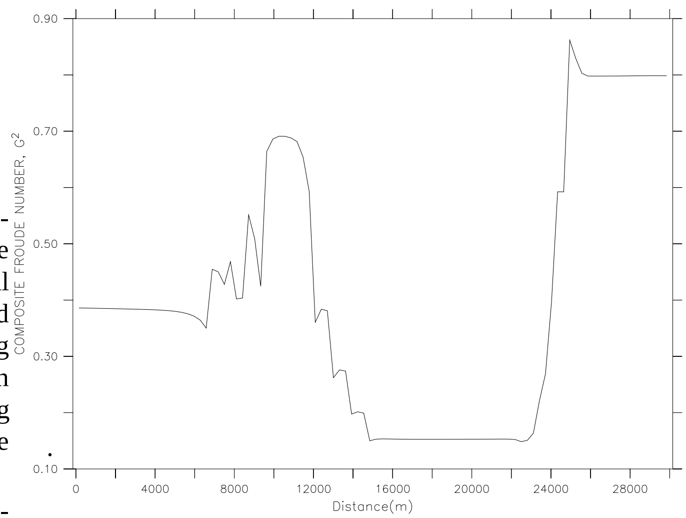

Figure 4. Composite Froude Number for the central run

Results

Open boundary conditions

In order to test the model behaviour, trials were made using various types of initial and boundary conditions. The choice of initial conditions were critical in reaching physical solutions. Because radiation boundary conditions were used for tracers at both ends, the tracer advection by inflowing waters tended partially to carry back into the model domain the properties of outflowing waters from the counter-flowing current. Instead, the 'lock-exchange' initial conditions were used as they avoided this behaviour.

Various types of free surface and velocity boundary conditions were tested at the two open boundaries. Because the cases tested were symmetrical along the long axis, and because free slip conditions were assumed, the normal velocity at solid boundaries and the tangential velocity at open boundaries were respectively always set equal to zero. The mixing coefficients were varied in the range mentioned earlier until more robust results were obtained in terms of free surface response and mass conservation. The mixing coefficients for momentum and tracers deremined from this exercise were $K_h = 250 m^2/s$ and $K_v = 10^{-4} m^2/s$, which were then used for the central run.

A special case with radiation boundary conditions for all variables (free surface elevation, velocity and tracers) on each side, started from a lock-exchange initial condition (with water properties in Figure 1), reached a stable solution shown in Figure 2. This result was remarkable, and confirmed the existence of a maximal exchange solution supported by the special geometry of a sill placed on the denser side of a contraction as shown by *Farmer and Armi* [1986]. The mean velocity corresponding to this case was calculated to be $\bar{u} = 0.065 m/s$. For a single sill or a single contraction with the same boundary and initial conditions such stable solutions could not be obtained. The two-layer composite Froude number $G^2 = F_1^2 + F_2^2$ (where $F_i^2 \equiv \bar{u}_i^2/gh_i$ are the individual Froude numbers of the layers i each with depth h_i and mean along-strait velocity $\bar{u}_i$, delineated by an interface where the horizontal velocity vanishes $\vec{u} = 0$) shown in Figure 2 indicates hydraulic controls established at the sill (where the lower layer is controlling) and at the contraction (where each of the layers contribute comparably to the control). The number G^2 peaks up, but fails to reach a value of 1 at the contraction, mainly because of the two-layer approximation used, as also the case in the observations [*Gregg et al.*, 1999; *Gregg and Özsoy*, 2001].

For most configurations, including the all-radiation case described above, the model had a robust response whenever stable solutions could be reached. There was a deficiency of the model in creating smooth sea level variations near the open boundaries under certain conditions. For such cases, the free surface fields produced by the model often were discontinuous exactly at the open boundary, while being continuous in the rest of the domain. This effect was minimized by appropriate choices of open boundary conditions and mixing

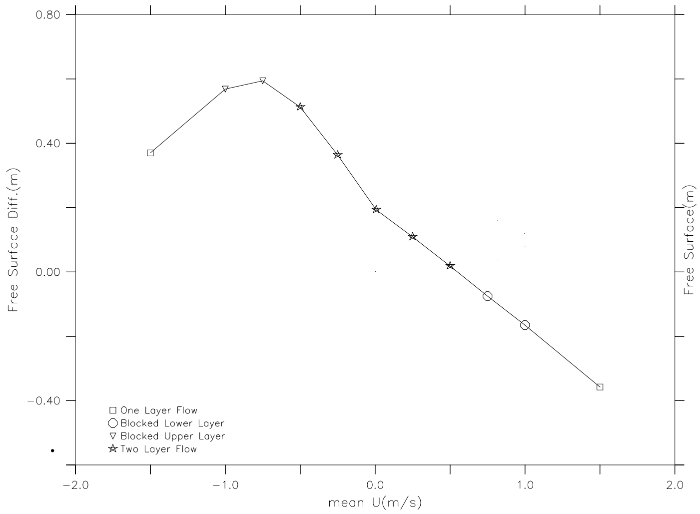

Figure 5. Sea level difference $\Delta\eta$ versus the mean current $\bar{u}$

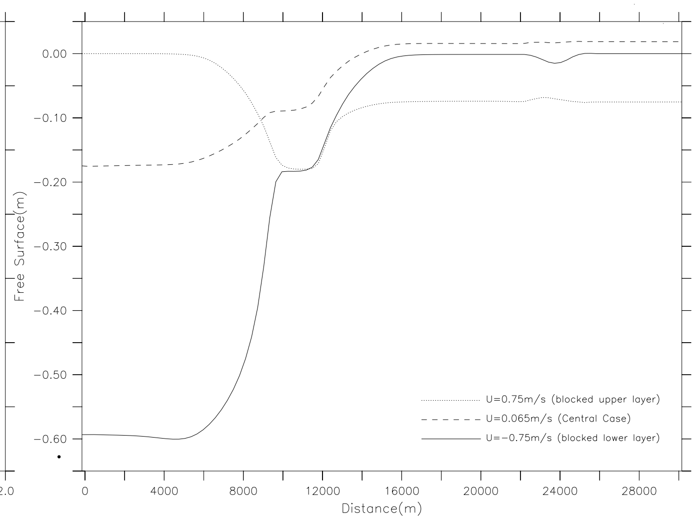

Figure 6. Along-channel variation of the free surface elevation η for different values of mean current $\bar{u}$. The dotted line corresponds to Figure 2, while the others correspond to the blocked cases in Figure 3

coefficients.

In order to seek solutions corresponding to a specific value of the barotropic flow through the Strait, a strategy had to be found for specifying open boundary conditions. The first case tested used radiation boundary conditions for the normal velocity components u, and specified free surface elevation η at open boundaries at the two ends of the Strait. This type of boundary conditions failed to create stable solutions, because the pressure difference between the two ends of the Strait could not set into motion the water masses in the Strait to generate a corresponding net flux. It was therefore required to specify barotropic velocities at the open boundaries, in order to produce a net flux and a corresponding pressure difference across the Strait.

Specifying the sea-level η and cross-sectional mean velocity $\bar{u}$ at the two ends of the strait did not produce stable results when it was left arbitrary on which side to apply these boundary conditions. It was apparent after many trials that the model produced reliable results only when the mean velocity $\bar{u}$ was specified at the outflowing boundary, together with the free surface η specified at the other (inflowing) end of the Strait. In addition, experiments were carried out in which the specified values of η or $\bar{u}$ were either applied alone or together with a radiation term. In general, the results were similar; however, the specified value of $\bar{u}$ at the southern end of the Strait resulted in stable solutions only if there was no additional radiation term applied.

Although the above specification of η and $\bar{u}$ at opposite ends depending on flow direction consists of a complete set of boundary conditions, steady solutions were also possible if only $\bar{u}$ was specified at the outflowing side, applying radiation boundary conditions for η on both sides of the Strait. In these cases, the solution converged to an absolute sea level value that corresponded to the specified net flow. However, to get consistent results corresponding to different flow rates, the free surface was specified to be $\eta = 0$ at the inflowing open boundary, so that the level was adjusted at the opposite

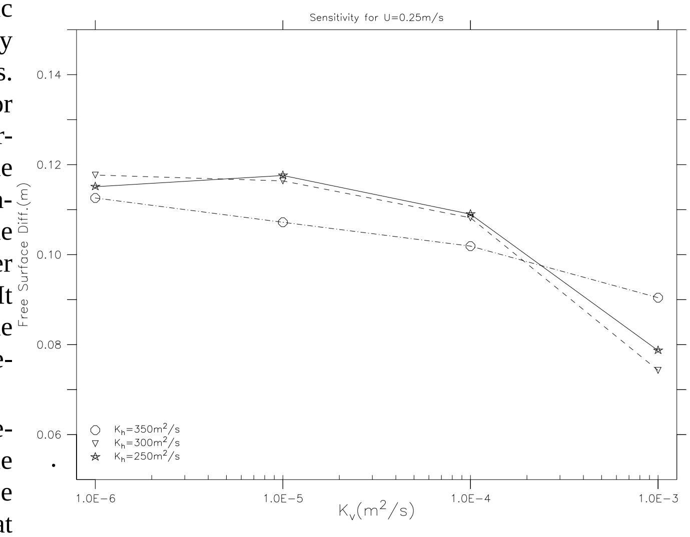

Figure 7. Sea level difference $\Delta\eta$ as a function of horizontal (K_h) and vertical (K_v) diffusion coefficients

side of the Strait.

A series of runs were performed with the above boundary conditions, while varying the net flow $\bar{u}$ from -1.5m/s to 1.5m/s. Figure 3 shows salinity cross-sections along the centerline of the Strait, for selected net flows producing blocking of the upper and the lower layers. Figure 4 shows the variation of the free surface elevation along the Strait, and Figure 5 shows the free surface difference between the two ends of the Strait as a function of the mean flow. The sea level variations in Figure 6 correspond to the the central run and the two blocked cases in Figures 2 and 3.

Parameter sensitivity

Sensitivity tests were carried out, by varying parameters about the central run with $\bar{u} = 0.25m/s$. In general, these sensitivity runs produced similar steady solutions with little change in behaviour. Yet, it was observed that the vertical diffusion coefficients controlled the sea level difference along the Strait, decreasing by about 30% when K_v was increased by three orders of magnitude between $K_v = 10^{-6} m^2/s$ and $K_v = 10^{-3} m^2/s$, as shown in Figure 7.

Discussion and conclusions

A three-dimensional dynamical model has been demonstrated to be applicable to the special case of strait exchange flows. The selection of open boundary conditions is a non-trivial first step for succesful applications of the model. The results obtained from tests with idealized cases corresponding to the Bosphorus Strait indicate the need for judicious choices of boundary conditions, which depend on the flow direction. However, the results obtained with these choices and even the case with purely radiation boundary with purely radiation boundary conditions started from 'lock exchange' initial conitions, support the existence of maximal exchange with controlled flows first pointed out by *Farmer and Armi* [1986], and exemplified by observations in the Bosphorus.

The results encourage us to use the model for a better understanding of the dynamis of the Bosphorus. While the simple cases reported here provide confidence in the combined use of observations of and modelling, the extensions of the model application to transient cases and realistic Bosphorus geometry through the use of curvilinear coordinates are the next few steps we are currently working on.

References

Brandt, P., A. Rubino, W. Alpers, and J. O. Backhaus, 1997. Internal Waves in the Strait of Messina studied by a numerical model and synthetic aperture radar images from the ERS 1/2 satellites, *J. Phys. Oceanogr., 27*, 648-663.

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

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

Gregg, M. C. and Özsoy, E., 2001. Flow, water mass changes, and hydraulics in the Bosphorus, *J. Geophys. Res.*, (in press).

Hedström, K. S., 1997. Draft User's Manual for an S-Coordinate Primitive Equation Ocean Circulation Model (SCRUM) Version 3.0, Institute of Marine and Coastal Sciences, Rutgers University, Rutgers University.

Hogg, A. McC., Winters, K. B. and G. N. Ivey, 2001. Linear Internal Waves and the Control of Stratified Exchange Flows, *J. Fluid. Mech., 447*, 357-375.

Oğuz, T., Özsoy, E., Latif, M. A. and Ünlüata, Ü., 1990. Modelling of hydraulically controlled exchange flow in the Bosphorus Strait, *J. Phys. Oceanogr.*, **20**, 945-965.

Özsoy, E., Latif, M. A., Sur, H. İ. and Goryachkin, Y., 1996. A review of the exchange flow regimes and mixing in the Bosphorus Strait, in: Briand, F. (editor), Mediterranean Tributary Seas, *Bulletin de l'Institut Oceéanographique, Monaco*, Special Number 17, CIESM Science Series No. 2, Monaco.

Özsoy, E., Latif, M. A., Beşiktepe, Ş., Çetin, N., Gregg, N. Belokopytov, V., Goryachkin, Y. and Diaconu, V., 1998a. The Bosphorus Strait: exchange fluxes, currents and sea-level changes, in: Ivanov, L. I. and Oğuz, T. (editors), *Ecosystem Modeling as a Management Tool for the Black Sea*, NATO Science Series 2: Environmental Security **47**, Kluwer Academic Publishers, Dordrecht, vol. 1, 367pp + vol. 2, 385 pp.

Ünlüata, Ü., Oğuz, T., Latif, M. A., and Özsoy, E., 1990. On the physical oceanography of the Turkish Straits, in: Pratt, L. J., (editor), *The Physical Oceanography of Sea Straits*, NATO/ASI Series, Kluwer, Dordrecht, 25-60.

Winters, K. B. and H. Seim, 2000. The Role of Dissipation and Mixing in Exchange Flow through a Contracting Channel, *J. Fluid. Mech., 407*, 265-290

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