The current system of the Bosphorus Strait based on recent measurements

Emin Özsoy
Middle East Technical University

The current system of the Bosphorus Strait based on recent measurements

Emin Özsoy, Mohammed A. Latif and Şükrü Beşiktepe

Institute of Marine Sciences, Middle East Technical University, Erdemli - İçel 33731 Turkey

Abstract. A series of measurements in the Bosphorus Strait using ADCP and CTD profiling, current-meter and sea-level recordings are analysed to yield three-dimensional mapping of hydrography and currents as well as the statistical characteristics of sea-level and current variability. The results show time-dependent meandering of currents, with separated eddies formed in sheltered areas along the coast. Spatial correlation along the Strait reflects these changes. Sea-level differences respond rapidly to changes in flows, and sudden change in wind direction leads to blocking conditions.

Introduction

The Bosphorus is a passageway of heavy marine traffic between the two seas, as well as of land traffic between the two continents that it connects. Information on the nature of the currents in the Bosphorus is thus essential for safe navigation and transit through the Strait. Furthermore, the Turkish Straits System (consisting of the Dardanelles, Bosphorus Straits and the Sea of Marmara) is sensitive to climatic changes, and potentially can induce such changes in the adjacent basins [*Özsoy*, 1999]. Acting as the limiting element of the The Turkish Straits System, the Bosphorus Strait controls the exchanges of mass and passive or active materials transported between the Black and the Mediterranean Seas [*Özsoy et al.*, 1995b; *Polat and Tuğrul*, 1995; *Ünlüata et al.*, 1990].

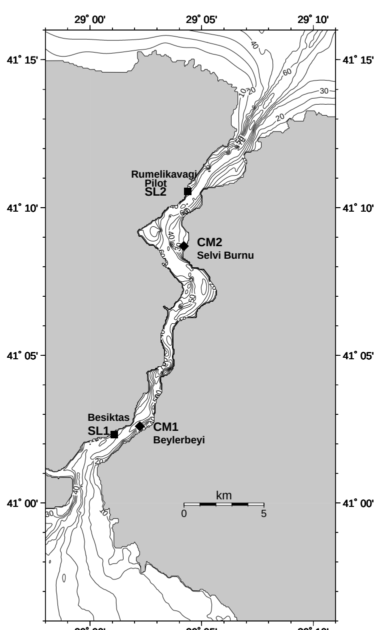

Figure 1. Bottom topography of the Bosphorus, and the locations of sea level (SL1, SL2) and current-meter (CM1, CM2) stations.

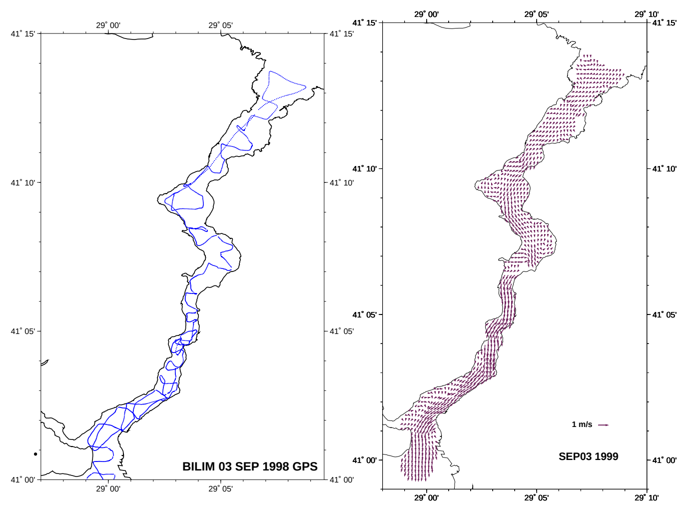

Figure 2. (a) GPS positions of the ship collecting data along the Bosphorus, and (b) interpolated surface currents from continuous ADCP measurements, on 03 September 1998.

Based on budgets calculated from average salinity the mass flux of the upper layer flow is about two times larger than that of the lower layer, yielding a net flux of about $300 km^3/yr$ from the Black Sea to the Sea of Marmara [*Latif et al.*, 1991; *Ünlüata et al.*, 1990]. Geometrical features [*Oğuz et al.*, 1990; *Ünlüata et al.*, 1990; *Özsoy et al.*, 1998] make the Bosphorus predisposed to 'maximal exchange', with contraction and sill controls as in *Farmer and Armi* [1986]. Local topographic features have significant influence on the flow, and determine its detailed structure [*Gregg and Özsoy*, 2001]. The exchange flows respond dynam-

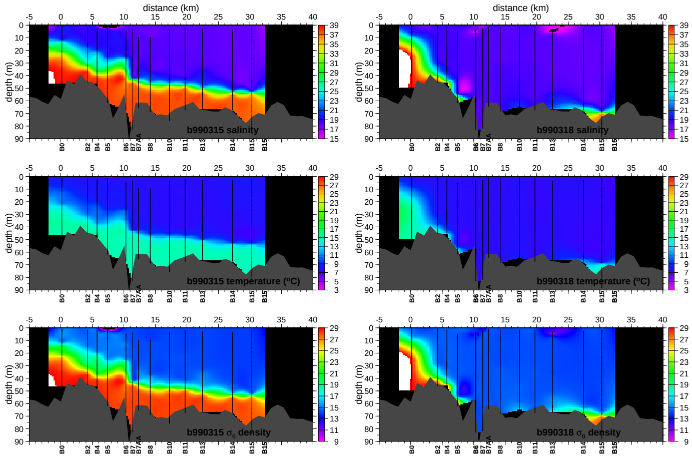

Figure 3. Salinity, temperature, and density cross sections obtained from CTD measurements along the Bosphorus on (a) 15 March 1999 and (b) 18 March 1999.

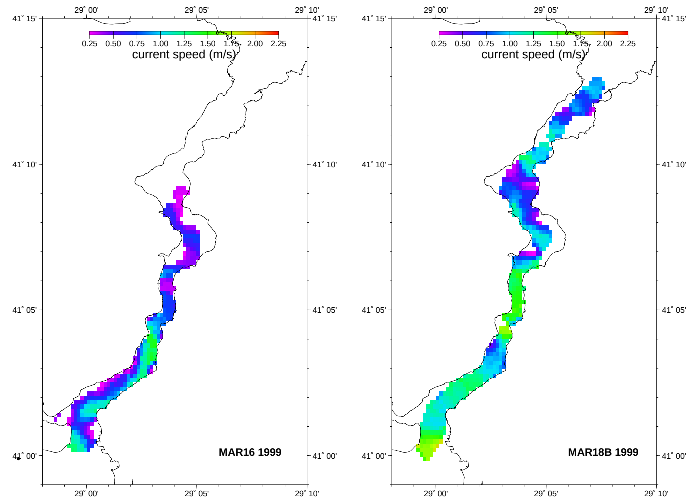

Figure 4. Interpolated speed of surface currents from continuous ADCP measurements on (a) March 16, 1999, (b) March 18, 1999.

ically to time-dependent meteorological and hydrological forcing in the adjacent basins [*Latif et al.*, 1991; *Özsoy et al.*, 1995a, 1996, 1998; *Özsoy and Ünlüata*, 1997, 1998; *Gregg et al.*, 1999; *Gregg and Özsoy*, 2001]. Observations suggest increased entrainment south of the contraction (upward) and past the northern sill (downward) in the Black Sea [*Gregg et al.*, 1999; *Özsoy et al.*, 2001].

The measurements and data processing

In the present study we have made detailed measurements to observe the fine scale variability in the Bosphorus currents and to determine their time and length scales. The intensive experiments carried out in the Bosphorus Strait included ADCP and CTD data collection during 3-6 September 1998, 4-22 March 1999 and 22 July-3 August 1999. The data were collected simultaneously by two ships (the R/V BİLİM of the IMS-METU, and ATMACA II, a commercial vessel) along repeated criss-cross patterns across the Strait attempting to sample the detailed structure of currents in the main channel and in the various bends and small embayments that line its coasts. A Seabird 911plus CTD profiler and a 150Khz RDI narrow-band ADCP were used on board the BİLİM while a Seabird 25 Sealogger CTD and a 300KHz RDI Workhorse Sentinel broad-band ADCP were used on ATMACA II. Accurate position fixes were obtained using Trimble NT200 GPS and Ensign XL GPS navigation systems on the two ships. In addition, sea level and current-meter measurements were performed respectively at stations near the two ends of the Strait Figure 2, where Aanderaa Instruments water level recorder WLR7 and Aanderaa recording current meter RCM7 were deployed. The current and sea level time series data were recorded at 5 min. interval. Absolute sea level at each station was determined relative to a common datum using leveling to benchmarks.

One of the greatest problems was in processing the navigation data to obtain position fixes and ground referenced velocity from the GPS and ADCP measurements. Noise in GPS data and magnetic deviations caused by the ship's steel hull were first removed by applying despiking filters, correlation techniques and a number of logical tests for ship speed and position. Independent measurements of bottom track and GPS velocity were used together in these corrections.

The ADCP measurements obtained by the broadband ADCP on board ATMACA II covered the Bosphorus in great detail, including the numerous small embayments on its banks, making use of the mnaeouverability of the smaller vessel. The current velocity data from the broad-band ADCP started from a depth of 3m. For interpretation of surface currents, the ADCP data were first averaged in the 0-10m depth range, then intepolated on a 0.15° latitude-longitude grid.

The current-meter and sea level measurements were interpreted based on standard time-series analyses, applying correlation and spectral methods. The current velocity data were rotated to maximize along-channel variance.

Results

Surface currents obtained along the ship track in Figure 2a are shown in Figure 2b. In the numerous realizations as shown in this example, the larger currents followed the main channel of the Bosphorus and affected by its topography (Figure 1). The surface currents intensified in the narrows in southern Bosphorus, and first followed the deep channel on the eastern side, then crossed to the western side following the main channel, forming a jet near the exit to the Sea of Marmara. Temporal changes as well as turbulent meandering accounted for day to day changes in the horizontal structure of the main current. There were numerous eddies and reversals in the currents consistently observed in

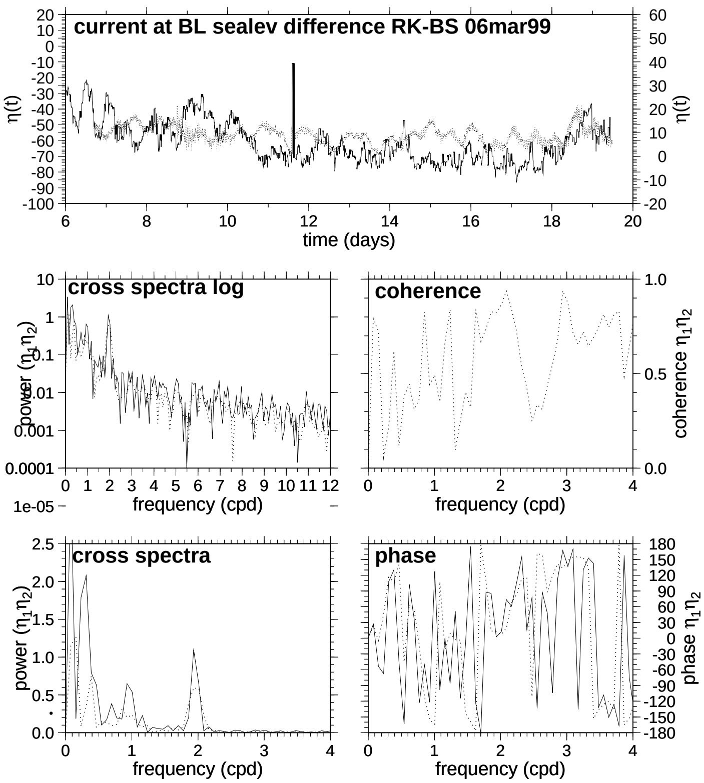

Figure 5. Time series displays and cross spectra between currents at Beylerbeyi (CM1/BL) and the along-Strait sea level difference between Rumeli Kavağı (SL2/RK) and Beşiktaş (SL1/BS) stations. Dotted lines represent spectral smoothing with a triple point moving average filter.

the various shallow banks and embayments.

During March 1999 measurements the winds were generally calm, from the south, when the Bosphorus had its typical two-layer stratiified flow structure shown in Figure 3a. On 18th of March the wind suddenly changed direction and increased in intensity, blowing at full force from the north. The upper layer flow increased and the lower layer flow was then blocked and pushed south of the contraction as shown in Figure 3b, leaving only a small trace of Mediterranean water near the bottom in the upper reaches of the Bosphorus. The magnitude of surface currents on March 16 and 18 respectively are shown in Figures 4a and b to illustrate the great increase in current velocity accompanying the flushing of the Mediterranean water from the Bosphorus following the northerly wind event.The greatest increase in surface currents occurs in the contraction region and in the southern Bosphorus.

Correlation between current components along the Strait and those perpendicular to it were computed (not shown) as a function of distance between pairs of data points to reveal structure relationships of currents. The results indicated lengthwise correlations on distances comparable to the length of the Strait, as expected for the conduit type of flow. There were also correlations at scales characteristic of the coastal features and bends of the Bosphorus channel.

The sea level and current measurements as well as temperature recorded at current-meter sites were individually analysed (not shown), computing correlations and spectra. The current velocity obtained from current-meters indicated reversals in direction, resulting from sheltering effects in the coastal region. The analyses revealed oscillations at diurnal (24h), inertial (18.3h) and semidiurnal (12h) periods, as well as those at periods longer than 2 days.

The time-series of currents at current-meter site CM1 and the sea level difference between stations SL2 and SL1 for the period starting on 06 March 1999 are shown in Figure 5, together with the cross-spectral estimates, coherence and pahse between the two time series. Correlated peaks occur at diurnal, semi-diurnal periods with high coherence. The phase differences indicate the sea level difference is totally out of phase (or has negative correlation) with the northeastward currents at the diurnal and longer than 2d periods; i.e. the sea level difference is positively correlated with southwestward currents. At semi-diurnal periods the phase difference is about 90°, which is typical for tidal currents.

Conclusions

The Bosphorus currents have fine features that depend on the topography and coastal features on its banks, revealing eddies and revesring currents in various of its embayments, as well as turbulent meandering of the main current. Transience on various time scales in addition to the spatial features make the Bosphorus currents highly variable. Yet the main features of the current system are familiar. Blocking events can flush the Strait almost completely pushing either the lower or the upper layer back to its origin in the adjacent Seas. The Bosphorus currents have a rapid response to sea level differences between the Black Sea and the Mediterranean.

Acknowledgments. This study has been made possible through a project carried out for the İstanbul Technical University Foundation / Defense Research Center. The authors wish to express their gratitude to the cooperative efforts of the scientists, technicians and graduate students of the IMS-METU who took part in the data collection and processing, and the captains and crew of the ships who were involved in various stages of the work.

References

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., 1999. Mixing on the Black Sea shelf north of the Bosphorus *Geophysical Research Letters* **26**, 1869-1872.

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

Latif, M. A., Özsoy, E., Oğuz, T. and Ünlüata, Ü., 1991. Observations of the Mediterranean inflow into the Black Sea, *Deep Sea Research*, **38**, Suppl. 2, S711-S723.

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., Tuğrul, S., and Ünlüata, Ü., 1995a. Exchanges with the Mediterranean, fluxes and boundary mixing processes in the Black Sea, In: F. Briand (editor), Mediterranean Tributary Seas, *Bulletin de l'Institut Oceéanographique, Monaco,* Special Number 15, CIESM Science Series No. 1, Monaco p. 1-25.

Özsoy, E., Latif, M. A., Beşiktepe, Ş. and Gaines, A. F., 1995b. Fluorescent dye measurements of the mixing and transport of wastewater discharge in the Bosphorus, *Wat. Sci. Tech.*, **32**(2), 61-68.

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. and Ünlüata, Ü., 1997. Oceanography of the Black Sea: a review of some recent results, *Earth Science Reviews*, **42**, 231-272.

Özsoy, E. and Ünlüata, Ü., 1998. The Black Sea, in: Robinson, A. R. and Brink, K. (editors), *The Sea: The Global Coastal Ocean: Regional Studies and Syntheses*, **11**, John Wiley and Sons, New York, pp. 889-914.

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.

Özsoy, E., 1999. Sensitivity to Global Change in temperate Euro-Asian seas (the Mediterranean, Black Sea and Caspian Sea): A review, in P. Malanotte-Rizzoli and V. N. Eremeev (editors), *The Eastern Mediterranean as a Laboratory Basin for the Assessment of Contrasting Ecosystems*, NATO Science Series 2, Environmental Security, **51**, Kluwer Academic Publishers, Dordrecht, pp. 281-300.

Özsoy E., Di Iorio D., Gregg M. and Backhaus J. 2001. Mixing in the Bosphorus Strait and the Black Sea Continental Shelf: Observations and a Model of the Dense Water Outflow, *J.Mar. Sys.*, *31*, 99-135.

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.

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

E. Özsoy, M. A. Latif and Ş. Beşiktepe, Institute of Marine Sciences, Middle East Technical University P.K. 28 Erdemli - İçel 33731 Turkey