GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO.1, PAGES 83-86, JANUARY 1, 1999

Quasi-Steady Exchange Flow in the Bosphorus

Michael C. Gregg
College of Ocean and Fishery Sciences, University of Washington, Seattle

Emin Özsoy and Mohammed A. Latif
Institute of Marine Sciences, Middle East Technical University, Erdemli, Turkey

Abstract. Current meter moorings and high-resolution surveys in the Bosphorus reveal important details of the exchange flow. During early September 1994, the flow was quasi-steady and demonstrated strong mixing, particularly in the surface layer after it entered the principal contraction of the strait. Composite Froude numbers in the contraction are lower than expected, consistent with recent modeling that shows friction producing significant deviations from predictions of inviscid two-layer hydraulic theory.

Introduction

The exchange flow through the Bosphorus was identified long ago, but increased shipping and the deteriorating ecology of the Black Sea provide impetus for understanding the dynamics of the Bosphorus [*Ünlüata et al.*, 1993]. Intermediate and bottom water in the Black Sea come only from the saline Mediterranean water transiting the strait.

Comparisons of theory with laboratory and field observations are rapidly developing the understanding of exchange flows, but one unresolved issue is when to apply inviscid steady-steady theories, e.g. *Armi and Farmer* [1986]. Consequently, we set the first current meter moorings ever put in the strait during September, when synoptic weather systems are weak-to-moderate. Mooring B7 was near Rumelihisarı, in the narrowest part of the strait, known as the Contraction (Fig. 1), and B5 was 4 km south (Table 1). We also installed sea level gauges at Anadolukavağı (Fig. 1) and Fenerbahce (not shown), on the Sea of Marmara south of the Bosphorus. In addition, we surveyed with a 150 kHz narrowband Acoustic Doppler Current Profiler (ADCP) in bottom-tracking mode while taking 450 CTD and turbulence casts with the Advanced Microstructure Profiler (AMP).

Table 1. Mooring thalweg distances, depth (D), bottom height (H), and maximum, mean, and minimum speeds.

Stn	Dist km	Meter	D/H m	Speed m/s
B5	8.1	6690	22/50	0.69/0.07/-0.47
		4819	63/8	0.83/0.61/0.43
B7	12.04	4015	22/41	0.67/-0.37/-0.86
		4016	55/8	0.99/0.78/0.62

Forcing and Flow

Winds were light with significant energy only in a weak daily land/sea breeze. This affected sea levels much less than the twice-daily tides, which were only 10 mm (Fig. 2). A 5-day signature of synoptic weather systems occurred at Fenerbahce but not at Anadolukavağı. The Fenerbahce fluctuations were out of phase with p_{atmos}, i.e., the Sea of Marmara responded as an 'inverted barometer'. Consequently, sea level difference, Δh, responded directly to fluctuations in p_{atmos} (Fig. 3). Its phase lagged by about one day, and its amplitude was larger than expected.

Helfrich [1995] classified narrow straits with the dimensionless parameter $\gamma \equiv (g'H)^{1/2}T/L$, which measures the distance traveled by long internal waves in a forcing period, T, relative to the strait's length, L. Assuming tidal forcing, he classified the Bosphorus close to the transient regime. Taking $T = 5$ days with $g' \equiv g\Delta\rho/\rho = 0.16$, $H = 35$ m for the minimum channel depth, and $L = 30$ km, gives $\gamma = 34.1$, far into the quasi-steady regime, where classical hydraulic theory applies.

Changes in p_{atmos} only partially modulated the barotropic forcing and never reversed it: Δh, varied $\pm 50\%$, from 0.181 to 0.495 m about a mean of 0.32 m (Fig. 3). The deeper currents were relatively more steady than Δh and were always northward. As expected for density-driven flows, they varied inversely to Δh. That is, they were fastest when the opposing surface slope, Δh, was least. Set at 22 m to avoid supertankers, the shallow pair of meters were not always in the upper layer. Temperature and salinity on the moorings confirmed that the changes in current direction resulted from movement of the interface.

Evolution Along the Strait

AMP profiles were taken between days 249 and 257. Because the deep currents were nearly steady (Fig. 3)

Paper number 1998GL900260.
0094-8276/99/1998GL900260$05.00

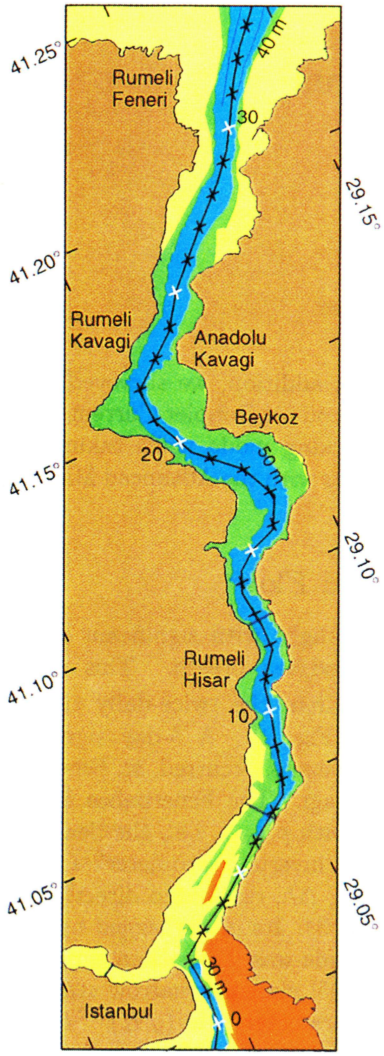

Figure 1. Bathymetry of the Bosphorus with the deepest path, or thalweg, marked in 1 km increments from an origin at 40.89846°N, 28.9230°E.

and individual AMP runs were similar, we averaged all of the data to form Figure 4. The Cold Intermediate Water (CIW) of the Black Sea pinched off at the northern exit. Defined by $T < 8°C$, the weakly stratified CIW core was above the density interface.

The Mediterranean water was only 20 m thick at 32 km, where it exited beneath the CIW. During its transit, the lower layer warmed 0.54°C and freshened 0.54 psu, resulting in $\Delta\sigma_\theta = -0.39$ kg m^{-3}. It changed most rapidly near the sills, at 5-10 km and 30-35 km. Deep salinity on the southern mooring varied inversely with the deep current speed, indicating that the degree of mixing over the southern sill varied with Δh. Average speeds were 0.6 to 1 m s^{-1} and were fastest near the northern exit, where the layer accelerated as it passed under the CIW (Fig. 5). Fluctuations along the channel resulted from variations in channel width.

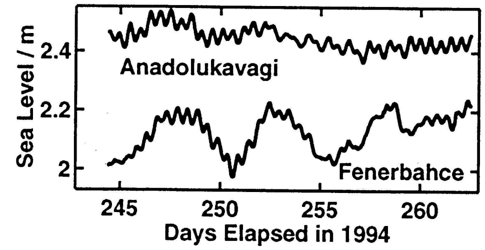

Figure 2. Observed sea levels.

Surface Slope

We estimated the surface slope by ignoring internal friction and noting that the no-flow surface is the depth at which barotropic and baroclinic forcing balance. First, $(dp/dx)_{\text{baroclinic}}$ was calculated between adjacent thalweg bins by assuming a level sea surface. This array was interpolated onto the no-flow surface to obtain $(dp/dx)^{\text{no-flow}}_{\text{baroclinic}}$. The barotropic pressure gradient has the same magnitude but opposite sign, and the surface slope needed to produce the barotropic gradient is $(dh/dx)_{\text{surface}} = -(dp/dx))^{\text{noflow}}_{\text{baroclinic}}/g\rho_{\text{surface}}$. The relative surface height, h', is the cumulative sum of the dh's from -11.5 km and changes most rapidly in the Contraction, at 10-15 km (Fig. 6). The net change is 0.25 m, compared to $\overline{\Delta h} = 0.32$ m for the fixed pressure gauges. The discrepancy could have resulted from temporal variability or from neglecting friction.

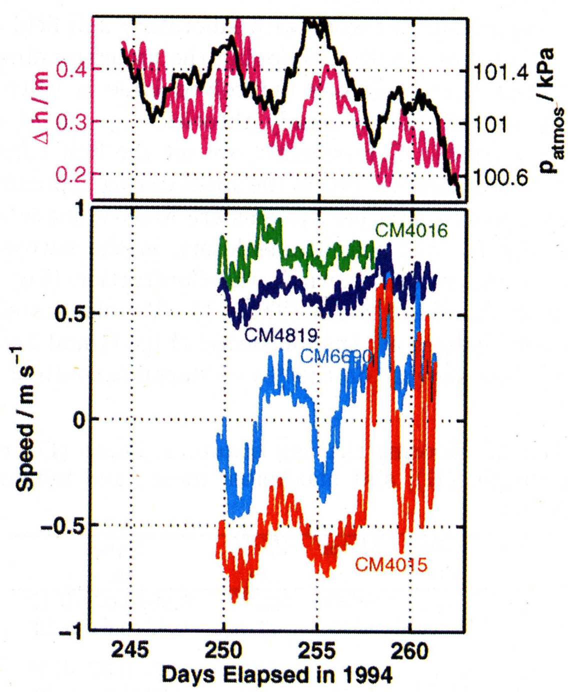

Figure 3. (Upper) Atmospheric pressure and difference in sea level, Δh. (Lower) Current speeds at the mooring, positive northward. January 1 was day 0.

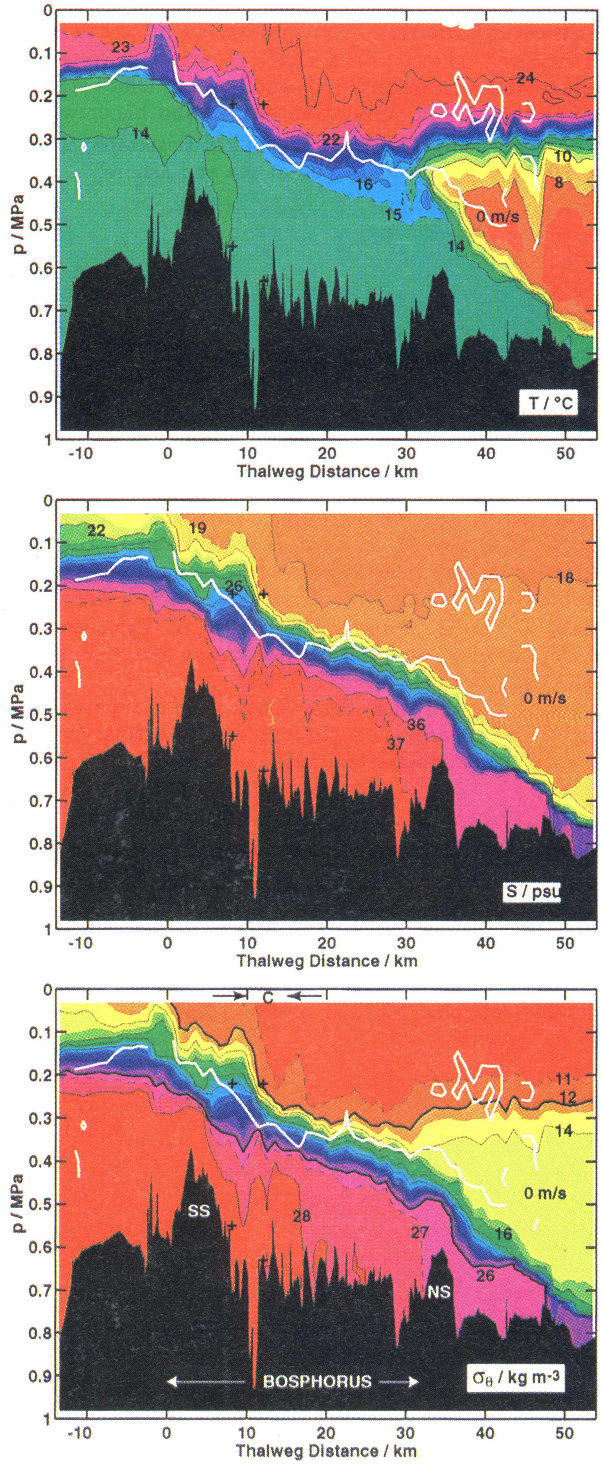

Figure 4. Contours of 1 km bin-averaged AMP data. White contours mark zero mean flow, + the locations of the current meters, NS and SS the northern and southern sills, and C the Contraction.

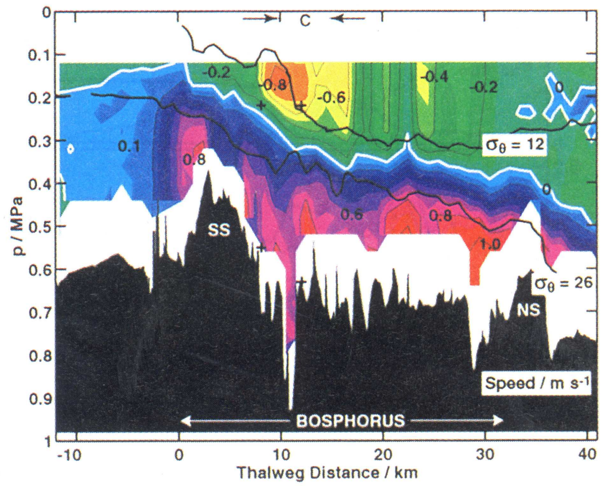

Figure 5. Contours of along-channel speed.

Hydraulic Control of the Upper Layer

The weakly stratified upper layer flowed south at 0.2 m s^{-1}, except for changes with channel cross-section, until it accelerated into the Contraction (Fig. 5), where the surface slope steepened (Fig. 6) and the interface rose more steeply (Fig. 4). Little remained of the surface layer south of 8 km, consistent with hydraulic control in the Contraction. Acoustic images of billows and turbulence profiles demonstrate that at least some of the thinning resulted from mixing, which formed the thick interface south of the Contraction.

According to inviscid hydraulic theory [*Armi and Farmer*, 1986], two-layer flows are controlled where the composite Froude number equals one, i.e., $G^2 \equiv F_1^2 + F_2^2 = 1$ with $F_i^2 \equiv u_i^2/g'h_i$. The model of *Oğuz et al.* [1990] shows controls over the northern and southern sills and in the Contraction. These are the first observations, however, in which G^2 can be estimated directly, and we find it much smaller than expected (Fig. 6). Between 10 and 30 km the interface was 10-15 m thick, which is significant but probably not enough to alter significantly the G^2 criterion. In the southern end of the Contraction, the upper layer is so thin that it is above the 12.1 m minimum depth bin of the ADCP. Reasonable extrapolations of the shallow shear give $G^2 > 1$ there, and the issue remains one for further work.

Conclusions and Discussion

During at least some times, barotropic forcing of the Bosphorus is modulated principally by synoptic pressure fluctuations. Evaluating Helfrich's equilibration parameter with a 5-day, instead of a half-day, period changes its classification to strongly quasi-steady.

Modulation by moderate synoptic weather systems changed the sea level difference by only ±50%. Because these observations were taken when atmospheric disturbances were minimal, they should represent one of the most steady regimes in the Bosphorus.

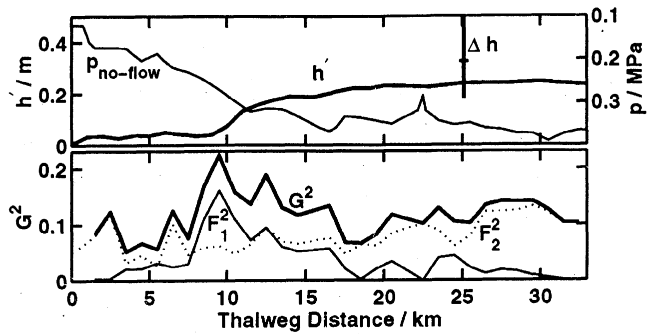

Figure 6. The upper panel compares $p_{\text{no-flow}}$ with h' and the range and mean sea level difference between Anadolukavaği and Fenerbahce (vertical line). The lower panel shows G^2 and its components.

Composite along-strait sections reveal more detail about the velocity field and scalar fields than available previously. The overall pattern is similar to that expected [*Oğuz et al.*, 1990], except for the much lower composite Froude numbers in the Contraction. The discrepancy is similar to that predicted by *Winters and Seim* [1999] who include turbulent mixing in a numerical model of flow through a simple contraction. In particular, they find lower G^2 and longer regions of subcritical flow in the contraction, so much so that $G^2 \geq 1$ would probably not be detected in natural systems. Therefore, further work is needed to compare the relative effects of the strong mixing and limitations of the observations resulting from the difficulty of observing the thin surface layer.

Acknowledgments. The Turkish Scientific and Technical Research Council (TÜBITAK), the Istanbul Water and Sewerage Administration (ISKI) and the U.S. Office of Naval Research funded this work. Captain An and his crew handled the R/V Bilim skillfully, and Şükrü Beşiktepe, Harvey Seim and Kraig Winters helped at sea and ashore.

References

Armi, L., and D. M. Farmer, Maximal two-layer exchange through a contraction with barotropic net flow, *J. Fluid Mech.*, *164*, 27–51, 1986.

Helfrich, K. R., Time-dependent two-layer hydraulic exchange flows, *J. Phys. Oceanogr.*, *25*, 359–373, 1995.

Oğuz, T., E. Özsoy, M. A. Latif, H. I. Sur, and U. Ünlüata, Modeling of hydraulically controlled exchange flow in the Bosphorus Strait, *J. Phys. Oceanogr.*, *20*, 945–965, 1990.

Ünlüata, U., D. G. Aubrey, Z. Belberov, V. Eremeev, and M. Vinogradov, International program investigates the Black Sea, *Eos*, *74*, 401–412, 1993.

Winters, K. B., and H. E. Seim, The role of dissipation and mixing in exchange flow through a contracting channel, *J. Fluid Mech.*, submitted, 1999.

M. C. Gregg, Applied Physics Laboratory, 1013 NE 40th St., Seattle, WA 98105-6698

Emin Özsoy, Institute of Marine Sciences, Middle East Technical University, P.O. Box 28, Erdemli, Içel 33731, Turkey

(Received September 28, 1998; accepted November 16, 1998.)