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SMR/1108 - 2

COURSE ON "MEDITERRANEAN SEA(S) CIRCULATION & ECOSYSTEM FUNCTIONING"

2 - 20 November 1998

Trieste, Italy

"The Bosphorus Strait & Its Shelf Outflow into the Black Sea: Experiments & Modelling"

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THE BOSPHORUS STRAIT AND ITS SHELF OUTFLOW INTO THE BLACK SEA: EXPERIMENTS AND MODELLING

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Abstract. We describe the exchange and mixing across the Bosphorus Strait and on the Black Sea continental shelf / slope, based on intensive measurements in 1994 and through modelling of the dense bottom current. The surface water entrains and mixes in the southern Bosphorus, while the the lower layer entrains throughout its route, and is affected by topography. Its cascade along the continental slope increases the entrainment. Results from a reduced gravity model of the dense bottom current confirm the crucial importance of topographic features of the continental shelf. Sensitivity to environmental parameters and the Black Sea ambient is investigated.

1. The Measurements

The two-layer, hydraulically controlled, 'maximal exchange' (Farmer and Armi, 1986) flows across the Turkish Straits System have direct influence on the environmental problems in the region, as well as on the fate of the Black

Sea, through its role in the mixing and renewal of its waters (Ünlüata *et al.*, 1990; Oğuz *et al.*, 1990; Latif *et al.*, 1991; Özsoy *et al.*, 1993, 1995a,b, 1996, 1998; Özsoy and Beşiktepe, 1995; Özsoy and Ünlüata, 1997). It is now clear, after extensive observations, that the Bosphorus, characterized with rapid along-strait variations in its geometry, its sharp stratification, nonlinear controls and temporary blocking of the flows in either direction, is driven by variable atmospheric pressure, wind set-up, sea level variations and water budgets in the adjacent basins (Özsoy *et al.*, 1998; Ducet and Le Traon, 1998), displaying time dependence on daily to interannual time scales.

The above unique characteristics of Bosphorus Strait, as well as its sharp two-layer interface with high levels of turbulent dissipation and entrainment has motivated intensive collaborative studies in September 1994 carried out by APL/UW and IMS/METU on board the R/V BİLİM, using ADCP, CTD, the Advanced Microstructure Profiler (AMP), current meter, sea-level recorder instruments and acoustic backscatter imaging of the physical features. The measurements and their results will be described in papers to appear. At present, we only describe the main temperature and salinity variations along the Strait and the main axis of the flow on the Black Sea continental shelf.

The geographical locations of bursts of stations along the thalweg, the interfacial depths, and the upper and lower layer average properties (*e.g.* Özsoy *et al.* are presented in Figure 1, with corresponding temperature and salinity cross-sections shown in Figure 2. The interfacial layer thickens and the upper layer salinity increases in the southern 10 *km* of the Strait, past the contraction where one of the two main hydraulic controls takes place. The interface also thickens past the northern sill in the Black Sea, where the other hydraulic control takes place, and finally becomes much thinner when the flow emerges on the flat shelf.

The temperature in the upper layer does not appear to change much in the Bosphorus because of the high contrast of the warm surface mixed layer originating from the Black Sea, but a decreasing trend caused by entrainment is evident south of the contraction. The rapid decrease in temperature in the Black Sea results from the inclusion in the layer average of two different layers with variable depths: the surface mixed layer and the underlying layer of Cold Intermediate Water (CIW).

The lower layer temperature first rises as one proceeds north in the Bosphorus, by entrainment of warm water from the surface mixed layer in direct contact with it, and later decreases by entrainment of the overlying CIW in the northern Bosphorus and the Black Sea shelf. The salinity is perhaps a better indicator of entrainment for the lower layer, because it is more conservative with regard to sources, and relatively more uniform in the

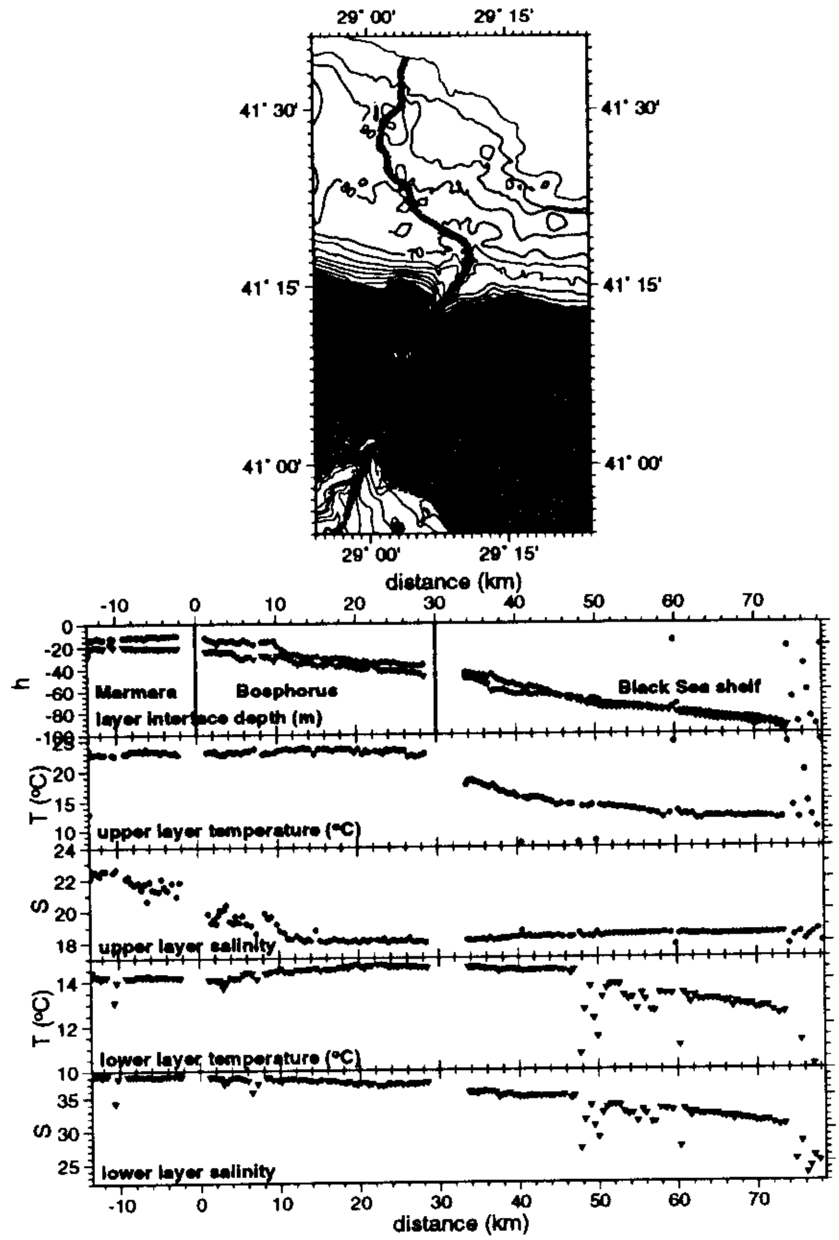

Figure 1. (a) A composite section of AMP drops across the Bosphorus Strait (179 profiles) during 13-19 September 1994. (b) Variation of upper and lower layer depths and average properties (temperature and salinity, along the same section

upper layer. The lower layer salinity decreases continuously from Marmara to the Black Sea, with changes of gradient in the different regions: In the northern Bosphorus where the interface stability is higher, the entrainment

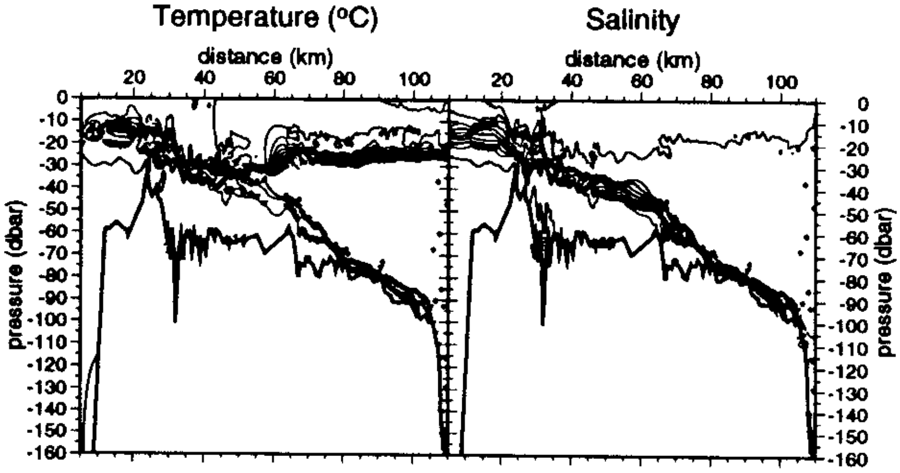

Figure 2. Contours of (a) temperature and (b) salinity along the transect in Figure 1 extending from the Marmara Sea to the Black Sea across the Bosphorus Strait, during 13-19 September 1994

rate appears to be smaller than the southern part. In comparison to the Bosphorus, flow past the northern sill (about $35km$ from the southern end) on the Black Sea shelf has greater entrainment, and increases further when the flow exits the narrow northwestward bending channel topography and spreads on the flat shelf region (at $50km$). Finally with the increased slope at the shelf edge, the bottom layer can only be identified with difficulty, but a few data points where it could be detected show that the entrainment has been increased by an order of magnitude there.

2. Model Results

We use the Jungclaus and Backhaus (1994) model to study the Mediterranean plume in the Black Sea, incorporating the effects of the complex topography in the Bosphorus exit region. It is a reduced gravity sinle layer approximation to the primitive equations (Jungclaus, 1994), including horizontal, bottom friction and entrainment. Either the Kochergin or the Pedersen entrainment parameterizations (Jungclaus and Backhaus, 1994) can be chosen, taking into account the ambient property distributions, represented by realistic vertical profiles of temperature and salinity in the Black Sea.

A sample run with indicated set of parameters and initial conditions is shown in Figure 3. Di Iorio and Yüce (1998) found the bottom drag coefficient in the range of 0.003 to 0.015 from their acoustical measurements of flow and dissipation over the sill, and we have selected the lower values in this range. The horizontal resolution of the model is $200m$. The detailed bathymetry has been constructed from a weighted combination of

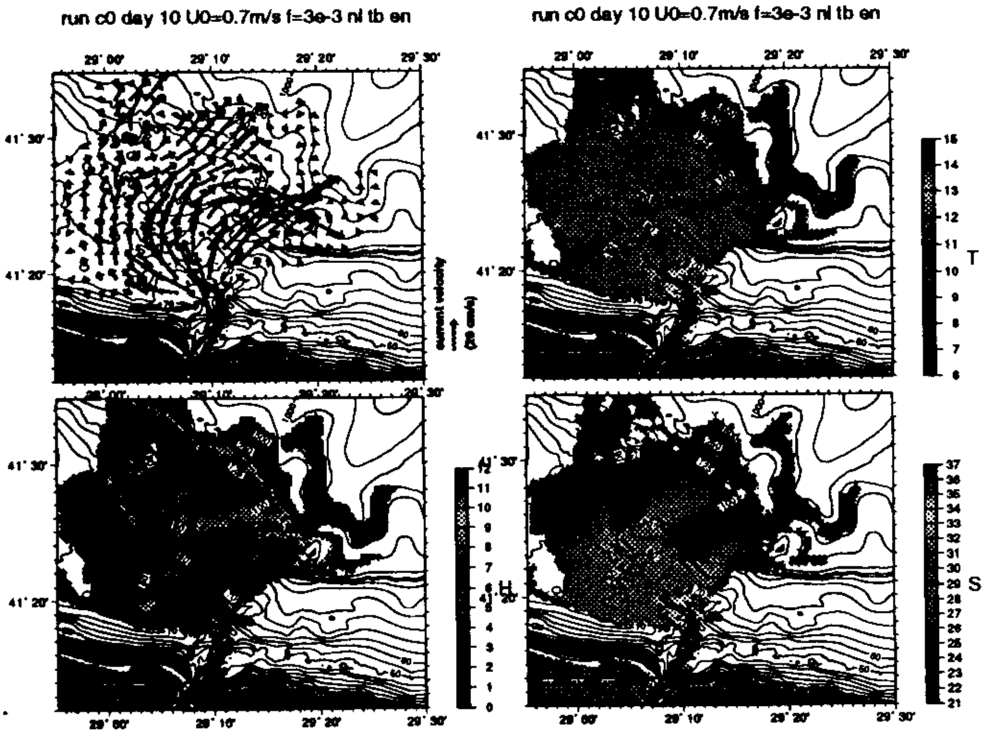

Figure 3. Model results for (a) flow velocity and (b) layer thickness 10 days after initialization. Run parameters are: $A_h = 150m^2/s$, $k = 0.003$ $u_o = 0.7m/s$, $S_o = 37$, $T_o = 14.5°C$, $H_0 = 40m$

adcp depth measurements, UNESCO digital bathymetric data and digitized hydrographic maps.

The model results are very sensitive to topographic details, the entrainment formulation, as well as variations of the parameters. The flow and property distributions reach a quasi-steady state on the shelf area after about 10 days from start-up. The flow along the continental slope is either in the form of a geostrophically adjusted motion along the bathymetric contours or the precipitous flow down hill to great depths, and continues to develop with time. The behaviour here is rather erratic because the solutions reach the limits of validity of the model itself: the rapid entrainment at the steep slope produces a very thick, diluted layer with vanishingly small density contrast at the edges of the plume. On the other hand, the assumptions with regard to entrainment are also expected to break down in this steep region affected by other processes, such as the double diffusive convection (Özsoy *et al.*, 1993; Özsoy and Beşiktepe, 1995), and numerous small-scale canyon features probably not adequately resolved in the peresent topography.

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