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Mixing on the Black Sea Shelf North of the Bosphorus

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Abstract. Microstructure observations over the Black Sea shelf and slope north of the Bosphorus reveal a very small turbulent diapycnal diffusivity, $K_\rho \approx 10^{-6}$ m^2 s^{-1} in the Cold Intermediate Water during late summer, when winds are at their seasonal minimum. Recent modeling by *Oğuz et al.* [1998] shows that only with such low diffusivity can the observed separation between dissolved oxygen, O_2, and hydrogen sulfide, H_2S, be maintained. The measurements also provide a reference for mixing over continental shelves where tides are negligible and when winds are light.

Introduction

The Black Sea is the world's largest anoxic basin; below 1 MPa O_2 is usually undetectable and H_2S increases strongly (Fig. 1). The role of diapycnal mixing in maintaining the oxic/anoxic interface is an important scientific issue with practical consequences for the deteriorating ecological state of the Black Sea [*Ünlüata et al.*, 1993].

Between 16 and 18 September 1994, while observing the outflow of dense Mediterranean water from the Bosphorus, we took microstructure profiles across the shelf and slope of the Black Sea (Fig. 2). These provide the first estimates in the Black Sea of the diapycnal eddy diffusivity from microstructure measurements. In addition to their relevance to chemical and biological balances, the K_ρ estimates provide a reference for comparison with those on other shelves where tides are negligible; Black Sea tides are typically less than 0.1 m.

Bathymetry and Hydrography

Using a 150 kHz narrowband ADCP and the Advanced Microstructure Profiler (AMP), we took 188 drops across the 15 to 25-km-wide shelf and part way down the steep slope. Averaging the data in 1 km bins by distance from the coast and contouring shows dense Mediterranean water exiting the strait with $T \approx 15°$C and $s \approx 0.035$ just below the interface separating the outflow from the shelf water (Fig. 3). The outflow subsequently thins and is diluted (which will be dealt with in a separate paper) by entraining the overlying Cold Intermediate Water (CIW) without significantly modifying the CIW. Defined by $T \leq 8°$C, the CIW has a minimum of 6.5°C and occurs within the permanent halocline (Figs. 1 and 3). Within 10 km of the coast the CIW is cut off by the outflow.

Except for the outflow, mean currents were weak and dominated by a 0.05 to 0.2 m s^{-1} along-shelf (eastward) flow (Fig.4) that is consistent in direction and structure but weaker in magnitude with the prevailing rim current in the Black Sea [*Özsoy and Ünlüata*, 1997]. There is a weak flow onto the shelf above the outflow, and both along and across-shelf currents contain more structure with 10 km of the coast.

Mixing

Below the surface mixed layer and above the outflow, the turbulent dissipation rate, ϵ, peaked at 10^{-8} W kg^{-1} in the seasonal thermocline and fell below 10^{-9} W kg^{-1} in the CIW (Fig. 5). Turbulent diapycnal diffusivities, $K_\rho \equiv 0.2\epsilon/N^2$ [*Osborn*, 1980], were mostly 10^{-6} to 10^{-5}m^2 s^{-1} in the CIW and less than 10^{-6} m^2 s^{-1} in the seasonal thermocline, where the mean stratification was $N^2 = 1.5 \times 10^{-4}$ s^{-2}.

The small turbulent diffusivities are confirmed by the relative scarcity and over short vertical scales of strati-

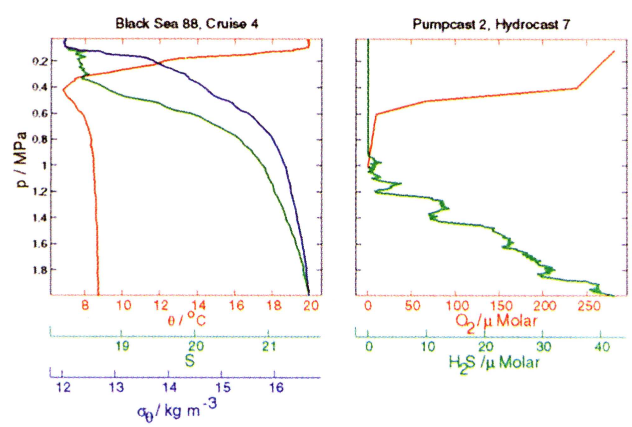

Figure 1. Hydrography, dissolved oxygen, and hydrogen sulfide in deep water north of the Bosphorus during Black Sea 88 [*Friederich et al.* 1990]. A pressure of 1 MPa nearly corresponds to 100 m depth.

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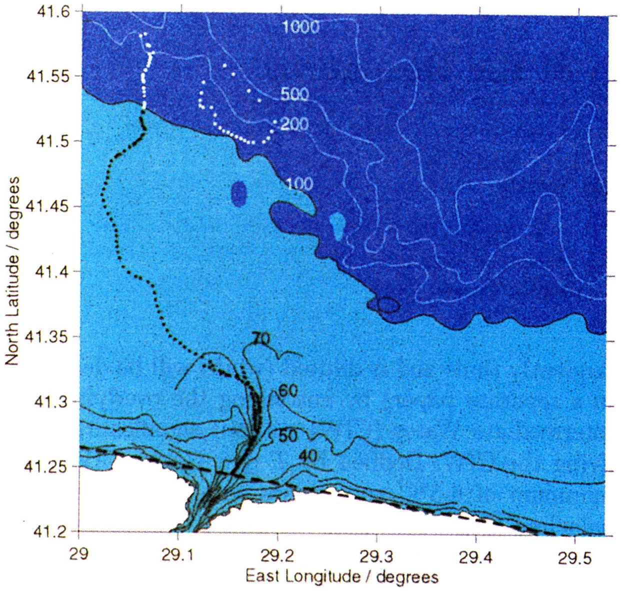

Figure 2. Shelf bathymetry. AMP drops are plotted as dots, and their distances from the coast are referenced to the dashed line across the Bosphorus headlands. The pre-Bosphorus channel ends near depths of 70 m.

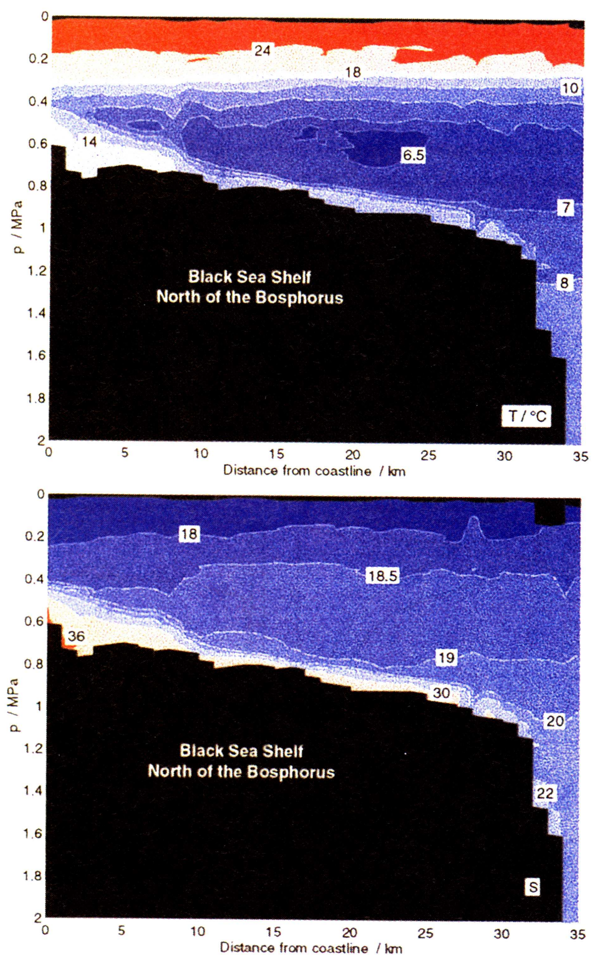

Figure 3. Temperature and salinity contours of 1 km bin averages.

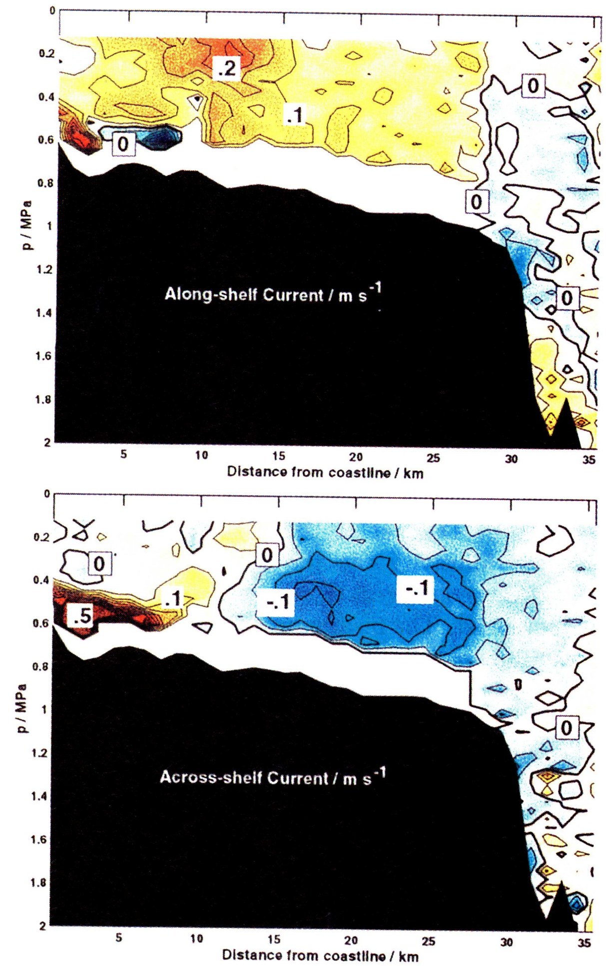

Figure 4. Contours of 1 km bin-averaged velocity decomposed into across (25° true) and along-shelf (115° true) components. ADCP velocities are not reliable above 15 m or within the bottom 15% of the water column. but appear closer to the bottom on the slope owing to the irregularity of the coast.

fication overturns (right panel of Fig. 5). The overturns were determined by comparing observed density profiles with monotonically sorted versions of the same records. Because temperature and salinity were sensed with an FP07 FastTip thermistor and a 30 mm N. Brown cell, the vertical resolution of density was between 50 and 100 mm. Of the eight overturns in AMP15031, one has maximum displacements of 0.4 m. The others are less than 0.2 m, and thick sections have no detectable overturns.

Contouring the bin averages reveals that AMP15031 represents most of the shelf and slope (Fig. 6). The irregular ϵ minimum between 0.4 and 0.7 MPa and offshore of 10 km occurs where both the along and across-shore currents are most uniform (Fig. 4). Where the currents are more sheared, within 10 km of the coast, $\epsilon \geq 10^{-8}$ W kg^{-1}. The average K_ρ profile over 21-35 km had no trend although N^2 decreased strongly (Fig. 7). The bootstrap procedure gives an average over 0.15-

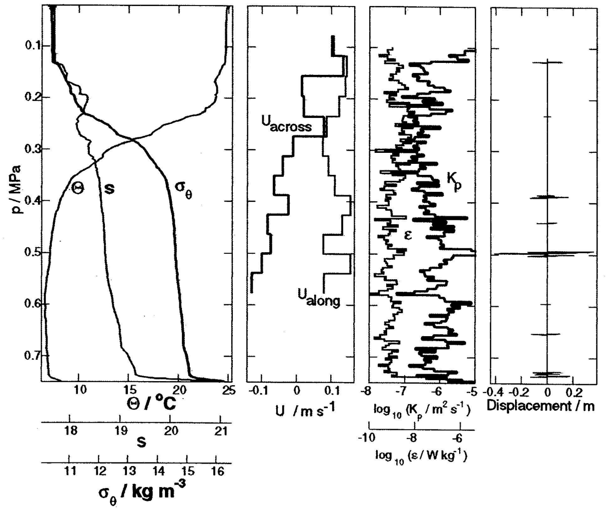

Figure 5. AMP15031 at 14 km from the coast. The plot is cut off at the top of the outflow, well above the bottom at 0.797 MPa. The right panel shows displacements in density inversions.

0.73 MPa of $K_\rho = 6.3 \times 10^{-7}$ m^2 s^{-1} with 95% confidence limits of $(0.12, 10.6) \times 10^{-6}$m^2 s^{-1}. This is at the lower bound of observations in the open ocean [*Gregg*, 1998], and only five times the molecular diffusivity of heat. For reference, internal waves at the background state described by *Garrett and Munk* [1975] produce $K_\rho \approx 5 \times 10^{-6}$ m^2 s^{-1}, independent of N^2 [*Gregg and Sanford*, 1988].

Discussion

In developing a one-dimensional biogeochemical model of the upper Black Sea, *Oğuz et al.* [1998] assumed that mixing below the surface layer is produced by internal waves. They adapted K_ρ from *Gargett* [1984] to be 2×10^{-5} m^2 s^{-1} above 60 m and to decrease linearly to 75 m, below which it is 2×10^{-6} m^2 s^{-1}. In addition to reproducing reasonably well the annual plankton structure and the nitrate maximum, the model yields a suboxic layer between σ_θ of 15.6 and 16.2 because vertical turbulence supplies O_2 and H_2S more slowly than chemical reactions consume them. Oxygen and hydrogen sulfide, however, do overlap significantly when the lower bound on K_ρ is increased from 2×10^{-6} m^2 s^{-1} to 5×10^{-6} m^2 s^{-1}. Models with larger diffusivities show markedly increased overlap [*Yakushev and Neretin*, 1997]. Therefore, existence of the suboxic layer appears to depend sensitively on K_ρ.

Mixing on the shelf and slope should be at least as intense as in the middle of the Black Sea, where the *Oğuz et al.* [1998] model is most realistic. Nevertheless, our overall average, $K_\rho \approx 10^{-6}$ m^2 s^{-1}, is at the low end of the diffusivities they used. Nor does our average profile vary as N^{-1}. Based on their model, our estimates imply that diapycnal mixing is too weak to sustain a vertical overlap of O_2 and H_2S. Our estimates, however, were

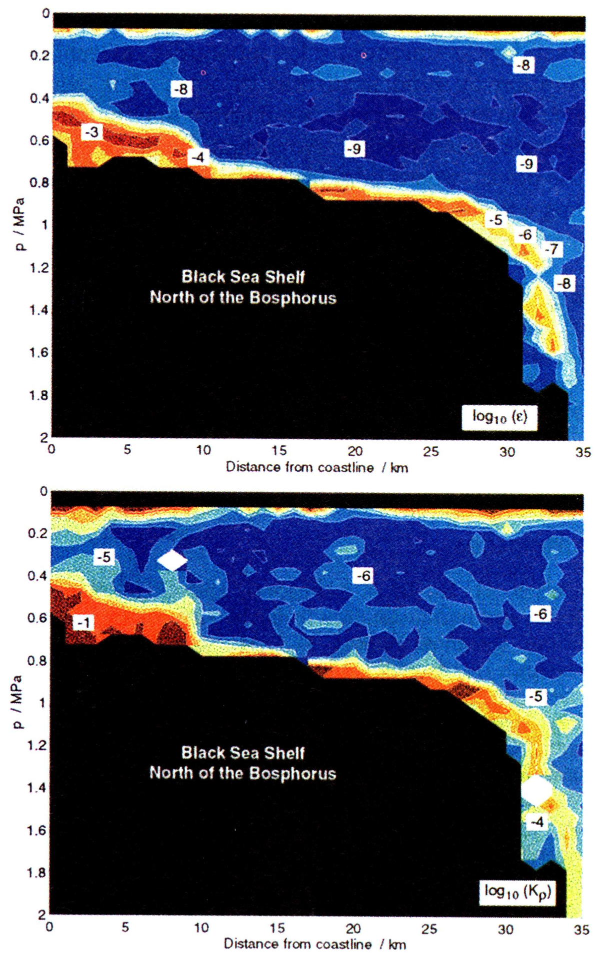

Figure 6. Contours of 1-km-averages of $\log_{10}(\epsilon)$ and $\log_{10}(K_\rho)$.

collected during a few days over a very small area and lacked matching observations of finescale shear. Winds were at their seasonal minimum; the mean was 3 m s^{-1}, and none exceeded 8 m s^{-1}. Consequently, it is probable that these results are indeed lower bounds in space and time.

Because microstructure can be measured only over a small range of time and space, K_ρ can best be estimated over the Black Sea and its shelf by understanding and describing the internal wave field. Owing to the very weak tides, winds should be the dominant source for

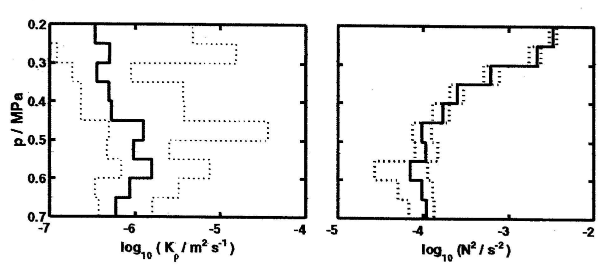

Figure 7. Averages of K_ρ and N^2 over 0.15-0.70 MPa and 21-35 km with 95% bootstrap confidence limits.

internal waves. As a deep, wide basin, the Black Sea is, therefore, a unique site for separating internal wave generation by wind from that by tides. For example, the strong annual cycle in wind stress may be mirrored in a larger yearly mixing signal than should be expected in the ocean, where tidal forcing is believed to supply a strong component of internal waves that does not vary annually.

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