High frequency acoustic observations of Mediterranean flow into the Black Sea

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Abstract

The physical behavior of Mediterranean flow entering the Black Sea through the Strait of Istanbul is described using a variety of high frequency acoustic systems. Because of the density difference between salty Mediterranean and fresh Black Sea water, a two layer exchange is formed which is confined within a canyon in the Black Sea exit region of the strait. A 120 kHz high resolution echo sounder is used to visualize the two layer dynamics which has a strong acoustic scattering strength. A 600 kHz broad band acoustic Doppler current profiler shows that the Mediterranean flow exhibits temporal variability associated with blockage. But during a time of maximum flow a balance of friction, Coriolis and pressure gradient forces give rise to Ekman current spirals and thus strong turbulence levels. A 307 kHz acoustical scintillation system over a 300 m path describes the turbulent boundary layer characteristics of the Mediterranean flow. The dominant component of the observed acoustic scintillation is from turbulent velocity rather than temperature variability. An assumption of isotropic and homogeneous turbulence leads to estimates of the turbulent kinetic energy dissipation rate, shear stress and bottom drag coefficient.

1. Introduction

The Strait of Istanbul separates two relatively large inland seas of differing hydrological characteristics (see Figure 1). Flow through the strait is a classic example of turbulent exchange flow. A high velocity surface current with relatively fresh Black sea water overlies a current running in the opposite direction, which transports the more saline water of the Mediterranean and Marmara Sea to the Black Sea. The higher salinity water, though warmer than the Black Sea surface layer, is more dense, and it flows through an underwater canyon which is an extension of the Bosporus canyon until it spreads on the shelf at some 80 m water depth (see Figure 1) and finally reaches the shelf break and sinks to the depth at which it finds a common density. This exchange through the strait entirely determines the hydrological properties of the Black Sea and is the only source of ventilation at depth. The surplus of fresh water from rivers and precipitation against evaporation keeps the surface layer in the Black Sea relatively fresh and leads to higher outflow through the Bosporus than the average amount of saline Mediterranean water that advances into the Black Sea (see Unluata *et.al.* [6]).

This paper describes oceanographic and acoustic measurements taken during a November/December 1995 sea trial to the Black Sea exit region. Collaboration with the Turkish Navy Department of Navigation, Hydrography and Oceanography (TN DNHO) made it possible to obtain a variety of data necessary to understand the physical oceanographic characteristics of this area during this time.

2. Experimental Results

A detailed hydrographic survey with SWATH mapping was obtained in order to determine the path of the Mediterranean inflow into the Black Sea as available bathymetry was not sufficient. The results in Figure 1 show that there is a narrow canyon extending from the Strait of Istanbul. At first the canyon is parallel with the strait and then turns to the North-West where it eventually merges with the continental shelf. Mediterranean water is confined and retained within this canyon over a distance of several kilometers until it spreads out on the shelf. In

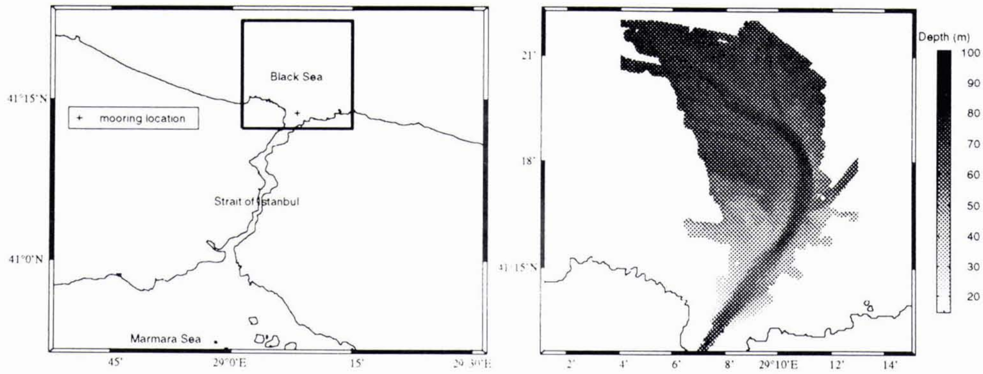

Figure 1: (left) The Strait of Istanbul separates the Black Sea and Marmara Sea basins. The enclosed area in the Black Sea exit region corresponds to the experimental site where acoustic scintillation and ADCP moorings were deployed. (right) Detailed bottom bathymetry obtained from SWATH multibeam soundings.

order to obtain accurate depth measurements simultaneous CTD profiles, from which sound speed is calculated, were obtained along the path of the underwater canyon.

The Mediterranean flow is observed within the canyon using a high resolution, high frequency (120 kHz) echo sounder (on loan from the Institute of Ocean Sciences, Sidney, B.C. CANADA) towed along side NRV ALLIANCE. Figure 2 shows a cross section of the canyon from West to East taken in the location of the moored instrumentation together with a temperature and salinity profile. A section along the canyon from South to North identifies a 60 m sill (located at 3 km in the echo sounding image) that controls the flow of Mediterranean Sea water into the Black Sea. The interface between Black Sea and Mediterranean Sea water is an area of intense turbulence associated with mixing of the two different waters and thus has strong acoustic back scatter characteristics. Measurements show that the echo level from the interface is 40% that of the bottom reflection. Much structure is visible at the interface which suggests strong spatial variations associated with turbulent mixing both across and along the canyon.

A high frequency (307.2 kHz) acoustic scintillation system (also on loan from IOS) was deployed within the canyon containing Mediterranean sea water (see Figure 2). This instrument is self contained and battery operated. The transmitter array was deployed on the western side (at approximately 700 m range) and the receiver array on the eastern side (at approximately 980 m range) at a depth of 62.5 m. Each array consists of two transducers separated by 0.2 m. In order to keep the transducer array aligned in the direction of flow, a vane and swivel were attached to the mooring. This allows measurement of current flow perpendicular to the acoustic axis and measurement of turbulent structures as they are advected past the acoustic path. Each transducer is horizontal omni-directional with a 10 degree vertical beam width. Short pulses (30 cycles) are transmitted with a high repetition rate (16 Hz) and with a delay of 20 ms between the two spatially separated transducers. The receiver unit complex demodulates the signals, digitizes and calculates the acoustic amplitude, phase and travel time for the direct path using quadratic interpolation of the received enveloped. The data are then recorded on flash EPROM recorder cards. Table 1 summarizes the experimental parameters.

Two deployments were made: 4.5 days of continuous data were collected on the first and 8 days of sub-sampled data (20 minutes of data every hour) on the second. The data covered a variety of oceanographic phenomena but some of the scintillation data could not be analyzed. Figure 3 shows ADCP current vectors (together with density contours when available) which cover the two deployment periods. Deployment 1 was during a time when the Mediterranean under current was strong. Contours of density over 36 hours show salt entrainment into the Black Sea layer and salt depletion in the Mediterranean layer. Deployment 2 was during a time when there was blockage of Mediterranean water so that the interface passed through the acoustic path. The blockage by the 60 m sill is a result of increased barotropic pressure and strong North-Easterly winds which cause an increase in sea level difference between the Black Sea and Marmara Sea basins.

The acoustic log-amplitude, $\chi = \ln(A/ < A >)$ (where A is the acoustic amplitude and $<>$ denotes a time average), for the two parallel paths (T1/R1 and T2/R2) are shown in Figure 4 during a time when the Mediterranean current was strong. Much variability exists because of the turbulent nature of the Mediterranean

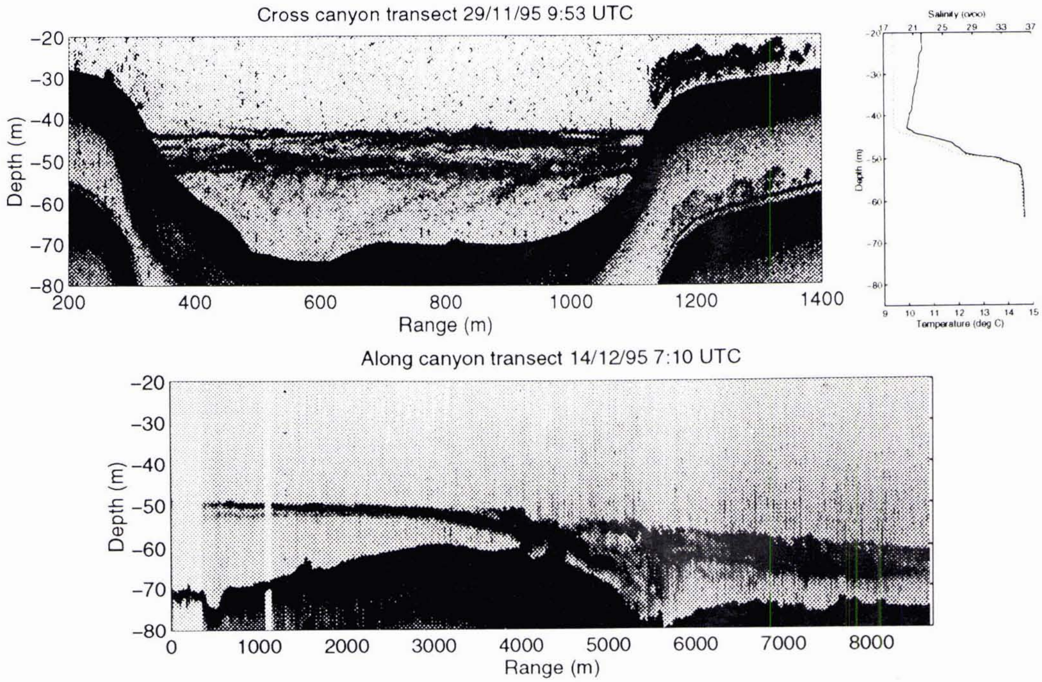

Figure 2: (top) A cross section of the canyon from West to East together with the temperature and salinity profile. (bottom) A section along the canyon from South to North.

Parameter	quantity
Deployment 1	27/11/95 1100 to 01/12/95 1700 UTC
Deployment 2	05/12/95 1000 to 13/12/95 1130 UTC
Transmission rate	16 Hz
– deployment 1	continuous
– deployment 2	20 minutes continuous every hour
Frequency	307.2 kHz
Pulse width	0.1 ms
Pulse delay	20 ms
Digitization rate	153600 Hz (1 sample/2 cycles)
Path length	282 m
Propagation direction	124 deg T
Transducer separation	0.2 m
Depth	62.5 m

Table 1: Acoustic scintillation instrument parameters.

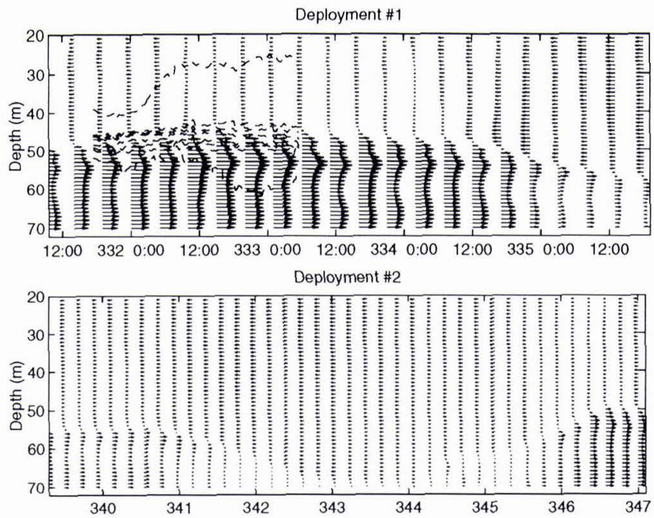

Figure 3: The ADCP current vectors as a function of Julian day, together with density contours ([1014, 1015, 1017, 1019, 1021, 1023, 1025, 1026.75] $kg \cdot m^{-3}$) when available, for each deployment.

flow. Also shown is the travel time difference between the two parallel paths. The periodic nature of this time series is a result of mooring oscillation. Since the transmission rate was high (16 Hz) and the oscillations small the direct path signal was tracked. The mooring motion does not affect amplitude variations but the phase and travel time could not be used as a measurement of medium properties.

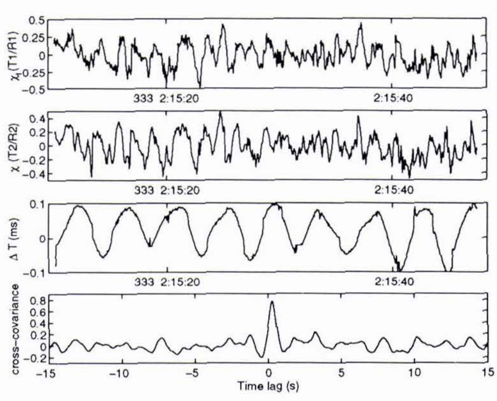

Figure 4: Acoustic scintillation during a time of strong current.

The statistics for the log-amplitude allow measurement of oceanographic parameters as discussed by Di Iorio and Farmer [1]. For example, Figure 4 shows the time-lagged log-amplitude cross-covariance function. This function shows the translation of turbulent structures perpendicular to the two acoustic paths separated by 0.2m. By measuring the time lag, the current speed is calculated and shown in Figure 5 for each deployment together with the ADCP measurement for comparison. Discrepancies between the scintillation technique and the ADCP can arise for a number of reasons. For example, the scintillation measurement is a path average whereas the ADCP measurement is essentially a volume measurement at a point location. Also because of mooring motion, there can be changes in the acoustic path separation of 0.2 m.

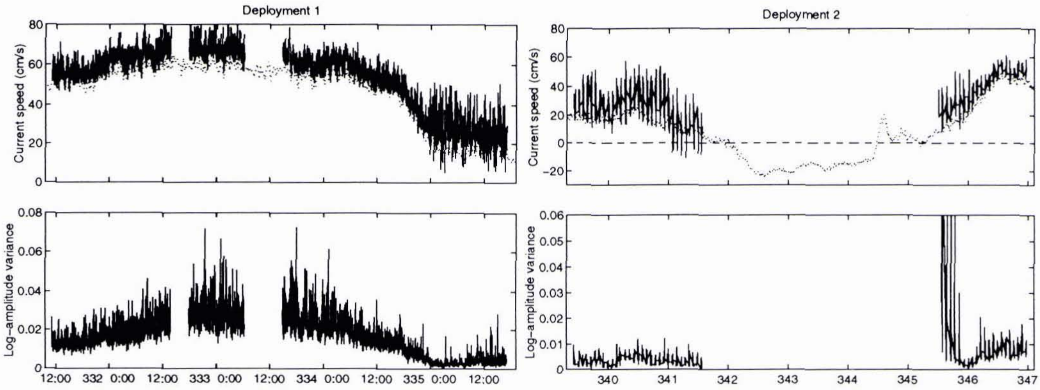

Figure 5: Current speed measured using acoustic scintillation and ADCP together with the log-amplitude variance for (left) deployment 1 and (right) deployment 2.

The log-amplitude variance shows increased variability associated with the increasing current. The large variance observed in deployment 2 may be the result of turbulent mixing between two very different water masses as the Mediterranean flow becomes unblocked. During blockage of the Mediterranean inflow the acoustic data for deployment 2 was not very good. This could be due to a number of reasons: misalignment of the transmitter/receiver arrays because of rotation, inability to track the direct path since the travel time of the acoustic signal changes by upto 3.9 ms and finally there may have been interference from multipaths so that path separation was not possible. Mediterranean water below the acoustic propagation axis creates strong upward refraction masking the effects of the bottom.

The level of the effective refractive index fluctuations defined by,

$$C^2_{n_{eff}} = C^2_{n_s} + \frac{11}{6} C^2_{n_v}, \tag{1}$$

(see Di Iorio and Farmer [2]) is expressed in terms of the refractive index fluctuations arising from temperature and salinity variability (scalars) and those arising from the current variability (vectors). The log-amplitude variance, σ^2_χ allows measurement of $C^2_{n_{eff}}$ through the equation,

$$\sigma^2_\chi = 0.124 C^2_{n_{eff}} k^{7/6} L^{11/6}, \tag{2}$$

where k is the acoustic wavenumber and L is the acoustic path length. Note that the acoustic amplitude variability cannot distinguish between fine scale variability from scalars and that from current. The dominant scale size which contributes to the log-amplitude variance as discussed by Tatarskii [5] is the Fresnel radius $\sqrt{\lambda L} = 1.2m$.

Independent measurements of the temperature and salinity structure was obtained by TRV CUBUKLU by lowering a conductivity, temperature and depth meter (CTD) to 62 m and collecting 10 minute time series at an 8 Hz sampling rate. This sampling rate can resolve scales sizes within 0.1 m to a few meters in size for a current 0.8 m/s. Thus the acoustics and CTD measurements probe the same scale sizes. Assuming isotropic and homogeneous turbulence the one-dimensional frequency spectrum for the refractive index fluctuations from temperature and salinity (see Di Iorio and Farmer [1] is defined as,

$$F_{\eta_s}(f) = 0.124 C_{\eta_s} (\frac{U}{2\pi})^{2/3} f^{-5/3}, \tag{3}$$

where U is the mean current speed resolved along the canyon which advects the small scale turbulence. Figure 6 shows a sample sound speed time series together with the one dimensional frequency spectrum for the refractive index fluctuations ($\eta_s = -c'/c_o$ where c_o and c' are the mean and fluctuating parts of the sound speed). A -5/3 slope is plotted to show that the variability can be modelled as described by (3) over the scales of most sensitivity. The level of the spectrum gives the structure parameter C_{η_s} which is compared to the acoustic forward scatter results.

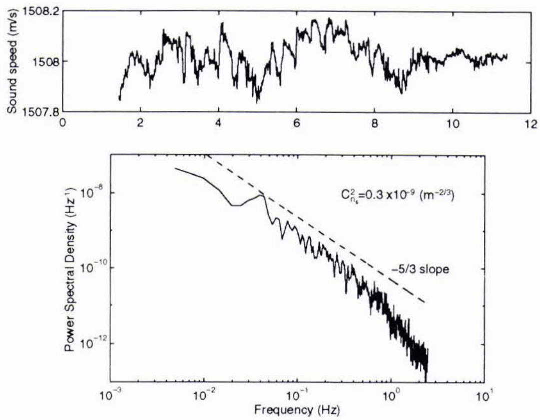

Figure 6: A sample sound speed time series together with the frequency spectrum for the refractive index fluctuations.

Figure 7 shows that the dominant acoustic scattering is from current velocity variability since $C^2_{n_s}$ is at most 10% of $C^2_{n_{eff}}$. Current velocity fluctuations arise because of hydrodynamic instability within the Mediterranean layer and also because flow over the bottom generates a turbulent boundary layer. The turbulence can be parameterized by the Reynolds number,

$$\mathrm{Re} = \frac{UL}{\nu}, \tag{4}$$

and the instability parameterized by the gradient Richardson number,

$$\begin{aligned} \mathrm{Ri} &= N^2\left[\left(\frac{dU}{dz}\right)^2 + \left(\frac{dV}{dz}\right)^2\right]^{-1}, \\ N^2 &= \frac{g}{\rho_o}\frac{d\rho_o}{dz}. \end{aligned} \tag{5}$$

The mean flow resolved along the canyon is U, the Mediterranean thickness is L and ν is the kinematic viscosity. The Brunt-Vaisala frequency is $N/(2\pi)$, ρ_o is the mean density as a function of depth, g is gravity, and V is the cross canyon flow component.

If the stratification is unstable, $\mathrm{Ri} < 0$ then density variations enhance the turbulence. If the gradient Richardson number becomes large then turbulence is suppressed since the density gradient stabilizes the variations caused by the current shear. More specifically stratified shear flow is hydrodynamically stable if $\mathrm{Ri} > 1/4$; if $\mathrm{Ri} < 1/4$ then turbulence is generated because of hydrodynamic instability (see Pond and Pickard [3]). Figure 8 shows an averaged profile of the Brunt-Vaisala frequency together with the current components U and V. From our time series measurements we find that throughout the Mediterranean layer the Richardson number was consistently $0 \le \mathrm{Ri} < 1/4$ and the Reynolds number of order 2×10^7.

Since Mediterranean flow is confined between two boundaries (the bottom boundary below and Black Sea water above), a balance of friction, Coriolis and pressure gradient forces will result in a cross stream shear over the full thickness of the Mediterranean layer as seen by the profiles of U and V. Figure 8 also shows the current vectors as a function of depth. As the bottom boundary and interface are approached the current swings to the left.

Since velocity fluctuations dominate the acoustic scattering, the turbulent kinetic energy dissipation rate is determined via,

$$\epsilon^{2/3} = \frac{C^2_{n_v} c_o^2}{1.97}, \tag{6}$$

where c_o is the mean sound speed at the depth of the acoustic path. Acoustic measurements of ϵ range from 1×10^{-6} to $5 \times 10^{-5} W/kg$. This parameter is useful since it gives the production of turbulent energy caused by shear stresses. Production of energy from buoyancy forces are assumed negligible since the Mediterranean layer is very well mixed. Following Monin and Ozmidov [4] the balance of production and dissipation of energy is then,

$$\frac{\tau_{xz}}{\rho_o}\frac{dU}{dz} + \frac{\tau_{yz}}{\rho_o}\frac{dV}{dz} = \epsilon, \tag{7}$$

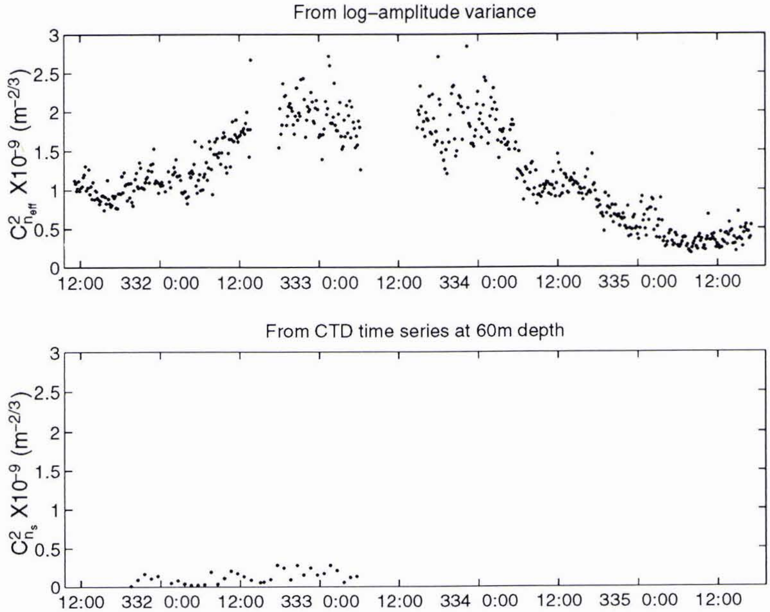

Figure 7: The level of effective refractive index fluctuations compared with the level of the scalar contribution to the refractive index fluctuations.

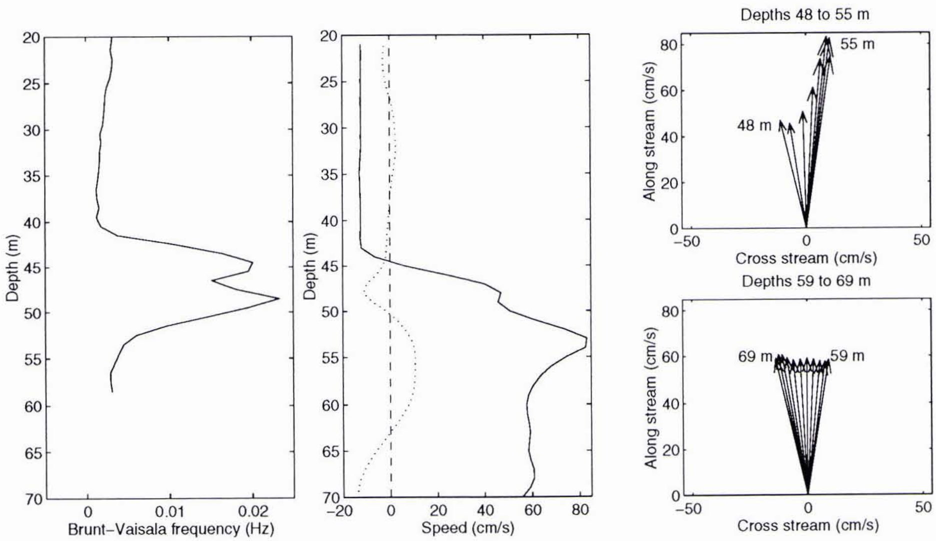

Figure 8: Averaged profiles for the Brunt-Vaisala frequency, U (solid) and V (dotted) current components together with the current vectors.

where the shear stresses are given by $\tau_{xz} =< u'w' >$ and $\tau_{yz} =< v'w' >$. To make estimates of the bottom drag coefficient the flow close to the boundary is modelled as a log-layer since $dV/dz \approx 0$. Therefore $\tau_{xz}/\rho_o \sim C_D U^2$. For a maximum dissipation rate of $5\times10^{-5} W/kg$ during the maximum outflow an estimated bottom drag coefficient is $C_D = 3.5 \times 10^{-3}$ which is consistent for a mixed sand and shell bottom.

3. Future Measurements

Future measurements in the Strait of Istanbul will be carried out in collaboration with IOS and the TN DNHO. At present a $50kHz$ reciprocal acoustic scintillation system is under development. This system is capable of transmitting pseudo random noise (PRN) m-sequences in both directions at a maximum rate of 5 Hz or at a rate of 20 Hz in one direction. The incoming signals are complex demodulated and all multipaths will be recorded. The use of PRN codes allows path separation within $180\mu s$.

The use of reciprocal transmission allows measurement of the temperature and current variability along the acoustic path as described by Di Iorio and Farmer [2]. The scintillation technique gives measurement of the advection of turbulent structures perpendicular to the acoustic path so that combining the two techniques one can determine the current velocity field (see [2]). In the Strait of Istanbul where a two layer flow exists the acoustic system will be deployed at two depths so as to measure turbulent temperature and velocity characteristics in each layer. Also since all multipaths are stored there is an opportunity to study the effects of bubbles from ship wakes on the surface reflected signals. Bottom reflected signals can also be studied to see if the Mediterranean undercurrent causes sediment transport.

In addition to the reciprocal acoustic scintillation system, a bottom mounted upward looking ADCP and echo sounder will be placed in the center of the strait so as to obtain temporal measurements of the interface structure.

It is hoped that these systems will remain in the strait for one year so that temporal variations associated with seasonal changes can be documented.

4. Conclusions

The use of high frequency acoustics is a valuable tool for obtaining fine structure characteristics of turbulent flow. In this paper, three acoustic systems were used to study Mediterranean flow into the Black Sea. High resolution echo sounding gave two dimensional imaging of the interface where mixing between two different water masses takes place. A scintillation system deployed within the Mediterranean layer was used to obtain turbulent boundary layer characteristics. It was shown that velocity variability dominated the acoustic scattering which leads to estimates of the turbulent kinetic energy dissipation rate and bottom drag coefficient.

5. Acknowledgements

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