# A review of the exchange flow regime and mixing in the Bosphorus Strait

by

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**ABSTRACT**

The Bosphorus Strait is a strongly stratified two-layer system and a unique case of the "maximal exchange" regime of strait flows, which largely determines the properties of the Black Sea. The strait operates in the full range of possible exchange flows, with great variability associated with transient features. The net freshwater input into the Black Sea, barometric pressure differences and wind setup are possible forcing mechanisms, and the response of the strait is strongly non-linear. The seasonal and interannual response is extremely variable because of non-linear behaviour and also as a result of significant variability in the forcing. The hydrological cycle and barometric pressure variations in the region both have strong relationships with the sea-level fluctuations in the Black Sea. Mixing occurs between the upper and lower layer flows via turbulent entrainment. Longitudinal dispersion estimates for each individual layer are comparable to other estuarine regions of the world.

**RÉSUMÉ**

Le détroit du Bosphore, système à deux couches fortement stratifiées et cas unique de régime d'échange maximal parmi les courants de détroit, détermine largement les propriétés de la mer Noire. Le détroit agit sur une gamme complète de flux d'échanges avec une grande variabilité associée à des phénomènes passagers. L'apport d'eau douce en mer Noire, les différences de pressions barométriques, le régime des vents sont de possibles mécanismes contraignants et la réponse du détroit est fortement non-linéaire que ce soit à l'échelle saisonnière ou interannuelle. Le cycle hydrologique et les variations de la pression barométrique dans la région sont tous deux fortement corrélés avec les fluctuations du niveau de la mer Noire. Le mélange entre flux supérieur et inférieur résulte de la turbulence du passage. Les dispersions longitudinales estimées pour chacune des couches sont comparables à celles observées dans les autres estuaires du monde.

## INTRODUCTION

The Bosphorus is one of the two straits in the Turkish Straits System controlling the exchange between two relatively large inland seas of greatly differing hydrological regimes, *i.e.* the Mediterranean and Black seas, which are connected via the Marmara Sea. The exchanges through the Turkish straits determine the inter-basin transport of pollution (POLAT and TUĞRUL, this volume; ÖZSOY *et al.*, 1995a). The fate of pollutants, such as the waste-water from the city of Istanbul, is largely determined by the stability of the two-layer exchange flows through the Turkish straits (DAMOC 1971; GUNNERSON and ÖZTURGUT, 1974; GUNNERSON, 1974; ORHON *et al.*, 1994; ÖZSOY *et al.*, 1994, 1995b).

The Black Sea is a landlocked basin, with precipitation (~300 km$^3$/yr) and runoff (~350 km$^3$/yr) exceeding evaporation (~350 km$^3$/yr); the excess is balanced by a net outflow of ~300 km$^3$/yr through the Bosphorus (ÜNLÜATA *et al.*, 1990). The Danube, Dniepr and Dniestr rivers in the north-west Black Sea are the important sources of freshwater, with the Danube contributing about a half of the total river runoff. Freshwater inflow into the Black Sea displays large seasonal and interannual natural variability (SUR *et al.*, 1994). A significant correlation exists between the Danube influx and sea-level, even at annual time scales, suggesting efficient control by the Bosphorus (SUR *et al.*, 1994; ÖZSOY *et al.*, 1995a).

Mass balance estimates of the two-layer exchange flows through the Bosphorus, based on long term salinity measurements (ÜNLÜATA *et al.*, 1990) yield an average upper layer outflow of ~600 km$^3$/yr and a lower layer inflow of ~300 km$^3$/yr. The steady-state salt budget of the Black Sea requires that the ratio $Q_1/Q_2 = S_2/S_1 \approx 2$, where $Q_1$, $S_1$ and $Q_2$, $S_2$ are the upper (1) and lower (2) layer volume fluxes and salinities at the Black Sea entrance of the Bosphorus. Because of turbulent entrainment, it is estimated that ~25% of the lower layer flux in the Bosphorus is entrained into the upper layer, and ~7% of the upper layer flux is entrained to the lower layer. Yet, the ADCP-based instantaneous fluxes greatly differ from these estimates, as they follow closely the transient meteorological and hydrological forcing in adjacent basins (LATIF *et al.*, 1991; ÖZSOY *et al.*, 1994, 1995a, 1995b), displaying significant variations over short time-scales.

## BOSPHORUS STRAIT HYDRAULICS

Among the two straits interconnecting the Mediterranean and Black seas, the Bosphorus is the more crucial one in determining the exchange, because it has two hydraulic controls imposed respectively at a sill and a constriction while hydraulic control occurs only at a constriction in the Dardanelles Strait. In fact, the Bosphorus Strait is the prime example for straits with "maximal exchange" (ARMI and FARMER, 1986; FARMER and ARMI, 1986; ARMI and FARMER, 1987), with two controls, favorable strait geometry and adjacent basin stratification. In the case of the Dardanelles, conditions are only favorable for "submaximal exchange" (ÖZSOY *et al.*, 1986, 1988; OĞUZ and SUR, 1989; ÜNLÜATA *et al.*, 1990; OĞUZ *et al.*, 1990). The Bosphorus is also a special case of straits with constriction located between the higher density basin and a sill (FARMER and ARMI, 1986), in which asymmetry with respect to net through-flow, depending on constriction/sill width ratios is expected.

The planform geometry of the Bosphorus is shown in Figure 1. Two pertinent features of immediate attention are the northern sill, with a depth of 60 m located about 3-4 km northeast of the Black Sea entrance, and the contraction at the Arnavutköy-Kandilli section in the southern part, with a width of about 600 m and a maximum depth of about 110 m. A further addition to these essential geometric characteristics is the southern sill and exit region geometry (OĞUZ *et al.*, 1990) near the Marmara Sea. Since the controls imposed by the northern sill and the mid-strait constriction sections are sufficient to establish maximal exchange, the existence of a secondary transition in south Bosphorus is not an essential element; in fact, south of the constriction, the upper layer flow undergoes dissipation and partially recovers before reaching the Marmara Sea exit (ÖZSOY *et al.*, 1986; OĞUZ *et al.*, 1990). Long-term observations has led to this schematization (ÖZSOY *et al.*, 1995a), also confirmed by numerical model results (OĞUZ *et al.*, 1990). Both observations and model results indicate that a possibility for the loss of control at the southern exit region and replacement by the control at the southern exit region is rare, and conjectured to occur only when either the net barotropic flow diminishes or the interfacial and bottom friction effects are negligibly small (OĞUZ *et al.*, 1990).

Other complexities of the Bosphorus flows include secondary and eddy circulations induced by the tortuous geometry of the strait, unsteady effects connected with wind set-up and changes in adjacent basins, along strait density variations, and entrainment of fluid from one layer into the other. Some of these effects, which are important (PRATT, 1987), but unconsequential in establishing the overall "maximal exchange" (ARMI and FARMER 1987), have been successfully incorporated in a two-layer model (OĞUZ *et al.*, 1990).

The Bosphorus responds rapidly to changes in the driving conditions, operating in the full range of weak to strong barotropic forcing in either direction (ÖZSOY *et al.*, 1995a). Under normal conditions, hydraulic controls exist at the two sections. In the case of increased net barotropic flow from the Black Sea or persistent northerly winds, the lower layer of the Bosphorus occasionally becomes blocked. Similarly, southerly winds cause the upper layer to be arrested and pushed back to the constriction and beyond by the Marmara waters backing up in the Bosphorus, and its flow

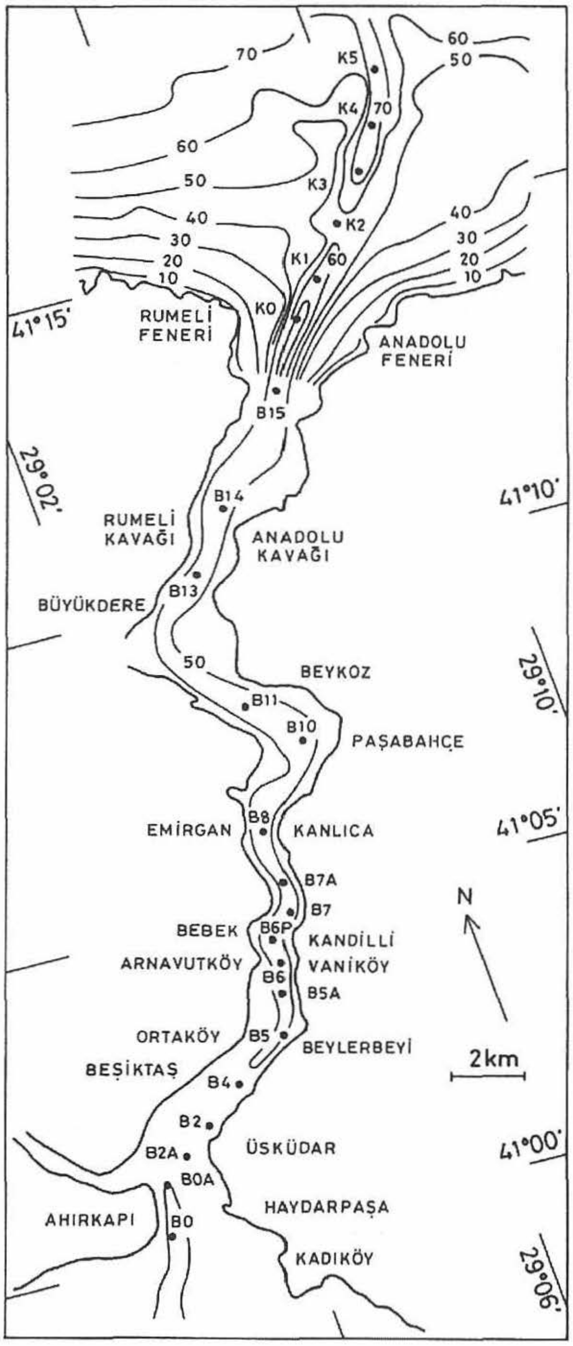


Figure 1 – Location map, showing planform geometry of the Bosphorus.

beneath the arrested wedge results in three-layer stratification. The upper-layer blocking is accompanied by diminishing sea-level difference between the two ends of the strait (DAMOC, 1971; GUNNERSON and ÖZTURGUT, 1974; ARISOY and AKYARLI, 1990). At the same time, increased surface salinity is observed in the southern Bosphorus (the so-called "Orkoz" events, cf. ARTÜZ and UĞUZ, 1976; ÖZSOY *et al.*, 1995a). Both the upper layer and the lower layer blocking conditions are short-term events, typically lasting a few days and often related to prevailing conditions in the adjacent basins. The blocking of the lower layer occurs during the late spring season, when the seasonal outflow from the Bosphorus is at its peak, while the arresting of the upper layer typically occurs during winter storms when the barotropic flow is at its minimum (ÖZSOY *et al.*, 1994, 1995a).

A summary of ADCP based flux measurements in the Bosphorus spanning the period of 1991-1995 (ÖZSOY *et al.*, 1994, 1995a,b; GREGG *et al.*, 1995) is given on a seasonal basis in Figure 2. A clear definition of seasonal

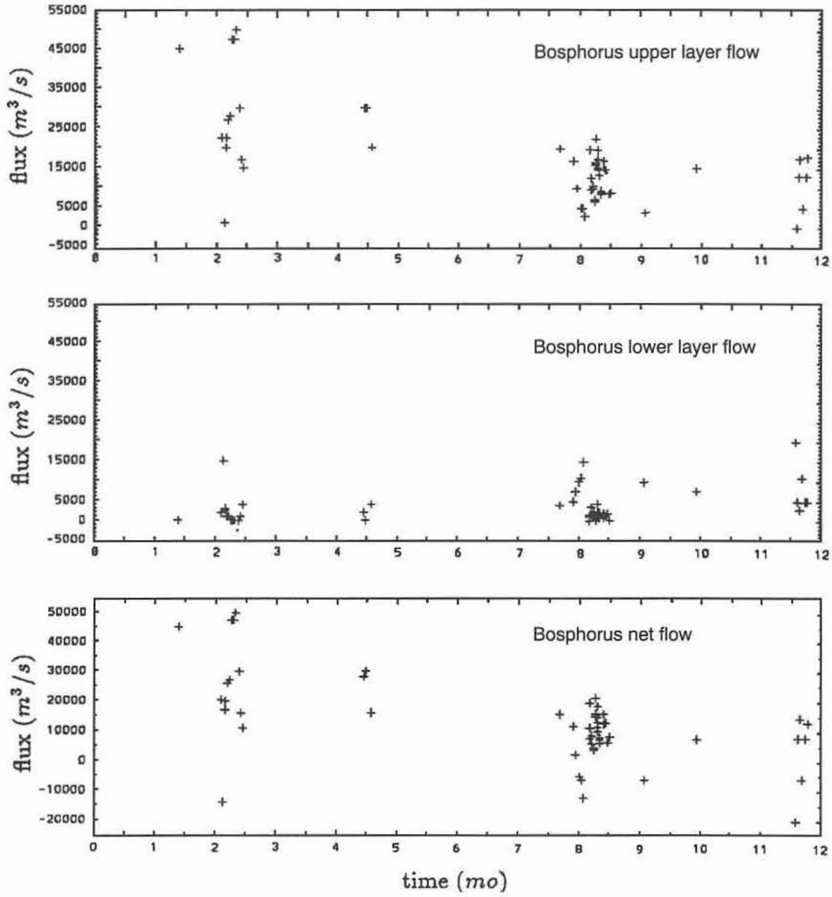


Figure 2 – 1991-1995 ADCP-based direct volume flux measurements in the Bosphorus plotted on a seasonal basis (after ÖZSOY *et al.*, 1994; GREGG, 1995).

signal is not possible, because it is masked by the great variability on shorter time scales, and an insufficient number of measurements with statistical reliability. It should also be noted that the estimates are subject to inaccuracies of the ADCP technique in the shallow and narrow waters of the strait (ÖZSOY *et al.*, 1994), due to loss of data near the bottom and the surface. The lower layer flow appears to be consistently underestimated, compared to mass budget estimates. Based on Figure 3, we can only suggest an increased net flow in spring and a decrease in winter months. Indirect measurements, based on hydrography, suggest an increasing influence of low salinity waters in the Marmara Sea surface layer during the spring and summer months, with a delay appropriate for the residence time of the Marmara basin (BEŞIKTEPE *et al.*, 1994).

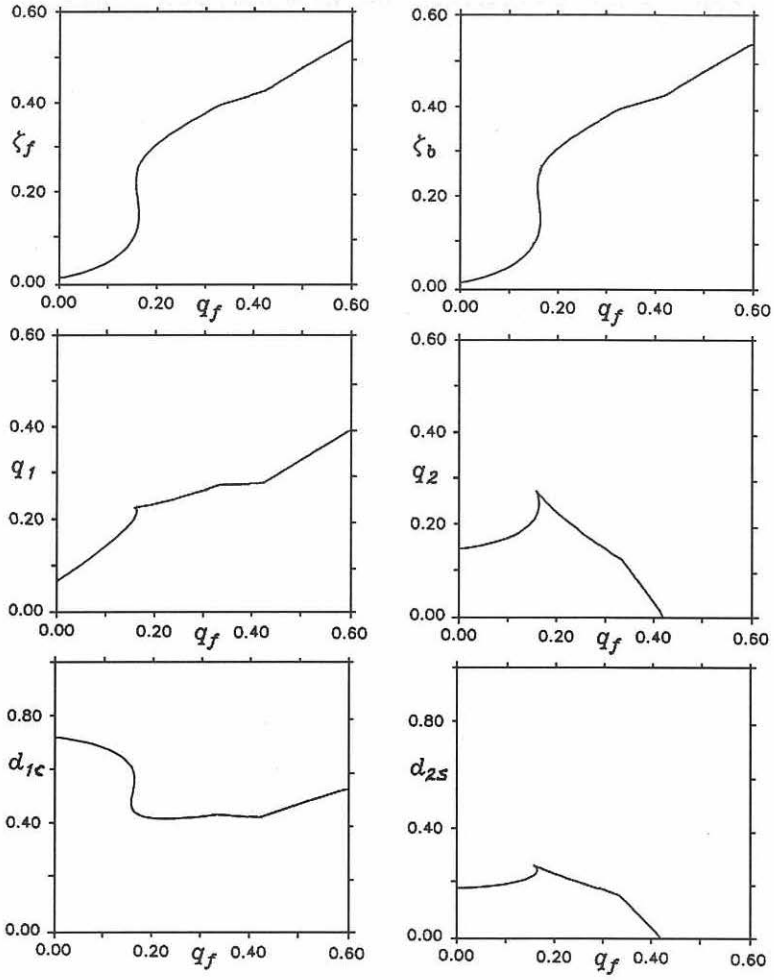


Figure 3 – Frictionless, steady-state solutions of Bosphorus hydraulics model for values $B_1 = 0.01$, $B_2 = 0.5$, $h_s = 0.15$, $\beta = 0.667$, plotted as a function of the barotropic flux $q_f$ (after ÖZSOY, 1990).

## A TWO LAYER MODEL OF THE BOSPHORUS STRAIT

Following on these observations, the purpose of our model is to investigate the functional dependence of the exchange flows on external influences, including the cases of blocking, and to construct a qualitative understanding of the strait behaviour in response to seasonal forcing. A similar approach has been followed by WELANDER (1974) in investigating the non-linear response of an estuary, based on the two-layer exchange at its mouth, and by MADERICH and EFROIMSON (1986) in the case of Bosphorus. We present a simple hydraulic model following ÖZSOY (1990).

We base the model on the features reviewed above. A quasi-steady response of the Bosphorus to seasonal forcing is considered, using a simple variation of the FARMER and ARMI (1986) model, allowing for a finite depth at the contraction and variable widths for each layer. A further trivial difference, *i.e.* the presence of a free surface, allows seasonal storage in the Black Sea basin. Although we can account for bottom and interfacial friction by suitable parameterization, *i.e.* integrating the frictional terms between the two control sections (SÜMER and BAKIOĞLU, 1981), barometric pressure differences and wind stress along the strait, we exclude explicit discussion of these complicating effects.

We first consider the equations of motion, governing a two-layer, unidirectional flow and integrate them between the two control sections. ($1a-c$) are the continuity requirements for the Black Sea and Bosphorus. A quasi-steady state assumption for strait flows leads to the Bernouilli equations ($1e, f$), and a similar one between the sill and the basin yields ($1d$). We add hydraulic control conditions ($2g, h$), *i.e.* $G^2 = F_1^2 + F_2^2 = 1$, where $F_1 = u_1/\sqrt{\varepsilon g y_1}$, $F_2 = u_2/\sqrt{\varepsilon g y_2}$, respectively at the constriction and sill sections. Equations ($1i, j$) are simple geometrical relations relative to a common datum.

$$S_b \frac{\partial \eta_b}{\partial t} = Q_f + Q_2 - Q_1$$

$$\frac{1}{2}\left\{u_{1s}^2\right\} = \frac{\Delta_{bs}}{\rho_1} + g(\eta_b - \eta_s)$$

$$\frac{1}{2}\left\{u_{1c}^2 - u_{1s}^2\right\} = \frac{\Delta_{sc}}{\rho_1} + g\eta_s - \int_{x_c}^{x_s} \frac{\tau_w}{\rho_1 y_1} dx - \int_{x_c}^{x_s} \frac{\tau_i}{\rho_1 y_1} dx$$

$$\frac{1}{2}\left\{u_{2c}^2 - u_{2s}^2\right\} = \frac{\Delta_{sc}}{\rho_2} + g\left\{\eta_s - \varepsilon(y_{1s} - y_{1c})\right\} + \int_{x_c}^{x_s} \frac{\tau_i}{\rho_1 y_2} dx + \int_{x_c}^{x_s} \frac{\tau_b}{\rho_2 y_2} dx$$

$$\frac{u_{1c}^2}{\varepsilon g y_{1c}} + \frac{u_{2c}^2}{\varepsilon g y_{2c}} = 1 \qquad (1a-h)$$

$$\frac{u_{1s}^2}{\varepsilon g y_{1s}} + \frac{u_{2s}^2}{\varepsilon g y_{2s}} = 1$$

$$y_{1c} + y_{2c} = y_o$$

$$y_{1s} + y_{2s} + H_s = \eta_s + y_o$$

where $u_j$, $b_j$, $h_j$ and $\rho_j$ respectively are the velocity, width, depth and density of the flow within each layer ($j$ = 1, 2), where subscript $s$ denotes the values at the sill and subscript $c$ denotes values at the constriction, $S_b$ and $\eta_b$ respectively the average surface area and sea level in the Black Sea, $y_o$ the depth at constriction, $H_s$ and $\eta_s$ respectively the bottom and surface elevation at the sill relative to the constriction, $Q_f$ the net freshwater inflow, $Q_1 = u_{1c}\, b_{1c}\, y_{1c} = u_{1s}\, b_{1s}\, y_{1s}$ and $Q_2 = u_{2c}\, b_{2c}\, y_{2c} = u_{2s}\, b_{2s}\, y_{2s}$ the respective layer fluxes, $\Delta_{bs} = P_b - P_s$ and $\Delta_{sc} = P_s - P_c$ the barometric pressure differences respectively between the Black Sea and the sill and the sill and constriction sections. $\tau_w$ is the along-strait wind stress and $\tau_i$ and $\tau_b$ are the frictional stresses, respectively at the two-layer interface and the bottom. $\varepsilon \equiv \Delta\rho/\rho_2$ is the density stratification parameter. We non-dimensionalize the variables and make the following definitions:

$$q_1 = \frac{Q_1}{Q_{1c}}, \quad q_2 = \frac{Q_2}{Q_{2c}}, \quad q_f = \frac{Q_f}{Q_c},$$

$$Q_{1c}^2 = \varepsilon g y_0^3 b_{1c}^2, \quad Q_{2c}^2 = \varepsilon g y_0^3 b_{2c}^2, \quad Q_c^2 = Q_{1c} Q_{2c} = \varepsilon g y_0^3 b_{1c} b_{2c}$$

$$\zeta_b = \frac{2}{\varepsilon}\frac{\eta_b}{y_o}, \quad \zeta_s = \frac{2}{\varepsilon}\frac{\eta_s}{y_o}, \quad d_{1c} = \frac{y_{1c}}{y_o}, \quad d_{2c} = \frac{y_{2c}}{y_o}, \quad d_{1s} = \frac{y_{1s}}{y_o}, \quad d_{2s} = \frac{y_{2s}}{y_o},$$

$$\tau = \frac{2Q_c}{\varepsilon S_b y_o} t, \quad \xi = x/\ell, \qquad (2a-v)$$

$$\delta = \frac{2}{\rho_1 \varepsilon g y_o}\Delta, \quad \pi_w = \frac{2}{\rho_1 \varepsilon g y_o}\frac{\ell}{y_o}\tau_w,$$

$$\kappa_i = \frac{2\ell}{\sqrt{\varepsilon g y_o}} k_i, \quad \kappa_b = \frac{2\ell}{\sqrt{\varepsilon g y_o}} k_b,$$

$$h_s = \frac{H_s}{y_o}, \quad B_1 = \frac{b_{1c}}{b_{1s}}, \quad B_2 = \frac{b_{2c}}{b_{2s}}, \quad \beta = \frac{b_{2c}}{b_{1c}},$$

Because friction effects are only secondary, we parameterize them with linear approximations to yield

$$\int_{x_c}^{x_s} \frac{\tau_w}{\rho_1 y_1} dx = \frac{\tau_w}{\rho_1}\int_{x_c}^{x_s} \frac{1}{y_1} dx, \quad \int_{x_c}^{x_s} \frac{\tau_b}{\rho_2 y_2} dx \approx \int_{x_c}^{x_s} k_b u_2\, dx = k_b Q_2 \int_{x_c}^{x_s} \frac{1}{b_2 y_2} dx.$$

$$\int_{x_c}^{x_s} \frac{\tau_i}{\rho_1 y_1} dx \approx \int_{x_c}^{x_s} \frac{\tau_i}{\rho_2 y_2} dx \approx \int_{x_c}^{x_s} k_i (u_1 + u_2)\, dx = k_i Q_1 \int_{x_c}^{x_s} \frac{1}{b_1 y_1} dx + k_i Q_2 \int_{x_c}^{x_s} \frac{1}{b_2 y_2} dx.$$

Further simplifications are made by using $(2a - v)$ and defining

$$\nu_j = \int_{\xi_c}^{\xi_s} \frac{1}{d_j} d\xi \approx \frac{\ln\left(d_{js}/d_{jc}\right)}{d_{js} - d_{jc}}, \quad \mu_j = \int_{\xi_c}^{\xi_s} \frac{b_{jc}}{b_j}\frac{1}{d_j} d\xi \approx \frac{b_{jc}}{\langle b_j \rangle}\nu_j, \ j = 1,2 \qquad (3a,b)$$

corresponding to the integrals on the right-hand side of (2 $e$, $f$), depending on the width $b_j(\xi)/b_{jc}$ and thickness $d_{js}$. They are approximated by linear variations between the two control sections, using the length scale for the strait $\ell = x_s - x_c$, where $\langle b_j \rangle$ is the average width between the two control sections. Since our purpose is to parameterize these terms, we assume $\nu_j$ and $\mu_j$ to be adjustable constants. The normalized versions of $(1a - j)$ using $(2a - v)$ are:

$$\begin{aligned}
\frac{\partial \zeta_b}{\partial \tau} &= q_f + \beta q_2 - \beta^{-1} q_1 \\
B_1^2 q_1^2 d_{1s}^{-2} &= \zeta_b - \zeta_s + \delta_{bs} \\
q_1^2 \left\{ d_{1c}^{-2} - B_1^2 d_{1s}^{-2} \right\} &= \zeta_s + \delta_{sc} - \left\{ \nu_1 \pi_w + \kappa_i \mu_1 q_1 + \beta^{-1} \kappa_i \mu_2 q_2 \right\} \\
q_2^2 \left\{ d_{2c}^{-2} - B_2^2 d_{2s}^{-2} \right\} &= \zeta_s - 2\left(d_{1s} - d_{1c}\right) + r\delta_{sc} + \left\{ \beta \kappa_i \mu_1 q_1 + \left(\kappa_i + \kappa_b\right) \mu_2 q_2 \right\} \\
B_1^2 q_1^2 d_{1s}^{-3} + B_2^2 q_2^2 d_{2s}^{-3} &= 1 \qquad (4a - h) \\
q_1^2 d_{1c}^{-3} + q_2^2 d_{2c}^{-3} &= 1 \\
d_{1c} + d_{2c} &= 1 \\
d_{1s} + d_{2s} + h_s &= \frac{\varepsilon}{2} \zeta_s + 1
\end{aligned}$$

Equations $(4a - h)$ are solved iteratively to determine the eight unknowns $\zeta_b$, $\zeta_s$, $q_1$, $q_2$, $d_{1c}$, $d_{2c}$, $d_{1s}$, $d_{2s}$, for given values of forcing $q_f$, $\delta_{bs}$, $\delta_{sc}$, $\pi_w$, geometry $B_1$, $B_2$, $\beta$, $h_s$, friction $\kappa_i$ $\kappa_b$, stratification $\varepsilon$, and adjustable constants $\nu_1$, $\mu_1$, $\mu_2$. Experience has shown that estimation of the adjustable constants at each iteration, using $(3a,b)$, produces better results. The blocking of the flow in either layer is treated by consistency checks during iterations.

## SEASONAL RESPONSE CHARACTERISTICS

We demonstrate the functional behaviour in the simplest case without wind-stress, barometric pressure or frictional effects ($\delta_{sc} = \delta_{bs} = \pi_w = \kappa_i = \kappa_b = 0$), and first study the steady-state case. An example solution with typical values of the Bosphorus geometrical parameters is shown in Figure 3. Note the non-linear dependence of $\zeta_b$ on $q_f$. For some limited range of $q_f$, there exist three different solutions in $\zeta_b$; two of these roots at the high and low ends are stable, while the third one located in between is unstable: *i.e.* the solution will shift from one fixed point to the other under unsteady conditions. An interesting feature of the solutions is the behaviour of the lower layer flux $q_2$: for lower range of net flows, the lower layer flux increases as the barotropic flow $q_f$ is increased; and in the other range it decreases with increasing $q_f$, until the lower layer becomes blocked. In contrast, the upper layer flow continues to increase with increasing barotropic flow. When the sea-level decreases to zero, the barotropic flow as well as the upper layer flow become small, but do not have to be exactly equal to zero.

These basic characteristics survive in the case of unsteady (seasonal) runs including the effect of Black Sea storage. Because the solution is multiple-valued, for some range of variables, there is a chance for the solution to oscillate about two stable fixed points. An example is shown in Figures 4a-c, with the same parameters as in the previous cases, but when the model is forced by a time-dependent barotropic flow, increasing from

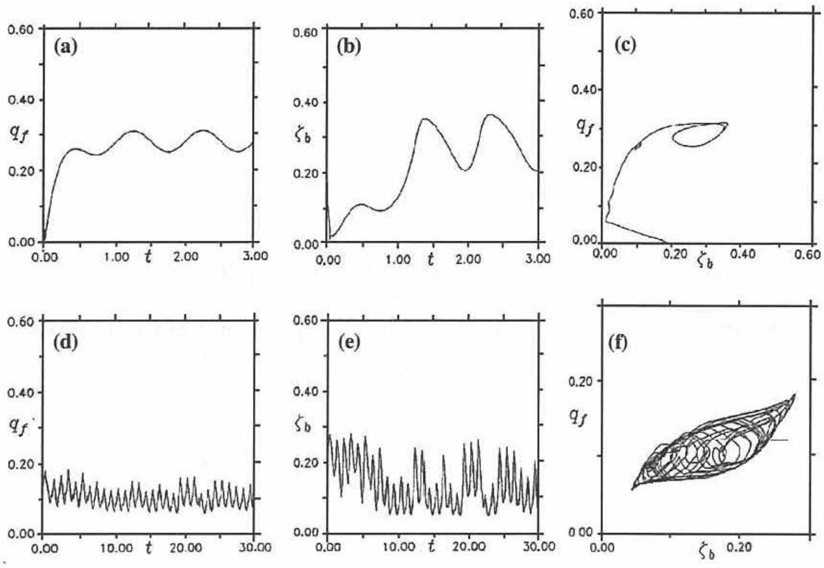


Figure 4 – Top: a three-year run of the seasonal model with (a) forcing $q_f$, and (b) the sea-level response, and (c) $q_f$ versus $\zeta_b$. Bottom: a thirty year simulated run of the seasonal model, with (d) synthetic fresh water inflow $q_f$, (e) the sea-level response $\zeta_b$, and (f) $q_f$ *versus* $\zeta_b$ (after ÖZSOY, 1990).

zero to a seasonally oscillating function displayed in the upper right panel. The sea-level is low during the first year, and oscillates about a higher level for the next two years. In Figure 4c, the solution oscillates about the two fixed points. In addition to the possible interannual variations imposed by the strait itself, the net freshwater inflow has its own natural variability. When the system is forced with a simulated freshwater inflow with modest interannual variations (Figure 4d), these variations are amplified in sea level (Figure 4e), with the solution vacillating between the two stable solutions. In phase space, the oscillations sketch a complicated pattern (Figure 4f).

The multiple valued simple solutions could be unrealistic, yet completely physical, because of the following reasons: (i) the occurrence of multiple-valued solutions may depend on a suitable range of forcing and may depend on the choice of parameters; (ii) the inclusion of further complicating factors, such as the variable channel geometry, friction, short-term inertial effects, etc., can further modify the behaviour of the solutions. In fact, when friction is included, the multiple-valued solutions become suppressed; yet, the "flat" response, *i.e.* the region where a large change in sea-level occurs in response to a small change in barotropic flow survives. The solutions are qualitatively similar to those discussed above.

## RESPONSE TO HYDROLOGICAL BALANCE AND BAROMETRIC PRESSURE

The adjustment of Black Sea sea-level to forcing is characterized by the time scale (equations $2f$ and $2m$)

$$T_a = \frac{\varepsilon S_b y_o}{2Q_c} = \frac{S_b\sqrt{\varepsilon}}{2\sqrt{g y_o b_{1c} b_{2c}}}$$

For appropriate values $\varepsilon = 0.015$, $S_b = 420 \times 10^3$ km$^2$, $y_o \approx 100$ m, $b_{1c} \approx b_{2c} \approx =1$ km, we find $T_a \approx 42$ d. This adjustment time scale is relatively short, compared to the filling time scale $T_f = S_b\, \overline{\eta}_b/\overline{Q}_f$ (required for sea level rise of $\overline{\eta}_b$ due to net river inflow of $\overline{Q}_f$ in a closed basin-equation 1*a*), estimated as $T_f$ = 240 *d*. In comparison, the time scales for the Strait of Gibraltar are estimated as $T_a \approx 9$ *d* and $T_f \approx 25$ *d*. Although the Bosphorus net flow is two orders smaller than the Gibraltar flow, the Black Sea adjusts relatively rapidly via Bosphorus exchanges.

Monthly time series of sea-level at Sevastopol and net freshwater inflow, with components of total river runoff, estimated precipitation and evaporation in the Black Sea (SIMONOV and AL'TMAN, 1991) displayed in Figure 5, verify the close relationship between various elements of the hydrological

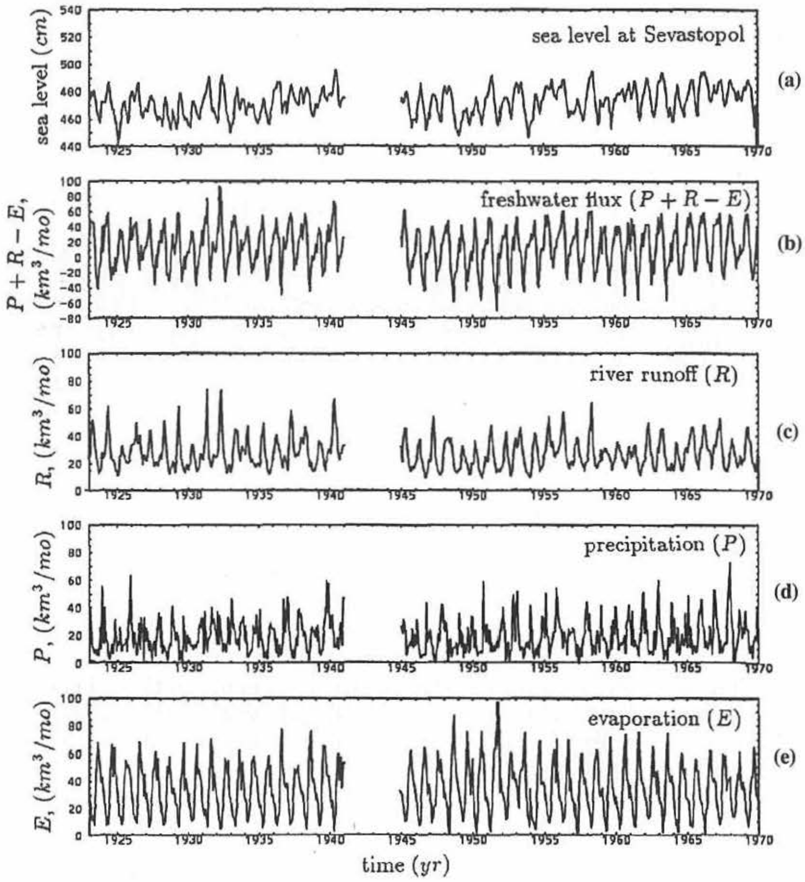


Figure 5 – 1923-1985 data on (a) sea-level at Sevastopol, (b) total freshwater inflow, (c) total river runoff, (d) total precipitation, (e) total evaporation (after SIMONOV and AL'TMAN, 1991).

cycle and sea-level variations. The most direct relationship is observed between the river inflow and sea-level, based on direct measurements. Although the other elements of surface fluxes involve certain assumptions and calculations, the relationship of sea level to total freshwater fluxes survives, especially for large events. To illustrate these relationships we plot the Black sea-level *versus* river runoff and total freshwater inflow in Figures 6a,b, showing a remarkable set of forced oscillations in phase space.

From a dynamical point of view, both the freshwater inflow and the barometric pressure differences are equally plausible forcing mechanisms controlling mean sea-level in the Black Sea; and it is not obvious *a priori* which one of these mechanisms play a greater role. Furthermore, we expect the response of sea-level to pressure in a closed basin to be different from an inverse barometer and in fact dominated by strait dynamics. Following our study of hydrological balance, we now examine the relationship between barometric pressure and sea-level in Figures 7a,b and 8. While a clear relationship cannot be established in Figures 7a,b, evidence for an inverse relationship modulated by seasonal dynamics can be found in Figure 8. This relationship is more evident on annual time-scales.

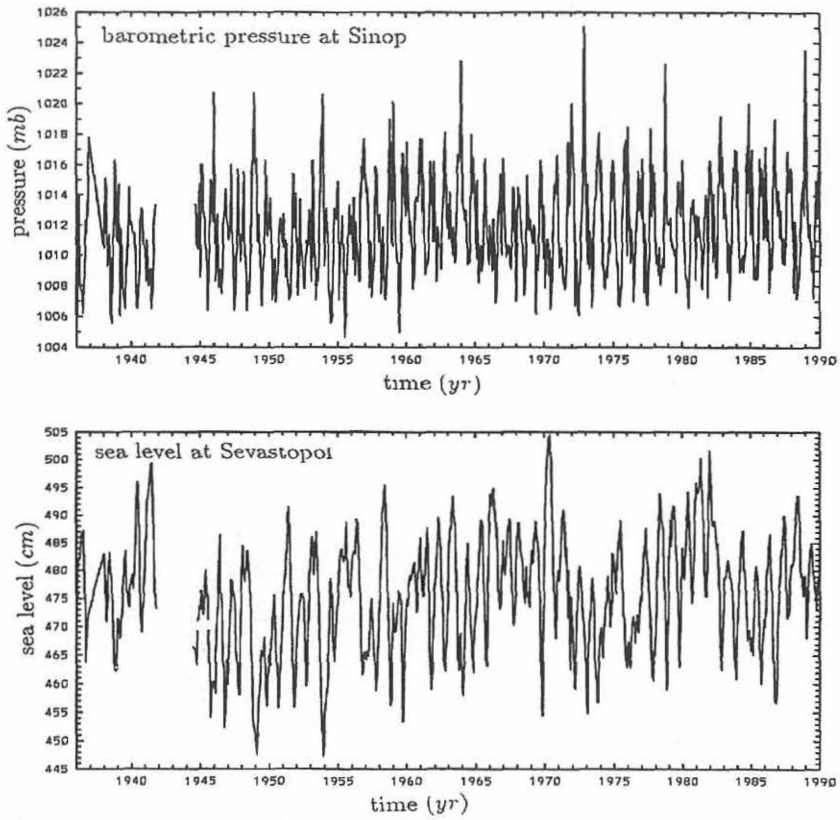


Figure 7 – Monthly time-series of (upper) pressure at Sinop and (bottom) sea-level at Sevastopol, 1936 - 1990.

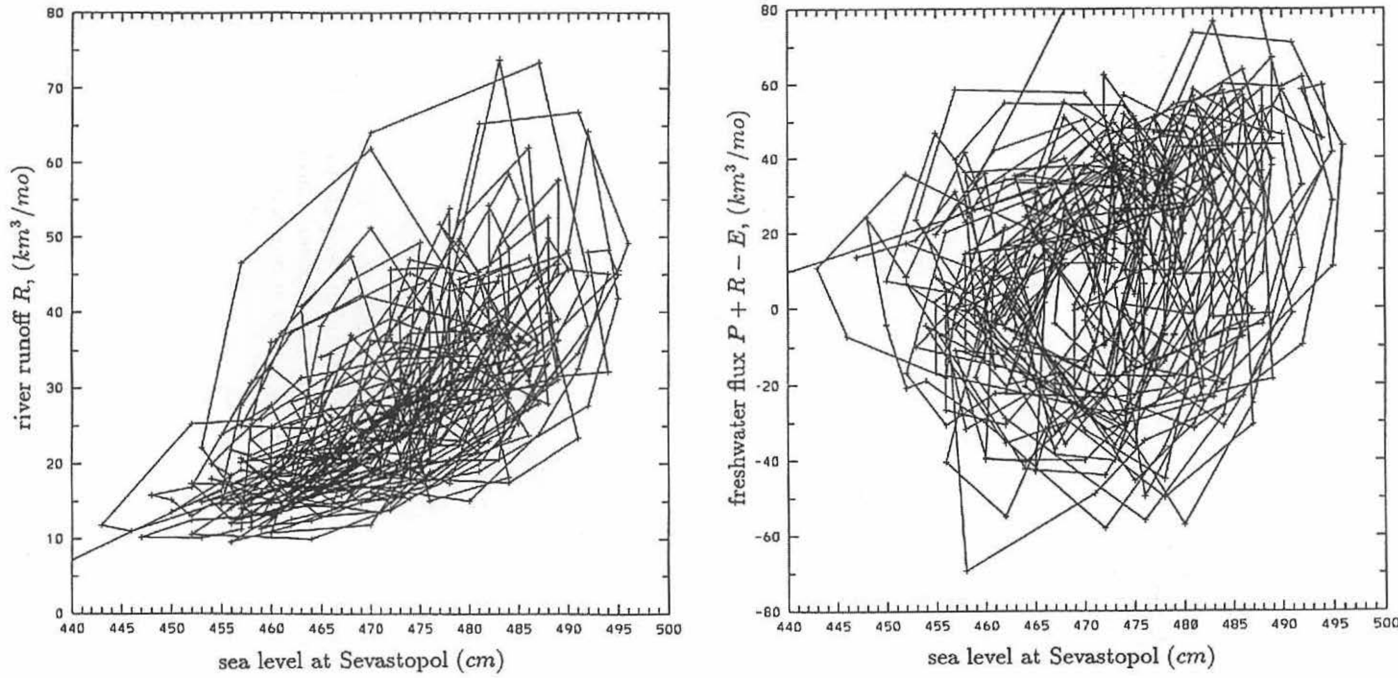


Figure 6 – Sea level at Sevastopol *versus* (left) total river runoff, (right) total freshwater inflow, 1923-1985.

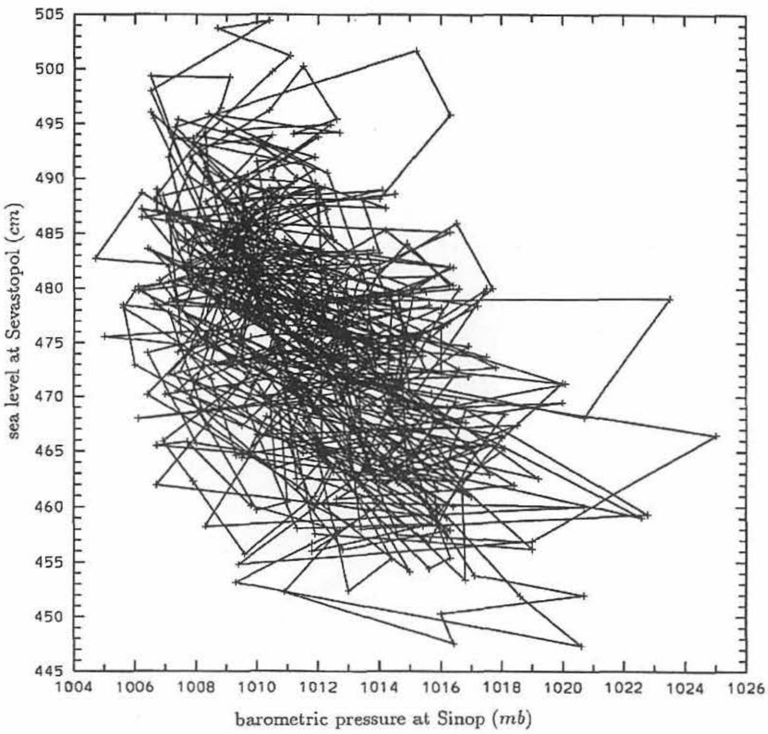


Figure 8 – Pressure at Sinop *versus* sea-level at Sevastopol, 1936 - 1990.

Figure 9 illustrates wether sea-level differences across the Bosphorus can be related to barometric pressure. Comparison of hourly barometric pressure in the Marmara region (Fig. 9a) with sea-level difference (Fig. 9b) reveals a close relationship with delays on the order of few days between the two signals. However such concurrent measurements are rare at present and the determination of the exact roles of various factors in driving the Bosphorus-Black Sea system awaits further studies.

## MIXING IN THE BOSPHORUS

Recently, fluorescent dye techniques have been used to study dispersion and mixing in the Bosphorus and to evaluate the performance of the waste-water discharge system of Istanbul. Rhodamine-B dye was introduced into the lower layer flow at the diffuser near station B0 (Figure 1), and followed in the Bosphorus using two ships equipped with fluormeters coupled to CTD. Dye flux calculations were made by matching and integrating simultaneous current velocity (ADCP) and CTD data (ÖZSOY *et al.*, 1994, 1995b). The vertical mixing within each layer was very fast (on the order of few tens of minutes), but the transverse mixing time of about 10 hours was comparable to the time of transit through the Bosphorus. Good agreement was found between the observations and simple models of longitudinal dispersion in the lower layer of the Bosphorus, accounting for

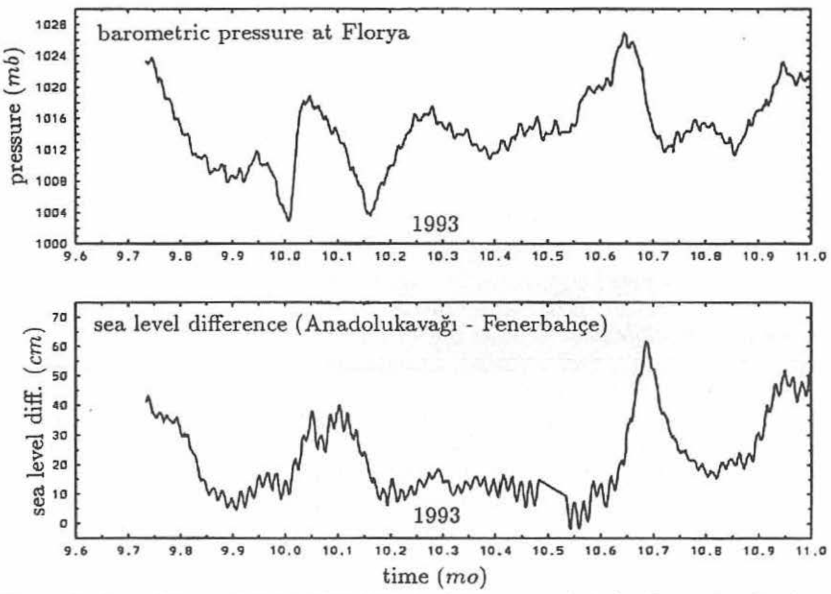


Figure 9 – (upper) barometric pressure at Florya (Marmara Sea) during September-October 1993, (bottom) sea level difference across Bosphorus (cm) calculated from sea-level measurements at Anadolukavaği and Fenerbahçe during the same period.

the loss to the upper layer with a sink term. With dispersion coefficient estimates of $E_x = 90\text{-}205\ m^2/s$ (Figures 10a,b), the measured lower layer dye concentrations compared well with analytical solutions for continuous and instantaneous release cases.

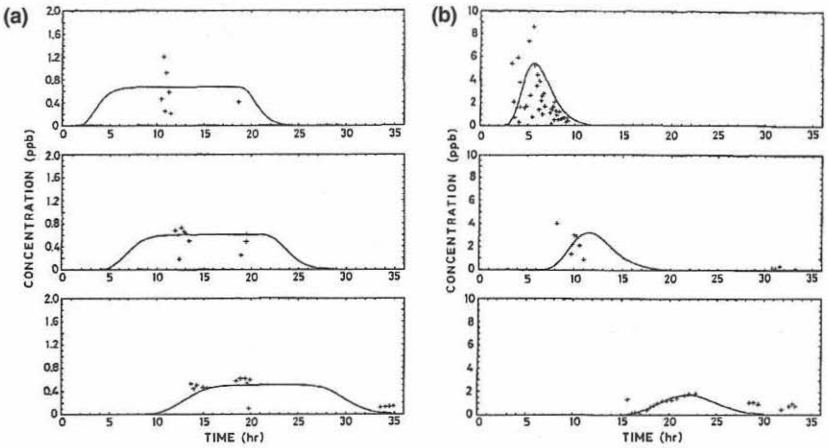


Figure 10 – Lower layer average Rhodamine-B concentration at different locations along the Bosphorus after (a) continuous dye release, September 1992, and (b) instantaneous release, March 1993 (after ÖZSOY *et al.*, 1994, 1995b. The analytical solutions at distances of 7.5, 15 and 28 km from the source, corresponding to the B5, B8 and B15 sections in Figure 1, are compared with mean lower layer concentrations observed nearby these sections).

Both the dispersion computations and the measurements indicated that the dye is rapidly diluted in the lower layer of the Bosphorus within short distances after the diffusers. Some of the dye injected in the lower layer was trapped within the interfacial layer, and only a small fraction – comparable to background levels – found its way to the surface, even under the most adverse conditions.

## CONCLUSIONS

The Bosphorus is an outstanding example and a very special case of "maximal exchange" conditions in a strait. While a great deal still needs to be learned about the exact nature of the exchange between two basins possessing the world's most distinct physical characteristics (the Black Sea and the Mediterranean), even a cursory examination reveals interesting possibilities for driving mechanisms and response characteristics on a variety of time scales. Further analyses of data and direct measurements of fluxes and sea-level are required for exact conclusions. Environmental concerns associated with increasing international traffic and industrial pressures, in a region of developing hinterland and deteriorating marine environmental quality, necessitates a better understanding of the Turkish straits.

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