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Energy balance and time-scales of mixing and stratification in the Jaboatão estuary, NE-Brazil

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- ***Abstract***: Estuarine systems undergo different physical processes that simultaneously control their stratification and mixing dynamics. This energy balance determines both, the estuarine hydrodynamics and the dynamics of water. This article presents a quantitative and comparative analyses between the forces maintaining stratification (surface heating; rainfall precipitation; and differential advection of the longitudinal density gradient due to the vertical velocity field) and those responsible for the vertical mixing (mechanical stirring of bottom tidal stress; mechanical stirring of surface wind stress; and surface evaporation) in the lower estuary of the Jaboatão River (JE), Pernambuco, NE-Brazil. The energy available to mix the water column at the lower Jaboatão was 2.2 and 2.0-fold greater than that available to promote stratification, during the dry and rainy seasons, respectively. The bottom shear turbulence caused by the tides was the major source of energy for the vertical mixing. A theoretical analyses revealed that the turbulence decay time-scale in both seasons was much greater (dry=29min; rainy=25 min) than the stratification time-scale (dry=8 min; rainy=7 min) and than the slack water time-scale (15 min). Thus the estuary was vertically well-mixed even during slack water periods during both, dry and rainy seasons. Theoretical results were confirmed by field data and are in agreement with earlier numerical simulations.

- ***Resumo***: Sistemas estuarinos estão sujeitos à influência simultânea de processos físicos que controlam tanto sua dinâmica de estratificação quanto de mistura. Este balanço energético determina seu comportamento hidrodinâmico e a dinâmica das propriedades da água. O presente artigo apresenta uma análise quantitativa e comparativa das forças de manutenção da estratificação (aquecimento superficial; precipitação pluviométrica e advecção diferencial do gradiente longitudinal da densidade devida ao campo vertical da velocidade), e daquelas responsáveis pela mistura vertical (turbulência de fundo devido às marés; turbulência de superfície devida à ação dos ventos e evaporação superficial) no baixo estuário do Rio Jaboatão (JE), Pernambuco, NE-Brasil. A quantidade de energia disponível para misturar a coluna d'água foi 2,2 e 2 vezes maior que aquela disponível para manter a estratificação durante as estações seca e chuvosa, respectivamente. O atrito turbulento de fundo pelas marés foi a principal fonte de energia do sistema para a mistura da coluna d'água. Uma análise teórica revelou que a escala de tempo para o decaimento turbulento nas duas estações sazonais foi superior (seca=29 min; chuvosa=25min) que a escala de tempo para estratificação (seca=8min; chuvosa=7 min) e que a escala de tempo dos estofos de maré (15 min). Assim, o estuário apresentou-se verticalmente bem misturado mesmo durante os estofos de preamar e baixa-mar tanto na estação seca quanto chuvosa. Os resultados teóricos foram confirmados pelos dados de campo e estão em concordância com aqueles obtidos em estudos prévios de simulação numérica.

- ***Descriptors:*** Energy balance, Turbulence-stratification, Tropical estuary, Jaboatão.

- ***Descritores*** : Balanço energético, Turbulência-estratificação, Estuário tropical, Jaboatão.

Introduction

The degree of stratification in estuaries is an important driving force as it controls water column stability and the vertical mixing (or vertical fluxes) of water properties such as momentum, heat, salt, dissolved oxygen and nutrients. Predicting when and for how long stratification will occur in these systems is difficult, and probably more complex than the equivalent off-shore heating-stirring problem that has been extensively studied over the last twenty years (Phillips 1977; Shay & Gregg 1986; Anis & Moun 1992). The difficulty arises from the variability in the time scales of the dominant processes acting in near shelf and estuarine areas. In spite of this inherent obstacle, understanding the processes that control mixture and stratification dynamics remains a priority.

One of the most important estuarine characteristics is the baroclinic (or gravitational) circulation resulting from the longitudinal density gradient which drives the system's dynamics in the longitudinal-vertical plane. As a function of estuary type, this behavior can lead to two contrasting situations: at one extreme, we find highly stratified estuaries, where the circulation may dominate the observed currents. At the other, we find unstratified or vertically-mixed estuaries, where circulation is resolved as a long-term mean flow, normally hidden by strong wind- or tide-driven currents.

The strength of gravitational circulation is a function of the intensity of the density gradient, as well as, in a non-linear way, of the intensity of the environmental turbulence. In highly turbulent systems, a considerable part of the momentum resulting from horizontal density gradient, is vertically diffused and circulation can be one to two orders of magnitude weaker than in less turbulent systems. The vertical turbulent flux of horizontal momentum acts by controlling the rate at which buoyancy is advected horizontally by the circulation. In its turn, buoyancy advection affects the vertical stability of the system and hence the turbulence itself. As a result of this non-linear feedback mechanism, turbulence exerts a fundamental role over the strength of the circulation in estuaries.

This study analyses the processes controlling the dynamics of the Jaboatão river estuary in NE-Brazil. In particular we identify the main turbulence-buoyancy flux interactions, which promotes mass and energy transports throughout the system and the time scale in which they operates. Field measurements (Araujo 1998; Araujo *et al.* 2000b) and results from recent numerical simulations studies (Araujo *et al.* 2000a, b) are used as input data and also as experimental evidence to validate the analysis. Since systems behavior is marked by strong differences in seasonal inputs of freshwater, dry and rainy seasons situations are considered separately.

Material and methods

The Jaboatão is a shallow (1-4m deep), 75 km long, tropical river in Northeastern Brazil, located 20 km to the south from the city of Recife-PE, between Lat. 8°13' and 8°16' S and Long. 34°55' and 34°59' W (Fig. 1). The Jaboatão and its tributaries drain a basin of 413 km^2 including areas covered by the original Atlantic forest, sugar cane fields and highly populated areas. It receives large loads of domestic and industrial wastes as well as a seasonal input of high levels of organic matter from sugar cane industries at its mid-course, while its lower section is surrounded by relatively well preserved fringing mangrove forests.

The Jaboatão discharges into the Atlantic, guarded by an extensive sandbar. Tides at its mouth are semidiurnal with a mean neap range of 1.3 m and a mean spring range of 2.2m. Climate in the Jaboatão basin is hot and humid, of type Aws according to the Köppen system. Annual mean air temperature is 26 °C and the mean thermal range is 2.8 °C (CPRH 1995, 1996). Prevailing winds are the southeast trades with a mean speed of 3.2 $m.s^{-1}$. Average annual rainfall and evaporation are respectively 1.5 and 1.2 m. The region experiences two well-defined seasons. The dry season extends from September to January, when the mean monthly rainfall is less than 0.06 m and the evaporation rate exceeds precipitation. The rainy season extends from February to August, with half of the annual rainfall occurring between April and June. During these months, precipitation sometimes exceeds 0.40 m/month and the hydrological balance is strongly positive (CPRH *op. cit.*).

The study area comprised the lower 7.5 km of the Jaboatão river estuary. Field work was carried out during 1997 and 1998, characterizing the system during the dry and rainy seasons as well as during high, ebb, low and flood stages of neap and spring tidal cycles. Eight cross-sections were selected along the estuary (S1 to S8). Each cross-section was sampled at three stations located at 20%, 50% (center) and 80% of the cross-section width (S11, S12, S13, S21, ... , S83) (Fig. 1). Current speed and direction were measured at two water depths: 0.5m below the Surface and 0.5m above the Bottom using a *Sensordata* SD-30 current meter. Simultaneously, CTD profiles were obtained from the surface to the bottom, using a *Sea Bird Electronics - SeaCat SBE-19*. Field work also included a bathymetric survey of 44 cross-sections of the river channel, done with a Raytheon DC2000Z depth fathometer. A more detailed description of the experimental field work is presented in Araujo (1998).

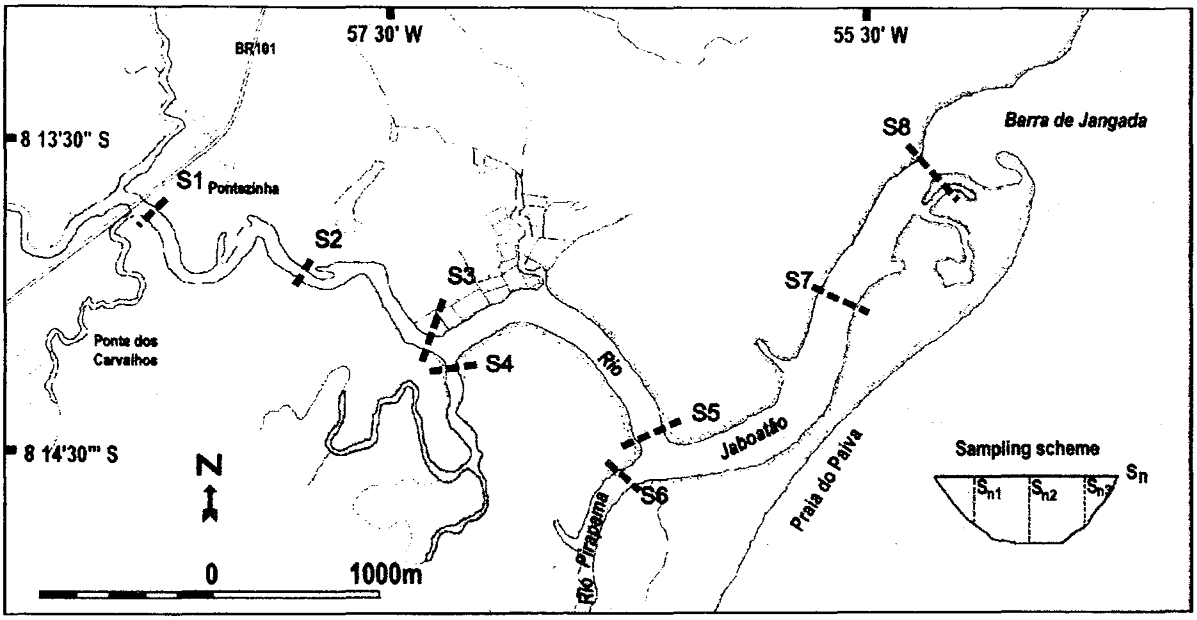

Fig. 1. Study area and detail of the sampling cross-sections and stations.

Theoretical Background

A simple and didactical approach to investigate the major mechanisms acting upon the estuarine dynamics, based on an energy balance, was proposed by Nunes Vaz *et al.* (1989). These authors define φ as the amount of energy per unit volume necessary to change a stratified water column to its corresponding well-mixed situation:

$$\varphi = \frac{g}{H}\int_{-H}^{0} (\bar{\rho} - \rho) z \, dz \qquad (1)$$

where z is the upward vertical coordinate with the origin at the water surface, g (m. s^{-2}) is the acceleration of gravity and $\bar{\rho} = \frac{1}{H}\int_{-H}^{0} \rho(z) dz$ is the depth mean density (kg m^{-3}) of the fluid column of depth H (H is the mean depth at the deeper portion of the estuary). Mixing or stratifying tendencies are measured as temporal variations of φ, which is related to the surface buoyancy flux B (m^2 s^{-3}) according to:

$$\frac{d\varphi}{dt} = \dot{\varphi} = \frac{g}{H}\frac{d}{dt}\left[\int_{-H}^{0} (\bar{\rho} - \rho) z \, dz\right] = \frac{1}{2}\rho B \qquad (2)$$

In the following discussion, the mechanisms causing stratification or mixing in JE are evaluated in terms of (2).

Causes of vertical stratification

The processes promoting estuarine stratification are: (i) Surface heating; (ii) Rainfall precipitation; and (iii) Differential advection of the longitudinal density gradient resulting from the vertical velocity structure. Each one of them is commented below.

(i) Surface heating - $\Delta_H \dot{\varphi}$

Surface heating is the most important and better documented external stratifying mechanism in ocean and shelf seas. Its influence could be quantified by:

$$\Delta_H \dot{\varphi} = \frac{1}{2}\frac{\beta_T \, g \, \dot{Q}}{c_p} \qquad (3)$$

where β_T (K^{-1}) is the volume expansion coefficient, c_p (m^2 s^{-2} K^{-1}) is the specific heat capacity at constant pressure, and $\dot{Q}$ (J m^{-2} s^{-1}) is the applied heating flux.

(ii) Rainfall precipitation - $\Delta_P \dot{\varphi}$

Similarly, the rainfall contribution to the stratification is given by:

$$\Delta_P\dot{\varphi} = \frac{1}{2}\beta_S\, S\, g\, \rho\, P \qquad (4)$$

where β_S is the dimensionless salt contraction coefficient, P ($\mathrm{m\,s^{-1}}$) is the observed precipitation rate, and S and ρ are respectively surface salinity and density (kg m^{-3}).

(iii) Differential advection resulting from the vertical velocity structure - $\Delta_A\dot{\varphi}$

Stratification induced by the freshwater buoyancy input is a key determinant of the system dynamics. In well mixed/weakly stratified environments, the vertical profile of axial velocity of the gravitational circulation may be approximated by the classical Hansen & Rattray's (1965) profile, also used by Nunes Vaz & Simpson (1985) as follows:

$$U(\eta) = -\frac{g\, H^3}{48\, \rho\, \overline{\nu_t}}\frac{\partial\rho}{\partial x}\left(8\,\eta^3 + \alpha\,\eta^2 - \mu\right) \qquad (5)$$

where $\eta = z/H$ is the normalized depth, x is the length measured along the estuary (x is positive seaward) and $\overline{\nu_t}$ ($m^2\, s^{-1}$) is a constant eddy viscosity. Here we considered a frictionless bottom boundary layer for which we have $\alpha = 12$ and $\mu = 2$. The vertical profile described in equation (5) may induce vertical stratification by differential advection of the longitudinal density gradient, as we have $\frac{\partial\rho(z)}{\partial t} = -U(z)\frac{\partial\rho}{\partial x}$ (z is positive upwards). This effect is quantified by:

$$\Delta_A\dot{\varphi} = \frac{g^2\, H^4}{120\, \rho\, \overline{\nu_t}}\left|\frac{\partial\rho}{\partial x}\right|^2 \qquad (6)$$

Causes of vertical mixing

Mixing in coastal seas fundamentally results from the mechanical stirring of tidal stress on the bottom and from the wind induced stress at air-water interface. Turbulence generated on both boundary layers will be used to mix the interior of the water column. Mixing intensity increases with increasing efficiency of the vertical diffusion of kinetic energy into the stratified region, and as more easily this energy is converted into potential (may also be expressed in terms of changes in φ).

Three main processes will be considered as causing vertical mixing in JE: (iv) Mechanical stirring of bottom tidal stress; (v) Mechanical stirring of surface wind stress; and (vi) Surface evaporation as it contributes to destabilization of stratification. Quantitative estimations for these mixing processes are presented bellow, following Simpson *et al.* (1991).

(iv) Stirring of bottom tidal stress - $\Delta_B\dot{\varphi}$

The rate of production of turbulent kinetic energy (TKE) by bottom tidal stirring has been associated to the rate of working of bottom stress, which is quantified as:

$$\Delta_B\dot{\varphi} = \frac{\xi_B\, k_B\, \rho\left|U_B\right|^3}{H} \qquad (7)$$

where k_B is the bottom drag coefficient, and U_B is the velocity (m s^{-1}) measured near the bottom. ξ_B is a coefficient of mixing efficiency, which represents the effect of diffusion of TKE from the bottom boundary layer to the interior of the fluid. Both, k_B and ξ_B are dimensionless.

(v) Stirring of surface wind stress - $\Delta_W\dot{\varphi}$

Analogous, TKE production by surface stirring associated to the wind stress is given by:

$$\Delta_W\dot{\varphi} = \frac{\xi_S\, k_S\, \rho_{air}\left|W\right|^3}{H} \qquad (8)$$

where k_S is the dimensionless surface drag coefficient, W is the wind speed (m s^{-1}), ρ_{air} is the air density (kg m^{-3}), and ξ_S is the dimensionless surface mixing efficiency coefficient.

(vi) Surface evaporation - $\Delta_E\dot{\varphi}$

The mixing influence of evaporation results from the buoyancy flux caused by increasing surface salinity and latent heat loss, these are respectively computed by the two terms below:

$$\Delta_E\dot{\varphi} = \frac{1}{2}\beta_S\, S\, g\, \rho\, E + \frac{1}{2}\frac{\beta_T\, g\, L\, E}{c_p} \qquad (9)$$

where L (J m^{-3}) is the latent heat of transformation from water to vapor, and E is the observed rate of evaporation (m s^{-1}).

Global time scale analysis for stratification

It should be remarked that even when the production of turbulence ceases abruptly (not an usual case, since it would simultaneously require calm waters and absence of surface wind stress), there is a finite decay time-scale during which turbulent kinetic energy is still available within the water column to work against buoyancy forces. This decaying delay is classically considered as the turnover time of the largest eddy, i.e.:

$$t_t = \frac{H}{\sqrt{u'^2}} \qquad (10)$$

where $\sqrt{u'^2}$ is the rms turbulent velocity. Taking $O\left(\frac{U}{\sqrt{u'^2}}\right) = 100$ (typically $\sqrt{u'^2}$ is of order of 1-5 % U), the turbulence decay time-scale may be estimated.

Alternatively, in a non-turbulent environment a set of initially vertical isopycnals may, following release, tilt under the action of gravity to produce stratification. This process has a magnitude of time-scale associated to the inverse of the Brunt-Väisälä frequency given by $t_S = \left|\frac{g}{\ell}\frac{\Delta\rho}{\rho}\right|^{-1/2}$, where ℓ is the length of the saline intrusion and $\Delta\rho$ is the density difference in the water column.

Results and discussion

Average salinity values in the surface and bottom layers of the cross-sections, for a neap tidal cycle during the dry season are presented in Table 1. The reference salinity (S_{ref}) values for each tidal stage are the averages for the six cross-sections and of the two water depths (surface and bottom). The longitudinal distribution of the ratio of instantaneous salinity to the reference salinity, for the same tidal cycle and season, is presented in Figure 2. A longitudinal salinity gradient was always present along the estuary, being more pronounced during the low (5.1 at S1 to 29.0 at S8) and the flood (5.6 at S1 to 27,2 at S8) stages. The water column is well-mixed and with vertical salinity differences from surface to bottom always less than one salinity unit.

Figure 3 illustrates the oscillation of the S/S_{ref} ratio during a tidal cycle in the inner estuary (Pontezinha, S1) (5.1-16.9) and near the estuarine mouth (S8) (26.8-35.4), showing a reduction on the amplitude of this oscillation at the mouth, due to a seaward dumping of salinity variability as the freshwater influence becomes smaller.

Combined effects and relative influences at the Jaboatão Estuary

We calculated the contribution of the six process described in the previous sections to stratify

Table 1. Average salinity values (n=3) in the surface and bottom layers of the cross-sections, for a neap tidal cycle during the dry season.

Cross-section	Tidal Stage							
	High		Ebb		Low		Flood	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
1	16.85	16.87	14.45	14.75	5.02	5.12	5.42	5.75
2	-	-	18.45	18.50	9.80	9.94	11.17	11.50
3	29.85	29.88	22.95	23.25	13.54	13.54	14.29	14.26
5	34.21	34.07	32.07	32.17	16.70	16.70	16.43	16.32
7	35.09	35.13	34.77	34.86	23.42	23.48	23.52	24.22
8	34.43	35.42	35.37	35.43	28.95	29.10	26.85	27.62
S_{ref}	30,18		26,42		16,58		16,45	

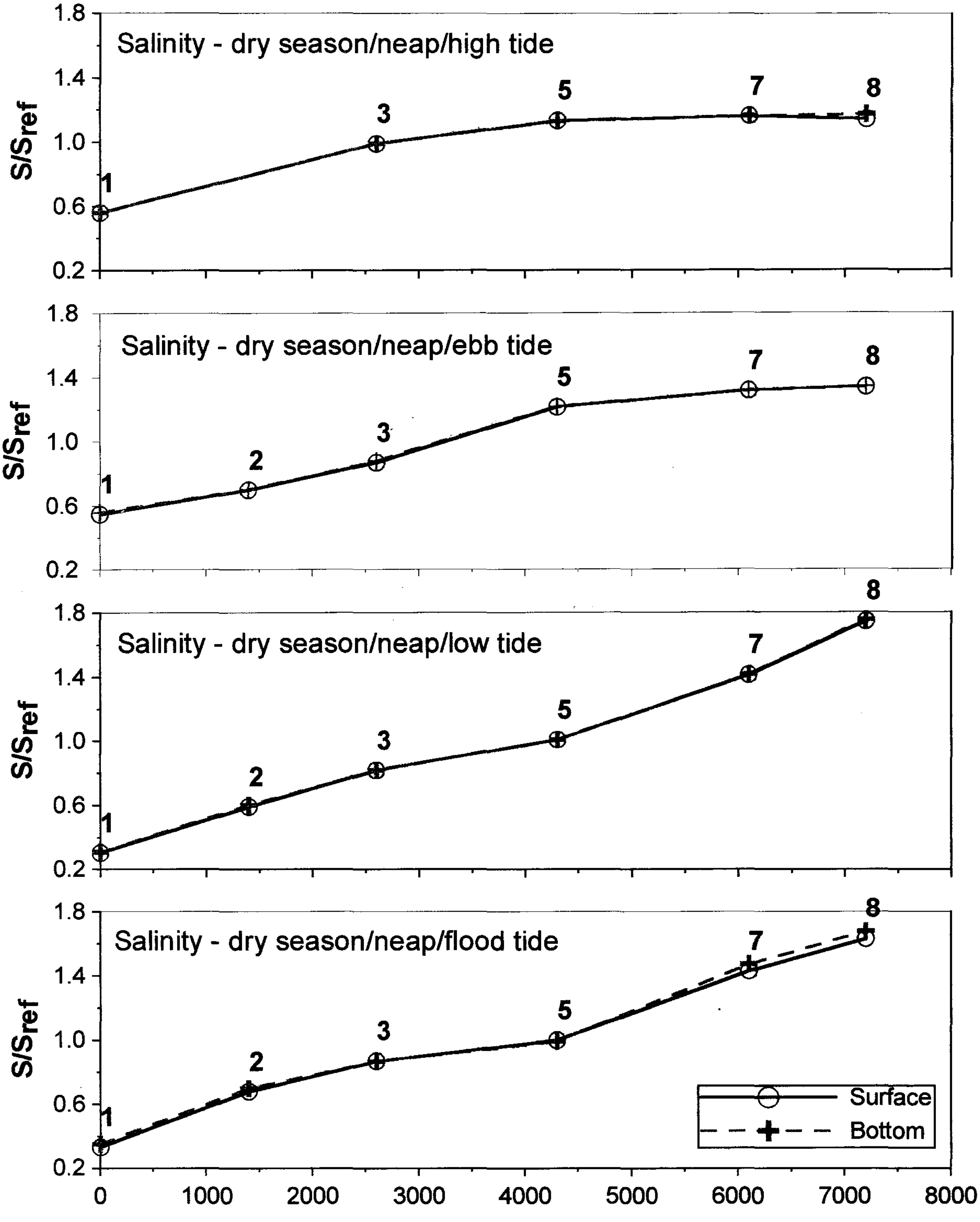

Fig. 2. Instantaneous to tide averaged salinity (S_{ref}) ratio at surface and bottom depths along the Jaboatão river during four stages of a neap cycle.

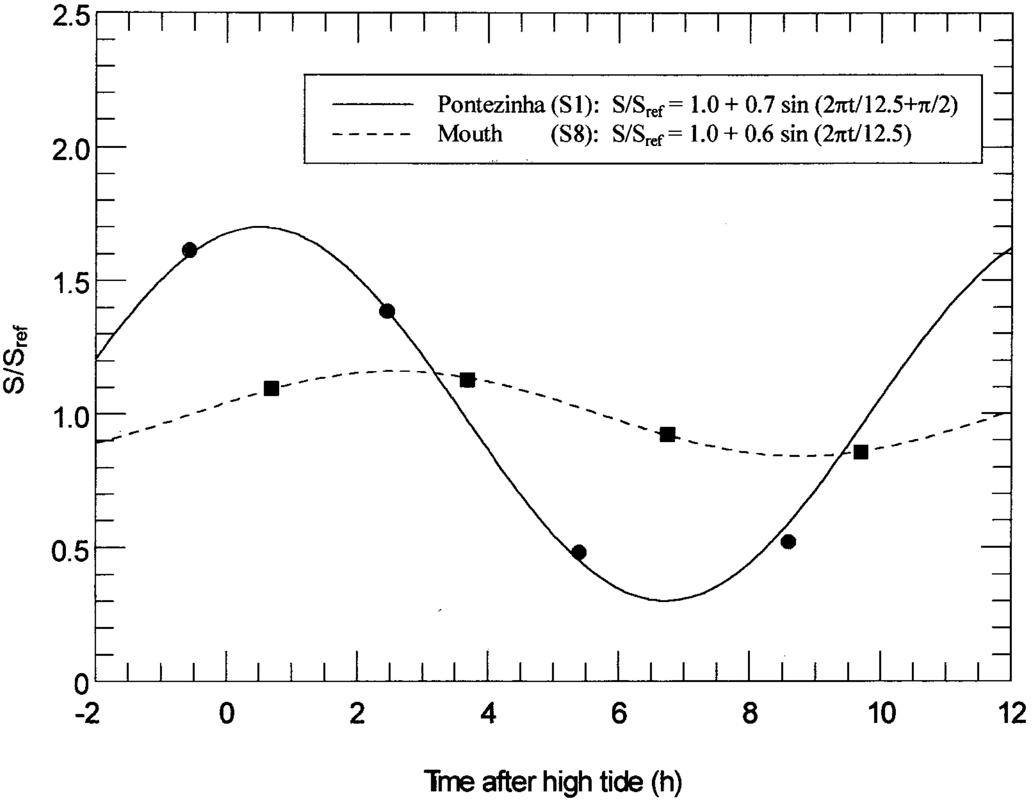

Fig. 3. Instantaneous to tide averaged salinity ($S_{ref.}$) ratio over the tidal cycle at S1 (Pontezinha) and S8 (Mouth) in dry season

or mix the water column at the Jaboatão estuary. Their combination gives the rate of change of potential energy in the water column. For both, dry and rainy seasons, the following inequality was obtained:

$$\underbrace{\Delta_B\dot{\phi} + \Delta_W\dot{\phi} + \Delta_E\dot{\phi}}_{\text{Mixing sources}} > \underbrace{\Delta_H\dot{\phi} + \Delta_P\dot{\phi} + \Delta_A\dot{\phi}}_{\text{Stratification sources}} \qquad (11)$$

indicating that JE is a well mixed system. As we were interested on the relative influences of these processes, each contribution was normalized by the major component, $\Delta_B\dot{\phi}$. Calculated values are presented in Table 2.

Results on Table 2 show diurnal surface heating (solar radiation) as a potential mechanism responsible for the vertical stratification, mainly during the dry season. Precipitation had negligible effect as a potential source for stratification in both seasons. A distinct seasonal behavior was observed in the influence of differential advection. The estuary receives about ten times more freshwater input during the rainy season than during the dry season. These freshwater inputs would tend to maintain higher horizontal density gradients along the estuary axis. As a consequence, the effect of differential advection of horizontal densities by the vertical velocity structure during the rainy season are twice the observed value for the dry season.

In both periods, mixing mechanisms dominate the estuary dynamics (Tab. 2). Bottom stirring of tidal currents appears as the most important component of vertical mixing. Small estuaries usually offer a great deal of sheltering from wind effects, but in large estuaries and gulfs the contribution from wind mixing can become quite important. The energy input from surface wind stress at JE is small (mean monthly averaged wind speeds do not exceed 4.0 m s^{-1}), as it accounts for only 6% to 10% of the total mixing sources. These results have also been confirmed by numerical experiments (Araujo *et al.*, 2000b). Water surface evaporation had no marked contribution in the mixing of the water column when compared to the stirring processes at the surface and bottom boundary layers.

The ratios between total mixing processes and total stratification processes were 2.25 and 2.09 during the dry and rainy season, respectively (Tab. 2). This means that in both seasons mixing intensities were twice as high as the potential capacity of external forcing in promoting vertical stratification.

Table 2. Normalized stratification-mixing components at the Jaboatão Estuary

Normalized component	Dry season	Rainy season
Stratification sources		
(i) Surface heating - $(\Delta_H \dot{\varphi} / \Delta_B \dot{\varphi})$	0.40	0.31
(ii) Precipitation - $(\Delta_P \dot{\varphi} / \Delta_B \dot{\varphi})$	<0.01	0.05
(iii) Differential advection - $(\Delta_A \dot{\varphi} / \Delta_B \dot{\varphi})$	0.07	0.17
(i)+(ii)+(iii)	0.47	0.53
Mixing sources		
(iv) Bottom tidal stirring - $(\Delta_B \dot{\varphi} / \Delta_B \dot{\varphi})$	**1.00**	**1.00**
(v) Surface wind stirring - $(\Delta_W \dot{\varphi} / \Delta_B \dot{\varphi})$	0.06	0.11
(vi) Surface evaporation - $(\Delta_E \dot{\varphi} / \Delta_B \dot{\varphi})$	<0.01	<0.01
(iv)+(v)+(vi)	1.06	1.11
Mixing/stratification ratio	2.25	2.09

Mixing efficiency and eddy viscosity. Parameter estimation

Equations (3) to (9) and (11) provide an energy balance and a means of deciding, on numerical grounds, the likelihood or not of encountering significant structure in the water column. Nevertheless, some cautionary remarks apply to some of the terms, based on the methodology used to obtain them.

Regardless of the use of geophysical field data obtained directly in JE and the use of physical fluid dependent constants, special attention was given to the estimation of parameters related to the turbulent properties of the flow. The first comment is about the appropriate choices of the mixing constants ξ_B and ξ_S in equations (7) and (8) respectively. They represent the efficiency of conversion of bottom and surface-generated TKE into potential energy.

Simpson and Bowers (1981), for example, suggested $\xi_B = 3.7 \times 10^{-3}$ (which means that only about 0.4% of the TKE generated by tidal stirring works against buoyancy forces) and the ratio $\xi_S \cong 6\xi_S$ for shelf seas regions (depth of the order of one hundred meters). On the other hand, Nunes Vaz & Lennon (1987) found that $\xi_S \cong \xi_B$ gave a better fit to their data. This discrepancy appears to be due to the different forms of buoyancy inputs in the two cases, since Nunes Vaz & Lennon (*op. cit.*) worked at a near shore area normally submitted to the stronger effects of a modulated turbulence. In spite of a possible dependence of ξ_B and ξ_S to the vertical coordinate z, we used values of mixing constants (mixing efficiency parameter and drag coefficient) very close to those proposed by Simpson *et al.* (1991) for the estuarine Liverpool Bay area. Constants used herein are presented in Table 3.

Table 3. Mixing constants used in our calculations (same magnitude as used by Simpson *et al.* 1991).

Mixing constant	Value
Bottom mixing efficiency - ξ_B	4.0×10^{-3}
Bottom drag coefficient - k_B	2.5×10^{-3}
Surface mixing efficiency - ξ_S	3.5×10^{-2}
Surface drag coefficient(1) - k_S	7.0×10^{-5}

It should be pointed out that the ranges of variation found in geophysical fluid mechanics literature for these constants will not produce sensible changes in the estimations (and the relative influence) of the mixing terms for JE (see Table 2). The effects of bottom tidal stirring will be always much more important than the action of surface wind for the vertical mixing of the estuary.

A second remark is related to the values of eddy viscosity, used for estimating the contributions of the differential advection of vertical structure as a stratification-producing mechanism (equation (6)).

Estimated values of $\overline{\nu}_t$ are normally based on the vertical integration of the more realistic theoretical parabolic profiles, where the surface turbulent boundary layer is considered analogous to the bottom turbulent boundary layer (*Couette* flow).

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(1) Since the classical formulation $U_W \cong 0.03\, W$ is incorporated into the drag coefficient, where U_W is the surface drift velocity, given as a function of the wind speed W.

On the other hand, the use of constant eddy viscosity seems to be less critical in well mixed systems like JE, because significant density variations in the water column (variations in buoyancy flux) should be computed in terms of changes in vertical distribution of momentum diffusivity.

A simpler (and therefore broader) method for estimating global diffusivity values uses dimensional basis to propose semi-empirical formulations, normally established on typical spatial and velocity flow scales. An example of this approach is the Bowden's classical formulation, $\bar{\nu}_t = 3.3 \times 10^{-3}\, H\, U_B$, which has been currently used in various estuarine studies (i.e., Nunes Vaz *et al.* (1989) and Simpson *et al.* (1991).

In spite of the attractive simplicity of semi-empirical formulations, average vertical eddy viscosity can be estimated from numerical simulations results (Araujo *et al.*, 2000b). These authors used a modified $(k-\varepsilon)$ model including buoyancy effects to investigate the transport of momentum, salt and turbulent kinetic energy at JE. Results from numerical experiments showed good agreement with field measurements. A spatial discretization of the estuary allowed the computation of eddy viscosity values ν_t for each control volume, for which the Prandtl-Kolmogorov formulae gives $\nu_t = C_\mu k^2 \varepsilon^{-1}$, where k is the TKE, ε is the dissipation rate of TKE and C_μ is a diffusivity coefficient.

The values of $\bar{\nu}_t$ used in equation (6) were calculated by integrating numerical results obtained for n-cells situated in the deeper central part of the estuary as follows:

$$\bar{\nu}_t = \frac{1}{\mathrm{Vol}} \sum_{1}^{\mathrm{ncell}} \nu_t(x,y,z)\,\mathrm{Vcell} \qquad (12)$$

where Vcell is the cell volume and $\mathrm{Vol} = \sum_{1}^{\mathrm{ncell}} \mathrm{Vcell}$.

Time scale analysis at Jaboatão River Estuary

In this section the JE dynamics is studied using a time scale analysis. As a first approach we considered an initial vertically-mixed state, often observed at the JE system. A theoretical question might be posed: what is the time elapsed before significant stratification can develop, if we remove all sources of turbulence? This question seems relevant when we want to anticipate a stratification to be observed during slack waters periods, in an otherwise well-mixed estuary. Calculated values of t_t and t_S were not the same for dry and rainy seasons (Tab. 4).

Table 4. Turbulence decay and stratification time-scales at the Jaboatão River Estuary.

Time-scale (min.)	Dry season	Rainy season
Turbulence decay time-scale - t_t	29	25
Stratification timer-scale - t_S	8	7

Consequently it is reasonable to assume from Table 4 that under these situations the available TKE does not falls to minimal levels during slack water periods. For dry and rainy periods $t_S \cong 30$ minutes. These results show that under natural conditions in JE, the time necessary for turbulence decay after the source is removed, is greater than the time-scale to establish stratification (and also greater than typical slack water time scales at JE): so the estuary will be vertically well-mixed during both dry and rainy slack waters periods. These results are also in agreement with field data and numerical simulations prognosis pointed out by previous work (Araujo 1998; Araujo *et al.* 2000a, b).

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