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An Analytic Approach to Model the Tidal Circulation in a Double-inlet Estuary

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ABSTRACT

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Estuaries comprise broad spectra of systems whose morphology often rule theirs hydrodynamics. The Itamaracá estuarine system (NE-Brazil) is formed by the Santa Cruz Channel (SCC), connecting to the Atlantic Ocean through two inlets. Water level and in depth current measurements were used to evaluate an analytical approach for representing its tidal circulation. Depth-averaged currents were analytically predicted with 11% error ($\delta_1 = 0.11$). Currents measurements for five different sampling stations and depths were compared to model responses for various values of eddy viscosity (ν) and bottom friction parameter (r). The best-fit quadratic error $\delta_2 = 0.155$ was obtained with $\nu = 6.3 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ and $r = 6.5 \times 10^{-3} \text{ m s}^{-1}$. Model improvements, considering bottom friction and eddy diffusivity formulations, indicated a boundary layer depth of 0.10H (H=channel depth), and a large ($6.1 \times 10^{-3} \text{ m}$) mean roughness length of the sea-bed to couple with the intricate roots system of red mangroves along the SCC. Simulations were also used to test Taylor's (1954) scale analysis, yielding $c = 0.080$ as best value ($c = \nu / u_* H$ constant; u_* = bottom friction velocity) and a mean eddy viscosity of $5.8 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$. The low sensibility of momentum distribution to changes in eddy viscosity verified suggests that stronger viscosity dumping may be compensated by higher bottom shear stress. This simple analytical approach could also be used to predict spatial and temporal distribution of pollutants and other materials at SSC and at similar systems as advection of those components could easily be simulated combining modelled currents with measurements of theirs concentrations.

ADDITIONAL INDEX WORDS: *Itamaracá, hydrodynamic, analytical model.*

INTRODUCTION

The longitudinal density gradient often present in estuaries results in a baroclinic (or gravitational) circulation, which drives the system dynamics in the longitudinal-vertical plane. To be able to rely on approximations/formulations that allow analytical solutions and satisfactorily reproduce the main features of the tidal-driven circulation would be highly desirable and helpful for making management decisions, as it would contribute to a better understanding of the distribution of energy and of the fate of materials within and from/to the system.

This study aimed to evaluate the performance of a somewhat simple model of open coastal dynamics (Wang and Craig, 1993) applied to Itamaracá's own specific case, as a tool to develop a better description of the hydrodynamics of tropical well-mixed estuaries and to provide an analytic solution of the vertical and axial structure of tidal currents in an estuary.

METHODS

The Itamaracá estuarine system (Figure 1) in tropical NE-Brazil ($7^\circ 34' 55'' \text{S}$; $34^\circ 48' 52'' \text{W}$), is formed by the Santa Cruz Channel (SCC), a 20-km long channel that surrounds the Itamaracá island, and connects to the Atlantic through the Catuama and Orange Inlets. The SCC is surrounded by mangroves, and receives fresh water from six small rivers. Extensive shore-parallel sandstone reefs and sandbanks shield

the offshore area of the estuary, which reduces water exchange.

Along the channel, vertical salinity stratification is weak; and normal levels of turbulence result in a uniform temperature distribution from surface to bottom (Medeiros and Kjerfve, 1993; 2005). Tides at both inlets are semi-diurnal, in phase and have a mean and spring ranges of 1.8m and 2.2m, respectively,

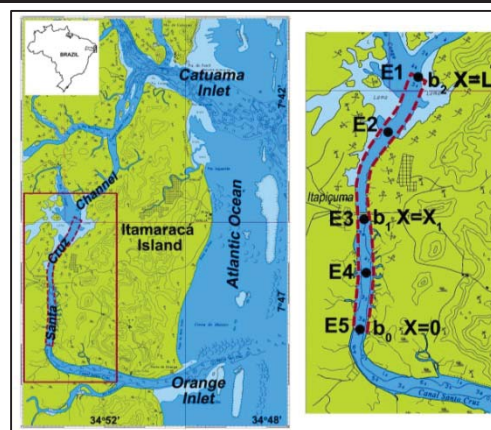


Figure 1. The Itamaracá estuarine system, NE-Brazil and modelled stretch of the Santa Cruz Channel and sampling stations E1-E5.

with a nodal point 1.7 km north of the Itapissuma bridge. Water salinity at the SCC changes seasonally, with a higher salt content during the dry season (Sep-Jan), and lower salt

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concentrations during the rainy season (Feb-Aug). This behavior acts as a selective forcing function for the development of autochthonous and migratory fish species which use the Itamaracá estuary. The study area comprised a 6km stretch of the SCC centered on the Itapissuma bridge, where most of the fishing and tourist activities take place.

Sampling and Field Data Acquisition

Field work was carried out during the rainy season on Aug 15-16th/2000. It included current measurements along the channel over the tidal cycle to determine the distribution of the velocities in time, depth and abscise, as well as a bathymetric survey and time-series measurements of currents and water level variation to set the model physical and boundary conditions.

Current measurements were obtained hourly at stations E1-E5 (Figure1). Sampling stations were located along the main channel axis, as a way of minimizing the influence of local cross-channel currents and to produce accurate current profiles. At each sampling station, measurements were carried out over two spring tidal cycles, 0.5m below the surface, at mid-depth and 0.5m above the bottom, with a Sensordata SD-30 current meter. The choice of spring tide was intended to maximize the effects of tidal forcing.

Cross sectional bathymetric profiles were taken with a Raytheon DC2000Z depth fathometer from E1 to E5 to determine channel morphobathymetry.

Registers of the sea-level evolution were gathered at intervals of 15 minutes at station E5 with a Sea-Bird Electronics SBE-26 wave and tide-gauge; and time-series measurements of flow (current and depth) were gathered at intervals of 10 minutes at station E1 using a Sensordata SD-6000 and a pressure sensor.

An Analytical Model for Tidal Currents

The analytic model of tidal currents is based on a depth-averaged coastal model proposed by Battisti and Clarke (1982) and subsequently extended by Craig (1989) to include the vertical dimension. The simplification in the model that enables analytic solutions follows the property that the topographic length scale is much less than the horizontal wavelength of the tides (Rossby radius), which is observed at the SCC.

To apply this model to Itamaracá we assumed that major tidal currents components are confined to the axial channel direction and Coriolis effects are neglectable. The canal cross-section is rectangular with depth $H(x,t)$ and width $b(x)$. These physical assumptions enable to pose the analytic problem in terms of the surface elevation ζ , the depth-averaged velocity \bar{u} , and the depth varying velocity u (Craig, 1989) to give:

$$-i\omega b \zeta + (\partial/\partial x)(H b \bar{u}) = 0 \quad (1)$$

$$-i\omega \bar{u} = -r(u_b + \bar{u})/H \quad (2)$$

$$-i\omega u = (\partial/\partial z)(\nu \partial u/\partial z) + r(u_b + \bar{u})/H \quad (3)$$

where ω is the semidiurnal tidal frequency, r is the linear friction coefficient, ν is the kinematic viscosity of water, and the subscript b indicates the bottom conditions. Here ω , ν and r are assumed constants and time derivatives have been replaced by the factor $-i\omega$ where i is the complex $\sqrt{-1}$, assuming harmonic motion at fixed frequency ω .

Horizontal boundary conditions for (1) and (2) are fixed by the particularities of the Itamaracá system, a hydrodynamics channel with two inlets. They are expressed by:

$$x=0: \quad \bar{u}(0,t) = \bar{u}_0(t); \quad H(0,t) = H_0(t) \quad (4a,b)$$

$$x=L: \quad \zeta = \zeta(t) \quad (5)$$

For each of the tidal constituents, $\zeta(t)$ is determined from field measurements of amplitudes and phases. The time-dependent formulation for tidal amplitude (Eq. 5) is relevant only if the tidal celerity ωL is negligible when compared to local wave celerity \sqrt{gH} . In the Santa Cruz Channel the authors found $\omega L/\sqrt{gH} \cong 0.06$.

Previous field measurements and numerical studies indicate that flow structures in the SCC are largely dominated by bottom shear, when compared to the effects of surface wind stress over vertical distribution of momentum (Medeiros and Kjerfve 1993; Araujo *et al.*, 2000a; Leite *et al.*, 2008) mainly during the dry season. As so, boundary conditions at the bottom introduce log-law behavior for tangential velocities, which are expressed here through a linear behavior. A zero value for surface stress boundaries was considered, and vertical boundaries in the model may be written as following:

$$z=-H: \quad \nu(\partial u/\partial z)_{-H} = r(u_b + \bar{u}) \quad (6)$$

$$z=0: \quad \nu(\partial u/\partial z)_0 = 0 \quad (7)$$

For model calculations, the SCC was assumed to have a polygonal shape and its geometry is given by:

$$b(x) = \begin{cases} b_0 + (b_1 - b_0)x/x_1, & x \leq x_1 \\ b_1 + (b_2 - b_1)(x - x_1)/(L - x_1), & x_1 \leq x \leq L \end{cases} \quad (8)$$

Previous formulation of the model, once applied to the geometry and the boundary conditions of SCC, give us respective previous notations:

$$\bar{u}(x,t) = \begin{cases} \frac{i\omega\zeta(t)}{2b(x)H(x,t)}[b_0 + b(x)]x + \frac{\bar{u}_0(t)b_0H_0(t)}{b(x)H(x,t)}, & 0 \leq x \leq x_1 \\ \frac{i\omega\zeta(t)}{2b(x)H(x,t)}[b_1 - b(x)]x_1 + [b_1 + b(x)]x + \frac{\bar{u}_0(t)b_1H_0(t)}{b(x)H(x,t)}, & x_1 \leq x \leq L \end{cases} \quad (9)$$

The solution for \bar{u} can now be substituted into Eq. (3), which is an ordinary differential equation for u . The solution for u is then given by:

$$u(x,z,t) = A \cosh(\gamma z) + \frac{i\bar{u}_b + \bar{u}(x,t)}{\omega H(x,t)} \quad (10)$$

$$A = \frac{-\bar{u}_r \omega H}{\omega H r \cosh(\gamma H) - (i r - \omega H) \gamma \nu \sinh(\gamma H)} \quad (11a)$$

$$u_b = -\bar{u} \frac{r H \omega \cosh(\gamma H) - i r \gamma \nu \sinh(\gamma H)}{\omega H r \cosh(\gamma H) - (i r - \omega H) \gamma \nu \sinh(\gamma H)} \quad (11b)$$

$$\gamma = (1-i)(\omega/2\nu)^{1/2} \quad (11c)$$

where the depth-average for u in Eq. (10) is zero as required.

If ν and r are specified, for a given tidal amplitude, the velocity at any location of the estuary can be calculated using Eqs. (9) and (10). Alternatively, field measurements of tidal currents may be used to estimate the eddy viscosity and friction parameters, approach adopted in this paper.

RESULTS

The time evolution of mean current speed at station E1 - $u_0(t)$, and of sea-level at station E5- $\zeta(t)$, used as boundary conditions for calculation of the modeled currents, are presented in Figure 2 compared to harmonic behavior.

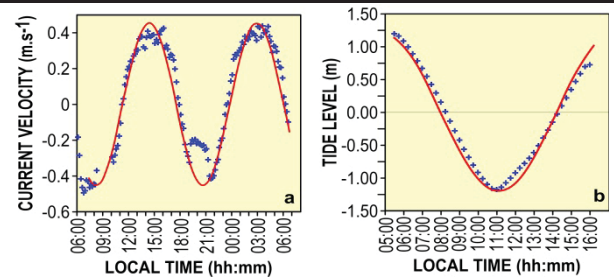


Figure 2. Temporal evolution of (a) mean current speed at station E1, Aug 16-17th (— Harmonic model ; + Current meter) and (b) of tides at station E5, Aug 16th (— Harmonic model ; + Tide gauge).

The close fit between modeled and *in situ* measurements suggest that the assumption of harmonic motion is verified, and

it seems possible to have an analytical description of the boundary conditions respecting the model formulation.

Model results are compared with measurements for longitudinal and depth varying currents.

A mean velocity had to be defined in order to verify at best the hypothesis of uniform repartition of the current across the section and to minimize non-representative variations. For calculation, it was necessary to consider only the velocity along abscise for comparison with the modeled current.

The current meter provides information about the direction and the intensity of the currents. A mean direction of the flow (main deeper channel) was defined thanks to the bathymetry maps and measurements made were projected along that direction. The depth-averaged velocity was defined as a sum of all those measurements, that is:

$$z = -H: \nu (\partial u / \partial z)_{-H} = r(u_b + \bar{U}) \quad (11)$$

$$z = 0: \nu (\partial u / \partial z)_0 = 0 \quad (12)$$

$$U_m = \bar{U} = 1/H \int_{-H}^0 U dz \approx 1/H \sum_i U_i (z_{i+1} - z_i) \quad (13)$$

To evaluate the relevance of the model in the description of the vertical and longitudinal structures of the currents, it is necessary to define two different functions. δ_1 quantifies the fitting between modeled and measured depth-averaged currents and δ_2 quantifies the fitting between modeled and measured depth-varying currents. Those expressions are:

$$\delta_1^2 = \frac{\sum_i \sum_t |U_{it} - \bar{U}_{it}|^2}{\sum_i \sum_t |\bar{U}_{it}|^2}; \quad \delta_2^2 = \frac{\sum_i \sum_k \sum_t \left| \frac{U_{ikt}}{\bar{U}_{it}} - \frac{\hat{U}_{ikt}}{\hat{U}_{it}} \right|^2}{\sum_i \sum_k \sum_t \left| \frac{\hat{U}_{ikt}}{\hat{U}_{it}} \right|^2} \quad (14)$$

Where i is the cross section, k is the depth and t , the time. U_{it} and \bar{U}_{it} are the modeled and measured depth-averaged currents, respectively. U_{ikt} and \hat{U}_{ikt} are the modeled and measured total ($U+u$) current velocities, respectively.

The term δ_1 is the most important difference function as far as the global relevance of the model is concerned. Later analysis of δ_2 is defined on the assumption that modeled and measured depth-averaged currents are roughly the same ($\delta_1 \approx 0$). This assumption is justified insofar as the aim of this study, which is to estimate distinct model robustness in both (longitudinal and vertical) directions.

According to previous definition of difference function (Eq. 14), the experimental data set gives $\delta_1 = 0.11$. This value of fitting is obtained for depth-averaged velocities. Previous calculations showed that depth-integrated mean velocities are very close to the values measured at mid-depth. Table 1 lists the most representative values of modeled and measured depth-averaged velocities for stations E2 and E3.

Table 1. Modelled and measured depth-averaged currents at stations E2 and E3, Santa Cruz Channel.

STATION	LOCAL TIME / TIDAL STAGE	CURRENTS (m.s ⁻¹)	
		Modelled	Measured
E2	06:14 / High-Ebb	-0.20	-0.22
	12:50 / Low-Flood	0.36	0.35
E3	06:23 / High-Ebb	-0.46	-0.45
	09:10 / Ebb-Low	-0.28	-0.34
	12:37 / Low-Flood	0.40	0.35

From Table 1 and the order of magnitude of δ_1 , it is clear that the analytic solution provides a good description of the longitudinal structure of currents in the SCC. Nevertheless, the weak dependence on time and abscise of the fitting suggests that

the existence of cross-channel currents and the secondary flow from the northern part of the channel may impair the quality of the agreement between the model and the measurements.

First, the eddy viscosity and bottom friction parameters are assumed to be constant in depth, time and space (along SCC). δ_2 is assumed to be a function of ν and r . The best estimates of the eddy viscosity and bottom friction parameter are those values of ν and r that minimize δ_2 . Modeled currents for different abscises and depths corresponding to the sites selected along the reach of the channel may be calculated for any couple (ν, r). A contour plot of δ_2 (Eq. 14) is shown in Figure 3.

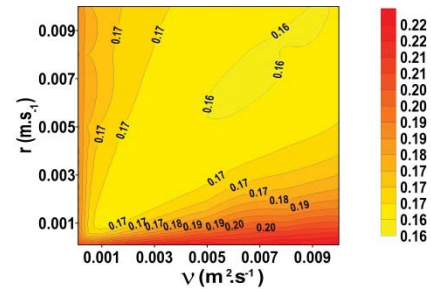


Figure 3. Contour plot for δ_2 (ν in m² s⁻¹ and r in m s⁻¹).

This Figure was constructed by performing two hundred stochastic simulations using the Monte Carlo method. It permitted the two parameters to be varied randomly according to a Normal distribution, based on the previous numerical modeling results of Araujo *et al.* (2000b) for SCC, and allowed simulations to be repeated so that δ_2 could be compiled.

The best-fit ($\delta_2 = 0.155$) was obtained for $\nu = 6.3 \times 10^{-3}$ m² s⁻¹ and $r = 6.5 \times 10^{-3}$ m s⁻¹. The close fit between measurements and simulations (Figure 4) suggests that the model provides a good description of the vertical tidal current distribution.

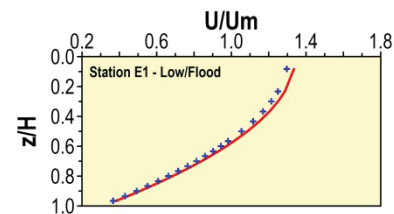


Figure 4. Comparison between analytical current profiles: — ($\nu = 5.0 \times 10^{-3}$ m² s⁻¹, $r = 5.5 \times 10^{-3}$ m s⁻¹); + ($\nu = 9.0 \times 10^{-3}$ m² s⁻¹, $r = 1.0 \times 10^{-2}$ m s⁻¹).

Nevertheless, the solution accuracy appears to be relatively insensitive to the values of ν and r . The presence of the large "valley", limited by $\delta_2 = 0.16$, confirms the apparent robustness of modeled currents to ν and r . This robustness is demonstrated in Figure 4, which compares profiles obtained for ($\nu = 5.0 \times 10^{-3}$ m² s⁻¹, $r = 5.5 \times 10^{-3}$ m s⁻¹) and for ($\nu = 9.0 \times 10^{-3}$ m² s⁻¹, $r = 1.0 \times 10^{-2}$ m s⁻¹). Both couples occur in the "valley" of the Figure 3. Despite this parameter change, the solutions are still accurate. As remarked by Wang and Craig (1993), increasing the eddy viscosity reduces the vertical shear, thus reducing the variation from the mean velocity. By contrast, an increase in the bottom friction coefficient leads to an increase in shear and in depth-varying velocity. Consequently, increases in both ν and r have the potential to cancel one another and are likely to do so along the "valley" in Figure 3. Representative comparisons between simulated and measured currents are presented in Figure 5.

The global shape of the curves is the same, so this assumption

can be considered as qualitatively relevant. This result is in agreement with previous studies (e.g., Clarke, 1990; Maas and van Haren, 1987; Pingree and Griffiths, 1987; Wang and Craig, 1993). The model seems to give a reasonable description of the vertical evolution of currents. However, the solution provided by the model does not fit exactly for every station and sea level, suggesting a weak dependence on space and time. While the model is globally accurate, improvements may be attempted to obtain a better fitting to reality.

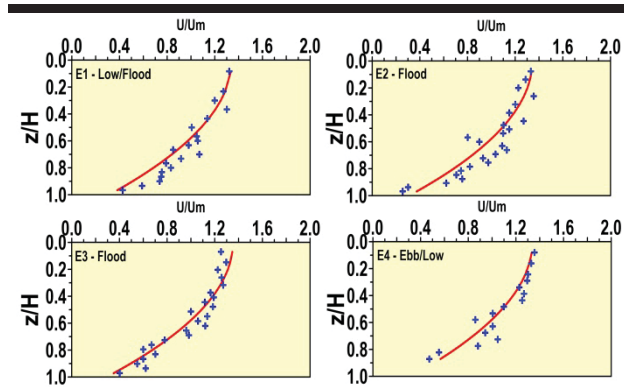


Figure 5. Representative comparison of measured (+) and analytical (—) current profiles for $\nu = 6.3 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ and $r = 6.5 \times 10^{-3} \text{ m s}^{-1}$.

Bottom Boundary Layer Parameters

The first model formulations with the hypothesis of constant eddy viscosity do not describe accurately the bottom boundary layer, in which the current drops from its free-stream value to zero. Theoretically, the bottom boundary layer is assumed to be a region of constant stress, in which the eddy viscosity varies linearly with the distance from the bottom, as $\nu = \kappa u_* (z + H + z_0)$, where κ is the von Karman's constant, u_* is the friction velocity previously defined and z_0 is the roughness length of the sea bed associated to a small-scale turbulence. The major justification for above equation is that it yields classical logarithmic velocity profiles, providing accurate description for bottom boundary layers in similar studies (Araujo *et al.*, 2000a,b; Leite *et al.*, 2008; Wang and Craig, 1993). Denoting u' the total velocity in the bottom boundary layer, where $(z+H)$ is small, the solution for u' derived from Eqs. (1) and (3) is given by $u' = A \ln((z+H+z_0)/z_0)$, which satisfies the boundary condition $u'=0$ at $z=-H$ for a constant value of A (Craig *et al.*, 1993). The solution of linearly varying viscosity and logarithmic velocity profile is valid in the boundary layer defined between $z=-H$ and $z=z_1$. Thus, by assumed continuity of velocity, viscosity and shear stress at the top of the boundary layer, it is possible to estimate A , z_1 and z_0 , whose are relevant data about the hydrodynamics of the SCC. On the assumptions that $z_1/H = o(1)$ and $z_0/z_1 = o(1)$, one may write:

$$A \ln(z_1/z_0) = |u_* + \bar{U}| \quad (15)$$

$$\nu_0 = \kappa u_* z_1 \quad (16)$$

$$\frac{A}{z_1} = \left| \frac{du}{dz} \right|_{z=-H} = \frac{r}{\nu H} (u_b + \bar{U}) \quad (17)$$

where ν_0 is the interior eddy viscosity. Using previous values for eddy viscosity and bottom friction parameter, i.e. $\nu = 6.3 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ and $r = 6.5 \times 10^{-3} \text{ m s}^{-1}$, the mean values of A , z_1 and z_0 for SCC are: $A = 0.09 \text{ ms}^{-1}$; $z_1 = 0.70 \text{ m}$ e $z_0 = 6.1 \times 10^{-3}$.

DISCUSSION

From the calculated mean value of z_1 , the boundary layer

depth in SCC is deduced to be $0.10H$. It seems to be in the same range as other studies. Previous results from turbulence modelling of a stirring tropical estuary, for example, indicate $0.05H \leq z_1 \leq 0.20H$ (Araujo *et al.*, 2000b); Wang and Craig (1993) suggested a depth $0.06H$; Bowden *et al.* (1959) found $z_1 = 0.14H$; and Jenter and Madsen (1989) values ranged between $0.10H$ and $0.15H$. For the mean roughness length of the sea bed, Wang and Craig (1993) found $z_0 = 1.6 \times 10^{-3} \text{ m}$, that we believe to be associated to sand or mud ripples bed (Jenter and Madsen, 1989). We found $z_0 = 6.1 \times 10^{-3} \text{ m}$ for SCC, which is a large value that may be associated with the presence of sea bed roots and typical mangrove vegetation in the study area (Medeiros and Kjerfve, 1993; Medeiros *et al.*, 2001).

The model described can also be used to test the water-depth dependence for the interior eddy viscosity formulations.

The most common model for interior viscosity is based on Taylor's (1954) analysis, where the eddy diffusivity may be written as a function of a turbulent velocity scale and length scale. In estuaries these parameters are typically the shear velocity u_* and the depth of the estuary (e.g., Koseff *et al.*, 1993, among others), and eddy viscosity may be written as $\nu = c u_* H$, where c is a constant in the range 0.01 to 0.10 and u_* is the bottom friction velocity defined as $u_*^2 = \nu \partial u / \partial z$. Here we considered bottom stress as the only primary source of turbulence for vertical mixing at SCC, once measured wind speeds and surface forcing were insignificant. In practice, one may estimate $u_* = O(1\% - 5\%U)$ (e.g., Klebanoff, 1954; Nezu and Rodi, 1986), and we have taken $u_*(x,t) \cong 0.05 \bar{U}(x,t)$ in this study (Araujo, Medeiros and Ribeiro, 1999; Araujo *et al.*, 2000b; Leite *et al.*, 2008). This new assumption does not modify the governing equations, as viscosity is still a constant in depth, i.e. $\partial \nu / \partial z = 0$.

The best modelling results were obtained for $\nu = 6.3 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ and $r = 6.5 \times 10^{-3} \text{ m s}^{-1}$ but sometimes constant parameters do not fully represent reality. Improvements can be searched considering the expression of the bottom friction parameter and/or the eddy viscosity, looking for expressions and assumptions that enable better modeling results without modifying previous governing equations.

As far as the bottom friction parameter is concerned, it is clear that r is function of the nature of the estuarine bed (e.g., sand, mud, etc.), i.e., along the channel axis. Considering a different bottom friction for each measurement station can be the first step to improve the accuracy of the model. Nevertheless, justifying in practice the link between the values and the nature of the channel bed is much more difficult. As a consequence, our first approach considering a mean bottom friction seems to be the best and our improvement will not focus on that point. As far as the eddy viscosity is concerned, it is necessary to distinguish interior viscosity from bottom viscosity. Therefore, as previously mentioned, the point is to consider improvements that will not modify the formulation of the analytical solution. The introduction of a depth-dependent eddy viscosity requires a considerably more complicated analytic solution scheme, which defeats the aim of this study. Different studies gave estimations of c . Bowden, Fairbairn and Hugues (1959) estimated a value of 0.056 from data in a tidal estuary; Hearn and Holloway (1990) found $c = 0.025$ for a wind driven flow over an open shelf, and Wang and Craig (1993) proposed $c = 0.028$ from their analysis of the Hey river estuary.

The best value of c for the SCC must be the one that will minimize the global difference between modeled and field currents at every section and for every stage of the sea level as far as the measurement performed at Itamaracá is concerned. As consequence δ_2 can now be defined as a function of r and c . In our case, c is 0.080, with a value for the best fit indicator of 0.15. This value may appear larger to previous ones but it was obtained with an assumed friction velocity of $0.05 \bar{U}$. With more

data about this velocity, this value should be more accurate. Nevertheless, the main interest of ϵ is to provide an order of magnitude of the eddy viscosity thanks to the values of water level and speed. Calculated eddy viscosities as a function of $u_b H$ (for $\nu/u_b H = c = 0.080$) had a mean value of $5.8 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$, range of $1.0 \times 10^{-3} \text{ m}^2 \text{ s}^{-1} < \nu < 1.2 \times 10^{-2} \text{ m}^2 \text{ s}^{-1}$, which is very close to that global initial estimation $\nu = 6.3 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ obtained for SCC.

CONCLUSIONS

Field depth-averaged currents were predicted analytically with 11% error ($\delta_2 = 0.11$). Modeled currents for different sample station and depths were calculated for different values of eddy viscosity and bottom friction parameters. Differences between analytical and field values were computed through a quadratic error estimator δ_2 . The best-fit solution indicator, $\delta_2 = 0.155$, was obtained for $\nu = 6.3 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ and $r = 6.5 \times 10^{-3} \text{ m s}^{-1}$. The close fit between the measurements and the model obtained for those values of ν and r indicates that the model describes well the vertical tidal currents distribution. Nevertheless, the solution accuracy appears to be relatively insensitive to the exact value of ν and r , since increases in both ν and r have the potential to cancel each other as stronger viscosity dumping may be compensated by higher bottom shear stress.

Field data and error analysis allowed estimating bottom boundary layer parameters for the SCC. The deduced boundary layer depth in the study area was $0.10H$, where H is channel depth, with a mean roughness length of the sea-bed about $6.1 \times 10^{-3} \text{ m}$, a large value that may be associated to the presence of sea-bed roots and typical mangrove vegetation.

Measurements and modeling results were also used to test the water-depth dependence for the classical eddy viscosity formulation issued from Taylor's (1954) scale analysis, $\nu = cu_b H$, where c is a constant and u_b is the bottom friction velocity. Calculated quadratic error $\delta_2 = 0.155$ indicates that the best value of c for the SCC is $\nu/u_b H = c = 0.080$, and derived eddy viscosities range $1.0 \times 10^{-3} \text{ m}^2 \text{ s}^{-1} < \nu < 1.2 \times 10^{-2} \text{ m}^2 \text{ s}^{-1}$, with a mean value of $5.8 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$.

Results were very encouraging and the approach should prove to be of good use to estuary managers as it would contribute to a better understanding of the hydrodynamic behavior of this system, as well as in predicting flux and distribution of salt, nutrients, pollutants, planktonic species, etc. within, and to and from, the system.

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LITERATURE CITED

- Araujo, M., Medeiros, C. and Ribeiro, C., 1999. Energy balance and time-scales of mixing and stratification in the Jaboatão estuary, NE-Brazil. *Brazilian Journal of Oceanography* 47, 145-154.
- Araujo, M., Medeiros, C., Ribeiro, C. and Freitas, I., 2000a. Testing surface boundary conditions for turbulent modelling in tidal systems. In: J.M. Redondo, A. Babiano (eds.), *Turbulent diffusion in the environment*. Barcelona, Spain, CIMNE, p. 25-38.
- Araujo, M., Medeiros, C., Ribeiro, C., Freitas, I. and Bezerra, M. O., 2000b. Turbulence modelling in a stirring tropical estuary. In: J.M. Redondo, A. Babiano (eds.), *Turbulent diffusion in the environment*. Barcelona, Spain, CIMNE, p. 56-66.
- Battisti, D.S. and Clarke, A.J., 1982. A simple method for

- estimating barotropic tidal currents on continental margins with specific applications to the M2 tide off the Atlantic and Pacific coasts of the United States. *Journal of Physical Oceanography*, 12, 8-16.
- Bowden, K.F., Fairbairn, L.A. and Hughes, P., 1959. The distribution of shearing stresses in a tidal current. *Geophysical Journal of the Royal Astronomic Society*, 2, 288-305.
- Clarke, A.J., 1990. Application of a frictional channel flow theory to flow in the Prince of Whales Channel, Torres Strait. *Journal of Physical Oceanography*, 20, 890-899.
- Craig, P.D., 1989. A model of diurnally forced vertical current structure near 30° latitude. *Continental Shelf Research*, 9, 965-980.
- Craig, P.D., Hunter, J.R. and Johnston, B.L., 1993. The applications of linearly varying eddy viscosity for wind-driven current profiles. *Continental Shelf Research*, 13, 1-24.
- Hearn, C.J. and Holloway, P.E., 1990. Application of a three-dimensional turbulence energy model to the determination of tidal currents on the northwest European shelf. *Journal of Geophysical Research*, 95, 18143-18162.
- Jenter, H.L. and Madsen, O.S., 1989. Bottom stress in wind-driven depth-averaged coastal flows. *Journal of Physical Oceanography*, 19, 962-974.
- Klebanoff, P.S., 1954. Characteristics of turbulence in a boundary layer flow with zero pressure gradient. <http://naca.central.cranfield.ac.uk/reports/1955/naca-report-1247.pdf>. NACA Report. 1247 p.
- Koseff, J.R., Holen, J.K., Monismith, S.G. and Cloern, J.E., 1993. Coupled effects of vertical mixing and benthic grazing on phytoplankton populations in shallow, turbid estuaries. *Journal of Marine Research*, 51, 843-868.
- Leite, F.S., Araujo, M., Medeiros C. and Endres, J-P., 2008. Energy balance and mixing timescales in a stirring tropical estuary, Itamaracá, Brazil. *Journal of Coastal Research*, 24, 151-160.
- Mass, L.R. and van Haren, J.J.M., 1987. Observations of the vertical structure of tidal and inertial currents in the central North Sea. *Journal Marine Research*, 45, 293-318.
- Medeiros, C. and Kjerfve, B., 1993. Hydrology of a tropical estuarine system: Itamaracá, Brazil. *Estuarine Coastal Shelf Science*, 36, 495-515.
- Medeiros, C., Kjerfve, B., Araújo, M. and Neumann-Leitão, S., 2001. *The Itamaracá estuarine ecosystem, Brazil*. In: U. Seeliger, B. Kjerfve (eds.), *Coastal marine systems of Latin America*. Springer-Verlag, p. 71-81.
- Medeiros, C. and Kjerfve, B., 2005. Longitudinal Salt and Sediment Fluxes in a Tropical Estuary: Itamaracá, Brazil. *Journal of Coastal Research*, 21(4), 751-758.
- Nezu, I. and Rodi, W., 1986. Open-channel flow measurements with Laser Doppler Anemometer. *Journal of Hydraulic Engineering-ASCE*, 112, 335-355.
- Pingree, R.D., Griffiths, D.K., 1987. Tidal friction for semidiurnal tides. *Continental Shelf Research* 7, 1181-1209.
- Taylor, G.I., 1954. The dispersion of matter in turbulent flow through a pipe. *Proceedings of the Royal Society of London*, Ser. A223, p. 446-448.
- Wang, X.N. and Craig, P.D., 1993. An analytic model of tidal circulation in a narrow estuary. *Journal of Marine Research*, 51, 447-465.