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MODELING OF WIND WAVE-INDUCED BOTTOM CURRENTS AND FINE SAND TRANSPORT IN TAMPA BAY, FLORIDA, USA

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Abstract: A stationary shallow water wave model, SWAN, was applied to predict wind wave-induced rms bottom orbital currents in Tampa Bay on a 70×100 curvilinear grid. Simulations were performed by using one idealized wind forcing (i.e., northeasterly wind of 20 $m \cdot s^{-1}$) and high-resolution bathymetry. Calculation of total load of fine sand was made by using the transport formula of Engelund-Hansen (1972). Simulations of wind wave-induced currents reveal that they are important for fine sand transport along the shallow margins of the Tampa Bay. Modeled bottom orbital currents ranged from 0.14 to 0.39 $m \cdot s^{-1}$. Total load of fine sand ranged from 2.46×10^{-8} to 3.21×10^{-3} $kg \cdot m^{-1} \cdot s^{-1}$ for northeasterly wind of 20 $m \cdot s^{-1}$. Wind wave-induced bottom resuspension is an important process affecting biogeochemical fluxes and thus water quality in Tampa Bay.

Key words: Modeling, Wind waves, Sand transport, Tampa Bay

1. INTRODUCTION

Wave boundary layer currents induce shear stresses that resuspend and transport materials from the sea floor (Myhaug et al. 1998). Wind waves have been observed to resuspend and transport bottom non-cohesive sediments in the Long Island Sound (Lavelle et al. 1978), and the Chesapeake Bay, USA (Ward et al. 1984). Lou and Ridd (1996) analyzed wave-current bottom shear stresses and sediment resuspension in Cleveland Bay, Australia. Booth et al. (2000) derived an empirical model of wind-induced bottom sediment resuspension for the Barataria Basin, Louisiana, USA. They found that winds of 4.00 $m \cdot s^{-1}$ could resuspend approximately 50% of bottom sediments. Signell et al. (2000) carried out a modeling study of bottom currents and sediment (medium sand) transport in the Long Island Sound, USA.

The Tampa Bay is a microtidal estuary incised into Tertiary platform carbonates (Brooks and Doyle 1998). As shown in Fig. 1, it consists of the Old Tampa Bay, the Hillsborough Bay, the Middle Tampa Bay, and the Lower Tampa Bay (Wang et al. 1999). Total Bay water area is about 3.20 km^2 with a mean depth of about 3.30 m (Goodwin 1987). Winds are generally from the northeast during the winter. Annual average wind speed is 3.40 ms^{-1} from the northeast. Tides are mixed, diurnal, and semidiurnal, with a mean range of about 0.67 m. The tidal range gradually increases from the mouth of the Bay to its upper reaches. Maximum tidal currents were less than 0.15 $m \cdot s^{-1}$ in Old Tampa Bay (Schoellhamer 1995). The vertically-averaged currents in Tampa Bay during a typical flood tide were generally less than 0.50 $m \cdot s^{-1}$ (Sheng et al. 1995). The Tampa Bay is well-mixed because of the shallow water depths, relatively small freshwater inflows, small range of tides, and effects of wind (Goodwin 1987; Schoellhamer 1991). It exhibits horizontal salinity gradients (Weisberg and Williams 1991).

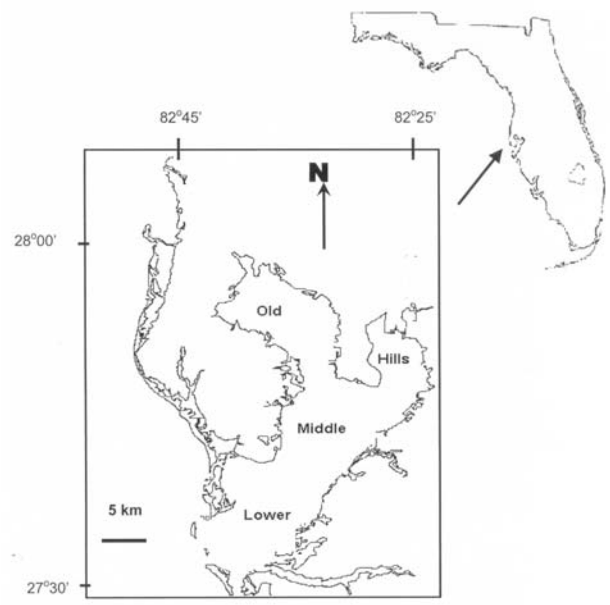


Fig. 1 Tampa Bay, west-central Florida

Knowledge of the characteristics of bottom sediment resuspension is critical for understanding the distribution and transformation of natural materials and contaminants in Tampa Bay. According to Florida Marine Research Institute, the Tampa Bay system, which has been highly developed and urbanized, has lost 81% of its seagrass acreage over the past 100 years. Studies of wind wave-induced bottom currents and sand transport have physical, biological significances in water quality and eutrophication in Tampa Bay (Sheng et al. 1997; Wang et al. 1999) and seagrass meadows in Tampa Bay (Lewis et al. 1985; Fonseca et al. 1996).

Observations of hydrodynamics (wind waves, tides) and sediment resuspension have been carried out in Tampa Bay (Schoellhamer 1990, 1995; Levesque and Schoellhamer 1995; Sheng et al. 1995, 1997). Modeling studies have also been attempted for describing tidal hydrodynamics and density-driven circulation in Tampa Bay: 1) two dimensional horizontal (2DH) (Goodwin 1987); and 2) three-dimensional (3D) tidal hydrodynamic model for Tampa Bay (Galperin 1992a; Hess and Bosley 1992; Sheng and Peere 1992; Hess 1993; Sheng and Yassuda 1995; Vincent et al. 1998, 2000). Three dimensional (3D) density-driven circulation model was also developed for Tampa Bay (Galperin 1992b).

However, little modeling has been done for wind wave boundary layer dynamics and fine sand transport in Tampa Bay. One-dimensional vertical (1 DV) cohesive sediment transport modeling has been confined to the Hillsborough Bay (Sheng et al. 1995, 1997). Types of bed sediments vary in the Old Tampa Bay, the Hillsborough Bay, the Middle Tampa Bay and the Lower Tampa Bay, but most sediments are non-cohesive fine sand (Schoellhamer 1995). Cohesive sediments are present in the Hillsborough Bay. How can these variations be accounted for in sediment transport model? Little data on suspended sediment concentration is available for Tampa Bay. What are their relative contributions of bed load and suspended load of fine sand to sediment transport in Tampa Bay?

With these above in our mind, objectives of this work: 1) to model wind waves-induced bottom orbital currents under one idealized wind condition; 2) calculate regional total load of fine sand under one idealized wind condition in Tampa Bay.

2. WIND WAVE MODEL

Although both local and remote winds can drive currents in Tampa Bay, local winds are taken into account in this study. The patterns of bottom orbital currents in Tampa Bay were simulated with the numerical wave-prediction model, **SWAN** (**S**imulating **WA**ves **N**earshore), being developed by the Delft University of Technology, The Netherlands. Detailed introductions into the background of **SWAN** can be found in Booij *et al*. (1999). The **SWAN** wave model is used for computing wind wave-induced bottom orbital velocity maximum U_b at each model grid cell under two idealized wind conditions. The grid matches that used by Vincent et al. (1998, 2000) in an ECOM model of Tampa Bay.

The following friction models have been used for **SWAN**: a) the empirical model of JONSWAP (Hasselmann et al. 1972); b) the drag law model of Collins (1972); and c) the eddy-viscosity model of Madsen *et al*. (1988). The formulations for those bottom friction models can all be expressed in the form:

$$S_{ds,b}(\delta,\theta) = -C_b \frac{\delta^2}{g^2 \sin h^2(kd)} E(\delta,\theta) \tag{1}$$

in which $S_{ds,b}(\delta,\theta)$ is the bottom friction; δ is the wave frequency; θ is the wave direction; g is the gravity acceleration (9.8 ms^{-2}); k is the wave number; d is the total water depth; $E(\delta,\theta)$ is the energy density; C_b is a bottom friction coefficient that generally depends on the bottom orbital motion represented by U_{rms}:

$$U_{rms}^2 = \int_0^{2\pi}\int_0^{\infty} \frac{\delta^2}{\sin h^2(kd)} E(\delta,\theta) d_\delta d_\theta \tag{2}$$

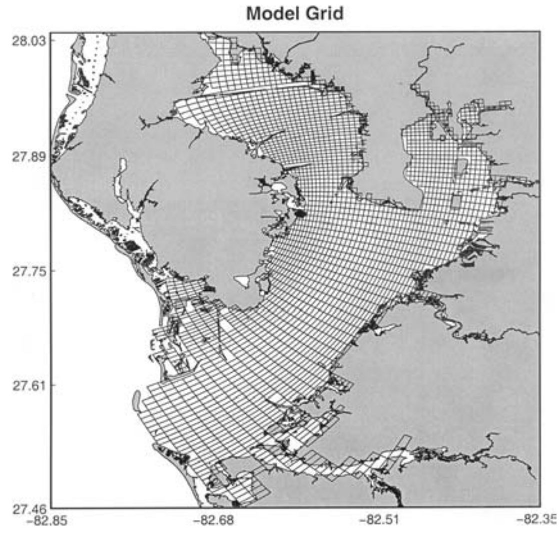
where U_{rms} is the root mean square bottom orbital velocity, which is taken equal to U_b, will be used for calculating bottom shear stresses and thus total load and bed load of fine sand in Tampa Bay.

The Tampa Bay SWAN uses a high-resolution grid with 70×100 cells in a curvilinear domain (Fig. 2). A total of 2,244 cells are computationally active. The dimensions of active cells range from 2240 m to 308 m, with a mean of 668 m. The mean cell area is 0.425 km^2. So that the potential or magnitude of fine sand resuspension throughout the Tampa Bay could be better understood. Since the northeaster is the predominant wind direction in Tampa Bay, simulations of the bottom wave-orbital velocity maximum, U_b, were made for one idealized wind of 20 $\mathrm{m \cdot s^{-1}}$, for northeast direction. Schoellhamer (1995) reported 9 $\mathrm{m \cdot s^{-1}}$ northeasterly winds on March 8, 1990 and 12 $\mathrm{m \cdot s^{-1}}$ during the afternoon of November 30, 1990. Therefore, our assumptions for two idealized winds are acceptable.

3. FINE SAND TRANSPORT MODEL

Total load of fine sand, was modeled because of non-cohesive sediments, mainly fine sands, are present in Tampa Bay. There are several bed load and total load transport formulas available in the literature. The Engelund-Hansen (1972) total load formula was used for determining the magnitude of fine sand transport in Tampa Bay. The same curvilinear model grid as the SWAN wave model is used for fine sand transport model.

Size classifications of bed sediments are based on Tables 11 (middle Tampa Bay), 12 (Hillsborough Bay) and 13 (Old Tampa Bay) in Schoellhamer (1991). Medium particle size D_{50}=130-150μm for bed sand was used throughout Tampa Bay. The value of the bottom roughness length z_0 for fine sand bed in Tampa Bay was set to be 0.005 m. Because it is not possible to determine the spatial variability in roughness length z_0. 0.005 m for roughness length z_0 was used throughout Tampa Bay. The model was run with uniform density of sea water (1028 $\mathrm{kg \cdot m^{-3}}$). The Manning's coefficient n is set equal to 0.025 as used by Goodwin (1987).



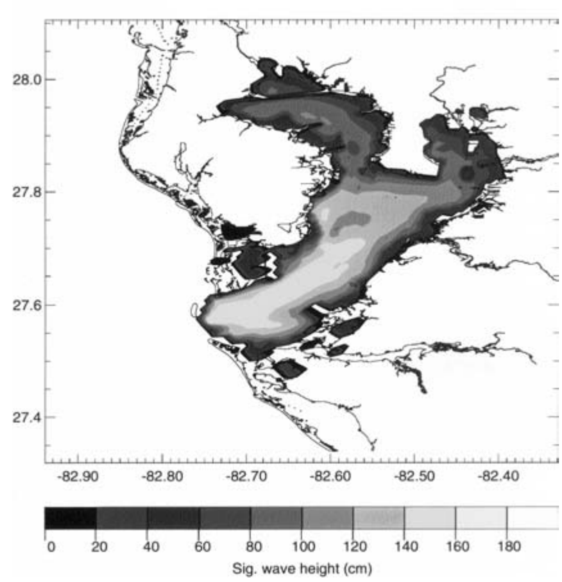


Fig. 2 The curvilinear model grid for Tampa Bay contains 70×100 cells.

Fig. 3 Modeled wind wave-induced significant wave heights for steady northeasterly wind of 20 m·s^{-1}

Local equilibrium of fine sand transport rate is assumed for Tampa Bay. The Engelund-Hansen (1972) formula is employed in estimating the total load (bed load and suspended load) of fine sand in Tampa Bay.

$$Q_{total} = 5.0 \times \left\{ 0.05 / [g^3 (\frac{\rho_s}{\rho_w} - 1)^2 D_{50}] \right\} \times (\sqrt{g} \times U / Ch)^5 \times C'^2 \tag{3}$$

where Q_{total} is the total load of fine sand (kg·m^{-1}·s^{-1}); ρ_s =the density of suspended sediment (kg·m^{-3}); ρ_w =the density of sea water (kg·m^{-3}), 1028 kg·m^{-3} is used; D_{50}= the medium diameter of bed sediments (m); U is the current velocity (ms^{-1}) in calculation, it was set equal to the rms bottom orbital current speed, i.e., $U \approx U_b$; Ch is the Chezy value, 0.025 is used throughout Tampa Bay (Table 1); C' is the Chezy's coefficient due to particle friction (m$^{0.5}$·s^{-1}):

$$C = 18.0 \ln(12.0h / 3D_{90}) \tag{4}$$

where h is the water depth (m), high resolution bathymetry is used throughout Tampa Bay; D_{90} is the sediment diameter with 90% finer (m), 130 μm is used throughout Tampa Bay.

Table 1 Summary of parameters used in the models

the kinematic viscosity ν	1.47×10^{-6} m^2·s^{-1}
Roughness length z_0	0.005 m
the Chezy value Ch	0.025
The Manning's coefficient n	0.025
Density of suspended sediment ρ_s	2650 kg·m^{-3}
Density of sea water ρ_w	1028 kg·m^{-3}
Medium particle size D_{50}	150μm
D_{90}	130μm

4. RESULTS AND DISCUSSIONS

4.1 WIND WAVE-INDUCED BOTTOM ORBITAL CURRENTS

Wind wave-induced bottom orbital currents can be significant mechanism for bottom fine sand transport in Tampa Bay. Several frontal systems pass through Tampa Bay and generate strong winds that increase wave action and can resuspend fine sands. Low bottom orbital velocities for wind of 20 $m \cdot s^{-1}$ are present in the most part of Hillsborough Bay and the northeastern Old Tampa Bay (Fig. 3). These low bottom orbital velocities might be accounted for fine cohesive sediment deposition in the Hillsborough Bay and Old Tampa Bay, as observed by Schoellhamer (1995) and Sheng et al. (1995).

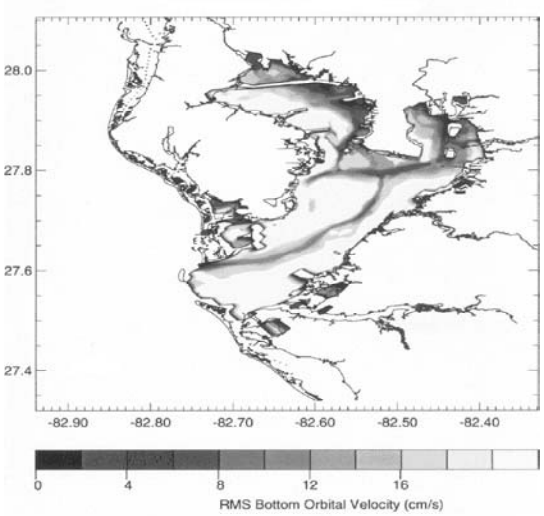


Fig. 4 Modeled wind wave-induced bottom orbital speed for steady northeasterly winds of 20 $m \cdot s^{-1}$

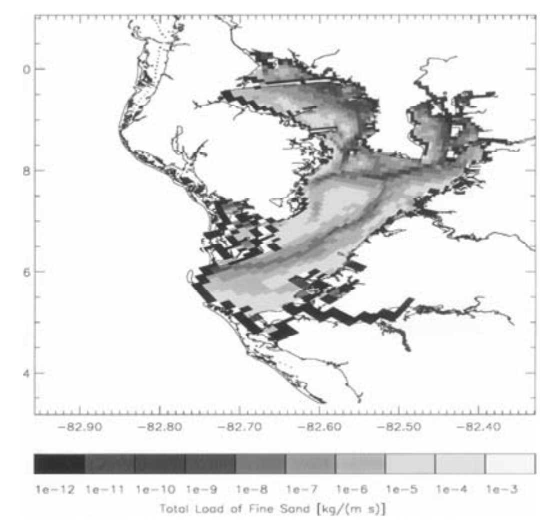


Fig. 5 Modeled total load of fine sand driven by wind wave-induced bottom orbital currents (northeasterly winds of 20 $m \cdot s^{-1}$)

Modeled results also revealed that the significant wave heights ranged from 0.40 to 1.50 m for northeasterly winds of 20 $m \cdot s^{-1}$ (Fig. 3). Schoellhamer (1995) observed the waves periods of about 2.6-2.8 seconds during the storm (winds) on March 8-9, 1990. The bottom velocities ranged from less than 0.14 $m \cdot s^{-1}$ in the channel (deep regions) to more than 0.39 $m \cdot s^{-1}$ in the intertidal (shallow regions) zone, for northeasterly winds of 20 $m \cdot s^{-1}$ (Fig. 4). During episodic events, wind wave-induced bottom shear stresses are very effective in causing significant resuspension of non-cohesive sediments in Tampa Bay (Schoellhamer 1995; Sheng et al. 1995).

4.2 TOTAL LOAD OF FINE SAND

The magnitude of fine sand transport driven by wind wave-induced bottom currents (Figure 4) in Tampa Bay is shown in Fig. 5. Spatial gradients in total load of fine sand would cause erosion and accretion of the sand bed in Tampa Bay. High total loads of fine sand are present in the southwestern Old Tampa Bay, the northwestern Middle Tampa Bay and the southeastern Lower Tampa Bay (Fig. 5). As expected, total loads of fine sand are very low along the channel (deep region) in Tampa Bay and north of Bay (Fig. 5). Very low total loads of fine sand are also present in Hillsborough Bay (Fig. 5). Calculated total loads of fine sand are shown in Fig. 4. Total loads of fine sand ranged from 2.46×10^{-5} to 3.21×10^{-5} $kg \cdot m^{-1} \cdot s^{-1}$ for northeasterly wind of 20 $m \cdot s^{-1}$ (Fig. 5). There is a strong correlation between the patterns of modeled wind wave-induced bottom orbital currents and total loads of fine sand (Fig. 4 and 5).

It is noted that total load of fine sands might be underestimated or overestimated because of several assumptions. For example, these simulations assume a constant particle size of bed sediments. However, it is difficult to know how much loads would have been underestimated or overestimated due to lacking of observational data. It is clear that the wind wave-induced bottom current is an effective transport mechanism for fine sand in Tampa Bay. Maximum suspended-solids concentration could be up to 40 $mg \cdot L^{-1}$ in winter in Old Tampa Bay (Schoellhamer, 1995). Suspended load of fine sand should be calculated in the future.

5. CONCLUSIONS

Although this modeling study is based upon several assumptions, several preliminary conclusions can be drawn from this study. Magnitude of potential fine sand transport is determined by modeling bed load and total load of fine sand in Tampa Bay. Wind wave-induced bottom orbital speeds range from less than 0.14 $m \cdot s^{-1}$ in the deep channel to more than 0.39 $m \cdot s^{-1}$ in the shallow regions for northeasterly winds of 20 $m \cdot s^{-1}$. Total loads of fine sand range from 2.46×10^{-5} to 3.21×10^{-5} $kg \cdot m^{-1} \cdot s^{-1}$ for northeasterly wind of 20 $m \cdot s^{-1}$.

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