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Anthropogenic Sediment Resuspension Mechanisms in a Shallow Microtidal Estuary

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The mechanisms that resuspend bottom sediments in Hillsborough Bay, a shallow, microtidal, subtropical estuary in West-central Florida, were determined by analysing hydrodynamic and suspended-solids concentration data collected during several instrument deployments made in 1990 and 1991. Large vessels in a dredged ship channel can generate forced solitary long waves that cause large water velocities and sediment resuspension at the study sites. An experiment was conducted with a trawler that resuspended bottom sediments, and some of the resuspended sediments remained in suspension for at least 8 h. A secondary impact of vessel-generated long waves and trawling is that sediments that are resuspended and newly deposited are more susceptible to resuspension by tidal currents than undisturbed bottom sediments. Natural sediment resuspension by wind waves and tidal current is less frequent or of smaller magnitude than anthropogenic sediment resuspension. The annual mass of sediment resuspended by vessel-generated long waves is estimated to be one order of magnitude greater than the annual mass of sediment resuspended by wind waves generated by winter storms.

Introduction

Sediment at the bottom of estuaries and continental shelves can be resuspended by tidal currents, wind waves, wave–current interaction, trawling and large vessels. Resuspension by tidal currents has been observed in many estuaries (Roman & Tenore, 1978; Lavelle *et al.*, 1984; Cloern *et al.*, 1989; Hamblin, 1989). Wind waves have been observed to resuspend bottom sediments in water depths of 10·5 m in Long Island Sound, U.S.A. (Lavelle *et al.*, 1978), less than 2 m in Chesapeake Bay, U.S.A. (Ward *et al.*, 1984), 4–10 m in Start Bay, U.K. (Davies, 1985), 2 m in the Ho Bugt Estuary, Denmark (Perjup, 1986), and 1·5 and 4 m in Old Tampa Bay, U.S.A. (Schoellhamer, 1995). Bohlen (1987) observed that tidal currents and wind waves resuspended bottom sediments at a site with a water depth of 12 m in Chesapeake Bay. Non-linear interaction of waves and current during winter storms on the northern California continental shelf increases the bottom shear stress, resuspends bottom sediments, and is a major factor controlling the distribution of surficial sediment on the shelf (Cacchione *et al.*, 1987;

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Drake *et al.*, 1992). Trawling, the dragging of weighted nets along the bottom to catch fish, is a more important sediment resuspension mechanism than wind waves on the Middle Atlantic Bight continental shelf (Churchill, 1989) and in the Kattegat Sea (Floderus & Pihl, 1990). Large vessels can resuspend bottom sediments in harbours (Schoellhamer, 1993). The critical shear stress for sediment resuspension has been observed to increase after lengthy periods without resuspension due to biological and chemical bonding of sediment grains (Churchill *et al.*, 1994).

Sediment resuspension is an important process in Tampa Bay, a shallow microtidal estuary in West-central Florida (Figure 1), because resuspended sediments may decrease available light for seagrasses, release nutrients and contaminants into the water column, and deposit in harbours and shipping channels. For example, seagrass meadows, which are an important ecological habitat, have declined by 81% from their historical coverage in Tampa Bay (Lewis *et al.*, 1985). Most of the loss in seagrass has occurred in deeper waters, where decreased light availability may be the cause, and in the northern part of Tampa Bay, where water quality is probably affected more by point and non-point nutrient loading and by reduced tidal flushing (Lewis *et al.*, 1985; Goodwin, 1987).

The U.S. Geological Survey, in cooperation with several local agencies, has been studying the causes of attenuation of sunlight in the water column, the effect of resuspended sediment on light attenuation, and the mechanisms that resuspend bottom sediments in Tampa Bay. The purpose of this paper is to describe anthropogenic sediment resuspension mechanisms in Hillsborough Bay, the north-east sub-embayment of Tampa Bay (Figure 1).

Study sites

Hillsborough Bay is on the west-central coast of Florida (Figure 1). It has a surface area of 96 km^2, an average depth of 3·2 m, a vertically well-mixed water column, a spring tide range of about 1 m, and an average mean water temperature of about 24·5 °C (in 1991) (Goodwin, 1987; Boler, 1992). The subtropical weather includes almost daily thunderstorms during the summer, several winter storms each year, and the possibility of a tropical storm (about a 2-year recurrence interval), primarily during the autumn. An 11–13-m-deep dredged shipping channel serves the Port of Tampa on the northern shore of Hillsborough Bay. Dredged material is deposited on two spoil islands east of the channel. Generally, bottom sediments in Hillsborough Bay are fine non-cohesive material (mean particle diameter less than 63 μm), with some clay minerals, in deeper water (5 m), and fine sands in shallow water (less than 2 m) near the shoreline (Goodell & Gorsline, 1961; Schoellhamer, 1991). Regular bed forms and fluid mud are not present and undulations in the bed are probably caused by bioturbation. Shrimp trawling can occur during evenings from November through April, but there has been virtually no commercial trawling activity in Hillsborough Bay during the first half of the 1990s due to a lack of shrimp and a prohibition on trawling by non-local vessels. Commercial bait fish are caught in Hillsborough Bay with a purse seine, a large net with weights at one end and floats at the other end that is set by two boats and closed around a school of fish.

The bottom material was studied initially to delineate typical and relatively homogeneous areas of bottom sediment to locate representative resuspension monitoring sites in Hillsborough Bay (Schoellhamer, 1991). A shallow-water site (depth about 1 m) was selected that had fine sand with an average grain size of 166 μm (Figure 1, Site A). A

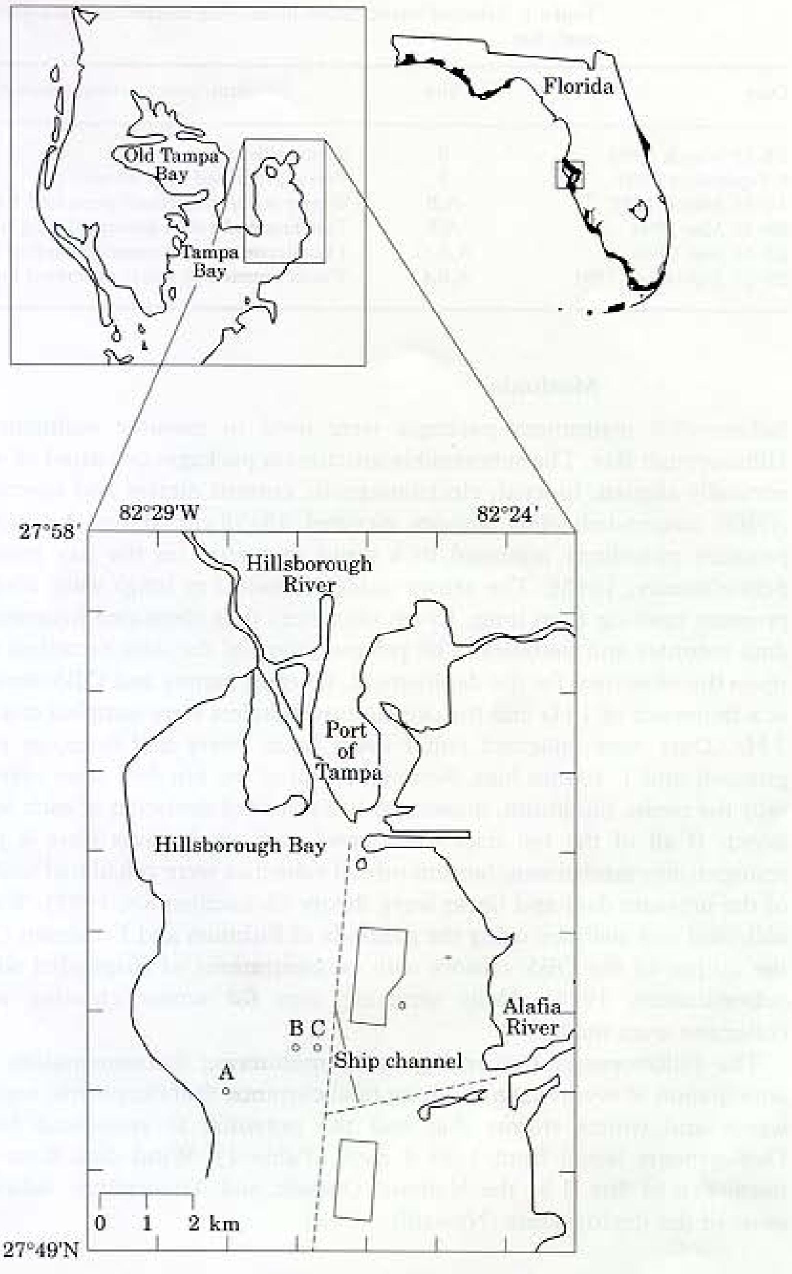

Figure 1. Hillsborough Bay study area. Site A is the shallow-water study site and Sites B and C are the deep-water study sites.

deep-water site (depth about 5 m), 1·9 km north-east of Site A, was selected that had 88% fine material (Figure 1, Site B). Another deep-water site, 0·5 km east of Site B, had bottom material that was nearly identical to Site B (Figure 1, Site C). The terms 'shallow water' and 'deep water' are relative to each other and to water depths in Hillsborough Bay.

TABLE 1. Selected resuspension monitoring instrumentation deployments in Hillsborough Bay

Date	Site	Anticipated resuspension event
14–15 March 1990	B	Spring tide
6 September 1990	B	Vessel-generated long waves
11–15 March 1991	A,B	Winter storm and vessel-generated long waves
28–31 May 1991	A,B	Trawling and vessel-generated long waves
22–24 July 1991	A,B,C	Thunderstorms and vessel-generated long waves
25–27 September 1991	A,B,C	Winter storm and vessel-generated long waves

Methods

Submersible instrument packages were used to monitor sediment resuspension in Hillsborough Bay. The submersible instrument packages consisted of one or two pairs of vertically-aligned, bi-axial, electromagnetic current meters and optical backscatterance (OBS) suspended-solids sensors elevated 15–58 cm above the bay bottom, and a pressure transducer mounted to a stand that rests on the bay bottom (Levesque & Schoellhamer, 1995). The sensor cables (about 3 m long) were connected to a PVC pressure housing (2 m long, 15 cm diameter) that contained instrument electronics, a data recorder and batteries. The programming of the data recorders varied depending upon the objectives for the deployment. Current meters and OBS sensors were sampled at a frequency of 1 Hz and the pressure transducers were sampled at a frequency of 1 or 2 Hz. Data were collected either every hour, every half hour, or continuously, and grouped into 1–10 min bins. Sometimes, all of the bin data were saved; at other times, only the mean, minimum, maximum and standard deviation of each sensor output were saved. If all of the bin data were saved and wind waves were a possible sediment resuspension mechanism, bottom orbital velocities were calculated with spectral analysis of the pressure data and linear wave theory (Schoellhamer, 1995). Water samples were collected and analysed using the methods of Fishman and Friedman (1989) to calibrate the output of the OBS sensors with concentrations of suspended solids (Levesque & Schoellhamer, 1995). Daily servicing trips for sensor cleaning and water-sample collection were made.

The Hillsborough Bay resuspension monitoring instrumentation was deployed in anticipation of events such as strong tidal currents, thunderstorms, vessel-generated long waves and winter storms that had the potential to resuspend bottom sediments. Deployments lasted from 1 to 4 days (Table 1). Wind data were collected 4·7 km north-east of Site B by the National Oceanic and Atmospheric Administration during most of the deployments (Nowadly, 1992).

Observations of sediment resuspension

During the Hillsborough Bay instrument deployments, sediment resuspension by anthropogenic and natural mechanisms was observed.

Long waves generated by large vessels in the ship channel

The Port of Tampa on the northern shore of Hillsborough Bay is connected to the Gulf of Mexico by a dredged ship channel that is aligned with the primary axis of the bay

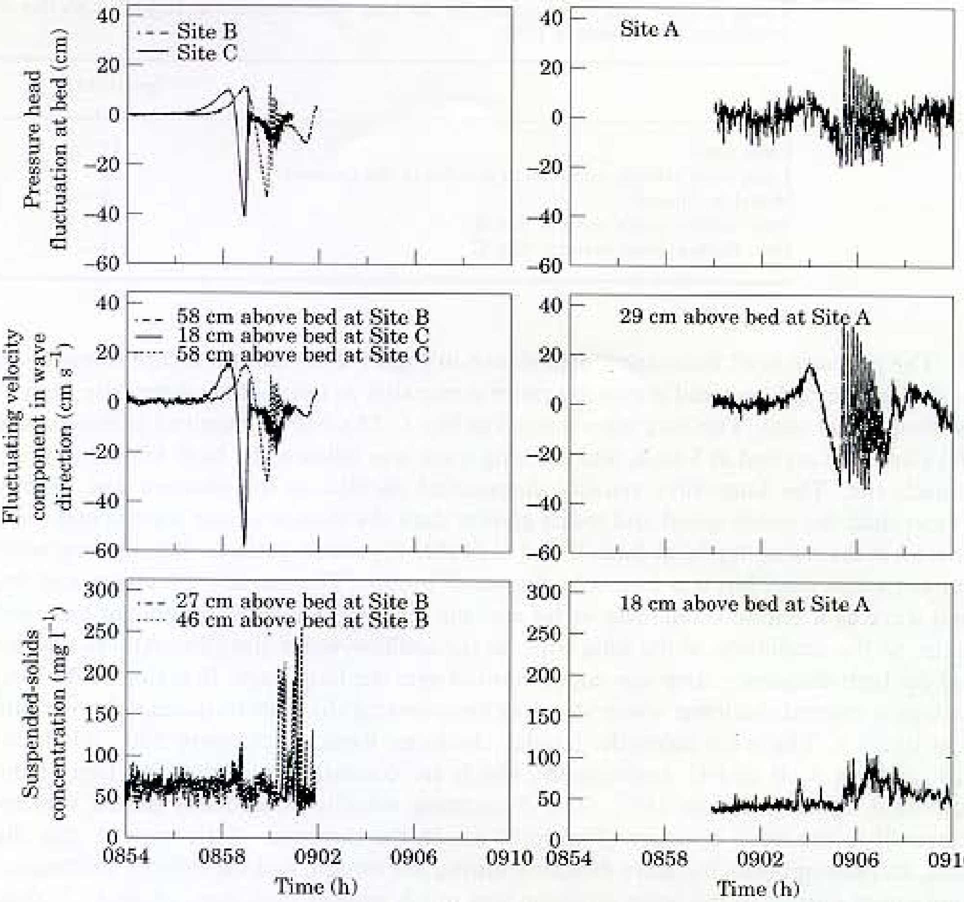

Figure 2. Vessel-generated long wave at 09.00 h, 26 September 1991. Data from the deep-water sites near the channel (Sites B and C) are shown in the left column and data from the shallow water (Site A) are shown in the right column.

(Figure 1). The channel is 11–13 m deep and 150 m wide. The water depth adjacent to the channel is about 5 m. Several large vessels (typically of 100–250 m length and 7–13 m draft) utilize the channel on a typical day.

Some large vessels generate a forced solitary long wave (shallow-water wave) that propagates in the direction of vessel motion and away from the channel that can cause large water velocities and sediment resuspension. A long wave generated by an outbound vessel at 09.00 h on 26 September 1991 is a typical example (Figure 2). Velocities 18 and 58 cm above the bed at Site C were virtually identical and, from the beginning of the peak to the end of the trough, the elapsed time was 170 s, so the wave was a long (or shallow-water) wave. The measured pressure head fluctuation at the bed [$(p-\bar{p})/\rho g$, where p is pressure, $\bar{p}$ is the mean pressure, ρ is water density, and g is gravitational acceleration] is equal to the vertical displacement of the water surface by the long wave for small velocity head $v^2/2g$ (<1·8 cm in this case). The peak amplitude of the long wave was 10 cm, the trough amplitude was 40 cm, and the duration of the trough was smaller than the duration of the crest at the two deep-water sites near the channel (Sites B and

TABLE 2. Wave and vessel speeds for the long wave observed in Hillsborough Bay at 09.00 h on 26 September 1991

	Speed (m s^{-1})
Long wave	11
Long-wave velocity component parallel to the channel	9·7
Vessel in channel	8·7
Free shallow-water wave at Site B	6·7
Free shallow-water wave at Site C	7·2

C). The pressure head fluctuation data shown in Figure 2 are from pressure transducers located at the bed, so wind waves are more noticeable at the shallow-water site than at the deep-water sites. The long wave arrived at Site C 55 s before it arrived at Site B, and 360 s before it arrived at Site A, and the long wave was followed by high-frequency chop at each site. The long-wave velocity component parallel to the channel was slightly greater than the vessel speed and much greater than the shallow-water wave speed ($\sqrt{gh}$, where h is the water depth) at Sites B and C (Table 2), which indicate that the long wave was not a free wave but was forced by the vessel motion. Bottom friction attenuated the long wave as it entered shallower water and the higher-frequency component travelled faster, so the amplitude of the long wave at the shallow-water site (Site A) was smaller and the high-frequency chop was superimposed over the long wave. Breaking of the long wave as it entered shallower water also may have created the high-frequency chop at Site A at 09.06 h. The wave azimuths (angles clockwise from north) were 220°, 210° and 215° at Sites A, B and C, respectively, which are consistent with the direction of the outbound vessel (azimuth 185°). The fluctuating velocity component (mean velocity removed) in the wave direction (Figure 2) was in the direction of the wave during the crest, and was opposite the wave direction during the trough, and the velocity fluctuation component normal to the wave direction was much smaller (less than 10 cm s^{-1}) than the velocity fluctuation component in the wave direction, both of which are expected for a progressive wave. The maximum wave velocities (60 cm s^{-1}) were greater than the maximum tidal velocities (10–15 cm s^{-1}). The long wave resuspended bottom sediments at Sites A and B, and the resuspended sediments settled rapidly as the wave motion diminished.

Other long waves, similar to but usually smaller than shown in Figure 2, were observed in Hillsborough Bay, and all were generated by a large vessel in the channel, although not all large vessels generated a long wave (Levesque & Schoellhamer, 1995). Instruments were programmed to record continuously for at least several hours during most deployments to observe vessel-generated long waves. During periods of continuous sampling, 57% of large vessels created a long wave that was observed at the deep-water sites (B and C), and 29% of large vessels created a long wave that was observed at the shallow-water site (A, Table 3). About half of the long waves observed at the deep-water sites were not observed at the shallow-water site because of wave attenuation and distance from the channel. Barges, tugboats, fishing vessels and recreational vessels did not generate long waves during the sampling periods and are not included in Table 3. Both inbound and outbound large vessels generated long waves and resuspended bottom sediments. Typical wave azimuths were 200° for outbound vessels and 0° for inbound vessels at the deep-water sites. Vessel speeds and wave speeds were much greater than

TABLE 3. Vessel-generated long waves and associated sediment resuspension observed in Hillsborough Bay

	Site A	Site B	Site C
Days of continuous observations	2·71	4·79	4·00
Number of large vessels	17	33	28
Number of large vessels per day	6·3	6·9	7·0
Number of long waves	5	19	16
Number of long waves per day	1·9	4·0	4·0
Number of long waves that resuspended bottom sediments	2	3	4
Number of long waves that resuspended bottom sediments per day	0·74	0·63	1·0

tidal current speed and therefore no dependence of tidal current on wave characteristics was observed. Between 9 and 14% of large vessels resuspended bottom sediments at the deployment sites, and the average time between resuspension events was 1·0–1·6 days. Long waves with heights greater than 30 cm and velocities greater than 30 cm s^{-1} typically resuspended bottom sediments, and suspended-solids concentrations usually returned to ambient values (typically 25–50 mg l^{-1}) within minutes of resuspension due to settling after the long wave passed. When relatively large (9–14 cm s^{-1}) tidal currents were present, however, resuspended sediments remained in suspension for about 2 h.

Analysis of vessel-generated long waves

The height of the long wave generated by a vessel is a function of the Froude number and blocking coefficient (Mei, 1986; Katsis & Akylas, 1987; Pedersen, 1988; Lee *et al.*, 1989; Bai *et al.*, 1990; Ertekin & Qian, 1990; Choi *et al.*, 1991). The Froude number is the ratio of the vessel velocity, V, and the shallow-water wave velocity in the channel and is given by:

$$F=\frac{V}{\sqrt{gh}} \qquad (1)$$

The channel depth h was not measured directly, but nautical charts indicate that the western quarter of the channel is 6·5 m deeper than Site B. The blocking coefficient is the fraction of the cross-sectional area of the channel occupied by the vessel. The exact hull shapes of the vessels could not be determined, so the blocking coefficient is estimated as:

$$S=\frac{BD}{bh} \qquad (2)$$

where B is the beam (maximum width) of the vessel, D is the draft of the vessel, and b is the width of the channel. Equation (2) probably overestimates the blocking coefficient. The speeds of 14 vessels were measured and the best available estimates of V, B and D were used to calculate F and S. The Froude number was always less than 1, F varied from 0·29 to 0·84, and S varied from 0·033 to 0·22. Regression analysis indicated that the height of the long wave non-dimensionalized by the local water depth at the deep-water sites was correlated linearly to $F^{2\cdot4}S^{1\cdot6}$ (r=0·992, Figure 3). Thus, the non-dimensional long-wave height increases as F (for F<1) and S increase, and is more sensitive to F (and vessel velocity) than to S (vessel size). Long waves were not observed

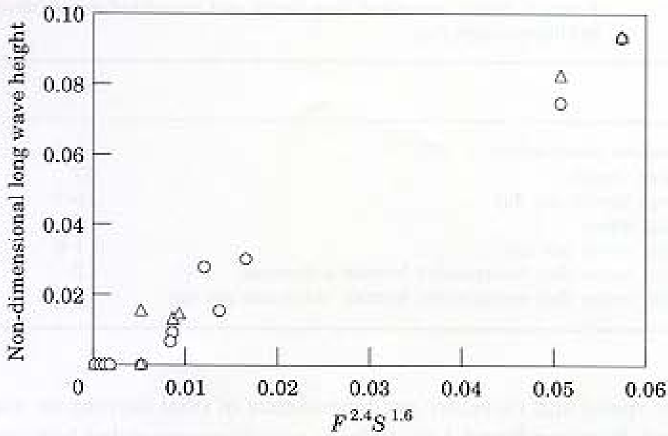

Figure 3. Relation between non-dimensional long-wave height at Sites B and C, Froude number (less than 1), and blocking coefficient. ○, Site B; △, Site C.

when $F<0{\cdot}48$ and long waves were always observed when $F>0{\cdot}54$. The critical non-dimensional long-wave height for sediment resuspension was approximately 0·05.

These results are consistent with previous theoretical, numerical and laboratory studies of forced long waves generated by vessels (Mei, 1986, Katsis & Akylas, 1987; Pedersen, 1988; Lee *et al.*, 1989; Bai *et al.*, 1990; Ertekin & Qian, 1990; Choi *et al.*, 1991). For Froude numbers slightly greater than or equal to 1, a vessel moving in a finite-width channel generates forced non-linear solitary long waves periodically. If the Froude number is less than 1, a vessel which starts moving at velocity V impulsively from rest will generate some solitary waves that travel ahead of the vessel and diminish in size and vanish with time. Vessels in Hillsborough Bay do not start impulsively from rest and $F<1$, so no periodic vessel-generated long waves were observed in Hillsborough Bay. Previous studies report that a shelf of water will be in front of the vessel for $F<1$, and this may explain the long-wave peak in Figure 2. The observed increase in the size of the vessel-generated long wave as F increases toward unity and, as S increases (Figure 3), is consistent with previous studies. The stern of a vessel is a discontinuity with flow separation that may cause the amplitude of the trough to be greater, and the duration of the trough to be less relative to the observed peak. Results of previous studies do not include a deep asymmetric trough because either a symmetric surface pressure distribution or an idealized hull shape were used to represent a vessel with little or no flow separation at the stern. The Hillsborough Bay channel is adjacent to shallower water. This common bathymetry has not been included in previous studies, which usually assume a constant depth, but it may affect the formation and propagation of the long waves in Hillsborough Bay.

Trawling

Experimental trawls were conducted at Site B to determine the effect of the dragging of weighted nets along the bed by trawlers. A pressure transducer and two pairs of electromagnetic current meters and OBS sensors were deployed at Site B on the morning of 28 May 1991, and a shrimp trawler made six experimental trawls from 09.15 to 10.50 h on 28 May. The trawler pulled two weighted 7·6-m-long nets along the

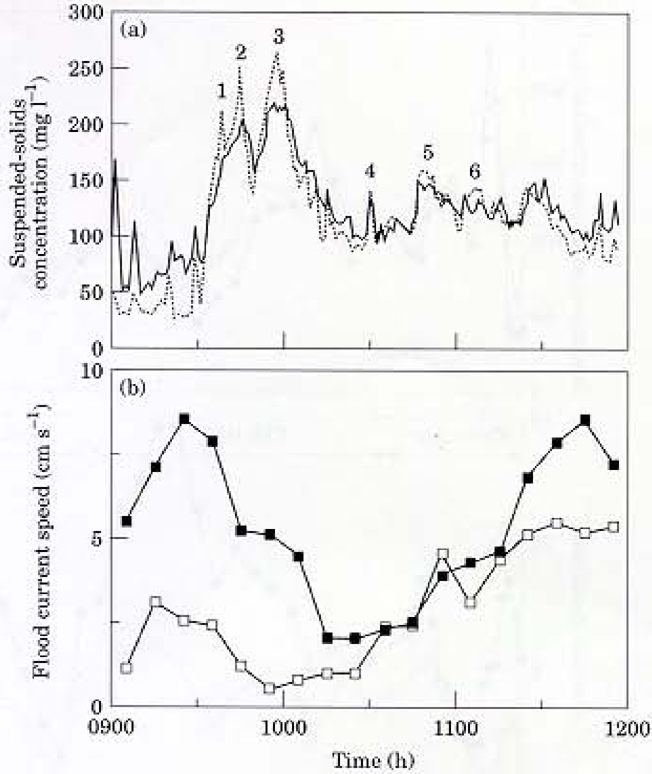

Figure 4. (a) One-minute average suspended-solids concentration and (b) 10-min average flood current speed at Site B during trawling experiment, 28 May 1991. The arrival times of the six trawler plumes were confirmed with aerial photography (Levesque & Schoellhamer, 1995). (a) ——, 27 cm above bed; · · ·, 46 cm above bed; numbers indicate trawler plume numbers. (b) □, 15 cm above bed; ■, 58 cm above bed.

bottom. The trawls were made along an east–west line about 30 m south of the site because the current was to the north during a flood tide.

Concentrations of suspended solids 27 and 46 cm above the bed at Site B increased during the trawling experiment (1-min averages, Figure 4). The concentrations were at background levels until the first two plumes arrived at 09.32 and 09.36 h. Coarser sediments resuspended by the trawler probably deposited on the bed before the plume arrived at Site B. The first two plumes had virtually merged, and the concentration 46 cm above the bed was greater than the concentration 27 cm above the bed because the plume arrived at the higher elevation first due to greater advection farther from the bed. The concentrations decreased until the third plume arrived at 09.50 h. The fourth plume at 10.30 h is barely distinguishable and the fifth and sixth plumes at 10.46 and 11.07 h, respectively, are smaller than the first three plumes because the flood tide was stronger when the first three plumes were generated (10-min averages, Figure 4). Thus, a smaller fraction of the first three plumes had deposited when they arrived at Site B because the stronger current increased vertical mixing and advected the plumes more rapidly. The increase in suspended-solids concentration rate 11.20 h is not related to one of the six trawler plumes, but was caused by increased current speed of the flood tide and

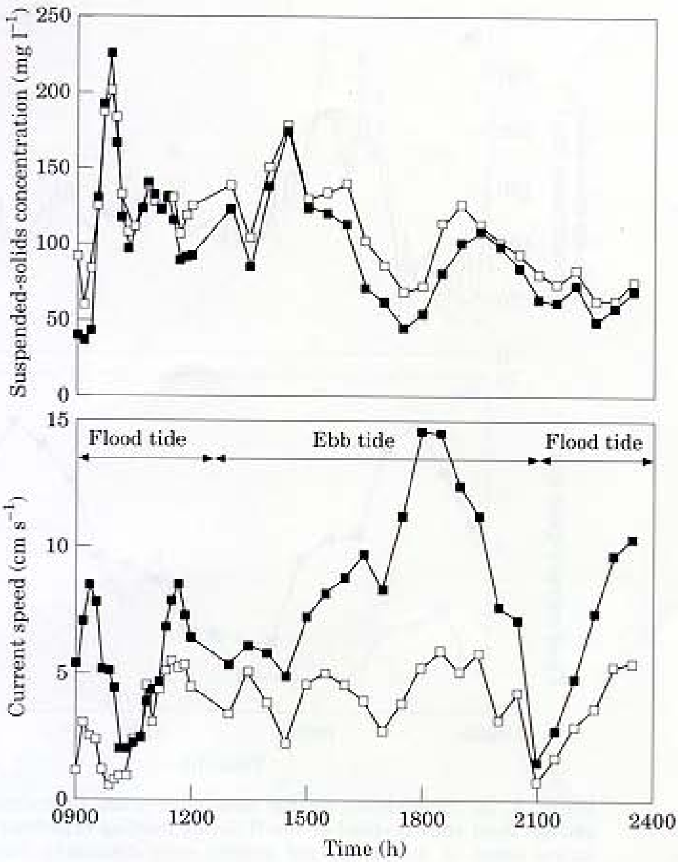

Figure 5. (a) Suspended-solids concentration and (b) current speed at Site B, 28 May 1991. Ten-minute averages from 09.00 to 12.00 h and discrete values every 30 min after 12.00 h. (a) □, 27 cm above bed; ■, 46 cm above bed. (b) □, 15 cm above bed; ■, 58 cm above bed.

resulting resuspension of sediments that had been suspended by the trawler and deposited. In the absence of newly-deposited sediments, tidal currents did not resuspend bottom sediments measurably at Site B.

The tide reversed between 12.00 and 13.00 h, and the plumes passed over Site B during the afternoon (Figure 5). A Lagrangian coordinate (ξ) that moves with the mean northerly velocity component can be used to show that the trawler plume returns to Site B after the tide reverses. The origin is defined at Site B at 09.00 h and ξ is positive to the south. The ξ axis is moved by integrating the mean of the northerly velocity components measured 15 and 58 cm above the bed; therefore, the northerly velocity component is assumed to be homogeneous within the plume, and the easterly velocity component is neglected. The mean of the measured suspended-solids concentrations 27 and 46 cm above the bed at Site B as a function of ξ during the flood tide from 09.00 to 12.00 h and during the ebb tide from 13.00 to 17.30 h is shown in Figure 6. The flood tide and ebb tide concentrations for $\xi = 100$–300 m are nearly identical. The maximum concentrations for both flood tide and ebb tide occur at about $\xi = 100$ m. The maximum concentration during the ebb tide at 14.30 h is smaller than the maximum flood tide

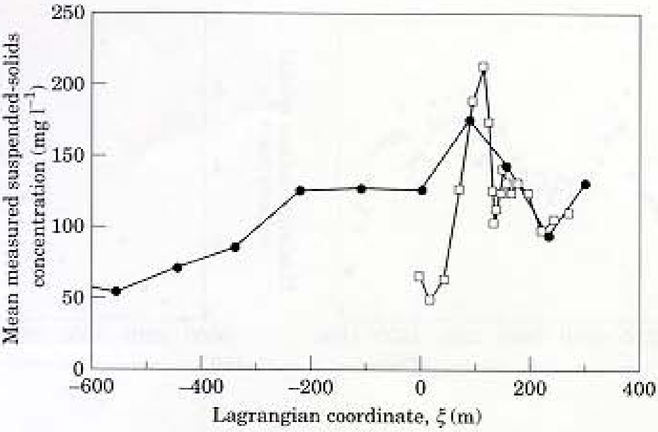

Figure 6. Mean measured suspended-solids concentration at Site B in Lagrangian coordinate, 28 May 1991. □, flood tide; ●, ebb tide.

concentration at 09.50 h (Figure 5) due to settling and dispersion. High concentrations for $\xi<0$ during the ebb tide are caused by suspended sediments in the upper water column being advected farther north during the flood tide than indicated by the Lagrangian calculation with near bed velocities, settling to the lower water column, and then advecting south during the ebb tide. Plume sediments that deposited north of Site B and were resuspended during the ebb tide also may contribute to the observed lag. There are fewer observations during the ebb tide because the submerged instruments were programmed to make continuous measurements until 12.00 h and every 30 min thereafter. The concentrations at Site B return to pre-trawl values at about 17.30 h when the plume of resuspended sediments is south of the site ($\xi = -550$ m). Thus, some of the sediments resuspended by the trawler remained in suspension for at least 8 h.

Tidal currents

During the instrument deployments, tidal currents were not large enough to resuspend bottom sediments in measurable quantities, with the exception of newly-deposited sediments. Tides in Hillsborough Bay are mixed diurnal/semi-diurnal with a maximum range of about 1 m, and maximum tidal currents at the study sites are typically 10–15 cm s^{-1}. As initiation of particle motion is a stochastic process (Lavelle & Mofjeld, 1987), tidal currents will cause some particle motion at the bed, but the resuspension of particles was not measurable in the estuary, except for newly-deposited sediments.

Newly-deposited sediments are more erodible than undisturbed sediments because several hours are needed for binding of bottom sediments by benthic communities and consolidation of clay minerals. For example, flood currents of 5–8 cm s^{-1} at 11.20 h on 28 May 1991 resuspended sediments that had been suspended and deposited south of Site B during the trawler experiment 1–2 h earlier (Figure 4). Ebb currents from 6 to 14 cm s^{-1} from 17.30 to 19.30 h on 28 May 1991 (Figure 5) resuspended some of the sediment that was suspended during the trawler experiment, moved north of Site B, and settled. Sediments suspended by long waves on the morning of 26 September 1991 (one of which is shown in Figure 2) settled rapidly at the deep-water site, but early afternoon tidal currents of about 12 cm s^{-1} resuspended the newly-deposited bottom sediments and maintained them in suspension for several hours.

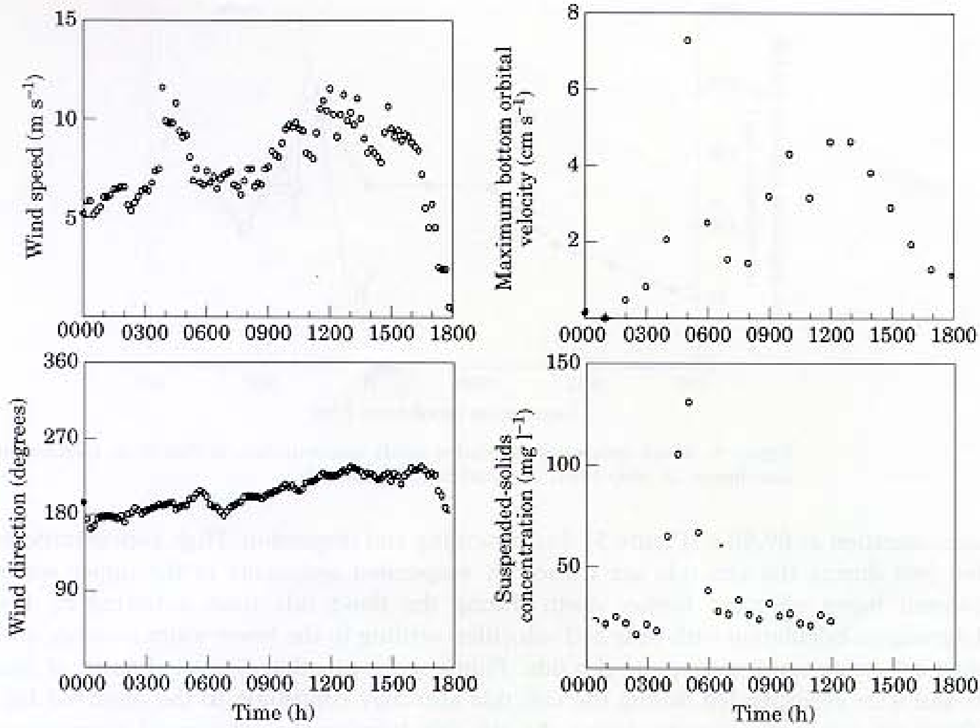

Figure 7. Wind speed, wind direction, maximum bottom orbital velocity and suspended-solids concentration 12 cm above the bed at Site B, 13 March 1991.

Wind waves

Wind waves generated by thunderstorms, tropical storms or winter storms are a natural sediment resuspension mechanism. Southerly winds provide the greatest fetch in Hillsborough Bay. Strong thunderstorms were observed over Hillsborough Bay during the afternoons of 30 May 1991 and 23 July 1991 while the instruments were deployed, but these storms did not resuspend bottom sediments. Maximum wind speeds of 10–13 $m s^{-1}$ were sustained for less than 1 h (Nowadly, 1992). Thunderstorms typically affect only localized parts of the study area at a given time, and they affect a given location for only a short amount of time. The spatial and temporal limitations of thunderstorms, especially in relatively deep water, limit the transfer of energy from the thunderstorm wind field through the water surface to the bed, so sediment resuspension is unlikely. No instrument deployments were concurrent with tropical storms, which have been observed to generate larger waves and resuspend more sediment in Old Tampa Bay than winter storms (Schoellhamer, 1995).

Fetch limits wind-wave formation by winter storms. One such winter storm occurred on 13 March 1991, when strong (7–11 $m s^{-1}$) sustained southerly winds (Nowadly, 1992) generated wind waves and resuspended bottom sediments at the deep-water site (Site B) (Figure 7). The strongest southerly winds occurred from 04.00 to 05.00 h, and the greatest bottom orbital velocity (7·4 $cm s^{-1}$) occurred at 05.00 h (Figure 7). The suspended-solids concentration 12 cm above the bed increased from the ambient value (about 28 $mg l^{-1}$) at 04.00 h, was greatest at 05.30 h (130 $mg l^{-1}$), and returned to the

TABLE 4. Controlling factors, average recurrence intervals, potential locations, relative suspended-solids concentrations and typical duration for each sediment resuspension mechanism

Sediment resuspension mechanism	Controlling factors	Average recurrence interval	Potential locations	Relative suspended-solids concentration	Typical duration
Vessel-generated long waves	Vessel speed and size	1·0–1·6 days	More likely near channel	Moderate	Minutes
Trawling	Availability of shrimp	As much as nightly November–April	Deep water with fine sediments	High	Hours
Purse seining	Availability of bait fish	Several hours (estimate)	Virtually a point source	High	Hours (estimate)
Thunder storms	Wind duration	Daily in summer	Not applicable	Typically no increase	Not applicable
Winter storms	Wind, waves and depth	Weekly to monthly in winter	Anywhere	Moderate	Hours
Tropical storms	Wind, waves and depth	2 years	Anywhere	High (estimate)	Hours (estimate)
Tidal currents	Velocity, deposition within several hours	Depends on deposition and tides	Unconsolidated sediments	Low	Hours

ambient value at 07.00 h as the southerly winds decreased and the bottom orbital velocity decreased to about 2 cm s^{-1} (Figure 7). The critical bottom orbital velocity for sediment resuspension was between 4·6 and 7·4 cm s^{-1}. The wind speed increased in the late morning, but the wind direction had begun to shift to the south-west, so the bottom orbital velocity did not exceed 4·6 cm s^{-1} and no sediment resuspension was observed. Wind speed and wave activity diminished after 13.00 h. The OBS sensor began to foul after 13.00 h, so no reliable suspended-solids concentration data are available after 13.00 h. During the storm, sediment resuspension was not observed at the shallow-water site (Site A) where the bottom orbital velocity did not exceed 20 cm s^{-1}. An early winter storm produced 10 m s^{-1} south-westerly winds on 25 September 1991, while instrumentation was deployed at the three study sites. No sediment resuspension was observed, however, because the winds were from the south-west and the limited fetch prevented formation of large waves.

Discussion

Estuaries are altered commonly by dredging to accommodate vessel traffic, and trawling is used commonly to harvest fish in estuaries. One effect of vessel traffic and trawling is resuspension of bottom sediments.

Large vessels traverse dredged channels that are deeper than the natural undisturbed bathymetry in many estuaries. Hillsborough Bay is an example of this altered bathymetry and vessel traffic. Vessel size and speed, and channel depth and cross-sectional area determine the occurrence and magnitude of a forced solitary long wave (Figure 3) that produces large water velocities and sediment resuspension. The average recurrence interval of resuspension by vessel-generated long waves is almost daily in Hillsborough

Bay, and the area over which resuspension occurs can be extensive (Table 4). Sediment resuspension by vessel-generated long waves is significant in Hillsborough Bay, and the factors that create these waves are present in many estuaries.

Trawling disrupts and resuspends estuarine bottom sediments. Experimental trawls resuspended bottom sediments in Hillsborough Bay and some of these sediment remained in suspension for at least 8 h. Few shrimp were present in Hillsborough Bay during the instrument deployments, so little or no commercial trawling occurred; therefore, the cumulative effect of several trawlers operating in the bay for a period of several hours was not measured. Based on the experimental trawls, however, commercial trawling can resuspend sediments over a large area and can be a significant resuspension mechanism when abundant fisheries are available. Resuspension by purse seining was not observed near the study sites during the instrument deployments but has been observed visually (R. Johansson, written comm.).

A secondary impact of vessel-generated long waves and trawling is that sediments that are resuspended and newly deposited are more susceptible to resuspension by tidal currents than undisturbed bottom sediments. Several instances of sediment resuspension by tidal currents after resuspension by the trawler or by a vessel-generated long wave were observed in Hillsborough Bay, where tidal currents do not usually resuspend bottom sediment. Thus, these anthropogenic disturbances immediately resuspend bottom sediment and increase the likelihood of future resuspension.

Natural sediment resuspension by wind waves and tidal currents is less frequent or of smaller magnitude than anthropogenic sediment resuspension in Hillsborough Bay (Table 4). Tropical storms and winter storms are relatively infrequent. Winds associated with winter storms and thunderstorms are often not southerly and are of insufficient duration to resuspend bottom sediments over a large area of the Bay. Attenuation of wave energy with water depth also limits the ability of wind waves to resuspend bottom sediments.

To compare the importance of anthropogenic and natural sediment resuspension quantitatively, the data from this study can be used to estimate the annual mass of resuspended sediment from vessel-generated long waves and wind waves generated by winter storms. For vessel-generated long waves, assuming 0·7 waves day^{-1} that increase suspended-solids concentration 50 $mg\,l^{-1}$ in one-quarter of the volume of Hillsborough Bay (the approximate volume of the Bay in which vessel-generated long waves were observed), the annual mass of resuspended sediment is 1×10^9 kg. For wind waves generated by winter storms, assuming six occurrences per year that increase suspended-solids concentration 100 $mg\,l^{-1}$ in one-half of the Bay volume (due to fetch limitation of wind waves), the annual mass of resuspended sediment is 9×10^7 kg. Although these amounts are somewhat speculative, they indicate that sediment resuspension by vessel-generated long waves is one order of magnitude more important than natural sediment resuspension by winter storms. Commercial trawling and tropical storms did not occur during the study period, so similar estimates cannot be made for these resuspension mechanisms.

Conclusion

Sediment resuspension by natural mechanisms is either less frequent or of smaller magnitude than resuspension associated with anthropogenic mechanisms in Hillsborough Bay, Florida. Some large vessels in the dredged ship channel generated a forced solitary long wave that produced large water velocities and sediment resuspension at the study sites. A dredged ship channel adjacent to shallow water is a common bathymetric feature in shallow estuaries, so similar long waves may be generated by large vessels in other shallow estuaries. Experimental trawls resuspended bottom sediments and some of these sediments remained in suspension for at least 8 h. A secondary effect of sediment resuspension by vessel-generated long waves and trawling is that the resulting newly-deposited bottom sediments are more susceptible to resuspension by tidal currents that do not normally cause resuspension. Resuspension by wind waves is limited by either wind speed, wind duration, or fetch. The annual mass of sediment resuspended by vessel-generated long waves is estimated to be one order of magnitude greater than the annual mass of sediment resuspended by wind waves generated by winter storms.

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