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The Role of Turbulence in the Settling of Mud Flocs

Eric Wolanski†, Ronald J. Gibbs‡, Yoshihiro Mazda*, Ashish Mehta+ and Brian King†

†Australian Institute of Marine Science
PMB No.3
Townsville M.C., Queensland
4810, Australia

‡College of Marine Studies
University of Delaware
Newark, DE 19716, U.S.A.

*School of Marine Science and Technology
Tokai University
3-20-1 Orido
Shimizu City
Shizuoka Prefecture 424, Japan

+Coastal and Oceanographic Engineering Department
University of Florida
Gainesville, FL 32611, U.S.A.

ABSTRACT

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The compaction rate of suspended mud depends not only on the sediment concentration but also on the turbulent intensity. This effect appears to be due to the turbulence plugging micro-channels used in the dewatering process. The compaction rate decreases by a factor of up to 10 with increasing stirring or turbulence in the inhibited settling (fluid mud) range. Our findings are based on the results of laboratory experiments where this effect was measured directly, and on observations of the suspended sediment stratification cycle at tidal frequency in the Normanby River estuary, Australia.

ADDITIONAL INDEX WORDS: *Cohesive sediments, compaction rate, fluid mud, lutocline, settling velocity, suspended mud, suspended sediment concentration, turbulence regime.*

INTRODUCTION

Fluid mud is common in estuarine and coastal waters and has profound ecological and economical implications. For instance, the benthic fauna inhabiting mud banks of the Malabar coast of western India is destroyed when the southwest monsoon in July to September resuspends the mud (SESHAPPA, 1953). Similar effects have been observed in the Bight of Biafra and the Bay of Bengal (LONGHURST and PAULY, 1987). This liquid mud calms the sea by thixotropic damping of the offshore swell, and this often results in the formation of a two-layer fluid, with a fluidised fluid mud layer at the bottom and a clearer water layer on top, as was found originally in coastal waters off Surinam and since then in various other muddy coastal environments (WELLS, 1977, 1983; WELLS and ROBERTS, 1981). Lutoclines, *i.e.* layers of strong vertical gradient in the suspended sediment concentration (SSC), are often found a few cm to tens of cm from the bottom when sediments are resuspended by waves (MAA and MEHTA, 1987). The presence of fluid mud below the lutocline has major engineering implications in dredging, disposal of dredged spoil, siltation of harbours and coastal waters, and the fate of heavy metals. The lutocline is not always restricted to being very close to the bottom. Indeed, mid-water lutoclines are often found in muddy tidal estuaries (*e.g.* KIRBY and PARKER, 1977; WOLANSKI *et al.*, 1988; SMITH and KIRBY, 1989).

The formation of a lutocline for the case of cohesive sediments in shear-free turbulence can be explained by a simple balance between the turbulent upward flux of suspended sediment and the downward flux due to the settling velocity, w_f, which at high SSC decreases with increasing values of the concentration (THORN, 1981; NICHOLS, 1984-1985; ROSS, 1988; ROSS and MEHTA, 1989).

A lutocline also forms in non-cohesive sediment suspensions, *i.e.* when w_f is independent of SSC, at the elevation where the buoyancy flux determined by the particle fall velocity is balanced by the rate of kinetic energy input (E and HOPFINGER, 1987). The eddy diffusivity of solid particles is reduced in comparison to the value of the diffusivity of the fluid particles with zero fall velocity. NOH and FERNANDO (1990) parameterised this effect by extending the model of MONIN and YAGLOM (1971) to show that lutoclines (for non-cohesive sediments) can form as a result of the interaction of turbulence and particle diffusion. These studies

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were made for ensemble-averaged shear-free turbulence generated at a horizontal boundary. Applications of such studies may include field situations where sediment is fluidised by waves or oceanic bottom-generated turbulence. In the presence of a mean shear, turbulence energy is produced at all depths and the above results do not necessarily apply.

Sediment-induced buoyancy effects inhibit mixing across a lutocline, hence preserving the lutocline (SMITH and KIRBY, 1989; WOLANSKI *et al.*, 1988). By this process, turbulence does not propagate across a lutocline. Erosion of the lutocline is still possible but only by turbulent entrainment above and below the lutocline.

One-dimensional turbulence models are inappropriate at high values of SSC because of the strong sediment-induced anisotropy of the turbulence. KENNEY (1985) argued that the presence of a near-bottom layer of high SSC in shallow coastal waters of Lake Manitoba results in decoupling lake turbulence between the turbid bottom layer and the clearer upper layer. To explain the presence of several-meter-thick unsorted mud deposits from single depositional events in the Madeira Abyssal plain, McCAVE and JONES (1988) proposed that the turbulence collapsed under the influence of the suspended sediment resulting in 'freezing' the turbidity current. Turbulence collapse in high sediment concentrations was also hypothesised by PARKER *et al.* (1986) as the key mechanism of limiting the growth of, and ultimately arresting, turbidity currents. There are no detailed field studies yet of the properties of turbulence in fluid mud, although laboratory studies in sediment-laden fluids suggest a turbulence collapse in shear flow (*e.g.* FUKUSHIMA and FUKUDA, 1986; COSTA, 1989) and in shear-free flow (WOLANSKI *et al.*, 1989). Entrainment of suspended sediment across a lutocline is controlled by the Richardson number, but is also found to be smaller for a sediment-stratified fluid than for salt-stratified fluids, a finding that implies sediment-laden waters use a significant fraction of the turbulent kinetic energy to maintain the sediment in suspension (WOLANSKI and BRUSH, 1975; SRINIVAS and MEHTA, 1990). Turbulence can also result in shearing and breaking down the flocs (VAN LEUSSEN, 1986). This may modify the settling velocity of the suspended sediment, hence the buoyancy flux, and thus may have a feedback effect on the turbulence regime.

This paper illustrates some of these feedback processes. First, results of a laboratory study of the compaction of kaolinite fluid mud are described, both in quiescent and in turbulent flows. It is shown that w_f not only decreases with increasing SSC in the hindered settling range, but also decreases with increasing ambient turbulence. This result does not depend on the presence of a solid bottom boundary and is thus different from the process described by VAN LEUSSEN (1988) of floc break-up in more dilute suspensions and decreased settling velocity near the bottom in turbulent flow. In fact, floc break-up did not occur in our laboratory studies. In addition, the suspended mud is found to strongly control the internal waves riding on the lutocline, hence also the wave breaking and the turbulence.

These results are used to explain observations of fluid mud entrainment and settling in the Normanby River estuary, Australia.

METHODS

The laboratory column is similar to but much taller than that used by WOLANSKI *et al.*, (1989) and offers the additional facility to enable the measurement of vertical profile of suspended sediment concentration (SSC) by use of a profiling Analite optical-fiber back-scattering nephelometer. The column is a Plexiglas cylinder of 10 cm internal diameter and 140 cm tall. Turbulence is generated by oscillating 1 cm wide rings along the walls, spaced 2 cm apart, and using a stroke of 0.75 cm. Commercially available kaolinite was used with a median diameter of 1 μm. The Analite nephelometer has a linear response with suspended sediment in the range 0–20 g l^{-1}, and a non-linear response at higher concentrations. Concentrations up to 60 g l^{-1} can be resolved with saturation occurring at about 80 g l^{-1}. The settling velocity, w_f, in quiescent water in the flocculation settling range was determined from the conservation of mass equation

$$\partial c/\partial t = -\partial(w_f c)/\partial z \qquad (1)$$

where c is the suspended sediment concentration, measured with the nephelometer, t is the time and z the vertical axis. The settling velocity w_f was also determined by measuring the settling velocity of individual flocs observed with a horizontal axis microscope. In the inhibited settling range, a sharp interface (a lutocline) forms and $\partial c/\partial z$ becomes discontinuous. In that case it was easier to bypass equation (1) and to measure w_f by measuring the velocity of the sharp interface.

The horizontal axis microscope was also utilised to measure the floc size and fluid mud microchannels. The experiments were carried out in 32‰ natural sea water.

In September 1989 a study was undertaken in the Normanby River estuary in tropical Australia (Figure 1). The estuary is about 50 km long, is very muddy, and is surrounded by a strip of mangrove swamps located principally along the outer side of the meanders. At site A (km 8.9), we deployed over the mud bottom a string of Analite optical fiber nephelometers which recorded data every 5 minutes representing the one minute average. There were six sensors, located from 0.5 m to 3 m above the bottom. Water depth at low tide was 3.5 m. We also deployed a mooring with three Inter-Ocean S4 current meters which logged one minute average velocity data every 5 minutes. The current meters were 1.2 m, 2.2 m and 3.3 m above the bottom. Vertical profiles of salinity, temperature and suspended sediment were taken at various stations using the 'mudprobe' of WOLANSKI *et al.* (1988). Tidal data were collected from an Aanderaa WLR5 tide gauge bottom-mounted at site M (km 0).

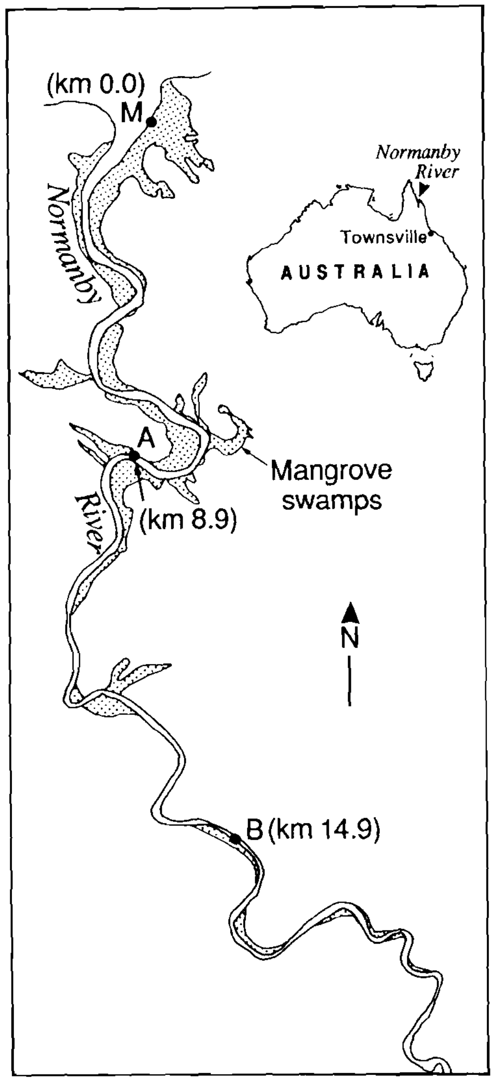

Figure 1. Map of the Normanby River estuary with location of sites M, A and B. The insert is a general location map.

LABORATORY EXPERIMENTS: RESULTS AND DISCUSSIONS

The salt water–mud mixture was first homogenised by strong stirring by the grid in 32‰ natural sea water.

Vertical profiles in quiescent water of SSC at various times are shown for initial SSC c_o = 8.4 g l^{-1} (Figure 2a), c_o = 12.5 g l^{-1} (Figure 2b), c_o = 22.9 g l^{-1} (Figure 2c) and c_o = 38.2 g l^{-1} (Figure 3a). For all four cases, a zone of sharp vertical gradient in SSC initially forms (*i.e.* the lutocline) in a few minutes and then slowly moves down the column. This is to be expected because SSC corresponds to the inhibited settling range where the settling velocity w_f decreases with increasing values of SSC. Once a density gradient forms it tends to sharpen or remain sharp as the sediment above the lutocline falls faster than sediment below the lutocline.

At later times, for lower SSC values, the lutocline becomes diffuse. This is apparent in Figure 2 at t = 20 min (a; c_o = 8.4 g l^{-1}), at t = 40 min (b; c_o = 12.5 g l^{-1}) and at t = 90 min (c; c_o = 22.9 g l^{-1}). For c_o = 32.8 g l^{-1} (Figure 3a), no such smearing of the lutocline occurs because SSC below the lutocline remained in the hindered settling range.

This development of a diffuse interface in quiescent water can be explained by the non-linear dependence of w_f on the SSC (Figure 4), in which a maximum value of w_f occurs in the range SSC ≃3–6 g l^{-1}. The relationship we find for the dependence of w_f in quiescent water on SSC correlates with the values of THORN (1981), NICHOLS (1984–1985), ROSS (1988) and VAN LEUSSEN (1988) for the hindered settling range (Figure 4).

Our experiments demonstrate that in quiescent water a lutocline may diffuse. Thus, finding a dif-

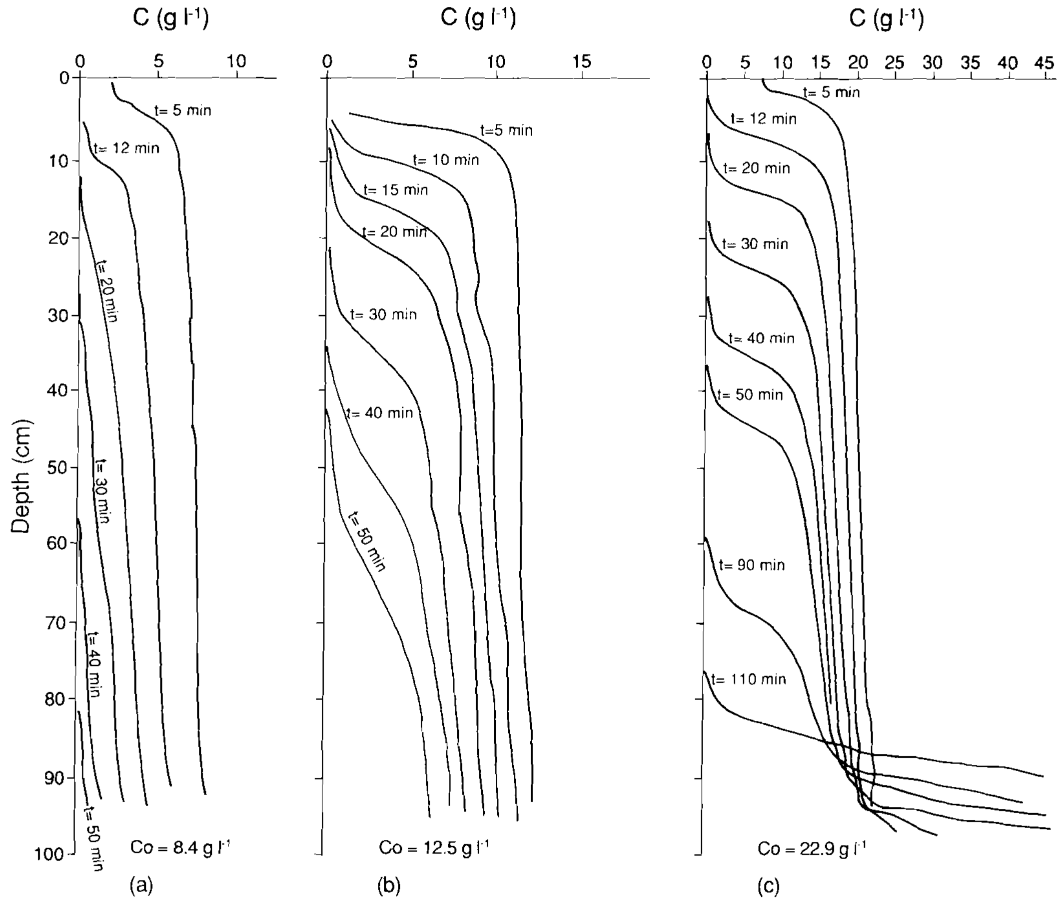

Figure 2. Vertical profiles of suspended sediment concentration for three different initial concentrations c_o of (a) 8.4, (b) 12.5 and (c) 22.9 g l^{-1}. These experiments were carried out in quiescent sea water.

fused lutocline in nature does not imply necessarily the presence of turbulence.

Recently settled fluid mud is not homogeneous. Figure 2c for instance shows strong vertical gradients in density in recently settled fluid mud. If this suspension was progressively eroded and entrained by shear from above, as in the experiment of SRINIVAS and MEHTA (1990), the entrainment rate would decrease by a factor of 10 according to whether the lutocline was at 85 cm or at 90 cm, *i.e.* in the space of 5 cm below the lutocline, because of changing density. Hence to predict the erosion rate of fluid mud, one needs to know accurately the SSC profile in the fluid mud along with other changing variables.

Next we investigated if those relationships are valid in the presence of turbulence. We recognise that even a small amount of turbulence may introduce an upward flux of sediment and modify the apparent SSC profile. This introduces a turbulent buoyancy flux in equation (1). What we can answer is the following question: is w_f measurably modified by a level of motion small enough to generate no mixing across the lutocline? Mixing could however occur below the lutocline. However we chose to generate stirring rates that are too small to generate much turbulent mixing, as we observed by studying the fate of dye in a clean water column. After 10 min of stirring, the dye had barely diffused. We generated motions throughout the entire column by oscillating the rings at velocities small enough that, from visual observations, we could determine that there was no mixing across the lutocline. Typically we found that, when oscillating the rings at peak velocities <2 cm sec^{-1} when SSC >20 g l^{-1}, the lutocline

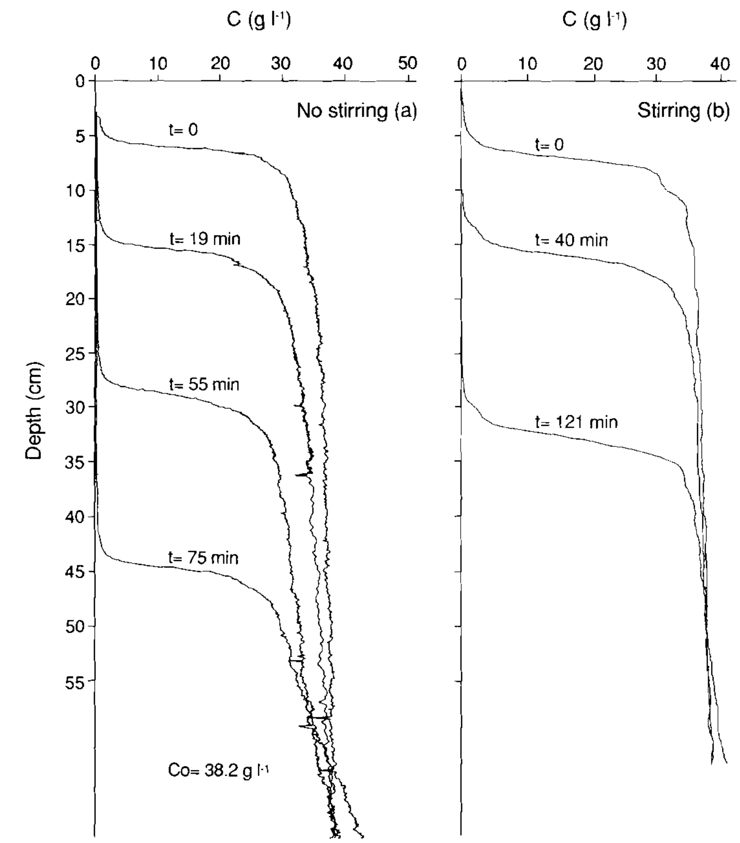

Figure 3. Vertical profiles of suspended sediment concentration with initial concentration c_o = 38.2 g l^{-1}, in (a) quiescent water and (b) under oscillating rings. In (b), the stroke was 0.75 cm and the period was 4 sec.

was convoluted by internal waves, but no mixing resulted across the lutocline. Mixing occurred at higher stirring rates when whisps of fluid were entrained from the convoluted interface (*e.g.* WOLANSKI and BRUSH, 1975; WOLANSKI *et al.*, 1989; SRINIVAS and MEHTA, 1990). Note that our stirring system introduces turbulence in both layers but that this turbulence should be depth-independent in a homogeneous fluid since the rings are uniformly spaced along the settling column.

There are two methods to check if w_f is dependent on the turbulence. In the first method we compare two settling experiments, one with the fluid at rest against one with the fluid continuously stirred. The second method consists of measuring the settling velocity in quiescent water, then stirring the fluid for a short time to measure the modified settling velocity, and then stopping the stirring and measuring w_f at rest. First a comparison with and without stirring is best summarised by comparing Figure 3a (settling in quiescent water) with Figure 3b (settling in turbulent waters), with c_o being the same in both experiments. It is apparent that w_f has been reduced, the non stirred having a fluid mud interface settling of 0.0086 cm sec^{-1}.

The second method is illustrated in Figure 5 showing the lutocline initially falling at a velocity of 0.003 cm sec^{-1} in quiescent water, then falling at a velocity $\frac{1}{10}$th when the rings are oscillated at a period of 4 sec (when no mixing occurred across the lutocline), and then falling again 10 times faster back to the pre-stirring value when stirring is stopped. In this second method the density gradient across the interface remains practically unchanged.

A decrease of w_f by a factor of 3 to 10 in the presence of very small amounts of turbulence is thus observed, independently of the presence of a solid bottom boundary. The level of turbulence

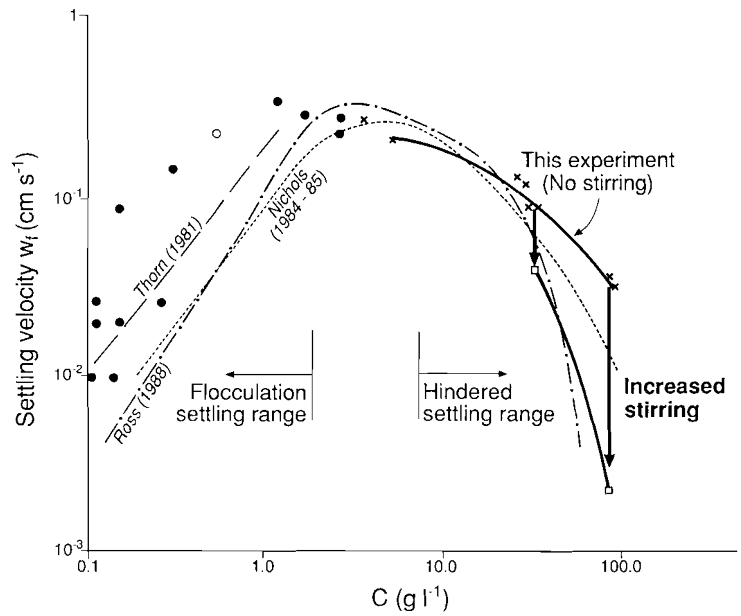

Figure 4. Dependence of the settling velocity, w_f, of the kaolinite suspension on the concentration of suspended sediment in quiescent waters. The open circle, the crosses and the full circles refer to settling in quiescent waters as derived, respectively, from microscopic observations, from visual observations of the interface, and from equation (1). The squares refer to settling velocities when stirring the rings at peak velocities of 1 cms^{-1}.

appeared too small to account for such a ten-fold decrease of w_f suggesting that settling was further inhibited by another mechanism. To elucidate the processes observed the floc size was measured with and without stirring. The floc size was only marginally smaller for the stirred case, 37 μm, than the 39 μm median diameter for the non stirred case. These kaolinite flocs should settle at 0.026 cm sec^{-1} (GIBBS, 1985) and were measured, without stirring, settling at 0.025 cm sec^{1} at low concentration where there were not significant hindrances from floc interactions (Figure 4, circle). It is obvious that all the settling rates of the fluid mud are equal to, or slower, up to 1,000 times the individual floc's settling rates (Figure 4, crosses). The observation thus showed no significant breakage at these turbulence levels. Since the obvious first effect of turbulence, that of breaking the flocs (VAN LEUSSEN, 1988), does not appear to be significant, next we studied the movement of water out of the fluid mud.

Microscopic observation of the upper few cm of the fluid mud layer (*i.e.* in the hindered settling range) revealed that under quiescent conditions it contained micro-channels that were permitting the pore water from the compacting fluid mud layer below to escape. However, the agitation, in the turbulent case, caused the smaller flocs to constantly plug these channels which therefore would cause a decrease in the dewatering rate. Upon stopping the agitation the pore water channels were reestablished within a minute which accounts for the return to nearly the same compaction rate as before agitation (Figure 5). The effect of decreasing the fluid mud compaction rate by stirring is plotted on Figure 4 (squares) along with the quiescent rates.

The fluid mud also introduces buoyancy effects and inhibits the turbulence. This is readily illustrated by placing the nephelometer a cm or so above the lutocline in quiescent water, then oscillating the rings at velocities where mixing occurs across the lutocline. Figure 6 shows an example of a typical time series. Mixing and erosion of the lutocline are rapid and after about 30 seconds a quasi-steady state occurs in this experiment. A stratified layer results separating the clear upper waters from the turbid waters below. The lutocline is thus diffused. The thickness of this stratified layer at steady state results from a balance between downward settling and upward turbulent mixing. This finding was hypothesised ear-

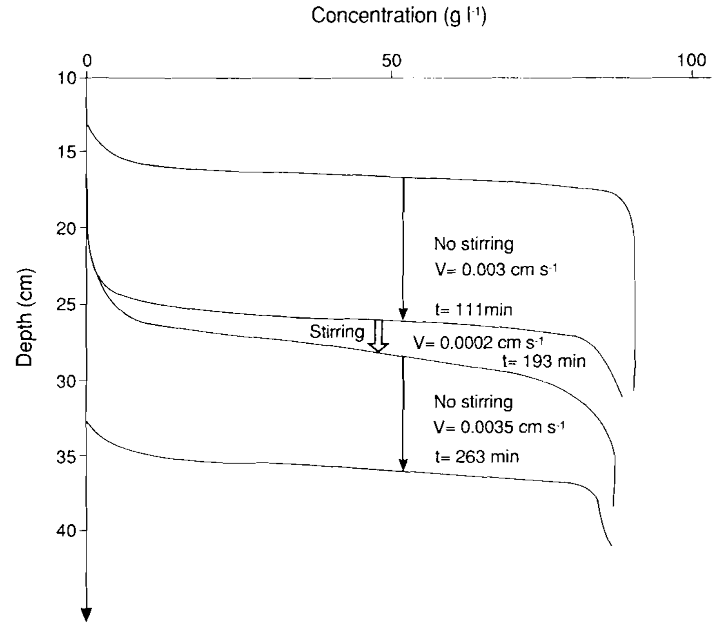

Figure 5. Vertical velocity profiles of suspended sediment at time t = 0, t = 111 min, t = 193 min and t = 263 min. The grids were only oscillating between 112 min and 192 min, quiescent conditions prevailed the rest of the time.

lier by WOLANSKI *et al.* (1989) who also proposed that the thickness of the stratified region should be much smaller than that for a non-cohesive sediment.

Examples of the stratification in SSC in this layer for various periods of oscillation are shown in Figure 7. The thickness of the stratified layer increases with increasing stirring rates, *i.e.* decreasing values of the bulk Richardson number.

Figure 8 shows examples of the internal waves experienced in the lutocline when the rings are oscillated. At low turbulent levels (long periods, T = 4.7 sec), the waves are sharp-crested with flat troughs. This indicates a turbulence collapse in the heavier fluid. This asymmetry, hence the turbulence collapse, decreases with increasing turbulent intensity (shorter periods, T = 2 sec and 1.45 sec in, respectively, Figure 8a and 8b).

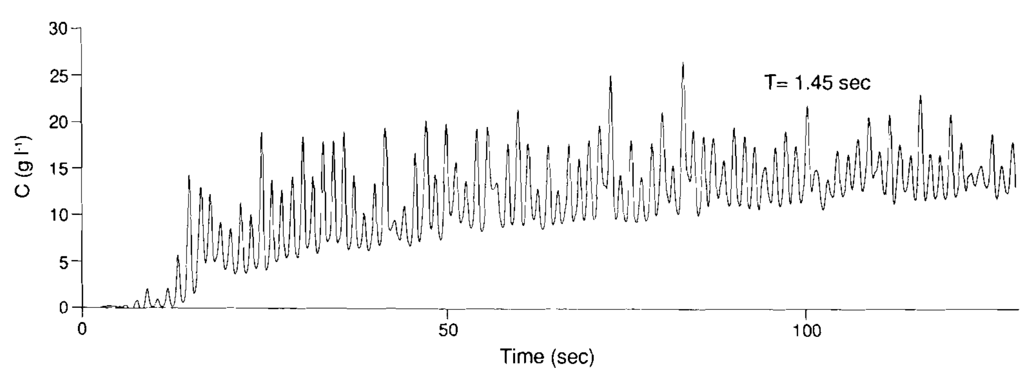

Figure 6. Time series of suspended sediment concentration when the grids are oscillated to generate mixing across the lutocline. The grid stroke was 0.75 cm and the period of oscillation was 1.45 sec. Note the initial rapid mixing and then a quasi-steady state.

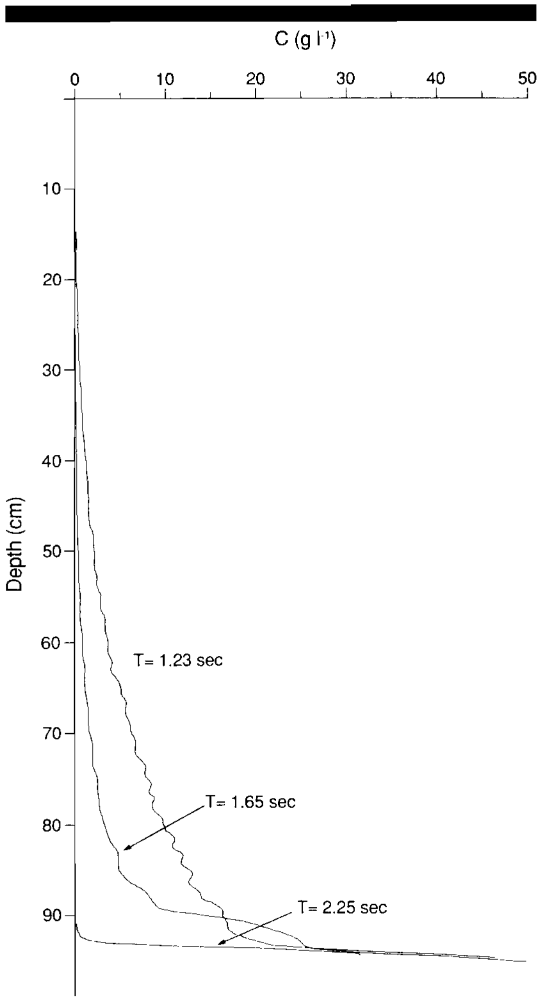

Figure 7. Typical vertical profiles of suspended sediment concentration above an initially very sharp lutocline when the rings were oscillated with a stroke of 0.75 cm and a period between 2.25 and 0.42 sec.

Our findings thus imply that w_f is not only a non-linear function of SSC, but also of the turbulent intensity. This result suggests that one should measure the turbulence characteristics in the field in order to properly interpret data on mud dynamics. This is a notoriously difficult measurement, especially in very muddy waters.

NORMANBY RIVER EXPERIMENT

Semi-diurnal spring tides prevailed (Figure 9). The increased tidal range resulted in increased tidal currents and in increased near-bottom maximum SSC from September 14 to September 17 (Figure 9). Note also in Figure 9 that the near-bottom (at the bottom sensor) SSC had a minimum value near slack high tide (events B), but that, at slack low tide (events A), it was instead at a maximum. However, 3 m above the bottom (at the top sensor of the string), minimum SSC were measured systematically at each high and low slack tide, *i.e.* at all events A and B (Figure 9). The pattern is very consistent over the three days of observation and suggests a systematic decoupling between SSC at 0.5 and 3 m above the bottom. This result cannot be explained by salinity and temperature effects since the waters were vertically well-mixed in these parameters. Temperature fluctuated with the tides in the range 27 to 28 °C, and salinity in the range 31 to 34 ppt and temperature and salinity were vertically homogeneous.

Figure 10 shows time series plots of the sea level, currents and SSC during spring tides. The patterns are very similar on other days. The SSC profiles were repetitive with the tides (not shown) and thus are not considered spurious. The vertical shear, if any, between the two bottom current meters was too small to be measured reliably and therefore is not a likely candidate for the decoupling of SSC between top and bottom sensors. The tidal currents were stronger at flood than at ebb. However, SSC were higher at peak ebb than at peak flood tidal currents. A similar finding was reported in the South Alligator River estuary and was explained in terms of a limited amount of sediment being available for fluidization and being diluted in a larger volume of water at high than at low water (Wolanski *et al.*, 1988). Note in Figure 10 the increase in SSC at the top of the nephelometer string at peak ebb tidal currents (event A1) and similar, but smaller peak, at peak flood tidal currents (event B1). At the bottom of the nephelometer string, high SSC values were also found at both peak flood and ebb tidal currents (events A1 and B1). However at slack low water (event C1), the upper waters became clear, while near the bottom maximum SSC were found. In contrast, at slack high waters, SSC decreased throughout the water columns (event D1). This pattern was consistently found in the three days of studies.

We speculate here that this pattern is due to the dependence of w_f on the turbulence. However, other explanations are also possible, *e.g.* the duration of the slack tide period and the time it takes for aggregation to form (Van Leussen and Winterwep, 1990). In this case all these hypoth-

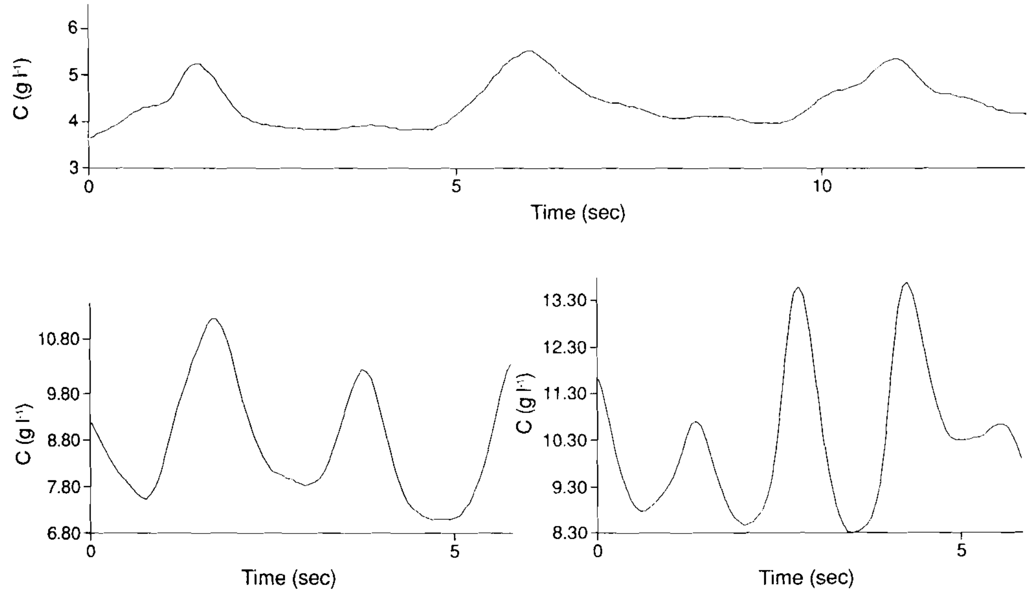

Figure 8. Example of time series of suspended sediment at a fixed elevation above the lutocline (about 1 cm) for three different periods of oscillations (a, 4.7 sec; b, 2 sec; c, 1.45 sec) and a fixed stroke of 0.75 cm.

eses are mutually compatible, while in our laboratory experiments, the quantitative model of Van Leussen and Winterwep fails to explain the observation. We have no measurements of turbulence but we can assume that turbulence only became 'small' when the currents were very small. The tidal asymmetry in currents was very strong and the tidal current reversed much faster from ebb to flood than from flood to ebb. Taking as a measurement of the slack water duration the time when the currents were <0.1 m s^{-1}, we find that the duration of slack water was twice as long near event D1 (slack high water) than near event C1 (slack low water). Since, as shown earlier, w_f is much larger (by a factor of 2 to 10) in quiescent than in turbulent waters, the sediment thus could fall out of suspension during event D1 and not during event C1 though water depth was higher during D1 than during C1. Hence at slack low water, the duration of the slack current period was so short that the water was never quiescent, and this decreased the settling velocity and a sharp

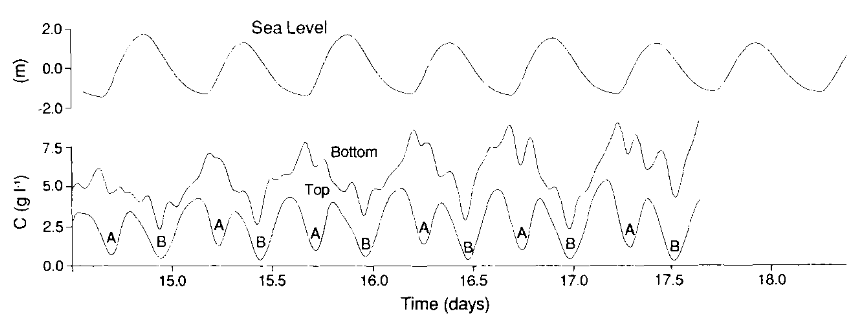

Figure 9. Time series of sea level at site A and suspended sediment concentration (in g l^{-1}) at 0.5 m above the bottom and 3.0 m above the bottom at site B in the Normanby River estuary. Time refers to days in September 1989.

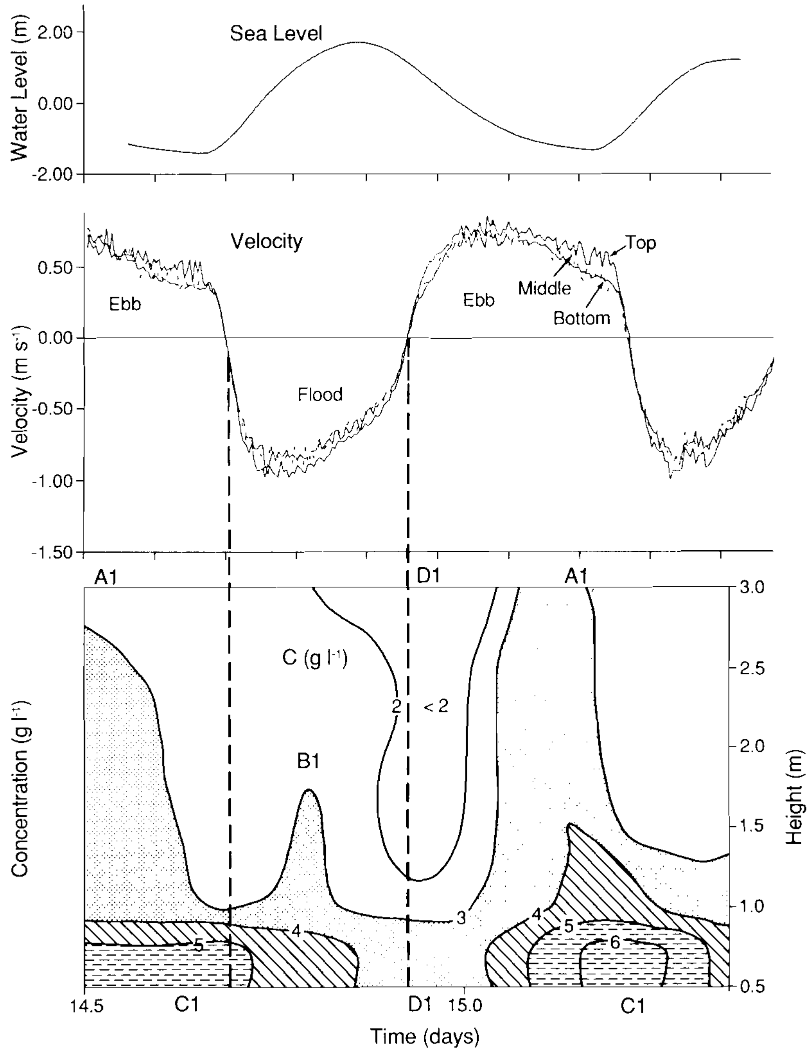

Figure 10. Time series plot of (a) water elevation at site M, (b) currents at site A at three elevations in the Normanby River estuary on September 13–14, 1989 spring tides, and (c) vertical distribution of suspended sediment concentration at site A. Events A1, B1, C1, and D1 are discussed in the text. Time refers to days in September 1989.

near-bottom lutocline remained. This simple explanation goes a long way in explaining why near-bottom SSC reached a maximum at slack low tide.

Our interpretation is speculative because we have no measurements of the turbulence. It is, however, interesting to note that we have 44 vertical profiles, reaching the bottom, at half hour intervals at station B where the tidal asymmetry of currents was also very pronounced. Those data show destratification in SSC at slack high water but not at slack low water when a turbid bottom layer remained. The thickness of that layer was about 1 m.

CONCLUSION

The sediment settling velocity is not only a non-linear function of the suspended sediments concentration, with a zone of flocculation settling and a zone of hindered settling, but is also a strong function of the turbulent intensity. Our results suggest that measurements of the settling velocity of fluid mud in quiescent laboratory conditions are likely to yield unrealistically high values when compared to field observations. This finding calls for a new technique of measuring the settling velocity of fluid mud in the field in turbulent conditions.

For the case of cohesive sediment, we find that in the inhibited settling range, the settling velocity of fluid mud depends on the ambient turbulence. Turbulence may introduce mixing in the fluid and result in an upward flux of suspended sediment, thereby decreasing the apparent settling velocity. We propose here another mechanism, which is based on our microscope observation, and which appears important because visual observation shows no mixing of the very low stirring rates we used. We propose that turbulence leads to clogging of the micro-channels used for dewatering. This produces much smaller fall velocities and has important implications in stratification–destratification cycles in estuaries.

Hence the fate of the material, and its environmental impact, can only be predicted when the dynamics of the near-bottom high concentration layer are incorporated in the calculations.

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