CHAPTER 201

A WAVE-CURRENT SEDIMENT BOUNDARY LAYER

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Abstract

A two-hour set of wave-current bottom boundary layer data collected at a dredged material placement site is examined with regard to establishing whether readily measured variables such as turbulent and wave kinetic energy (TWKE) correlate with more difficult to measure near bottom data. The data, collected in Mobile Bay, Gulf of Mexico, consisted of acoustic concentration profile data and velocity measurements at 50 and 114cm above bottom. The Reynolds Stress did not correlate well with any of the near bottom data including vertical flux and total water column mass. TWKE was a much more solid correlate with these variables but still was weak in correlating with near bottom mass. The wave kinetic energy was a solid correlate with near bottom data, particularly the mass in the bottom 5cm.

Introduction

Material from dredging operations is often placed in water where both currents (wind driven or tidal generated) and waves exert a pronounced effect on the bottom shear stress and the resulting long term stability of the material. The purpose of this article is to report on aspects of the near-bottom structure of a wave-current bottom boundary layer at a dredged material placement site in Mobile Bay, Gulf of Mexico. The information to be presented here is extracted from a comprehensive report by Bedford *et al.* (1990) which resulted from the authors participation in a comprehensive multi-investigator field experiment performed as part of the US Army Corps Dredging Research Program.

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Field Data Acquisition and Initial Results

Site Description and Instrumentation

The comprehensive project took place from August 18, 1989 to September 2, 1989 off shore of Mobil Bay, Alabama. The near bottom data presented here were collected by the ARMS (Acoustic Resuspension Measurement System) which was deployed on a Feeder Berm site in 5.75 m of water (low tide datum). The bottom materials were composed of fine grain sands and silts in the 40-60 micron range. While a 1.45° bottom slope existed on the western edge of the Feeder Berm, ARMS was placed in a flat plain almost 300 meters from this slope.

Two fifty-five hour continuously-recording data sets were collected at the site, and the data reported here came from the first deployment collected from 1301 hrs. Central Daylight time (CDT) 22 August '89 to 2033 hrs. CDT 24 August '92.

Table 1 contains a list of the instruments on the bottom sitting tripod and their sampling frequency. The uppermost Marsh McBirney current meter is used to determine wave and current magnitude and direction while vertical flux data are derived from the 50cm Above Bottom (AB) current meter. The acoustic backscatter profiler is interpreted as concentration following Libicki *et al.*, 1989 and the 1.14cm range bins provide an extremely dense profile of 1 Hertz sediment concentration profile data. ARMS wave data were corroborated with additional data supplied from the Shell Well (Shell Oil Company) site and two operational Army Corps PUV gages. The Shell Well data also contained one hour average wind speed, direction, pressure, and air-sea temperature data.

Table 1. Instrumentation and Sampling Summary

VARIABLE MEASURED	SYMBOL	MANUFACTURER	SAMPLING FREQUENCY	SPATIAL LOCATION[2]
Pressure	p	Celesco	2.0 Hz	
Temperature	T	Yellow Springs	1.0 Hz	114 cm
Velocity	u,v	Marsh McBirney	2.0 Hz	114 cm
Velocity	u,w	Marsh McBirney	2.0 Hz	50 cm
Conc. Profile[1]	C(z)	Edo Western 3MHz	1.0 Hz	130 cm

[1]positioned to meausre of concentration in a series of 100 range bins, each 1.16cm thick
[2]measured as distance above bottom

In reviewing the fifty-five hour data set, our intention was to focus attention on a wave current period of the record that was suitable for a detailed comparison of the data with proposed theoretical models, particularly the Glenn and Grant (1987) model. The conditions necessary for applying this model are quite severe (as they are with most theoretically simplified boundary layer models) and include i) constant or equilibrium vertical flux, ii) no horizontal sediment flux gradient, iii) a streamline coordinate system, iv) weak to non existent vertical tower or instrument tilt, and, for the Glenn and Grant model, v) waves and currents of somewhat equal magnitude. From the fifty-five hour data set, a two-hour period of data was exemplary in meeting all these criteria i.e. 1711 hrs. CDT to 1911 hrs. CDT 22 August '92. One of the noteable features of this piece of data is that the total horizontal current vector flows due east for the entire two hours which means that the 50cm AB current vector is sampling the full streamline coordinate average velocity. These two hour data are examined in more detail in the rest of the article and will be referred to as the "data set."

The Setting

A graphical and analytical review of the average conditions during the data set has appeared in Bedford *et al.*, 1991 and will not be repeated here. In summary, the winds were steady at 5m/sec. coming from 160° having just veered to that direction from 45° during the prior twelve hours. The tide was approaching slack tide at 1700 hrs having reached maximum ebb stage 4 hours earlier. As noted above then the current was directed the east (+x, +u) and uniformly increased over time from 15-22 and 6.5–12cm/sec at the top and bottom current meters, respectively. The significant wave height was approximately 1.0m with a peak period of 5.6 seconds. These data correspond to a wavelength of 37.0m and a bottom orbital velocity of 22cm/sec. The waves progressed to the north west (320°) in contrast to the eastward flowing current.

Local Averages and Turbulence Definition

The definition of turbulence requires that the local temporal average value be known. This local average must be from a record sufficiently long enough to achieve stationary conditions in the fluctuation statistics. With the short period gravity waves and wave groups being analyzed here, turbulence time scales and wave period fluctuations overlap and lacking any clear theoretical guidance on how to separate wave and turbulent fluctuations the only averaging operation attempted was the traditional Reynolds uniform weight function. The selection of the averaging interval T, is difficult in time varying flows. Methods suggested by Gross and Nowell (1983) and standard run tests (Bedford *et al.*. 1987) were applied to these data with a ten-minute period selected for averaging. Correspondingly, the data set was subdivided into 12 ten-minute long frames; averages performed for each frame and combined turbulent and wave induced instantaneous fluctuations were defined relative to that local average.

Average Concentration Field

Figure 1 contains the twelve average near bottom concentration profiles. The extremely sharp vertical gradient 10-20cm AB is a trademark of wave-current bottom boundary layers (WCBL) and separates the current driven region (z>20cm AB) from the combined wave-current driven region (<10cm AB). Unlike the Glenn and Grant model calculations, there is a smooth (continuous first derivative) transition region (10<z<25cm AB) between the two layers. Explicit comparisons of these profiles with the Glenn and Grant (1987) model are contained in the article by Bedford and Lee (1992). In summary, with no coefficient tuning of any kind, the model reproduced the profiles quite adequately. The near bottom (z<20cm) comparison was quite good with the comparisons at or above z>30cm being poorer than expected.

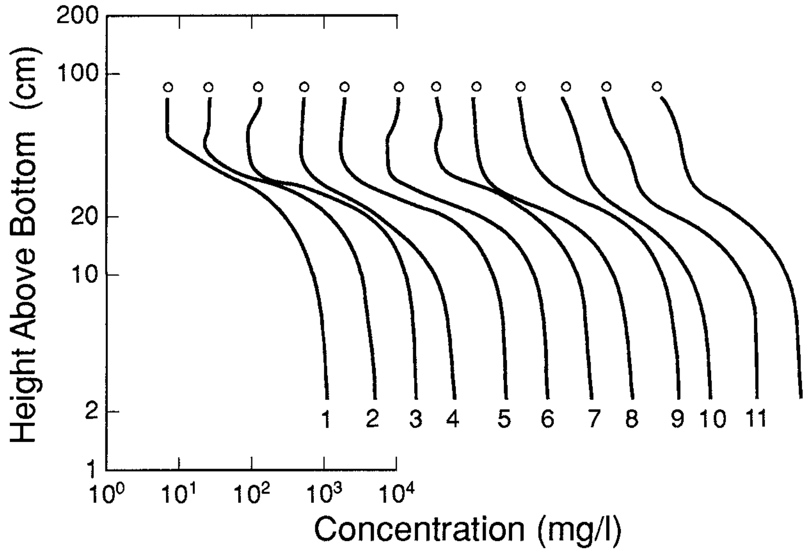

Figure 1. Profiles of the Twelve Ten-Minute Average Concentration Profiles

Turbulent and Flux Data

Turbulent Parameters

With the current meter being 50 cm AB, turbulent data as well as direct flux measurements in the thin WCBL are prohibited. Following are data on the turbulent quantities at 50 cm AB. Figure 2 contains plots of $\overline{u'w'}$ and the turbulent and wave kinetic energy (TWKE). The "Reynolds stress" varies between −2 and 0 with an average value of −1.3 cm^2/sec^2. In assessing these values it should be noted that the critical erosion stress for the bottom materials at the site is estimated by the modified Shields diagram (Glenn and Grant 1987) to be 1.34 $dynes/cm^2$ while the Achers and White value was estimated to be 0.95 $dynes/cm^2$. One can anticipate greater values of measured $\overline{u'w'}$ near the bottom and therefore assume that erosion is continuous during the period.

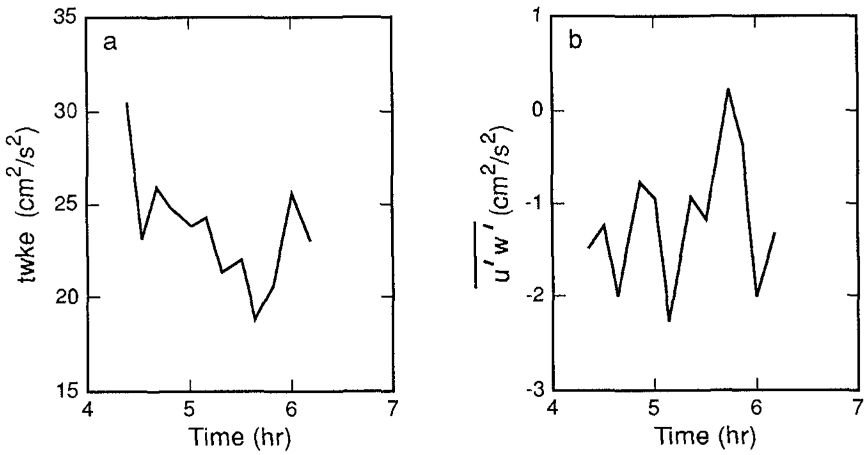

Figure 2. Time Traces of a.) Turbulent and Wave Kinetic Energy (TWKE); and b.) Reynolds Stress $\overline{u'w'}$

The TWKE average value is 24cm^2/sec^2 varying between 18–31cm^2/sec^2. The ratio of the TWKE to total energy is falling continuously during the data set from 0.45 to 0.2 with the average being 0.35.

Flux and Variance Data

The net vertical flux at 50 cm AB consists of advective $(\overline{w}\,\overline{c})$, settling $(w_s\overline{c})$ and turbulent $(\overline{w'c'})$ components. For this data set $\overline{w}\,\overline{c}$ is essentially zero; a requirement for boundary layer theories.

Figure 3a contains a time trace of the average concentration at 50cm AB and the normalized root mean square (NRMS) value. As seen, the concentrations are not high being less than 10% of the average values in the bottom 10cm. Also, the average is comprised of widely varying data achieving NRMS values of 1.0 but generally centering on 0.5. By contrast, Fig. 3b contains the same data for 5cm AB. Here again the NRMS is roughly 0.5. The average concentration is falling a bit more, probably in response to the slightly weakened wave field towards the end of the two hours. Figure 3c contains a plot of the total vertical flux at 50cm AB. It is seen to drop quickly during the first two frames to a value of $-5(10^{-3})$ mg/cm^2/sec and then change relatively little.

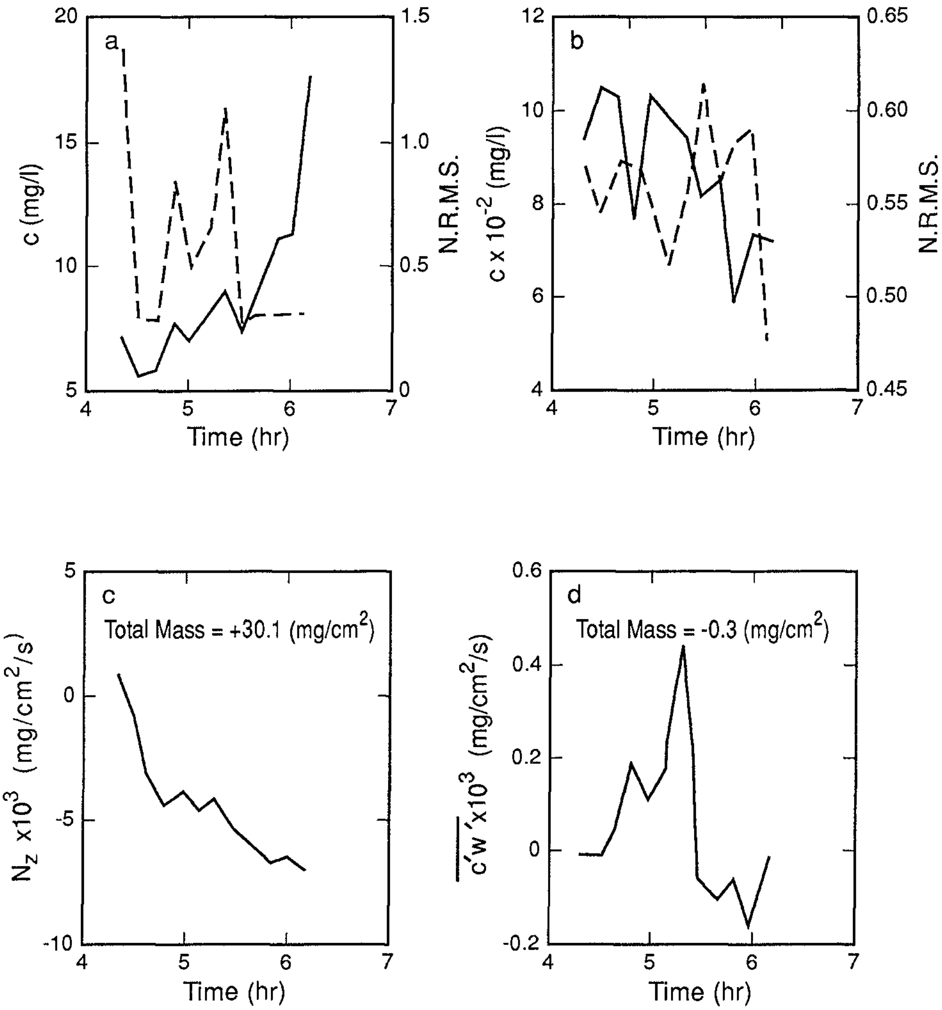

Figure 3. a.) Time Trace of Concentration at 50cm Above Bottom (AB); b.) Time Trace of Concentration at 5cm AB; c.) Time Trace of Vertical Flux, N_z, at 50cm AB; and d.) Time Trace of Turbulent Flux, $\overline{c'w'}$, at 50cm AB.

The net flux then is weakly depositional. Turbulent diffusive flux at 50cm AB (Fig 3d) is quite weak. These calculations assume a settling velocity for the particle size of 0.40 cm/sec. On Figures 4c and 4d the number "total mass" refers to the integrated flux or eqivalent mass per square centimeter that would accumulate on (+) or erode from (-) the bottom during the two-hour data set. As easily seen, the net equivalent deposition on the bottom totals 0.1 mm; i.e. a net accumulation of virtually zero.

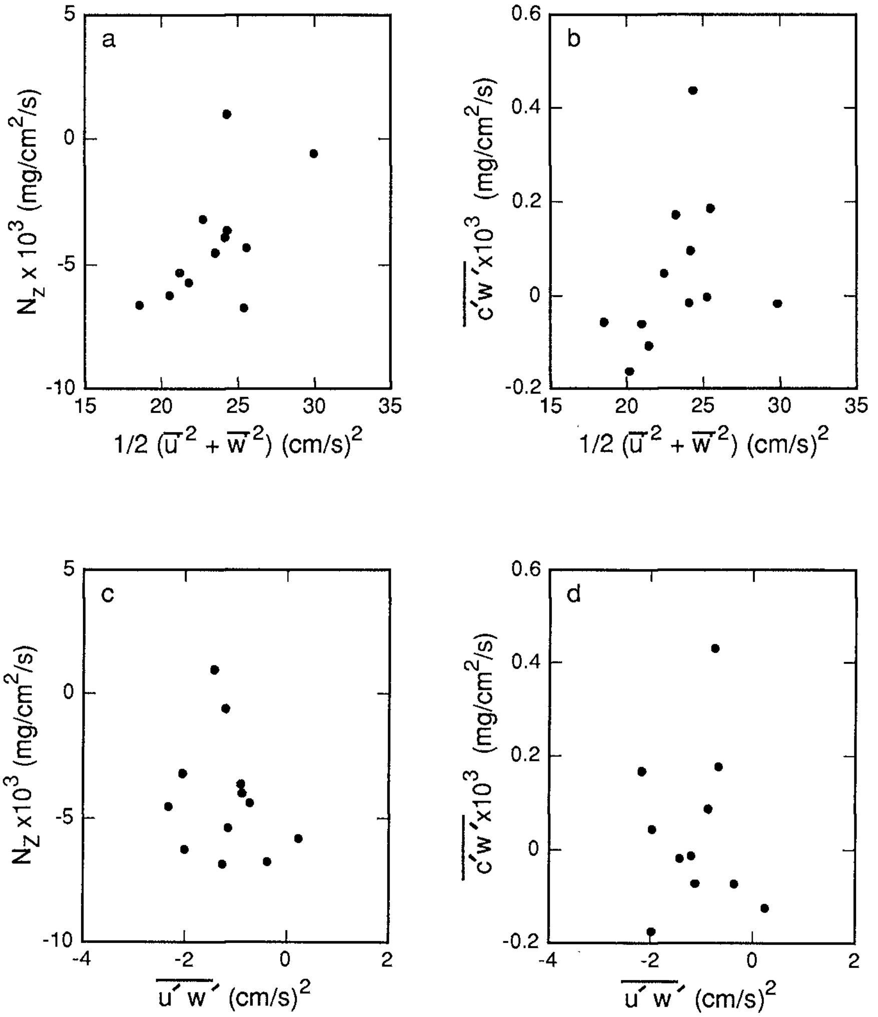

Figure 4. Scatterplots of a.) TWKE vs N_Z; b.) TWKE vs $\overline{c'w'}$; c.) $\overline{u'w'}$ vs N_Z; and d.) $\overline{u'w'}$ vs $\overline{c'w'}$

Flux Correlations

Of management interest to engineers are correlations of near bottom concentration, total mass and flux rates with other measured variables. Figures 4a-d present scatterplots of the TWKE and Reynolds stress with the total flux (N_z), and turbulent flux ($\overline{c'w'}$). As can be readily seen the correlations with $\overline{u'w'}$ or Reynolds stress are poor to nonexistent. The correlations between TWKE and the two fluxes are stronger. That the Reynolds stress is such a poor correlate should be a bit surprising as it is often thought to be strongly representative of the force necessary for erosion at the bottom. That it is such a poor correlate should bring comfort however, as it is very difficult to measure being filled with errors and subject to considerable scatter (Grant and Madsen 1986, Bedford 1992). TWKE, on the other hand, is a much simpler variable to measure and would prove to be an easier correlate to embed in empirical formulations for fluxes, etc. It should be further noted that the correlation between flux N_z or $\overline{c'w'}$ and TWKE is at the heart of many phenomenological models of turbulence (e.g. ASCE 1988) and lends field data support to that basic hypothothesis.

Concentration and Total Mass Correlations

Correlations of the average concentrations (at 50 and 5cm AB) with TWKE were inconclusive. This is a bit discouraging, especially at 50cm AB where the nonlinear and confounding effects of ripples, sediment stratification, and vortex shedding, etc., are minimal.

Another type of correlation of a sediment profile measure, the integrated profile mass, was a good deal more successful. Here the instantaneous profiles were integrated from z = 0 to various heights above bottom (e.g. 5 cm, 50 cm) and the resulting integrated mass time averaged. Figures 5a,b contain the integrated mass time variation for z = 50 and 5 cm AB, respectively. Q_{50} is generally falling in accordance with the gradual decrease of wave energy. Q_5, even though an integrated and therefore a smoothed measure, is a bit more irregular, an indication of the complexity of the near bottom physics.

Figures 5c,d contain correlations between TWKE and Q_{50} and Q_5, respectively. A clear linear relationship between TWKE and Q_{50} is noted. Again, the lack of clear correlation between TWKE at 50cm AB and local near bottom activity is noted. Clearly, using remote (50cm AB) turbulence data isn't advisable in establishing values of local near bottom concentration and interfacial exchange values.

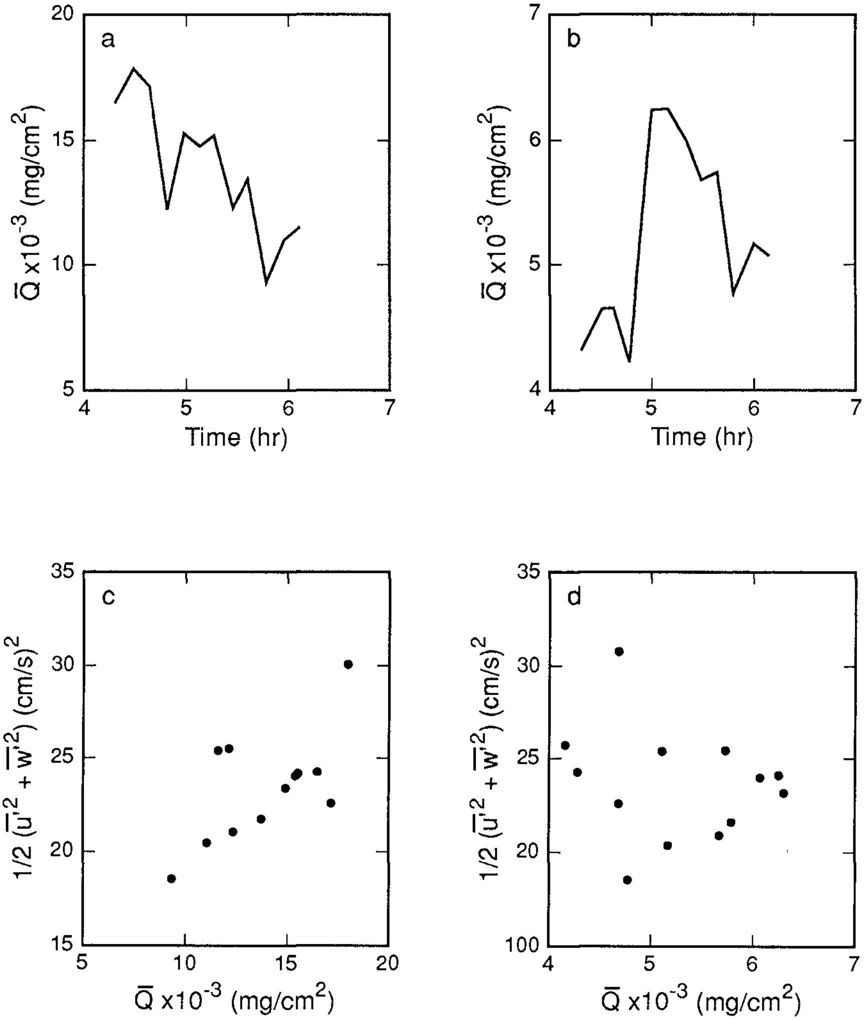

Figure 5. a.) Time Trace of Integrated Mass at 50cm AB, Q_{50};
b.) Time Trace of Q_5;
c.) Scatterplot of TWKE and Q_{50}; and
d.) Scatterplot of TWKE and Q_5.

While turbulence measures can be altered dramatically between 50 cm and 5cm AB by for example stratification and therefore provide poor correlation, wave data at 50 cm penetrate relatively unscathed to the near bottom region and thus might be a better correlate under certain conditions. Figures 6a,b contain scatter plots of the wave kinetic energy (as calculated by

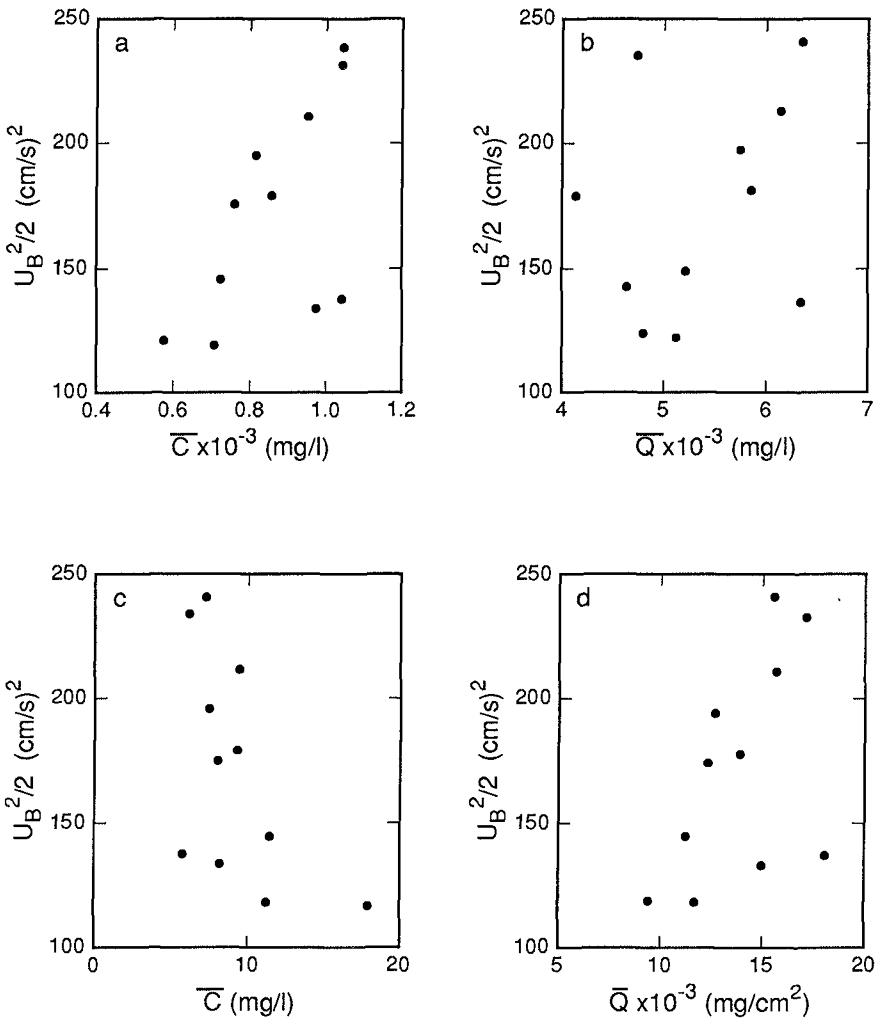

Figure 6. Scatterplots of a.) Bottom Orbital Velocity Energy, $U_B^2/2$ vs C at 50cm AB; b.) $U_B^2/2$ vs Q; c.) $U_B^2/2$ vs C at 50cm AB; and d.) $U_B^2/2$ vs Q_{50}

one half the bottom orbital velocity squared), and $\bar{c}$ and Q at 5cm AB. Here, a clear linear relationship is at hand; reflecting not only the dominance of the wave in local bottom activity but also a relatively simple procedure for perhaps constructing empirical relationships for bottom exchange. Figure 6cshows that $U_B^2/2$ also correlates quite well with the integrated mass measure Q_{50}. Figure 6d, quite by contrast, shows poor correlation between $U_B^2/2$ and $\bar{c}$ at 50cm AB, thus indicating that a more complex suite of physical processes is at work in controlling the values of the two sediment measures.

Shape Analyses and Correlation

Based upon a geometric shape analysis procedure developed by Velissariou and Bedford (1989) the 12 average profiles were analyzed and four relatively distinct regions separated by three "boundaries" were identified. Figure 7 contains the time series of the heights of the various boundaries. The top of the wave-current boundary layer is seen to be relatively steady at 10-11 cm AB; the transition region occupies the region between 12-24 cm AB and

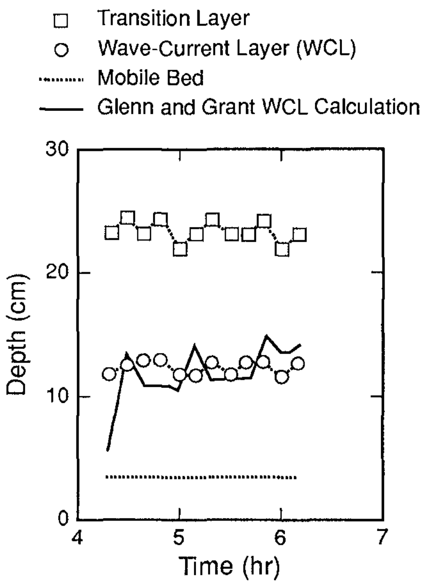

Figure 7. Time Trace of the Heights of the Measured Tansition Layer (□), the Measured Wave-Current Boundary Layer (O), the Measured Mobile Layer (---) and the Calculated Wave-Current Layer (_____).

below 3cm we found evidence for a mobile layer. The height of the wave-current boundary layer calculated by Glenn and Grant (1987) is also plotted and is seen to fall squarely on the geometrically determined heights.

Recognizing from the previous correlations how well TWKE and its subsumed but dominant wave kinetic energy correlated with integrated mass measures, it should come as no surprise that it also correlated very well with the total mass in the WCBL (Q_{11}) and the total mass just in the transition layer ($\overline{Q}_{11-24}$).

Summary

The tower by which these data were collected contained an extremely robust and exotic suite of instrumentation. By examining various correlations in these robust data, we can perhaps begin to identify simpler point measurements that can be made with more readily available instruments. Clearly, these results indicate that TWKE, with its subsumed wave kinetic energy component, is a fundamental correlate with a number of important parameters including N_z (z=50), $\overline{c'w'}$ (z = 50), Q_{50}, Q_{11} (the mass in the WCBL) and $\overline{Q}_{11-24}$ (the mass in the transitional layer). TWKE was a weaker correlate with near bottom Q_5 and provided no correlation with C_5.

The wave kinetic energy in the form of $U_B^2/2$ was a solid correlate with the bottom activity Q_5; C_5. $U_B^2/2$ didn't correlate well with C_{50}, nor did TWKE.

The WCBL height predicted by the Glenn and Grant model was identical to that measured by our devices indicating the soundness of that empirical representation as well.

While notable, these simplifications did come from a data set that was selected via some strong restrictions. That there are still many unexplained features and results in these data which suggests we have far to go in achieving understanding when we depart from the benign equilibrium conditions analyzed here.

Acknowledgements

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