Coherent Doppler Sonar: Sediment Flux and Turbulent Velocities in a Wave Flume

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1 ABSTRACT

Observations of vertical sediment flux and velocity structure are made under prototype scale waves in the Wave Research Flume at the National Research Council (NRC) in Ottawa. Observations were made under regular waves of 3.5 s period with heights ranging from 20 to 70 cm. Direct measurement of sediment flux is made possible using 1.7 MHz pulse-to-pulse coherent sonar which determines concentration from acoustic backscatter levels and velocity using acoustic Doppler. Operating over a 0.8 m range, velocity profiles with 1.4 cm range resolution and a 0.5 cm s^{-1} vertical velocity accuracy can be made at a rate of 30 profiles per second. We find that there is an apparent balance between the mean downward flux of sediment and the upward flux due to turbulent motions. The component of (upward) vertical flux caused by wave action is small compared to the turbulent and mean components. Profiles of turbulence intensity are provided by the vertical velocity fluctuations, these profiles show a rapid rise to a peak value within 5 cm of the bottom and then a subsequent decrease. The (near bottom) peak value of root-mean-square vertical velocity fluctuations are equal to the friction velocity characteristic of the bottom boundary layer. The decrease in turbulence with height above the bottom shows behavior consistent with the decrease in grid generated turbulence but appears sensitive to the length scales of the bed-forms rather than sand grain roughness.

2 INTRODUCTION

Knowledge of the vertical distribution of suspended sediment is required to model the transport of sediment due to wave action. In order to better understand the contributions of turbulent motions to the sediment suspension process coincident measurements of suspended particle concentration and velocity must be made. Such observations are lacking and are particularly needed for comparison with model predictions.

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We present acoustic measurements of vertical velocity and suspended sediment concentration using a coherent Doppler sonar (Zedel et al. 1996). The 1.7 MHz, Dopbeam system was configured to provide velocity profiles with 1.4 cm range resolution and a 0.5 $\mathrm{cm\,s^{-1}}$ vertical velocity accuracy at a rate of 30 profiles per second. Concentration measurements are acquired at the same time and location through calibration of the acoustic backscatter levels to absolute concentrations for the sediment samples used. The Dopbeam system has been calibrated using a sediment laden turbulent jet as described by (Hay 1991).

The measurements were made in the Wave Research Flume at the National Research Council (Ottawa), Canada. This facility has a length of 100 m, a width of 2.0 m and was filled to a water depth of 1.8 m. A 10 cm thick layer of 150 μm (sorted) sand was deposited through a 20 m long test section. Observations were made with regular and irregular waves with nominal heights of 20 to 70 cm.

3 VERTICAL FLUX

The vertical flux of sediment can be expressed as;

$$F = < \bar{w}\bar{c} + \tilde{w}\tilde{c} + w'c' > \tag{1}$$

where w is the vertical component of velocity, c is the concentration, the tilde and prime refer to wave and turbulent components respectively, $<>$ indicates a time average. The three terms on the right hand side of Equation (1) represent mean, wave induced, and turbulent vertical flux respectively: each of these terms are evaluated from the amplitude and Doppler shift of the backscattered signal as a function of height above the bed.

The mean component of flux results from the mean settling velocity and the concentration structure. In general, the mean flux component will depend on changes in concentration and velocity. One approach to modeling this component is to assume that the mean velocity is fixed at the free descent velocity of the particles (Nielsen 1992). For the present observations, where the particles have uniform size, we might expect mean velocities to be constant with height. Fig. 1 shows concentration profiles (Fig. 1a) and mean vertical velocities (Fig. 1b) for the present observations. The concentration profiles show the expected logarithmic form decreasing with height above the bottom. The velocities however are notable in that the mean downward velocity is not constant with height. In particular, there is a consistent trend for the mean velocity to decrease with proximity to the bottom in a region extending to within 5 cm of the bottom. Based on these observations, the assumption of a uniform mean velocity is not appropriate.

Wave components were isolated by selectively averaging data according to the wave phase, the turbulent components were then determined as the residual after mean and wave components were removed. We find that the sum of these flux terms is approximately balanced as is shown by the example in Fig. 2. The averaged mean flux is downward (settling) with the wave and turbulent flux being in an upward direction. The wave component of flux is relatively small and thus an approximate balance exists between the turbulent upward flux and the mean downward settling flux.

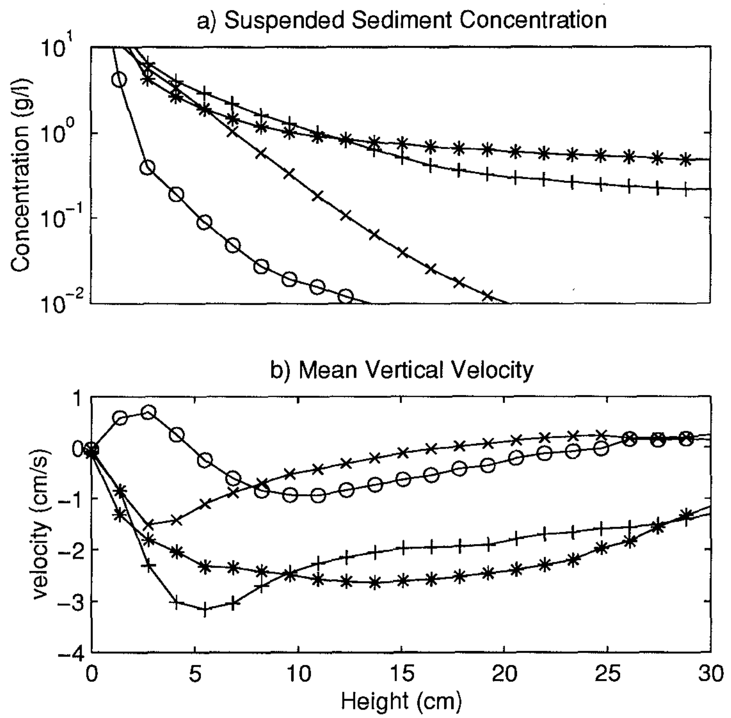

Figure 1: Mean profiles of a) suspended sediment concentration and b) vertical velocity for observations of 3.5 s period regular waves with heights of 20, 40, 60 and 70 cm indicated by $\circ$, $\times$, $+$, and $*$ respectively.

4 TURBULENCE INTENSITY

The energy driving sediment upward from the bottom is derived from turbulent fluid motions. This energy can be parameterized in terms of the friction velocity u_*. A parametric estimate of friction velocity can be determined from sand grain roughness, wave amplitude and frequency (Nielson 1992),

$$u_* = \sqrt{f_w/2}\,A\omega \tag{2}$$

where $\omega = 2\pi/T$, $T = 3.5\,\mathrm{s}$ is the wave period, A is the wave orbital excursion and f_w is the friction factor computed as,

$$f_w = exp(5.5(r/A)^{.2} - 6.3) \tag{3}$$

with $r = 150\,\mu$ m the sand particle diameter. Values for this parametric estimate of friction velocity are listed under u_* in Table 1 along with bed form characteristics and wave heights.

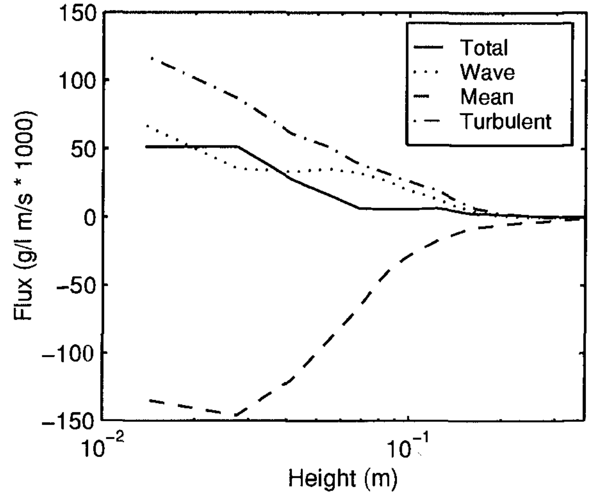

Figure 2: Profiles of mean, wave, turbulent and total sediment flux. Profiles are based on a 6 minute data sample under regular, 3.5 s period waves of 60 cm height.

H cm	Bed Form	u_* cm s^{-1}	u_*(sediment) cm s^{-1}	w'_{max} cm s^{-1}	b(parametric) s/m^2	b(observed) s/m^2
20	R_l	1.5	2.2	2.3	3200	920
30	R_s	2.3	2.5	2.5	1330	440
40	R_s	3.1	3.2	2.9	660	560
50	X	3.4	3.9	3.5	430	460
60	X	4.2	7.0	5.6	240	340
70	F	4.9	5.0	4.4	150	80

Table 1: Summary of trials under 3.5 s period waves with heights indicated as H; u_* is the friction velocity computed from parameterizations of wave height, u_*(sediment) is based on the near bottom profile of suspended sediment (Sheng and Hay, 1995), w'_{max} refers to the maximum observed variance in vertical velocity observations. Bedforms are indicated by R_l, R_s, X, and F for long crested, short crested, cross ripples, and flat bed respectively, b(parametric) and b(observed) are the predicted (see 5) and observed slope in $1/ < w'_{rms} >$ profiles.

Values of u_* can also be estimated from the observations through the slope of the suspended sediment concentration following the approach used by Sheng and Hay (1995). Table 1 compares the values of u_* derived from this technique ($u_*(sediment)$ in Table 1) with parameterizations based on the waves and grain roughness (Nielson, 1992) (u_* in Table 1).

An independent indicator of the turbulence characteristics of the boundary layer is provided in the present observations by profiles of $< w'_{rms} >$: example profiles are shown in Fig. 3a. Nielsen (1992, p. 72) reports that peak values of $< w'_{rms} >= 0.5u_*$ occurring at a height approximately equal to the top of the roughness elements. Similar relations are also seen in unidirectional boundary layer flow (Tennekes and Lumley, 1972 p. 162). The peak values of $< w'_{rms} >$ in the present observations are very close to the parametric estimates of friction velocity as well as those based on concentration profiles (see the values listed as w'_{max} in Table 1).

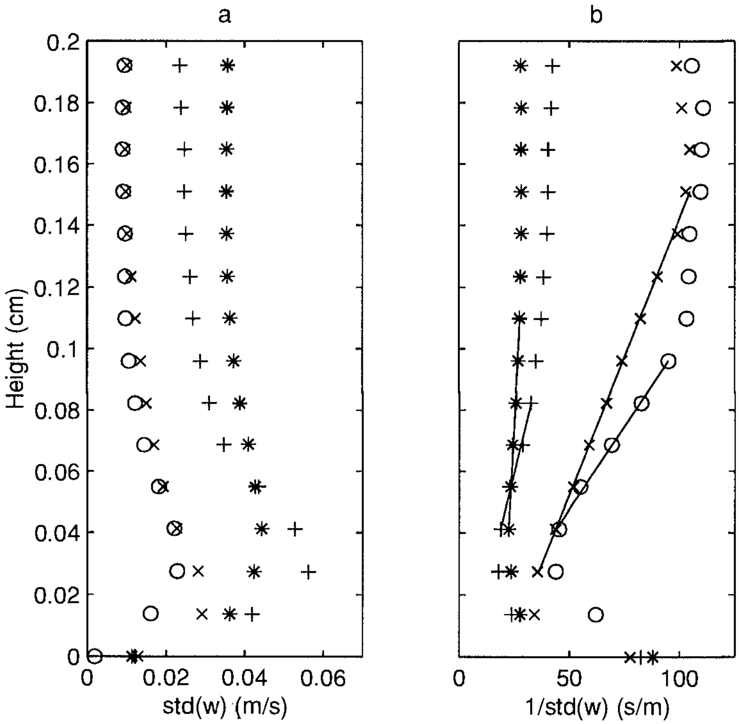

Figure 3: a) Profiles of $< w'_{rms} >$ and b) $1/ < w'_{rms} >$ as observed under 3.5 s period waves of height 20, 40, 60 and 70 cm indicated by $\circ$, $\times$, $+$, and $*$ respectively.

An important aspect of the data summarized in Table 1 is the apparent response to changing bedforms. In particular, the decrease in the observed indicators of friction velocity (u_*(sediment), and w'_{max} in Table 1), that occurs between 60 and 70 cm wave heights coincides with the disappearance of small scale bedforms. The associated change in roughness is not accounted for in the parametric estimate of friction velocity but it is clearly important to regulating the turbulent contribution to sediment flux.

5 TURBULENCE DECAY

Sleath (1991) suggests that oscillatory boundary layers can be modeled after the turbulence generated by an oscillating grid. Such a model is qualitatively consistent with the present observations where $< w'_{rms} >$ decreases with height beyond a point of maximum value near the bottom. Following Sleath's model, the turbulent intensity should decrease with distance from the bottom according to the relation (Sleath, 1991),

$$1/ < w'_{rms} >= bz \tag{4}$$

with

$$b = KA^{-3/2}r^{-1/2}T \tag{5}$$

where A is the wave orbital excursion, r is the bottom roughness (here we have set $r = \lambda_r$ because use of the sand grain roughness gave extremely inconsistent results), and $K \approx 6.29$ is a constant. Values for the expected slopes from (5) are indicated as b(parametric) in Table 1. Figure 3b shows observed values of $1/ < w'_{rms} >$ plotted as a function of height above the bottom for trials under wave heights of 20, 40, 60 and 70 cm. There is a well defined section where a straight line fit to the data is achieved. The slope from linear regression fits to this region (indicated by straight line segments in Fig. 3b), are identified in Table 1 as b(observed). Approximate agreement between predictions of (5) and the observations is seen for some of the trials, but in general, there are significant differences. In particular, at low wave energies, the value of b predicted by (5) is larger than the observations by a factor of 3 indicating that turbulence does not decay with height as rapidly as expected based on the grid turbulence model.

6 DISCUSSION

Doppler velocity estimates represent a backscatter strength weighted average over the velocity of any scatterers present in the sample volume. When Doppler sonar is used to measure water velocities, it is necessary to assume that the motion of the scattering particles is representative of the water motion as a whole. For the present application, the velocities observed will be those of the uniformly sized (150 μm diameter) sand particles added to the tank. Only when the concentration of these particles is extremely low will the small bubbles and dust particles in the tank provide an estimate of the water velocity itself. As a result, the mean vertical velocities shown in Fig. 1 are a direct measure of the in-situ settling velocity of the suspended sand particles.

The settling velocity for spherical particles can be calculated using Stokes law,

$$w_s = \frac{(s-1)gd^2}{18\nu} \tag{6}$$

where $s = 2.7$ is the relative density of the particle, d is the particle diameter (d =150 μm for the present sand particles), g is the acceleration of gravity and ν is the viscosity ($\nu = 1.0 \times 10^{-6}$ m^2 s^{-1}). For the present d =150 μm sand particles, $w_s \simeq 2.0$ cm s^{-1}.

Settling velocities of 2 to 3 $\mathrm{cm\,s^{-1}}$ were observed at heights of between 10 and 20 cm for the 60 and 70 cm height wave runs (Fig. 1b). These values are consistent with the prediction of the Stokes settling velocity given by (6). The low velocities seen in this depth range for lower wave heights are most likely caused by the low particle concentrations ($\approx 10^{-2}$ $\mathrm{g\,l^{-1}}$) that occur (see Fig. 1). Under such circumstances, the backscatter from small contaminants in the water would provide an adequate signal such that the true water velocity would be obtained.

In all cases, the mean velocity goes to zero as the bottom is approached. These decreased settling velocities clearly have a significant impact on the concentration profiles. The cause of the reduced velocities is not obvious but some disturbance is expected due to the presence of bedforms. These bedforms could not however account for the gradual transition to zero velocity that is observed. It is very likely that these near bottom reduced settling velocities are related to the presence of turbulence as described by Murray (1970).

Profiles of mean turbulent intensities based on values of $< w'_{rms} >$ demonstrate a rapid increase from 0 at the bottom to a peak value within 5 cm of the bottom and then an asymptotic decrease with greater height. In the present observations, $max(< w'_{rms} >)$ is clearly proportional to friction velocity, but it appears to vary as an equality; that is $max(< w'_{rms} >) = u_*$ (see Table 1). It is possible that the present observations do not resolve velocities close enough to the bottom to recover the true peak values. If this were the case, one would expect that the proportion of the fluctuations seen would change with the bed-form dimensions. No such dependence is seen and so we feel that we are sampling a consistent maximum in velocity fluctuations. It is also possible that the sonar system does not resolve the total turbulent spectrum. We consider this explanation unlikely as well because the 'red' nature of turbulent spectra places most of the energy at lower frequencies, (and larger scale structures) which the Dopbeam system does resolve.

7 CONCLUSIONS

Through the use of combined Doppler sonar and acoustic backscatter measurements it has been possible to make simultaneous estimates of particle velocity and concentration. This combination of measurements allows for direct observation of particle flux. Phase averaging under regular waves (possible in the tow tank test facility) allows the discrimination of both turbulent and wave components of flux ($w'c' + \tilde{w}\tilde{c}$) in addition to the mean (downward) flux.

The assumption of a balance between the upward wave and turbulence induced flux with the mean downward flux is fundamental to most models of vertical sediment transport (see for example Lee and Hanes, 1996). We have demonstrated that such a balance does exist in the present data. Previous estimates of the downward flux term have been made from independent measurements of particle descent rate and concentration: a common assumption is that the particle descent rate is given by the free descent rate of the particles (Sheng and Hay, 1995). This assumption appears to hold for most of the water column but breaks down within 5 cm of the bottom in the present observations.

The turbulent velocity represented by $< w'_{rms} >$ peaks a small distance above the bed (within 5 cm in the present observations). At heights above the peak value, $< w'_{rms} >$ decays as 1/height, consistent with Sleath (1991).

The near bottom peak values of $< w'_{rms} >$ are equal to the friction velocity characteristic of the bottom boundary layer (as estimated parametrically and from the concentration profile). We conclude that the direct observation of $< w'_{rms} >$ possible with the coherent Doppler system is an effective means of estimating friction velocity.

The three separate estimates of friction velocity (based on the sediment diffusivity, the wave parameters, and the $< w'_{rms} >$ measurements) are all consistent. The slight decrease in friction velocity occurring in the diffusivity and $< w'_{rms} >$ based estimates when going from the 60 cm to 70 cm wave height at first appears inconsistent. However, the fact that both of these direct observations show the same behavior supports their accuracy. The bed-form observations for these two wave conditions show that they correspond to the transition from cross ripples to 'mega-ripples'. The 'mega-ripples' result in a much reduced mean bottom slope and associated with this reduced bottom slope we would expect a reduced efficiency in turbulence generation. While the data is clearly limited, we believe that the reduced friction velocity is accurately being observed and is associated with the changing bed-forms. The parametric estimate of friction velocity (which ignores bed-forms) matches the observations reasonably well. This close agreement indicates that (in the present case), while bedforms effect the turbulence generation they do not account for a large contribution to turbulence important to sediment suspension.

8 REFERENCES

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