CHAPTER 108

Wave–Induced Flow And Nearshore Suspended Sediment

J.C. Doering* and A.J. Bowen

1. Introduction

It has been realized for nearly one hundred years that the transport of sediment is related to the characteristics of a wave, in particular its shape. Cornish (1898) noticed that the shoreward velocity associated with a wave crest was more effective at moving coarse sediment than was the seaward velocity associated with the wave trough. Cornish's observation was consistent with the theory of Stokes (1847), which predicts the onshore velocity associated with the wave crest is stronger and of shorter duration than the offshore velocity associated with the wave trough. This horizontal asymmetry of the cross–shore flow, which is a reflection of the wave shape, is known as velocity skewness. It has been suggested that "the existence of the beach depends on small departures from symmetry in the velocity field balancing the tendency for gravity to move material offshore"(Bowen, 1980). Although the concept of velocity skewness has been incorporated into detailed predictors of sediment transport (Bowen, 1980; Bailard and Inman, 1981) it is only one of many facets that needs to be understood in order to make the accurate prediction of sediment transport realizable. A comprehension of sediment transport is hampered by both an incomplete knowledge of the hydrodynamics and a lack of instrumentation to directly measure instantaneous sediment concentration and the accurate prediction of sediment transport is probably the most enigmatic problem in coastal engineering.

Occasionally, suspended sediment concentration has been inferred from *in situ* pumps and hand–held tubes, but these methods lack the temporal and spatial resolution necessary to elucidate the details of the interaction between the wave–induced flow and the sediment. Recently, a miniature optical backscatter sensor (MOBS), which provides a time series of suspended sediment concentration at a "point", was developed by Downing *et al.* (1981). During a recent field experiment a vertical array of 5 of these optical backscatter sensors and a colocated flow meter was deployed close to the sea bed. These colocated measurements provide a unique opportunity to investigate the response of near–bed suspended sediment concentration to the wave–induced flow.

Department of Oceanography, Dalhousie University, Halifax, Nova Scotia B3H 4J1 Canada

* Presently at Hydraulics Lab., National Water Research Institute, P.O. Box 5050, Burlington, ON L7R 4A6

2. Field Measurements

Data were collected at Pte. Sapin, New Brunswick, as part of the Canadian Coastal Sediment Study. This field experiment was conducted during October–November, 1983. Data from a Marsh–McBirney flow meter, measuring the horizontal components of the flow, and a colocated miniature optical backscatter sensor (MOBS) were used to examine the temporal response of suspended sediment to the wave-induced flow field. The MOBS and flow meter were located at 0.02 m and 0.12 m above the sea bed, respectively. Note that only the lowest MOBS sensor data is used in this paper; a description of the data from all five sensors can be found in Hanes and Huntley (1986).

Data for this paper is confined to a run collected on the 20^{th} of October (run FM). The significant wave height for run FM was 0.20 m. The instrument array was located well seawards of wave breaking in about 1.1 meters of water. Figures 1a and 1b show the first twelve minutes of cross–shore velocity (u) and near–bed sediment concentration (c) for the 20^{th} of October at Pte. Sapin, respectively. Since the alongshore velocity is much smaller than the cross–shore velocity ($\frac{\langle v^2 \rangle}{\langle u^2 \rangle} \sim 0.06$), the alongshore component of the flow is neglected from this analysis and discussion. It is obvious from figure 1 that the concentration of near–bed suspended sediment responds to both the individual waves and the wave groupiness. The response of the concentration to the flow associated with the passage of each wave is intriguing because the concentration seems to respond strongly and rapidly to the onshore flow associated with a wave crest, but very weakly to the offshore flow associated with a wave trough. A close inspection of figure 1a suggests that the cross–shore flow is strongly skewed; in particular, the onshore velocities are considerably stronger and of shorter duration than the offshore velocities (this can be readily seen with respect to the horizontal line denoting the mean flow). The suggestion from figure 1 is the stronger onshore flows associated with the skewed wave crests exceed the threshold velocity for the mobilization and subsequent suspension of sediment, while the weaker offshore flows associated with the "flattish" wave troughs do not. In addition, this suggestion implies that there should be a net onshore transport of sediment by the wind–waves at this height because the onshore flow will advect a high concentration of sediment shoreward whereas the offshore flow will advect a low concentration seaward. The cross–shore transport of suspended sediment at this height is given by the product $u \cdot c$, and is shown in figure 1c. The shoreward transport of suspended sediment associated with a wave crest is clearly larger than the seaward transport associated with a wave trough, as anticipated. For Bagnold–type models of sediment transport the instantaneous cross–shore sediment transport varies with the velocity moment $u^3|u|$, which is shown in figure 1e. However, $u^3|u|$ is in general very strongly correlated with u^3, the dimensional skewness of the flow (figures 1e and 1d, respectively). For the present case $r^2 = .93$. Thus, the transport of suspended sediment is intimately related to the skewness of the flow; the covariance of $u \cdot c$ and u^3 is readily apparent from figure 1.

Particularly interesting is the way the transport tracks u^3 even though the effect of a critical stress (threshold velocity) has not been included, nor has any representation of the settling characteristics of the sediment. Obviously both effects need to be included in a realistic model, the critical stress for suspension must

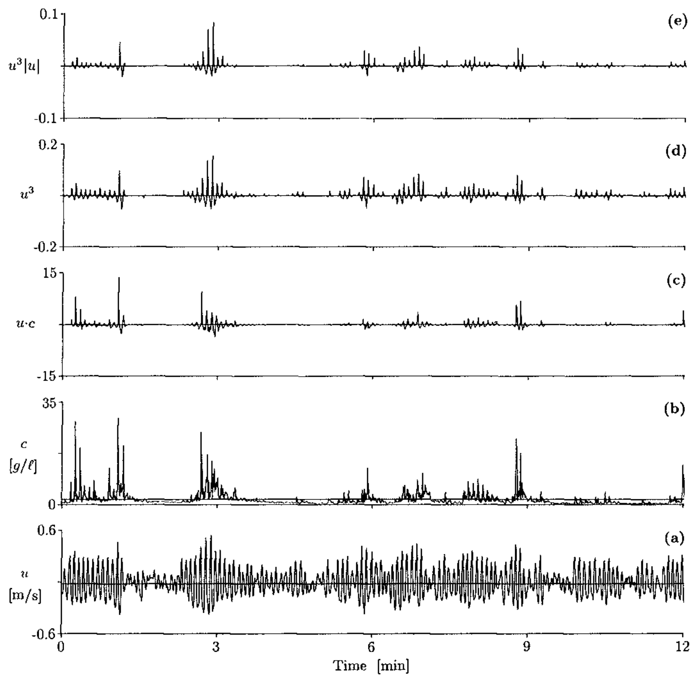

Figure 1 Time series of cross-shore velocity **(a)**, near-bed sediment concentration **(b)**, instantaneous suspended load transport **(c)**, and two moments of the cross-shore velocity field, u^3 **(d)** and $u^3|u|$ **(e)** for the first twelve minutes of run FM at Pte. Sapin. A positive velocity denotes an onshore flow. The horizontal line through each record denotes the mean.

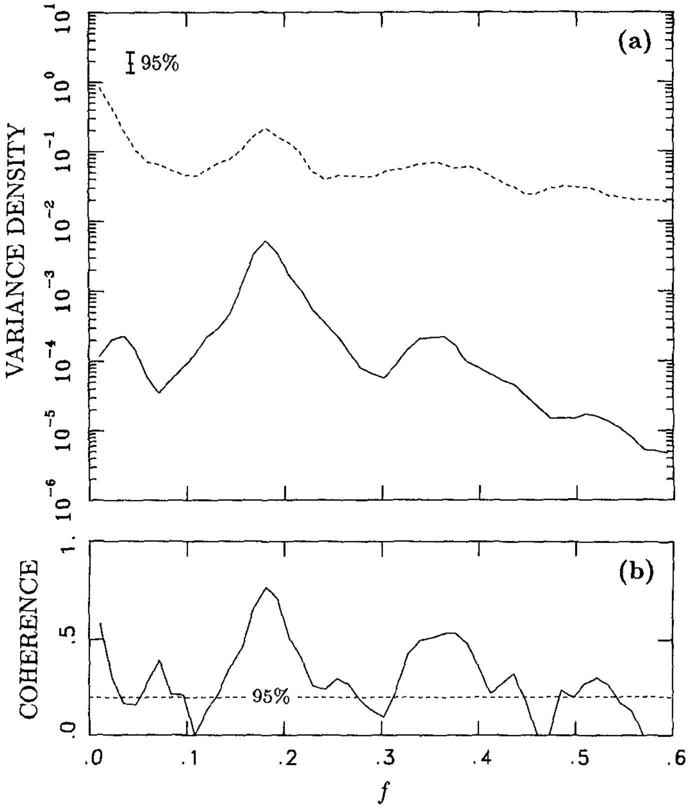

Figure 2 (a) Spectra of cross–shore velocity (——) and MOBS (- - -) for run FM at Pte. Sapin. Error bars show the 95% confidence limits. (b) Coherence between the spectra in (a). The 95% confidence limit for zero coherence is given by - - -. There are 100 degrees of freedom and $\delta f = 0.0121$ Hz.

become a critical parameter at large grain sizes, the settling velocity at small sizes (the parameter af/w where a is the wave amplitude and w the grain settling velocity seems to be the appropriate non-dimensional parameter).

3. Analysis

Figure 2 shows the cross-spectral analysis between the colocated flow and sediment concentration measurements. The "power" spectrum of the cross-shore flow shows a well-defined peak at 0.18 Hz ($T_p = 5.5$ s). A relatively well-defined first harmonic peak ($f = 0.36$ Hz) is also evident. The shape of the roll-off between 0.4–0.6 Hz is somewhat suggestive of a second harmonic "peak". The skewness observed in the time series of cross-shore flow (figure 1a) suggests that the primary and these harmonics are phase-coupled. This of course cannot be determined from a "power" spectral analysis (a bispectral analysis is discussed later). An infragravity wave peak at $f = 0.036$ Hz ($T \sim 28$ s) is also observed in the spectrum of the cross-shore flow.

If the response of the concentration to the offshore flow were comparable to that of the onshore flow, then the period of the concentration response would be twice that of the cross-shore flow. On the other hand, if the concentration responded more strongly to either the onshore flow or the offshore flow, then the period of the concentration response would be expected to be the same as that of the cross-shore flow. The "power" spectrum of the concentration time series shows that the peak period of the response is the same as the cross-shore flow. This observation is consistent with the suggestion that the concentration responds primarily to the flow associated with the wave crest. Finally, figure 2b indicates that except for the "valleys" in the "power" spectrum of the cross-shore flow, which separate the infragravity, primary, first harmonic, and second harmonic frequency bands, the concentration and cross-shore flow are significantly coherent.

Figure 3 shows the real and imaginary parts of the bispectrum of the cross-shore flow. The definition and properties of the bispectrum can be found in Elgar and Guza (1985), Doering and Bowen (1986), and many others. In a few words though, the bispectrum is used to identify triad(s) (*i.e.*, three phase-coupled frequencies) and to determine the relative contribution of a triad to the total skewness and asymmetry (a measure of the lack of vertical, as opposed to horizontal, symmetry) of the waves in a record. The peak centered at (0.18 Hz, 0.18 Hz) denotes phase-coupling between primary and first harmonic frequencies, and is suggestive of a self-self sum interaction between primary wavetrains. The smaller peak located at (0.36 Hz, 0.18 Hz) indicates phase-coupling between first, primary, and second harmonic frequencies. These two peaks clearly indicate that harmonic wavetrains are phase-coupled to the primary. The wind-wave skewness (S_{ww}) arising from these two interactions is relatively large, $S_{ww} = 0.676$. This confirms that the cross-shore flow is strongly skewed. However, the wind-wave asymmetry (A_{ww}) arising from these two interactions is relatively small, $A_{ww} = -0.159$; that is, the waves are almost vertically symmetric. The depression located at (0.16 Hz, 0.02 Hz) indicates that negative skewness arises from phase-coupling between primary wavetrains and long waves. The infragravity wave skewness and asymmetry arising from this interaction are -.176 and 0.017, respectively; hence, the biphase of this interaction

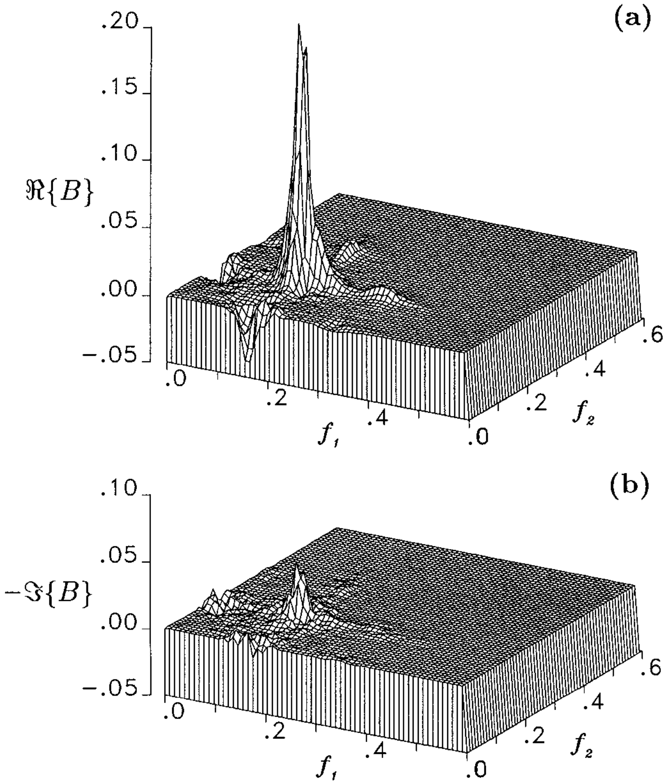

Figure 3 Real **(a)** and imaginary **(b)** parts of the bispectrum of cross–shore velocity for run FM at Pte. Sapin. $\delta f = 0.0098$ Hz.

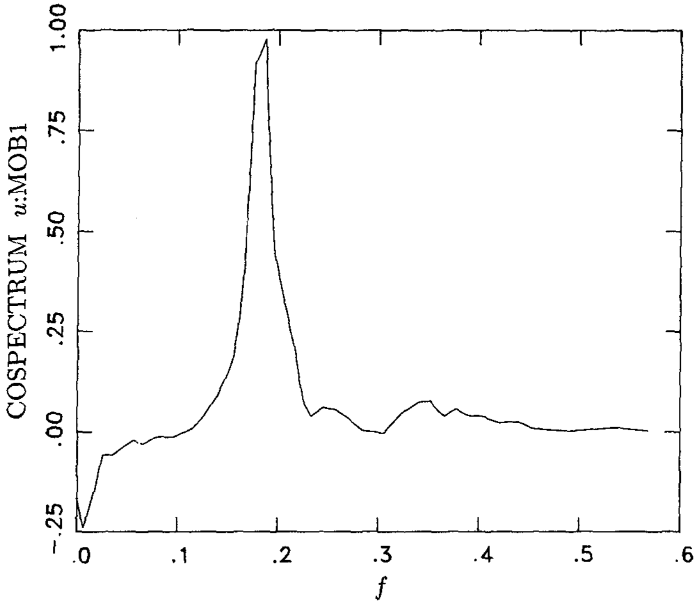

Figure 4 Cospectrum between cross-shore velocity and the MOBS for run FM at Pte. Sapin. The units of the cospectrum are $(g/\ell)(\mathrm{m/s})\mathrm{Hz}^{-1}$. There are 58 degrees of freedom and $\delta f = 0.0098$ Hz.

($= \tan^{-1}\{A/S\}$) is $-174°$. The negative skewness and biphase of $\sim -180°$ that are observed for this interaction are consistent with the classical concept of a bound wave (Longuet-Higgins and Stewart, 1962, 1964); that is, an interaction between two primary wavetrains forms a wave group, which forces a second-order bound wave at the difference frequency that is 180° out of phase with the envelope of the wave group (§2.2–2.3). For a Bagnold-type model of transport skewnesses that are opposite in sign imply transport in opposite directions. For the present data where a positive velocity denotes an onshore flow, positive skewness implies an onshore transport and negative skewness, an offshore transport.

To determine the net transport in the cross-shore direction at some height above the sea bed, the cospectrum of the cross-shore flow and concentration c at that height is formed, *i.e.*, $\langle u \cdot c \rangle$. Figure 4, reproduced from Huntley and Hanes (1987), shows the cospectrum between the MOBS sensor and the cross-shore velocity. The most striking feature is the large positive or onshore flux of sediment by the primary waves. The indication here is the strong onshore flow associated with the passage of a skewed wave crest leads not only to the mobilization and suspension of sediment, but also to an onshore transport. This implies that the bulk of the sediment at this height (of ~ 2 cm above the sea bed) settled before the offshore flow associated

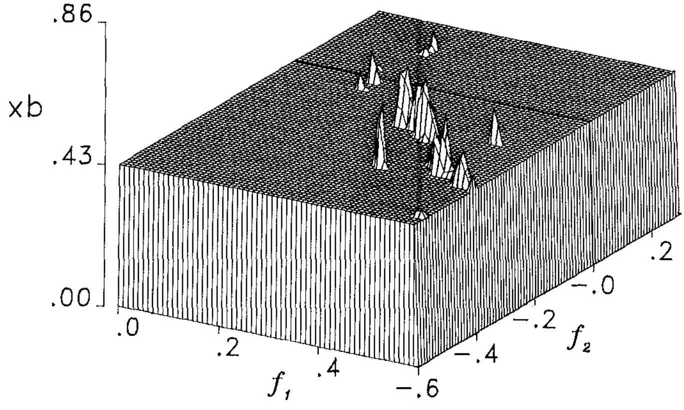

Figure 5 Cross-bispectrum between cross-shore velocity and the MOBS signal for run FM at Pte. Sapin. There are 32 degrees of freedom and $\delta f = 0.0098$ Hz.

with the wave trough could transport it back, *i.e.*, the net flux of sediment was onshore, which is consistent with figure 1 where a much higher concentration was observed during the onshore flow. The offshore transport of sediment by infragravity waves is probably due to the offshore skewed flow associated with the bound long wave forced by a wave group (Longuet-Higgins and Stewart, 1962; Wells, 1967); the general tendency for stronger offshore flow to occur when the waves are large, provides a perturbation which tends to move sediment seaward (Shi and Larsen, 1984). This cospectrum does not necessarily imply that the beach was locally accreting, as neither the transport by the alongshore current nor the mean flow have been considered.

The evidence presented so far is consistent with the idea that the wind-waves result in an onshore transport of sediment because the flow associated with them is skewed onshore (*i.e.*, the strong onshore velocities exceed the threshold velocity required to mobilize, suspend, and transport the sediment, whereas the offshore velocities generally do not), while the interaction of the infragravity waves with the sediment suspended by the wind-waves leads to an offshore transport of sediment because the flow associated with these long waves is skewed offshore. In other words, the suggestion is the response of concentration should be phase-coupled to the wave-induced flow. One can test this idea using the cross-bispectrum.

Figure 5 shows the unique part of the cross-bicoherence spectrum between velocity and concentration. The peaks shown are above the 95% significance level for zero cross-bicoherence. The convention adopted is that $u(f_1) \pm u(f_2) \rightarrow c(f_3)$, where $u(f_1)$, $u(f_2)$, and $c(f_3)$ denote frequencies in the velocity and concentration series, respectively, and $f_1 + f_2 = f_3$. This convention assumes that coupling between the spectral components of the wave-induced flow are phase-coupled to the variation in concentration. The broad peak centered at (0.36 Hz, -0.18 Hz) indicates that first harmonic and primary frequencies in velocity are phase-coupled to 0.36+(-0.18)=0.18 Hz, or the primary in concentration. The peak at (0.54 Hz, -0.36 Hz) indicates that phase-coupling between second and first harmonic frequencies in velocity are also coupled to fluctuations at the primary frequency in concentration. Collectively, these two peaks indicate that phase-coupling between the primary and its harmonics in velocity, which result in a strongly skewed flow (figure 3a), are coupled to primary fluctuations in concentration. The small peak at (0.19 Hz, -0.03 Hz) indicates that primary and long waves in velocity are also coupled to primary fluctuations in concentration; this peak suggests the interaction of long waves with the sediment suspended by the wind-waves.

4. DISCUSSION

The observations in the preceding section suggest that the response of concentration is strongly coupled to the wave-induced flow; for this grain size range the complexities of the critical stress for suspension and the fallout of sediment play a minor role and might be adequately modelled in a relatively simple way. The interesting part is that the sedimentary response depends critically on the instantaneous velocity, clearly reflecting the pattern of both the individual waves and the wave groups.

Historically, the predictors used to model nearshore sediment transport, assume that the total rate of sediment transport can be empirically related to simple, time-averaged characteristics of the incident wave field, *e.g.* breaker height, angle of incidence with respect to shore-normal, and the depth of water at the location of breaking. More detailed predictors assume that the sediment is suspended by the waves and then transported by the superposition of a mean flow. Most bulk predictors of sediment transport do not explicitly incorporate any of the effects of velocity skewness, wave groups, settling velocity, or a critical velocity. In light of this and the many other sweeping assumptions that are implicit in these models, it is not not surprising that they are not accurate predictors of sediment transport (Fleming *et al.*, 1986; Baird *et al.*, 1986).

If the skewness of the flow is linked to the mobilization, suspension, and transport of sediment as suggested by the observations in this paper, then the implication is the cross-shore variation of skewness should lead to convergences and divergences of sediment. For example, if the flow is skewed onshore through the shoaling region, reaches a maximum seaward of wave breaking, and then becomes skewed offshore in the surf zone due to a dominance of infragravity wave skewness, then this implies a convergence of sediment and thus the formation of a breakpoint bar. This idea for bar formation is consistent with the skewness observations on a barred beach by Greenwood and Sherman (1984), who observed that velocity skewness tended to be positive on the lakeward side of a bar and negative on the landward side of a bar. However, whether or not a bar actually forms and where it forms will also depend on the spatial variation of the mean flow; that is, it is the skewness of the total flow (*i.e.*, including the mean) that must be considered, not just the skewness of the the oscillatory component. Bowen (1980) has suggested that an onshore skewed flow is required to balance the downslope component of gravity; therefore, the bar would be expected to form seaward of the location of zero skewness. However, the bar could form closer to the location of zero skewness if the downslope component of gravity is partly balanced by an onshore mean flow in the bottom boundary layer (Longuet–Higgins, 1953).

The role of the wave skewness is the longshore direction is probably much less important due to the existence of strong longshore currents in the mean flow. However, the role of wave groups in mobilising the sediment may well be important and it is far from clear that this groupiness is well parameterised by a mean quantity such as incident wave energy.

5. Conclusions

Colocated measurements of near–bed suspended sediment concentration and velocity were used to investigate the variation of sediment concentration with respect to the wave–induced flow. The data clearly showed that sediment responds to both the individual waves and to wave groups. The response of sediment concentration to the individual waves within a wave group is particularly interesting because the concentration responds strongly to the onshore flow associated with wave crests, but very weakly to the offshore flow associated with a wave trough. These field measurements clearly show the behavior of sediment concentration and sediment transport depends on some high power of the velocity with very little time lag. They suggest that the traditional assumption that bulk transport is simply related to basic characteristics of the incident waves, such as peak period, breaker height, and angle of breaking, is tenuous.

The cospectrum of cross–shore velocity·concentration, which was used to examine the wave–induced transport of suspended sediment by the cross-shore velocity, showed that there was a strong onshore transport of sediment due to wind–wave frequencies and a weaker offshore transport due to infragravity waves. The onshore transport observed at the primary frequency suggests that the strong onshore flow associated with the passage of each skewed wave crest leads not only to the mobilization and suspension of sediment, but also to an onshore transport of the sediment. Moreover, the implication is the bulk of the sediment suspended by the passage of a wave crest (at this height of ~ 2 cm above the sea bed) settles before the offshore flow associated with the following wave trough can transport it back seaward; the net transport of suspended sediment at this height is strongly shoreward. The offshore transport by infragravity waves is apparently due to the offshore skewed flow associated with the bound long wave forced by a wave group (Longuet–Higgins and Stewart, 1962, 1964).

Shi and Larsen (1984) suggested that the offshore transport of fine silt and sand on the continental shelf might be due to the offshore flow associated with the long wave forced by a wave group. The cospectrum observation tends to confirm this suggestion. Moreover, this cospectrum observation underlines the sedimentary importance of infragravity wave energy in the nearshore, and again undermines the traditional assumption that the transport of sediment is strictly a wind–wave related phenomenon.

All the observations shown in this paper collectively suggest that sediment dynamics is fundamentally related to the time variability of the velocity field. The sediment is not simply stirred up by the waves and moved by the mean flow. The important parameters include the mean value of the high movements of the flow field such as skewness, as theoretically suggested. In light of this relation between sediment transport and velocity skewness, it was suggested that the cross-shore variation of skewness should lead to convergences and divergences of sediment. For example, if the flow is skewed onshore in the shoaling region due to a dominance of wind-wave skewness and offshore in the surf zone due to a dominance of infragravity wave skewness, then this leads to the possibility of a convergence of sediment and the formation of a break point bar. However, a complete model for transport should also include: the contribution to moments from the mean flow; the downslope component of gravity, *i.e.*, a beach slope dependence; higher order velocity moments such as those that appear in Bagnold-based models for bed and suspended load transport; a threshold velocity for the initiation of transport and a representation of the settling behavior of the grains.

REFERENCES

Baird, W. F., J. S. Readshaw, and O. J. Sayao, 1986. Nearshore sediment transport predictions Stanhope, Lane, Prince Edward Island, National Research Council Canada, C^2S^2 report **21**.

Bailard, J. A. and D. L. Inman, 1981. An energetics bedload model for a plane sloping beach: Local transport, *J. Geophys. Res.*, **86**, 2035-2043.

Bowen, A. J., 1980. Simple models of nearshore sedimentation; beach profiles and longshore bars, in *The Coastline of Canada*, S. B. McCann, editor, Geological Survey of Canada, Paper **80-10**, 1-11.

Cornish, V., 1898. On sea beaches and sand banks, *Geol.*, **2**, 628-674.

Doering, J. C. and A. J. Bowen, 1986. Shoaling surface gravity waves: A bispectral analysis, *Proc. of the* 20^{th} *Conf. on Coastal Eng.*, ASCE, 150-162.

Downing, J. P., R. W. Sternberg, and C. R. B. Lister, 1981. New instrumentation for the investigation of sediment suspension processes in shallow marine environments, *Mar. Geol.*, **42**, 14-34.

Elgar, S. L. and R. T. Guza, 1985. Observations of bispectra of shoaling surface gravity waves, *J. Fluid Mech.*, **161**, 425-448.

Fleming, C. A., B. M. Pinchin, and R. B. Nairn, 1986. Evaluation of coastal sediment transport estimation techniques, National Research Council Canada, C^2S^2 report **19**.

Greenwood, B. and D. J. Sherman, 1984. Wave, currents, sediment flux, and morphological response in a barred nearshore system, *Mar. Geol.*, **60**, 31-61.

Hanes, D. M. and D. A. Huntley, 1986. Continuous measurements of suspended sand concentration in a wave dominated nearshore environment, *Cont. Shelf Res.*, **6**, 585-596.

Huntley, D. A. and D. M. Hanes, 1987. Direct measurements of suspended sediment transport, *Proc. of Coastal Sediments 87*, ASCE, 723-737.

Longuet-Higgins, M. S., 1953. Mass transport in water waves, *Proc. Roy. Soc.*, **A245**, 535-581.

Longuet-Higgins, M. S. and R. W. Stewart, 1962. Radiation stress and mass transport in gravity waves, with application to "surf beats", *J. Fluid Mech.*, **13**, 481-504.

Longuet-Higgins, M. S. and R. W. Stewart, 1964. Radiation stresses in water waves; a physical discussion with applications, *Deep-Sea Res.*, **11**, 529-562.

Shi, N. C. and L. H. Larsen, 1984. Reverse sediment transport induced by amplitude–modulated waves, *Mar. Geol.*, **54**, 181-200.

Stokes, G. G., 1847. On the theory of oscillatory waves, *Trans. Cambridge Philos. Soc.*, **8**, 441-455.

Wells, D. R., 1967. Beach equilibrium and second–order wave theory, *J. Geophys. Res.*, **72**, 497-504.