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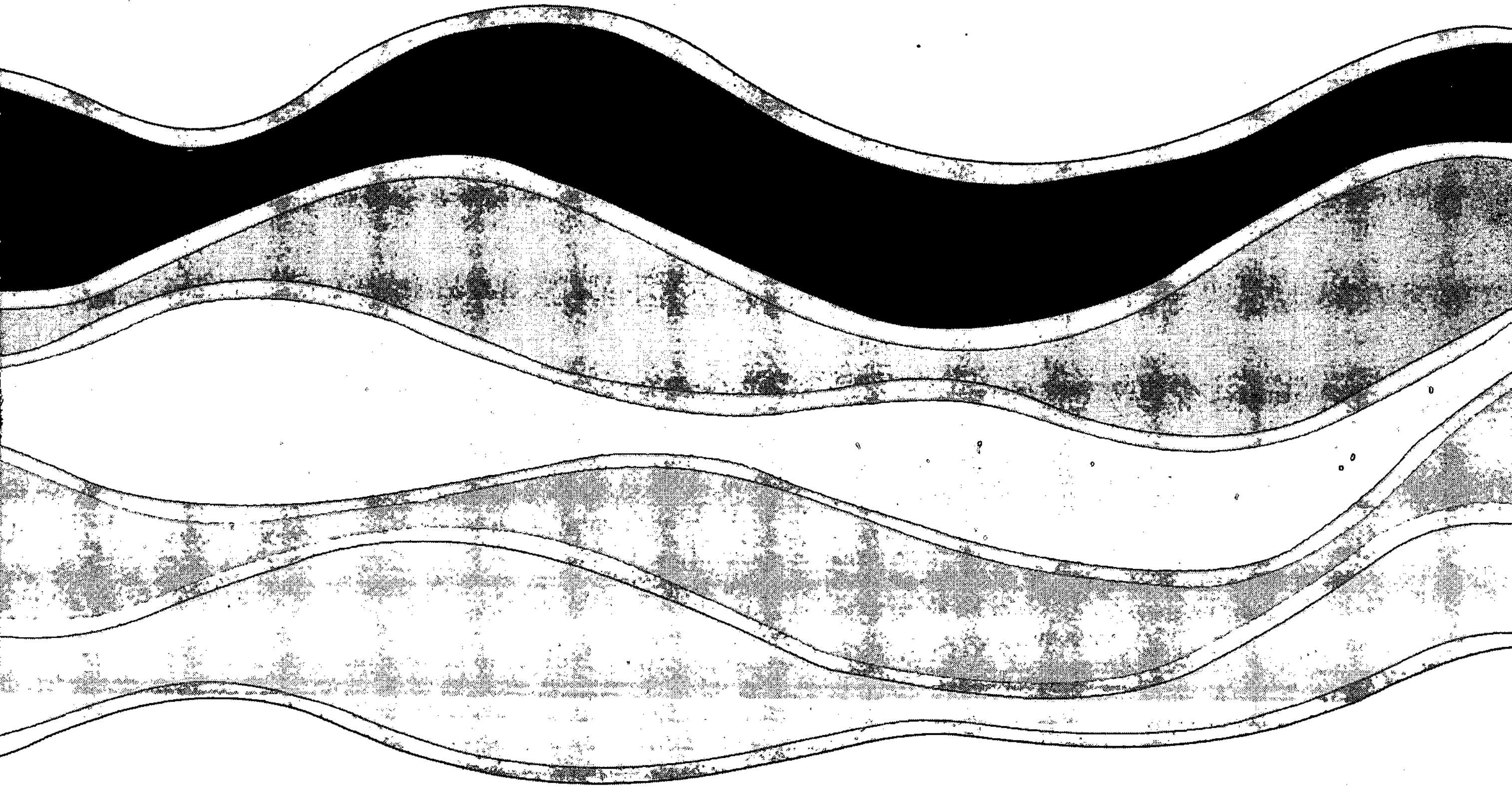

THE SHOALING PROCESS: SOME PHYSICAL INSIGHT

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Management Perspective

Effective and efficient coastal management requires accurate predictions of the evolution of the shoreline. Much progress has been made in the last twenty years in developing shore evolution models. However, there are portions of the models that are inadequate because the underlying physical processes are not well understood. This paper addresses some of those problems, in particular the influence of wave groups on the underlying sediment transport and indicates the type of research that needs to be undertaken to improve future modelling.

Dr. John Lawrence
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Perspective gestion

Pour être efficace, la gestion du littoral exige des prédictions précises de l'évolution du trait de côte. Des progrès considérables ont été enregistrés au cours des 20 dernières années dans l'élaboration des modèles d'évolution du littoral. Certaines parties des modèles demeurent cependant inadéquates à cause de la mauvaise compréhension des processus physiques qui les sous-tendent. Le présent article traite de certains de ces problèmes, notamment l'influence des groupes d'ondes sur le transport des sédiments sous-jacents, et oriente les études à poursuivre en vue d'améliorer les modèles futurs.

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The Shoaling Process: some physical insight

by

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ABSTRACT

Field data are used to examine the nonlinear (triad) interactions that arise during shoaling. The interactions associated with wave groups are identified and discussed; their potential importance to sediment transport is considered. Some of the problems inherent in using the laboratory to pursue similar studies are also discussed.

RÉSUMÉ

Des données de terrain sont utilisées pour l'étude des interactions non-linéaires (triades) qui surviennent lorsque les vagues subissent l'influence du fond marin. Les interactions attribuables au groupement des vagues sont indentifiées et interprétées; leur importance sur le transport sédimentaire est aussi considérée. Quelques difficultés inhérentes à l'utilisation d'essais de laboratoire pour atteindre un but semblable sont aussi discutées.

1. BACKGROUND

The waves we observe in nature are not all identical – rather they vary in terms of their height and period. An old rule–of–thumb is " every 7^{th} wave will be a big one". Indeed, observations, whether at sea or at the beach, indicate that large waves tend to occur successively; *i.e.*, large waves tend to be grouped together. Seldom is a large wave followed by a small wave, instead there is generally a gradual transition that occurs over several waves. For this reason, (deep water) wave heights have been successfully described in terms of a slow amplitude or envelope modulation, *e.g.*, Longuet–Higgins (1983).

In shallow water, shoaling rapidly modifies a group of waves. The shoaling of a wave is characterized by a peaking of the wave crest, flattening or elongation of the wave trough, and steepening or pitching forward of the forward face – eventually breaking ensues. This process, which includes the combined effects of amplitude and frequency dispersion, might be repeated many times before the shoreline is reached or the wave is completely dissipated. The extent to which the shape of a wave is modified by shoaling is, in part, dependent on its amplitude. The forward face of a relatively small wave doesn't pitch forward as much as a large wave because there is less finite depth amplitude dispersion in a small wave than a large wave. This can be readily seen in a synoptic set of sea surface fluctuation records. Shoaling, therefore tends to reduce groupiness, producing a wavetrain that is ultimately uniform in height.

Figure 1 shows a shore–normal synoptic set of cross–shore velocity records reproduced from Doering (1988). These measurements were obtained using Marsh–McBirney electromagnetic flow meters. Each flow meter was mounted at approximately 20 cm above the sea bed on a steep sloping, nearly planar, pocket beach (Queensland) in Nova Scotia. The directional spread of this incident wave field was very small, due in part to the narrow opening between the bay and the open ocean, and to the long–crested near–normal incidence on this particular day. For the peak period and range of water depths involved here, the linear transfer function for computing sea surface fluctuation from velocity is essentially flat over the spectral peak. Hence, these intermediate/shallow depth velocity records can be considered to be closely representative of the sea surface fluctuation. These six synoptic records nicely show the gradual peaking of the wave crests, flattening of the troughs, and steepening of the forward face associated with shoaling. It is also interesting to note that groups of waves can be readily followed from 5.5 m to 2.1 m water depth, but after breaking, which occurred between 2.1 and 0.6 m of water (panels e and f, respectively) no clear correlation remains.

In a spectral sense, these general changes in wave shape are characterized by an increase in harmonic energy. Phillips (1960) has shown theoretically that triads (two waves interacting to force a third) are resonant in the limit of shallow water; *i.e.*, $kh \rightarrow 0$, where k is a wavenumber and h is the local water depth. Nonlinear

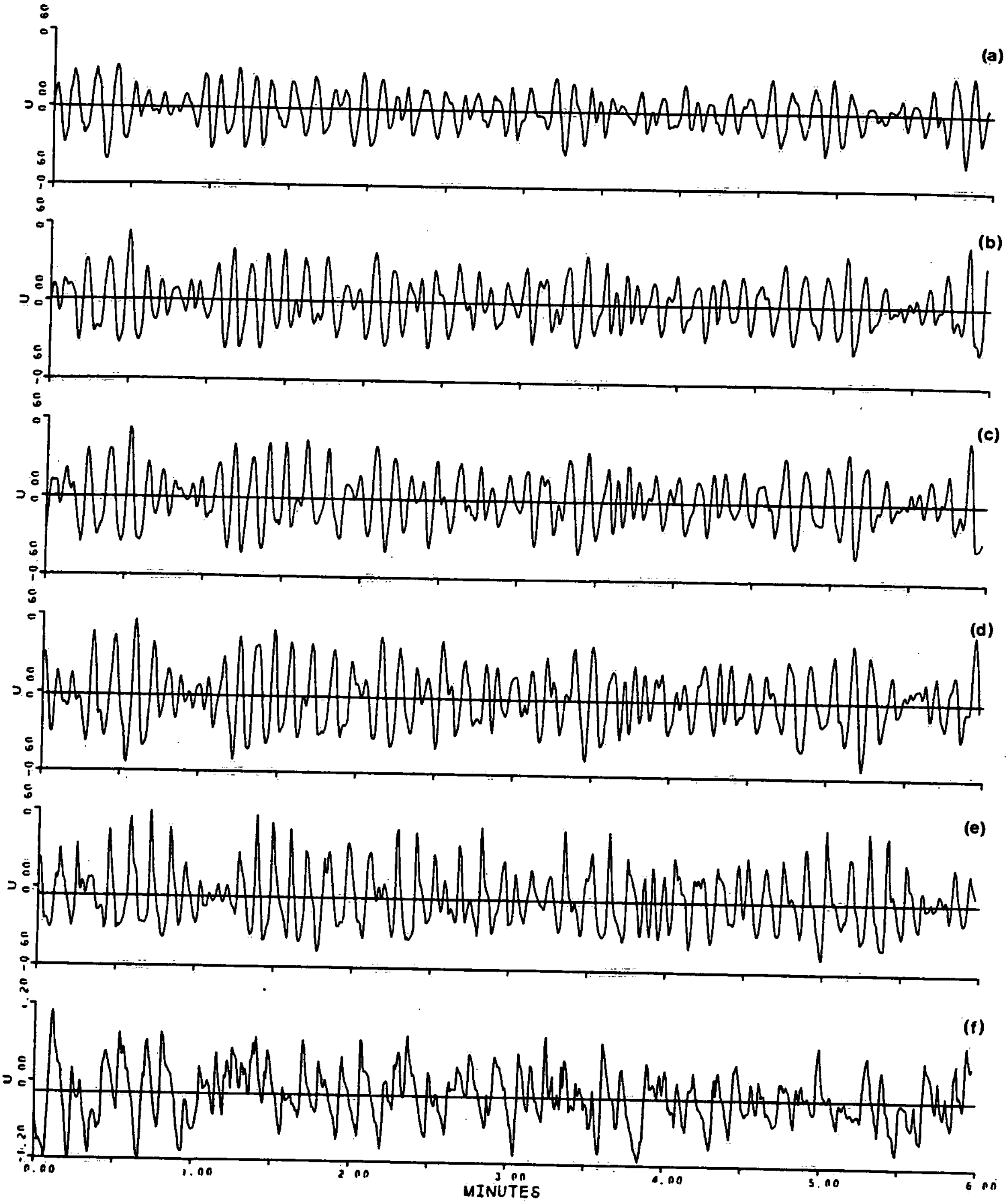

Figure 1 Time series of cross–shore velocity [m/s] from $h = 5.5$ m (**a**), $h = 4.2$ m (**b**), $h = 3.9$ m (**c**), $h = 3.2$ m (**d**), $h = 2.1$ m (**e**), and $h = 0.6$ m (**f**) for the 29th of October 1987 at Queensland Beach, Nova Scotia. A positive velocity denotes an onshore flow. The horizontal line through each record denotes the mean flow.

interactions therefore provide the mechanism for the increase in harmonic energy. It is the near–resonant nature of these triads in shallow water that admits the rapid exchange of energy between spectral components.

The relative increase in harmonic content that occurs during shoaling arises from sum interactions; *e.g.*, $f_p + f_p \rightarrow 2f_p$ or $f_p + 2f_p \rightarrow 3f_p$, where f_p is the peak frequency. Triad interactions such as these can be readily identified using a normalized form of the bispectrum, known as the bicoherence spectrum (see Haubrich, 1965; Kim and Powers, 1979). Figure 2 shows the bicoherence spectra for the same six records shown in figure 1. Only the bicoherence values above the 95% significance level for zero true bicoherence are shown. The convention here is $f_1 + f_2 \rightarrow f_3$, where $f_3 = f_1 + f_2$. Therefore, a peak in bifrequency space implicitly represents a triad interaction. Note, all frequencies are in Hertz.

In panel a, one unique peak is observed at (0.12 Hz, 0.02 Hz). This peak indicates phase–coupling between primary and infragravity frequencies. Physically, this peak is attributed to an interaction between "neighboring" primary frequencies; the resultant beat or wave group forces a bound long wave at the difference or group frequency (this group related interaction is discussed further below). After propagating further shoreward, panel b indicates very little change in phase–coupling. However, additional shoaling (panel c) produces a peak centered at (0.13 Hz, 0.13 Hz), that indicates phase–coupling between primary and first harmonic frequencies. This peak is indicative of a self–self interaction between primary (peak) frequencies, which forces first harmonics; this triad transfers energy to first harmonic frequencies thereby increasing first harmonic energy. Panel d shows the number of frequencies involved in the self–self interaction increases with shoaling. Just before breaking, panel e, strong phase–coupling is observed between primary, first, second, and third harmonic frequencies. Panel f indicates that the triads observed before breaking persist after breaking. Spectral analysis (see Doering, 1988) indicates a significant increase of both harmonic and infragravity energy content from $h = 5.5$ m to 2.1 m (panels a to e). Energy is transferred to harmonic frequencies by sum interactions while the transfer to infragravity frequencies occurs through difference interactions.

Figure 2 indicates that a group of waves, resulting from the beat formed by the superposition of two wavetrains of similar period, is associated (in fact bound to) a long wave. There are a number of models for the generation of group bound long waves. The most widely known is that due to Longuet–Higgins and Stewart (1962, 1964). They showed that there's a displacement of water beneath a group of waves, which is proportional to the amplitude of the group, arising from radiation stress (second–order) effects. This creates a forced wave that is 180° out–of–phase with the group. Bowen and Guza (1978) showed that the nonlinear interaction between a pair of primary wavetrains with non–normal incidence could lead to the generation of long waves, *viz.*, edge waves. Symonds *et al.* (1982) showed that a time varying

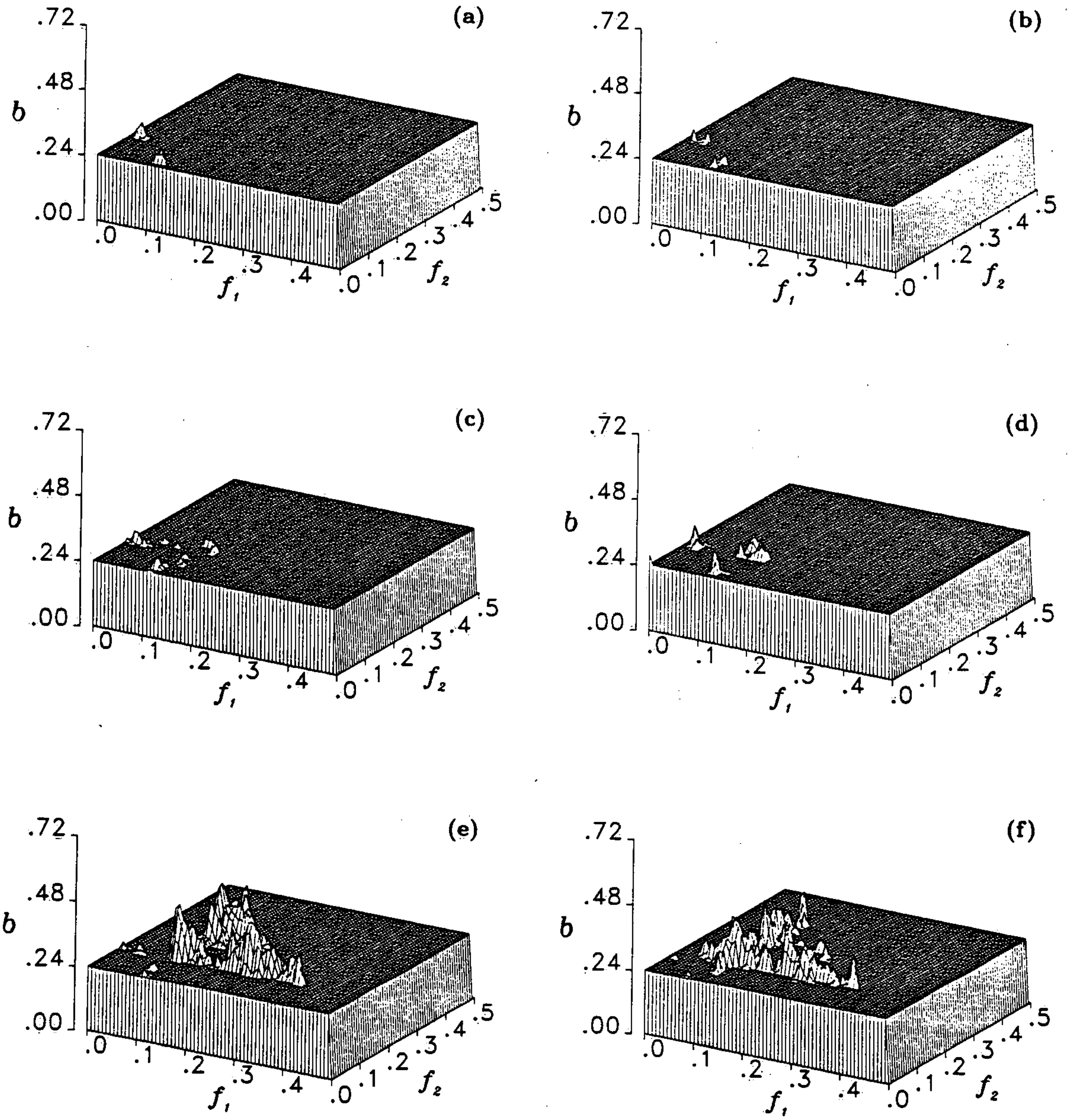

Figure 2 Bicoherence spectra for the 29th of October 1987 at Queensland Beach, Nova Scotia. The depths and cross–shore location for each panel are as follows: **(a)** $h = 5.5$ m at $x = 140$ m; **(b)** $h = 4.2$ m at $x = 100$ m; **(c)** $h = 3.9$ m at $x = 90$ m; **(d)** $h = 3.2$ m at $x = 70$ m; **(e)** $h = 2.1$ m at $x = 45$ m; and **(f)** $h = 0.6$ m at $x = 20$ m. There are 104 degrees of freedom and $\delta f = 0.0078$ Hz. Note, all frequencies are in Hertz and bicoherence is dimensionless.

breakpoint, arising from wave groupiness, could act as a nearshore wave maker that produces shoreward and seaward propagating waves. Although it is not possible to make a definitive statement regarding the origin of the long wave energy observed in figure 2, biphase evidence (Doering, 1988) suggests it is likely due to the bound long wave described by Longuet–Higgins and Stewart (1962, 1964).

2. IMPLICATIONS FOR SEDIMENT TRANSPORT

Until recently, the potential role of infragravity wave energy associated with wave groupiness has gone largely ignored by the engineering community. Now sediment transport studies are suggesting that sediment transport rates and cross–shore equilibrium profiles are linked to wave groupiness as measured by the groupiness factor (Kamphuis, *pers. comm.*). Some models of beach equilibrium now include an *ad hoc* influence of nearshore long waves. Recent field experiments (Greenwood *et al.*, 1990) using optical backscatter sensors and acoustic sediment profilers are confirming previous observations that suggested a link between wave groups and sediment transport.

Figure 3, reproduced from Hanes and Huntley (1986), shows the first five minutes of cross–shore velocity and near–bed suspended sediment concentration (at approximately 2 cm above the sea bed) obtained at Pte Sapin, New Brunswick, during the Canadian Coastal Sediment Study (C^2S^2). It is clear from figure 3 that the concentration of near–bed suspended sediment responds to both the wave groups and the individual waves. The response to the wave groupiness is evident in the slow modulation in the mean concentration, such as that observed with the passage of the wave group between 2 to 4 minutes. The response to the individual waves is intriguing.

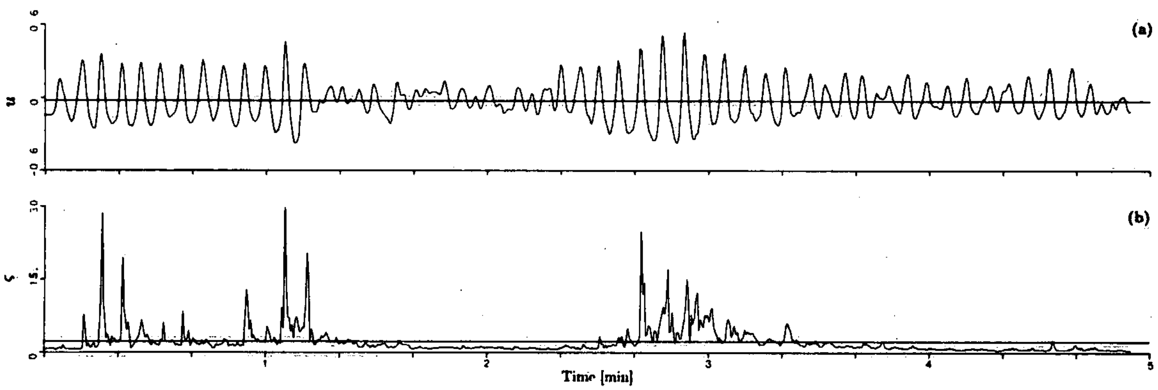

Figure 3 Time series of cross–shore velocity [m/s] **(a)** and near–bed sediment concentration [mg/m^3] **(b)** for the first five minutes of run FM at Pte. Sapin. A positive velocity denotes an onshore flow. The horizontal line through each record denotes the mean.

Close inspection of the two records shown in figure 3 indicates the sediment concentration responds strongly to the onshore flow associated with a wave crest, but weakly to the offshore flow associated with a wave trough; the suggestion is the stronger onshore flow associated with the noticeably skewed wave crests exceeds the threshold velocity for mobilization and subsequent suspension of sediment while the weaker offshore velocities associated with the "flattish" wave troughs do not. These field measurements support two concepts that are fundamental to some detailed predictors of sediment transport; *viz.*, a critical or threshold velocity and wave skewness.

Figure 4, reproduced from Huntley and Hanes (1987), shows the cospectrum (*i.e.*, $u \cdot \varsigma$) for the cross–shore flow and concentration shown in figure 3. The most noticeable feature is the large positive peak at 0.18 Hz, which indicates an onshore flux of sediment by the incident peak period waves. This peak 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. The implication is the bulk of the sediment suspended by the passage of a wave crest settles before the offshore flow associated with the following wave trough can transport it offshore; *i.e.*, there is a net onshore flux. The magnitude of this (positive) cospectral peak is, of course, dependent in part, on the sediment grain size. For example, a slightly finer sediment would settle more slowly, thereby remaining in suspension longer. A sustained concentration would yield a larger offshore flux by the wave–induced flow associated with the wave troughs. Hence, the net flux (in this case onshore) would be smaller than that for a larger grain size. In terms of the cospectral peak, the net transport [mg/m^2] by the peak period waves, which is given by the area under the peak at 0.18 Hz, would be reduced. Another factor controlling the cross–shore transport is the skewness of the flow. If the shoaling wind–waves were not skewed and there was equal suspension under crest and trough then this large positive peak would not exist; there would be a balanced on–offshore flux by the wind–waves. However, this raises some questions about beach stability. If there is an equal on–offshore flux by the wave crest/trough induced flow, then what balances the downslope component of gravity on a sloping beach? It has been suggested (Bowen, 1980) that the skewness of the cross–shore velocity field might (in part) counteract this component of gravity.

However, of particular interest in figure 4 is the negative or offshore flux of sediment by long waves; *i.e.*, frequencies less than 0.05 Hz. This transport is thought to arise from the offshore flow associated with the group bound long waves (Longuet–Higgins and Stewart, 1962, 1964). Similar cospectra have also been observed by Osborne and Greenwood (1991). The suggestion from this figure is the offshore flux of sediment is controlled in part by groupiness; *i.e.*, well–defined groups produce (through radiation stress effects) well–defined larger amplitude long wave(s) then weaker groups — the larger the long wave amplitude, the greater

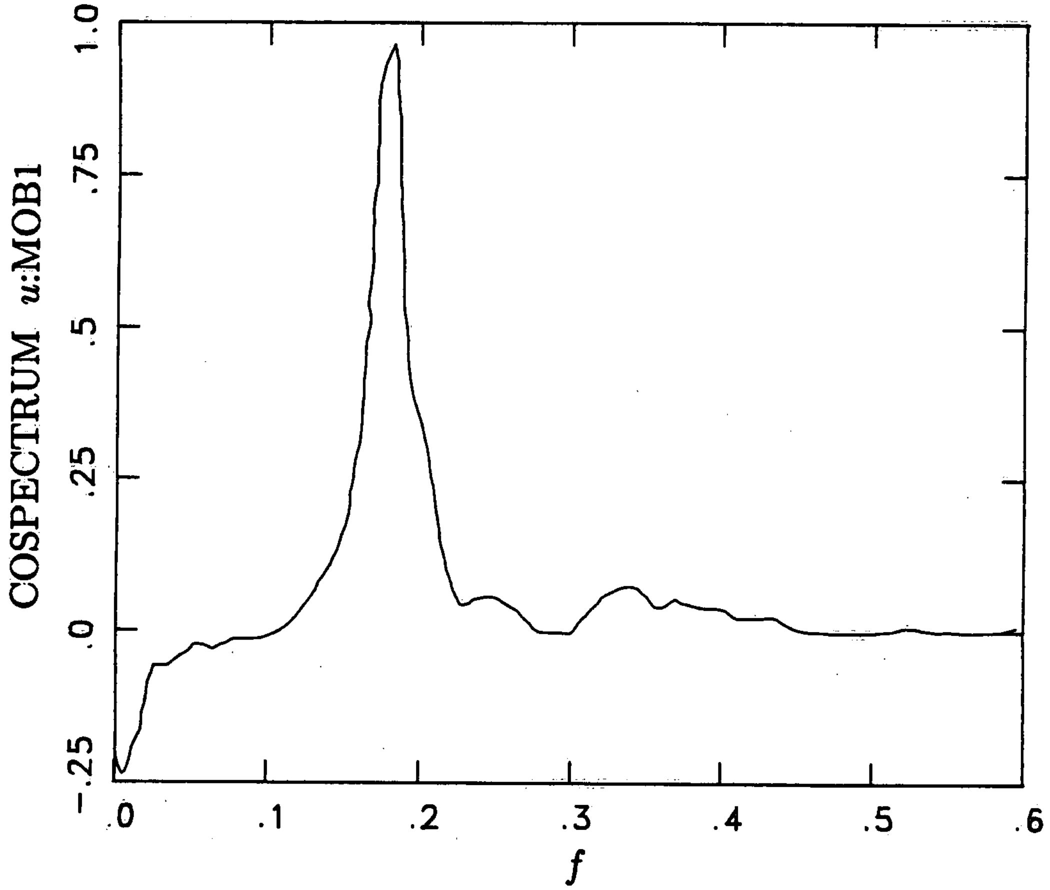

Figure 4 Cospectrum between cross–shore velocity and the lowest MOBS for run FM at Pte. Sapin. The units of the cospectrum are $(mg/m^3)(m/s)/Hz$. There are 58 degrees of freedom and $\delta f = 0.0098$ Hz.

the (offshore) induced flow, and hence the greater the associated offshore flux of sediment.

The intriguing implication here is the equilibrium profile of a beach is governed, at least in part, by the groupiness of the incident waves, and not just by the transport of the incident wind–waves. However, it is important to note that this single cospectrum does not necessarily imply that the beach was locally accreting, as neither the vertical structure of the flow, alongshore current, or contribution of the mean flow have been considered.

The offshore flow associated with group bound long waves was used by Shi and Larsen (1984) to account for the seaward transport of silt and sediment that has been observed on the continental shelf. These observations clearly support that idea.

3. TURNING TO THE LAB

There is little question that the laboratory provides a unique means of conducting tests under repeatable, controlled conditions. Virtually all facets of an experiment can be predetermined and manipulated at will. In the field though, one gets what nature provides. Anomalous field results are not readily dismissed by hand–waving arguments and cannot be deemed artifacts of the laboratory; field data is "the real thing". Nonetheless the laboratory nicely isolates parts of the "real" problem, or complements the parameter space of a limited field data set. However, the transition from field to lab is not an easy one, and it must be made with extreme caution. Among the plethora of problems associated with laboratory experiments is the accurate reproduction of waves observed in nature. The principal problem is suppressing the spurious free waves associated with mechanical wave generation. Laboratory experiments conducted in the 100 m flume located at the Canada Centre for Inland Waters, Burlington, underlines some of these difficulties. Wavetrains were generated using the GEDAP software developed by the National Research Council Canada (Funke and Mansard, 1984). The version of GEDAP employed included second–order correction for spurious long waves, but not for short waves (*i.e.*, frequencies at and above the spectral peak).

The first indication of short–comings in this data arose when a routine bispectral analysis was performed to examine deep water wave–wave interactions. The analysis of these wavetrains, which were generated from a fully–developed deep water DHH spectra (after Donelan *et al.*, 1985) whose spectral components were ascribed "random" phases, showed phase–coupling, significant at the 99% level for zero true bicoherence, between the primary and all its higher harmonic components. Relative to the field observations of Elgar and Guza (1985), Doering and Bowen (1986), and Doering (1988), the strong phase–coupling observed in this laboratory data is anomalous. However, what is difficult to ascertain is the proportion of the harmonic energy that is phase–coupled. A bicoherence spectrum simply indicate whether persistent phase–coupling occurs, it does not, unfortunately, indicate the relative proportion of coupled versus free wave energy. One indication of the extent of phase–coupling between frequency components within a record is given by the skewness and asymmetry. Typically, a deep water wavetrain in nature has a skewness of 0 to 0.1 and an asymmetry of approximately 0. For these mechanically generated waves skewness and asymmetry values of 0.2 and 0, respectively, were observed. The indication is a larger than "normal" proportion of the harmonic content of these wavetrains is phase–coupled. This probably occurs because spurious short waves arising from the wave generation process are distorting the "natural" profiles of the waves. The second–order correction of spurious short waves would therefore seem imperative for the accurate reproduction of mechanically generated "wind–waves". Moreover, these observations raise some concerns about the ability of laboratory experiments, which do not include second–order corrections to the short wave components of a wave–maker input signal, to accurately reproduce field conditions. If skewness, as suggested by the data in §2, is related to the mobilization, suspension and transport of sediment, then artificially enhanced skewnesses would likely produce enhanced transport estimates. In addition, if long waves transport sediment, as suggested by the observations above then correction of the long wave components is also necessary to obtain transport rates commensurate with those that occur in nature.

4. CONCLUSIONS

Field data was used to examine second–order wave–wave interactions which are linked to wave groupiness and sediment transport. Colocated measurements of near–bed suspended sediment and velocity were used to investigate the variation of sediment concentration with respect to the wave–induced flow. The data clearly showed that the sediment responds to the individual waves. Of particular interest though, is the response arising from wave groupiness. A cospectral analysis showed a small (relative to the onshore transport by the wind–waves) offshore transport by long waves, apparently due to the offshore skewed flow arising from the bound long waves forced by wave groupiness (Longuet–Higgins and Stewart, 1962, 1964). These observations suggest that wave groupiness is intimately linked to the flux of sediment and thus beach equilibrium.

Laboratory data that is used to study wave–wave interactions associated with shoaling must address the issue of second–order corrections to the wave–maker. An examination of laboratory data, which did not include second–order correction for spurious short waves, exhibited larger than "normal" skewnesses. This is believed to arise from a distortion of the "true" or natural wave profile as a result of not having included a second–order correction of the mechanically generated harmonic components of the wavetrains. These observations raise some concerns about the accuracy of laboratory studies examining sediment transport related phenomenon and shoaling wave statistics, that do not include a complete (both long and short wave) second-order correction of the wave-maker input signal. In short, this experience serves to underscore a small subset of the plethora of problems inherent in attempting to accurately reproduce natural processes in the laboratory.

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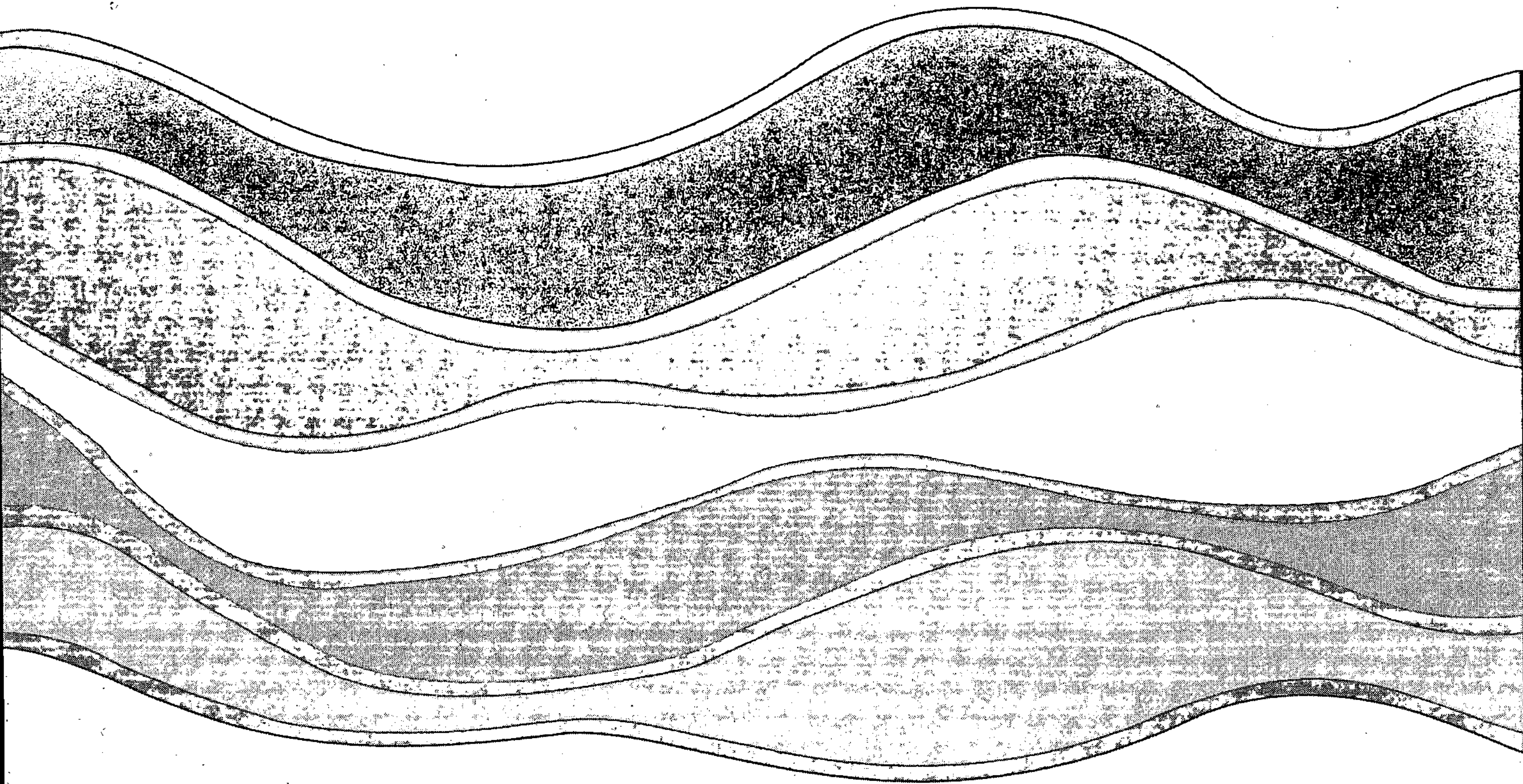

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