CHAPTER ONE HUNDRED FIFTEEN

Nearshore Sediment Transport: Estimates From Detailed Measurements Of The Nearshore Velocity Field

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Abstract

A very wide variety of conceptual models has been used to explain the movement of sediment in the nearshore region. While there is general agreement that the incident waves are primarily responsible for the mobilisation of sediment, many processes have been proposed as the transport agents, for example, wave drift velocities, wave assymetry, longshore and rip currents, undertow, the downslope component of gravity. As it is currently difficult to make reliable point measurements of sediment transport, many of these ideas can not be tested directly. However, in many cases, detailed measurements of the velocity field in the water can be used to examine at least the relative importance of these possible processes. The situation is complicated by the lack of accepted formulae for sediment transport. The result is that the velocity measurements are also being used to examine the 'reasonability' of the various formulations.

Introduction

A major obstacle to further understanding of nearshore sediment dynamics is the lack of instruments which directly measure sediment transport. Although various types of instrumentation are under development, at present the velocity field in the water can be determined much more accurately than any parameter directly related to sediment movement. We now have large data sets from flowmeters at various vertical and horizontal positions on a wide variety of beaches. It is not, however, altogether clear how this data can be best used. The classical approach in coastal engineering is to relate such sedimentary parameters as can be measured, for example accretion rates on a growing spit, to general properties of the incident waves, often properties which only involve measurements offshore in deep water.

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A number of specific models have recently been proposed which can make use of detailed current data, Grant and Madsen (1979), Bowen (1980a) Bailard and Inman (1981). These models, however, raise fundamental questions not only about the nature of the flow, for example, the vertical structure and particularly the scale of the boundary layer, but also about the relative importance of the various possible physical processes. The recent interest in undertow nicely illustrates both sets of problems as the measurement of undertow requires vertical resolution of a quasi-steady flow pattern over an appropriate vertical scale for sedimentary processes. As few appropriate observations exist from the field the significance of undertow is unclear although its possible importance can readily be demonstrated in two-dimensional laboratory experiments.

The overall problem is that there is no single, conceptual model to describe the important processes in any particular nearshore environment; there is no unique hypothesis to test. For example, there is no general agreement as to whether the downslope component of gravity (a physical force whose existence can not be denied) plays any significant role on sandy beaches. One way of using the current meter data that now exists is as the input for simple models based on a variety of assumptions about the relative importance of various processes. The result will be a set of predictive models for the sediment transport in the particular environment in which measurements were made. However, these predictions are not meant to be taken too seriously, the primary objective is to identify the most important processes operating in a particular environment. An initial step is, therefore, to examine the general properties of the velocity fields that have been observed and, in particular, to look at the contrast between the measurements in different coastal environments.

Properties of the Flow Field

In terms of sediment transport, the more obvious flow properties of interest are the mean, the variance (a measure of wave energy) and the skewness (a measure of wave assymetry). Other parameters which might be derived from a record of the instantaneous horizontal velocity vector u(t) at a given point are, for example, estimates of the bottom stress $u|u|$ and the sediment transport given by the velocity to some high power $u|u|^n$ (or a formula in which a velocity u_c related to a critical stress for movement is subtracted).

A more complex formulation, of particular interest in examining the possible role of gravity, is that of Bagnold

(1966) which explicitly includes the bottom slope. For example, Bailard and Inman (1981) define the bedload transport i_b as

$$i_b = K(u^3 + \alpha u^2|u|\nabla h)) \qquad (1)$$

where h is the water depth and α^{-1} the friction angle of the sediment. The basic result expressed is that the sediment is transported more easily downslope than upslope. In the absence of good measurement techniques, the prediction of an instantaneous transport rate is not a result that can readily be assessed. However, the net transport over a long period of time (at least several wave periods) is a prediction of considerable practical interest, focussing attention on the factors that determine the magnitude of terms such as $\langle u^3 \rangle, \langle u^2|u| \rangle$ where the bracket denotes the time average over a timescale T.

Note that in this particular model u is the total velocity and includes any mean, u^3 is then not skewness as normally defined. In other models, more cautious discrimination between the waves and the mean may be necessary (Grant and Madsen, 1979).

Interest in parameters such as u^3 focusses attention on three particular points:

(i) the statistical behaviour of the parameter as a function of time t and averaging time T; the probability distribution of u^3 and relative variation of this parameter, compared to $u^2|u|$ for example.

(ii) the factors that contribute to the value and variation of u^3; is it primarily the mean and low frequency variation in the 'mean' or is skewness arising from assymetry in the shape of the velocity distribution?

(iii) theoretical models to examine the variation of these parameters as functions of time and space (particularly space in the sense of water depth). Simple models in which the theoretical distribution of the wave field is either sinusoidal or Gaussian can be readily compared to the scalar moments u^2, $u^2|u|$ etc.

Field Measurements of the Flow Field

In practice observation are made with a limited set of current meters at specific positions in the nearshore region. In the Nearshore Sediment Transport Study (NSTS) on the west coast of the United States the horizontal variation of the flow field was of primary interest and only one flowmeter was deployed at any position (about

0.50 m above the bed). This leads to considerable uncertainty about the relevance of the measurement, particularly that of the mean flow, to conditions close to the bed. Consequently in our recent experiments on the Canadian east coast, at Queensland, Nova Scotia (Bowen, 1980b) and Pte. Sapin, New Brunswick (Canadian Coastal Sediment Study), vertical arrays of three or four electromagnetic flowmeters have been deployed at a single point. This enables us to address some of the uncertainties about our ability to measure flow parameters, such as the high order moments, which have been underlined by Aubrey, Spencer and Trowbridge (1984). These data sets can be used as a basis for a number of fundamental questions: -

(i) How well do we measure u, u^3 etc; do the vertical and horizontal distributions of various parameters make any sense?

(ii) Do the simple theoretical models provide guidance as to the quality of measurements necessary?

(iii) Where should measurements be made? In deeper water, a height of 1 m is often used as a standard (but not without problems).

(iv) Does the combination of data and models suggest that any factors can be neglected? For example, a critical stress (u_c) or the downslope component of gravity.

Figure 1 shows the on-offshore component of velocity u at three positions 0.10, 0.45 and 0.80 m above the bed in a depth of 1.40 m of water at Queensland, N.S. The significant wave height is approximately 0.7 m. The obvious result is the very high coherence between the measurements. When the small, and vertically variable, mean flows are removed the statistical properties of the records are essentially identical. This is encouraging. The various sensors have different locations on a support frame which necessarily provides some obstruction to the flow, the lowest sensor is held downwards, the mean flows are slightly different etc. Despite these differences the estimates of velocity are very similar. There is, however, no obvious way of estimating the validity of the measurement of the mean flow, some vertical structure is expected.

The general nature of the statistical distribution of flow speed is shown in Figure 2. Negative values are onshore. The observations are sufficiently close to the Gaussian distribution. (the Gaussian curve of equal variance is shown for comparison) that the ratios of even

moments $\langle u^4\rangle/\langle u^2\rangle^2$, $\langle u^2|u|\rangle/\langle u^2\rangle^{3/2}$ are close to that expected for a Gaussian distribution. A similar result was found in the NSTS results (Guza and Thornton, in press).

For a Gaussian distribution the odd moments are zero. In the data, contributions to u^3 arise from two sources, the mean flow and the skewness associated with the stronger onshore velocity under the wave crest, particularly evident in the record QE151BX.

Figure 3 shows low-passed records of u^3, $u^2|u|$ and the ratio $u^3/u^2|u|$, the filter removing the variation at the incident frequency. The light lines running horizontally show the mean values over this record. These parameters show a very obvious variability associated with the beat structure of the incident waves. This strong variability at relatively low frequency suggests that rather long records will be required to obtain stable estimates of the values of these high moments.

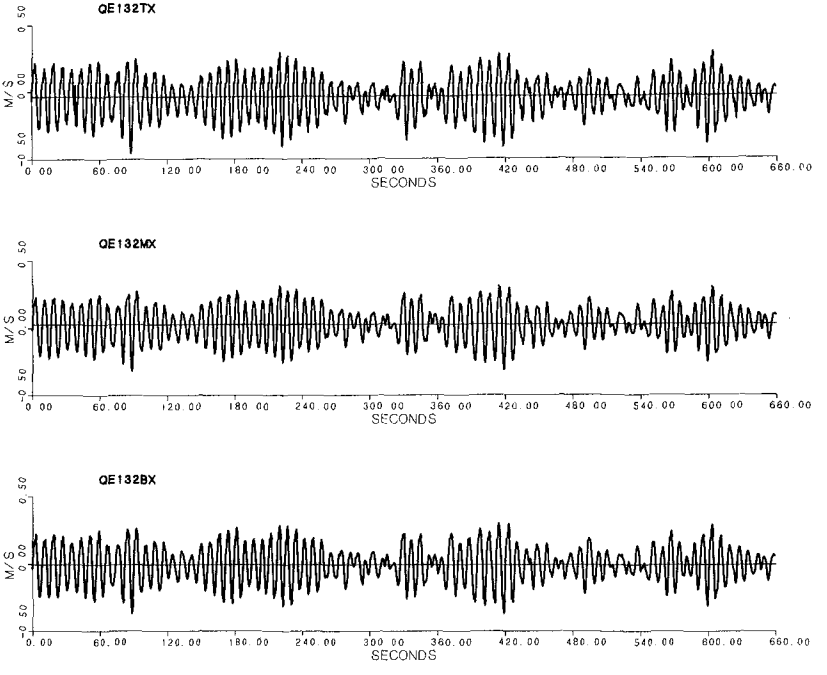

Figure 1. The on-offshore component of velocity u at 0.10 (bottom), 0.45 (middle) and 0.80 (top) m at Queensland Beach N.S.

Now Equation 1 can be considered in terms of an equilibrium condition. If the beach profile did not change appreciably during the experiment, which was in fact the case, $i_b \cong 0$. Then if the longshore velocities v are much smaller than u (again observationally confirmed), from (1)

$$\alpha \, dh/dx \sim \langle u^3 \rangle / \langle u^2 |u| \rangle \qquad (2)$$

For this data set, the ratio is approximately -0.013 so with α^{-1} of order of 0.63 the estimate for the beach slope is 0.080 very much of the order of the observed slope of 1:15. This does not imply the model is a complete

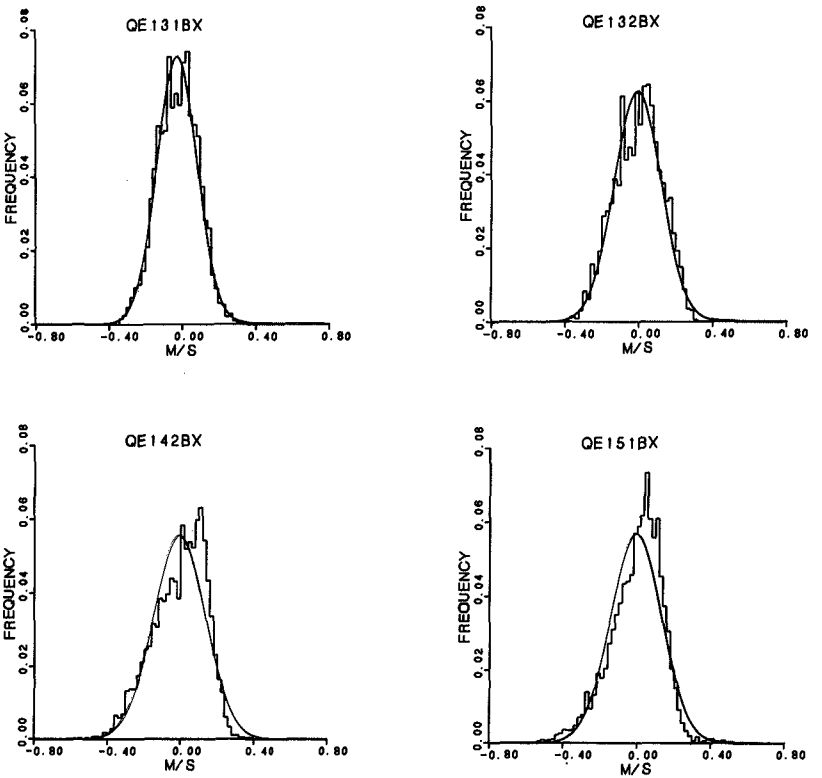

Figure 2. Statistical distribution of u for the bottom sensor, water depths 1.40 (131), 1.28 (132) 0.70 (142) and 0.55 (151) m at Queensland Beach. Observations at one station as the tide ebbed. Negative values are onshore.

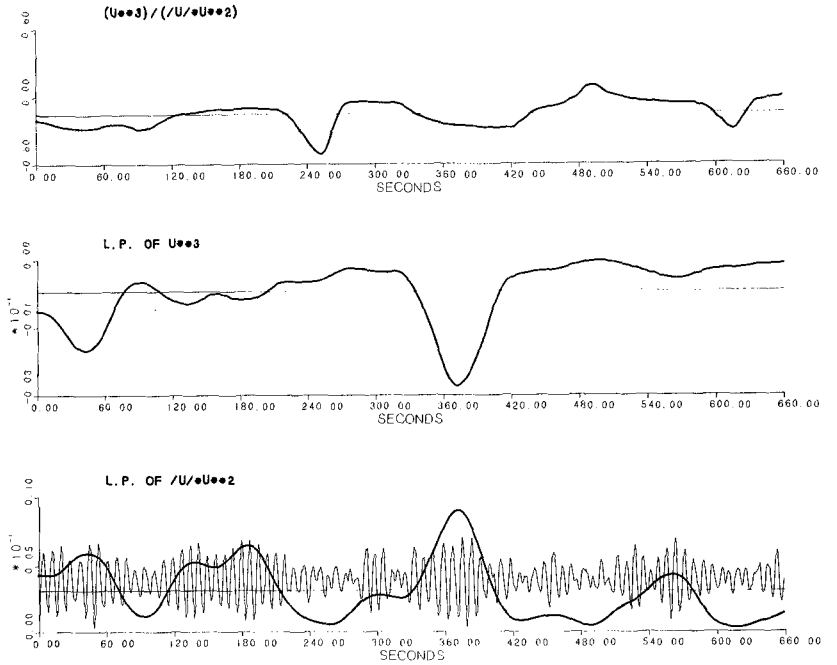

Figure 3. Parameters $u^2|u|$ (bottom), u^3 (middle) and their ratio (top), from the bottom record of Fig. 1. The results have been low passed to remove the variation at the incident frequency. The original record is shown for comparison.

description of the dynamics. Later in the tidal cycle, as the water becomes shallower, the onshore tendency is stronger (Figure 2). As the "equilibrium" is defined in terms of two surveys at successive low tides, an exact model should be the integral of the local sediment transport over the tidal cycle. However, the results do suggest that the effect of gravity can not be excluded from any discussion of sedimentary dynamics.

This model can readily be expanded to include the effects of the critical velocity u_c needed to move a sediment particle, the appropriate form of Equation (2) is

$$a\ dh/dx = -\langle u|u^2-u_c^2|\rangle / \langle |u||u^2-u_c^2|\rangle \text{ for } u > u_c \qquad (3)$$

In Figure 4, the change in the predicted equilibrium slope is shown as a function of $u_c/\langle u^2\rangle^{1/2}$ where $\langle u^2\rangle^{1/2}$ is the r.m.s. value of u. Two representative data sets both show that the effects of u_c are not likely to be

evident until $u_c > \langle u^2 \rangle^{1/2}$. Orbital velocities near the shoreline are typically of the order of 0.25 → 1.00 ms-1 so the effect of critical stress is likely to be important only for particles substantially larger than sand. Figure 4 is, in effect, another version of the explanation for the shoreward movement of large stones on a sandy beach. When $i_b \simeq 0$ for the smaller sizer, i_b will be onshore for all larger particles as $\langle u|u^2-u_c^2| \rangle_b$ is always increased relative to $\langle |u||u^2-u_c^2| \rangle$.

A rather different approach to the field data is to examine the spatial distribution of parameters relating to sediment transport. To do this sensibly, it is useful to remove the mean flow $\bar{u}$ from the data and define a velocity u_1 where

$$u_1(t) = u(t) - \bar{u} \qquad (4)$$

Mathematically, the higher moments will depend on both the value of the mean $\bar{u}$ and the skewness of u_1. However, in different depth and horizontal positions the relative

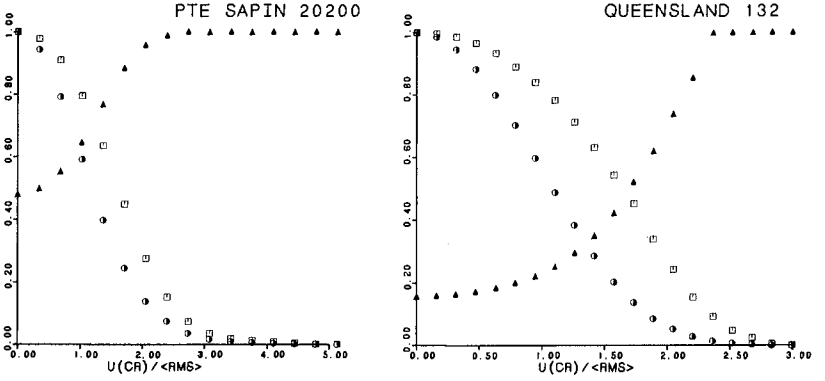

Figure 4. The parameters $\langle u|u^2-u_c^2| \rangle$ (◻), $\langle |u||u^2-u_c^2| \rangle$ (◐) normalized by their value at $u_c = 0$ and $\alpha dh/dx$ (▲).

contributions will vary significantly. In Figure 1, the data suggests that $u_1(t)$ does not vary greatly with depth (in shallow water) and a comparison between data from different horizontal positions and separate experiments should be of interest.

Figure 5 shows the skewness defined in the normal statistical sense as $\langle u_1^3 \rangle / \langle u_1^2 \rangle^{3/2}$ as a function simply of water depth. The data from inside the surf zone from the NSTS and UK experiments tends to lie on a straight line increasing from zero at the shoreline to a maximum (negative) value in the breaker region with skewness decreasing offshore. However the data for Queensland cuts right across the general trend, but again increases onshore to a maximum close to the break point.

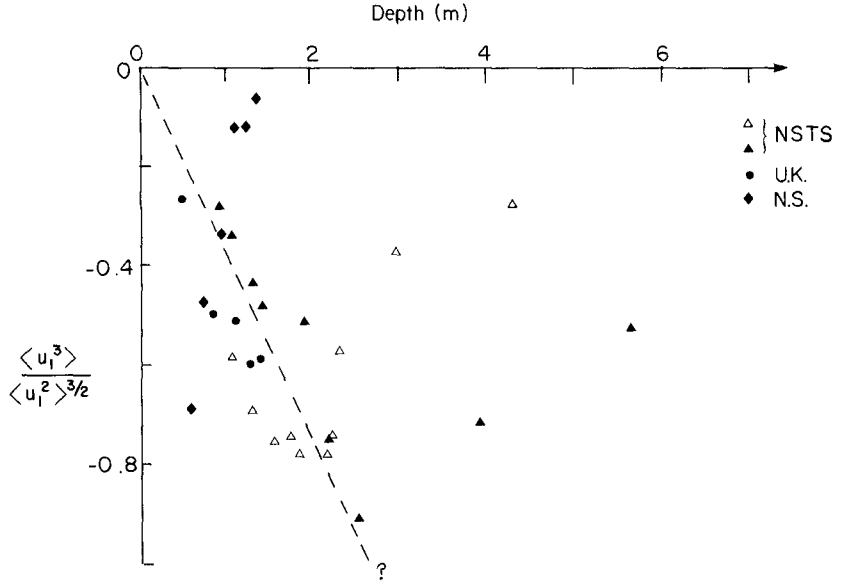

Figure 5. Skewness as a function of depth for data for NSTS (Guza and Thonton, in press), U.K. (Huntley and Bowen, 1975) and Queensland, N.S.

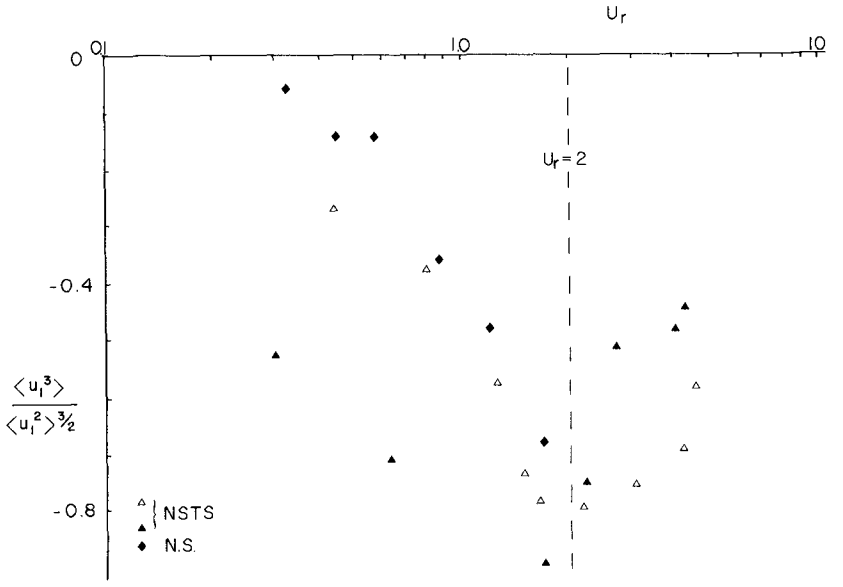

Figure 6. Skewness as a function of the Ursell Number, U_r.

It is not clear how to normalize this data, there are no simple theoretical models for wave skewness that adequately explain the observed phase shift between the first harmonic and the fundamental. However, the size of the first harmonic relative to the fundamental is given for a Stokes wave by the Ursell Number, U_r where

$$U_r = ak/(kh)^3 \qquad (5)$$

a being the wave amplitude, k the wavenumber. In Figure 6, the skewness is plotted against U_r which brings the Queensland data much more in to line with that of the NSTS. This is encouraging but the development of a predictor for the skewness is not likely to be a simple matter particularly as it obviously depends on the breaking process.

Conclusions

The existence of substantial sets of current meter data allows a much more realistic examination of the various ideas and formulae that have been proposed to describe nearshore sediment dynamics than would be possible using any idealized wave theory. Actual observation of the mean flow, the variance and the higher harmonics, both inside and outside the surf zone, provide an immediate assessment of the relative importance of some of the possible processes. As an example, Figure 7 shows the dependence of two transport measures, $\langle u^3 \rangle$, representing bed load, $\langle u^3|u| \rangle$ suspended load (Bagnold, 1966) on the strength of the mean velocity $\langle u \rangle$, positive offshore. Here real data from the Queensland experiment has been used to define $u_1(t)$ and the various mean values added. This defines, for this particular environment, the relative importance of the mean flow and the uncertainty in the transport parameters which will arise from uncertainties in its measurement.

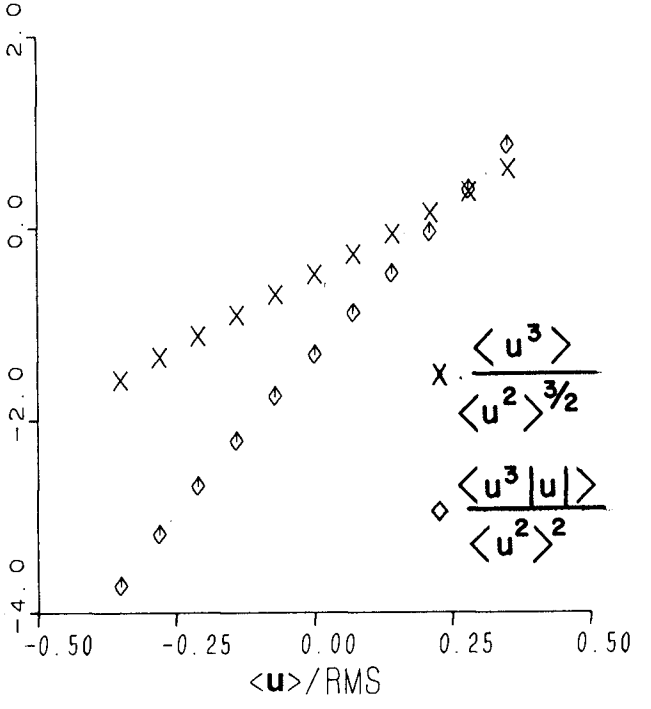

Figure 7. The parameters $\langle u^3 \rangle$ and $\langle u^3|u| \rangle$ as a function of the normalized mean flow $\langle u \rangle / \langle u^2 \rangle^{1/2}$.

The existing data suggest that the measurement of skewness and high moments of the velocity field are rather more consistent than might have been expected. However, the mean flow is uncertain and only measured with difficulty close to the sea bed. Figure 7 suggests that small velocities do play a significant role in contributing to the moments and good estimates of the mean flow are necessary. As this flow is generally an increasing function of wave height, the strongest signals are expected in severe conditions. As the sediment transport processes are themselves likely to be of most interest in severe conditions, this is convenient but suggests the likelihood of some distinctly uncomfortable moments in future field experiments. The Canadian Coastal Sediment Study has, for example, focussed on measurements in October-November in 1983, October in 1984.

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