CHAPTER 17

SET-UP DRIVEN UNDERTOWS ON A BARRED BEACH

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ABSTRACT

Field measurements of cross-shore velocity and water surface elevation from a natural barred surf zone during two storm events confirm the presence of undertow. The undertow is characterized by:

i) mean cross-shore velocities reaching 0.20 m s^{-1} and directed offshore;
ii) mean cross-shore velocity decreasing towards the surface with occasional reversals in the mean flow to a landward direction in the upper water column;
iii) a strongly oscillatory velocity field with speeds increasing towards the surface and a distinct landward skewness superimposed.

The undertow is strongly correlated with set-up of the mean water surface. The set-up is characterized by:

i) increasing values shoreward with perturbations closely following topography indicative of a primary forcing by waves;
ii) maxima (0.35 m in the inner system) occurring over the bar troughs in association with decreasing wave height over the preceding bar crest as predicted by theory and laboratory experiments.

INTRODUCTION

Traditionally, undertow was thought to be a major control on shoreface erosion and the development and maintenance of nearshore bars (e.g. Johnson (1919), Keulegan (1948), Dally (1980), Roelvink and Stive (1988)). Although attention shifted towards horizontal circulation mechanisms rather than vertically stratified flows following work by Shepard and LaFond (1939) and Shepard et al. (1941), the theoretical basis for a two-dimensional

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circulation was firmly established by Longuet-Higgins (1953), Longuet-Higgins and Stewart (1962; 1963; 1964) and Lundgren (1963). A considerable effort has now been directed at modelling cross-shore mean flows which occur under shoaling and breaking waves (e.g. Stive and Wind, 1986, and Svendsen and Hansen, 1988) and the driving mechanism, the pressure gradient due to set-up (and set-down) of the mean water surface (e.g. Battjes and Janssen, 1978, and Dally et al., 1985). However, field observations which document the spatial and temporal structure of undertow and which demonstrate a direct relationship to water level set-up by wave breaking have been lacking.

Recently, Greenwood and Osborne (1990a, 1990b) carried out eulerian measurements of the horizontal velocity field and water surface elevation from a natural barred surf zone in order to:

i) examine the spatial and temporal variability of cross-shore flow; especially its vertical structure;
ii) examine cross-shore flow in relation to topography; especially its possible role in bar formation;
iii) identify the mechanism(s) responsible for cross-shore flow; especially its relationship to wave-induced set-up.

Measurements were taken during two storm events in June 1986 at Wymbolwood Beach, Georgian Bay, Ontario, Canada. Measurements from the first storm event on June 16-18, 1986, clearly identified an undertow which was shown to respond in a coherent manner to measurements of wave-induced set-up of the mean water level. In this paper we illustrate that measurements from a second, smaller storm event on June 24-25, 1986, compare favourably with those from the previous event under similar surf zone conditions and confirm the existence of undertow on barred beaches.

LOCATION OF STUDY

Wymbolwood Beach is a lacustrine, barred shoreface composed of medium-to-fine sands situated on southern Georgian Bay, Ontario, Canada (Figure 1). The site is ideal for measuring set-up and cross-shore flows; periods of wave activity are restricted to discrete storm events associated with the passage of meteorological depressions and are separated by periods of flat calm. The beach is exposed to fetch-limited storm waves, which may reach 1.5 m at breaking. Water level shifts are restricted to seasonal hydrologic and climatic effects, higher frequency seiching and wind and wave set-up.

During the experiment two bars were present on a mean nearshore slope of 0.015 (Figure 2). The inner bar had relatively steep slopes (landward = 0.083; lakeward = 0.047 - 0.031). The outer bar consisted of a laterally extensive,

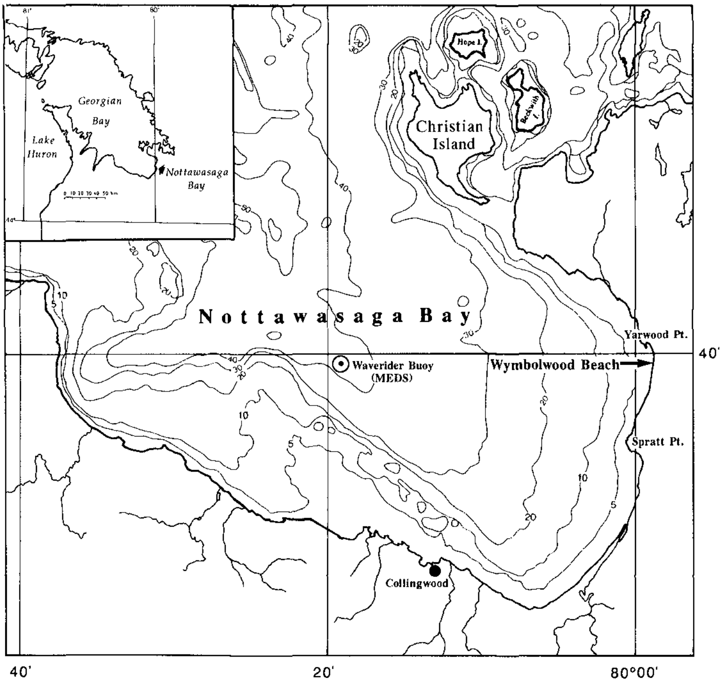

Figure 1. Location of study; bathymetric contours are in fathoms.

very gently sloping landward slope (0.005) and a lakeward slope approximately equal to that of the mean beach slope. Changes in the beach profile along the instrument transect during the two storm events were restricted essentially to the inner bar and beach face. The outer bar remained essentially two-dimensional and unchanged throughout the experimental period (Greenwood and Osborne, 1990a). No rip channels or other irregularities were present.

EXPERIMENTAL DESIGN

Sensor deployment was designed to satisfy two aims:
i) to relate waves, mean water-surface elevation and cross-shore flows to varying topographic constraints, horizontal spatial coverage should be as complete as possible;
ii) to relate cross-shore flows to elevation above the bed, a dense network of sensors in the vertical was necessary. However, deployment was constrained by the number of sensors available (15 continuous resistance wave staffs, 11 electromagnetic current meters). Figure 2 illustrates the final deployment of sensors along a shore-normal

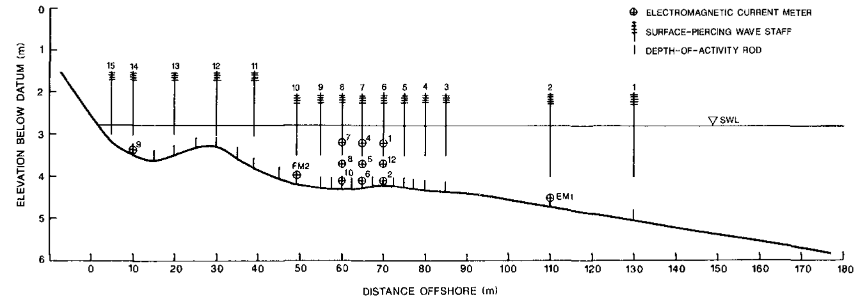

Figure 2. Nearshore profile and instrument deployment.

transect; note the fairly complete coverage of the nearshore by the wave sensors and the dense tri-level array of current meters on the landward slope of the outer bar. The latter might be expected to provide information on the character of any undertow that might occur and in a location where, according to theory, it might be expected to contribute to sediment transport causing bar growth. All sensors were scanned at 0.42 Hz for approximately 20 minutes. Wind speed and direction were measured at the beach face with a Beaufort anemometer and wind vane. Time-averaged statistics (such as the mean, standard deviation, and skewness) used to describe the wave and velocity fields, were computed over twenty minute sample periods (2925 points) as follows:

$$\bar{u} = 1/n\sum u_{(t)} \quad \text{or} \quad \bar{\eta} = 1/n\sum \eta_{(t)}$$

$$u_s = [1/n-1\sum(u_{(t)} - \bar{u})^2]^{1/2} \quad \text{or} \quad \eta_s = [1/n-1\sum(\eta_{(t)} - \bar{\eta})^2]^{1/2}$$

$$u_m = 2.8u_s \qquad H_s = 4\ _s$$

$$u_{sk} = [1/n-1\sum(u_{(t)} - \bar{u})^3]/u_s^3$$

Where n = sample size, $u_{(t)}$, $\eta_{(t)}$ = time-varying velocity, water-surface elevation, $\bar{u},\bar{\eta}$ = mean, u_m = maximum orbital speed, H_s = significant wave height, u_{sk} = velocity skewness. Water level set-up and set-down were computed using the difference between mean water levels during the storm events and mean water levels under flat-calm conditions on June 19-20 between the storms.

TEMPORAL VARIABILITY OF WAVE AND VELOCITY FIELDS

Both storms studied were of a magnitude frequently encountered in this location (e.g. the recurrence interval of the June 16 storm was 0.2 years). Temporal variation in wind speed and direction, significant wave height and peak wave period is presented in Figure 3. Incident wave heights reached 1.5 m with a peak period of 4 to 6 s in the June 16-18 storm. A relatively rapid reduction in wave height occurred following the storm peak due to a reduction in wind speed and a shift in wind direction away from maximum fetch. During the storm peak, a surf zone dominated by spilling breakers extended well beyond the outer bar crest for a period of at least 11 hours and breaking was present on the outer bar crest and area landward for a significantly longer period. Although wave activity lasted for 49 hours, the most intense activity was concentrated between 1600 h and 2330 h on June 16. In the June 24-25 storm, incident wave heights reached 1.1 m with a peak period of 4 s. Both wave height and period increased in response to wind from the WSW but decayed more gradually following the storm peak as wind direction shifted to the W and WNW (maximum fetch) and wind speeds were reduced. Spilling breakers dominated the outer bar crest and area landward for a period of approximately 6.5 hours between 1330 h and 2100 h.

Temporal variation in the near-bed velocity parameters: $\bar{u}$, u_s, and u_{sk} at 10 m, 65 m and 110 m offshore are shown in Figure 4. The first three moments of the cross-shore velocity field exhibit strong positive correlations with wave energy and a high degree of spatial coherence (Greenwood and Osborne, 1990b). Near identical values of wave-induced orbital currents (u_s) were recorded from the closely spaced flowmeters on the outer bar throughout the two storms.

On June 16, a distinct offshore mean flow was superimposed on the oscillatory motion at all measurement stations from 1300 h until 2330 h. The cross-shore mean-flow was not a local anomaly, but was coherent spatially and temporally. During the storm growth mean flows decreased across the landward slope of the outer bar; in contrast, a lakeward increase in mean flow speeds from 0.12 m s^{-1} to 0.18 m s^{-1} was observed during the storm peak.

On June 24, mean flows were again predominantly offshore, but of much smaller magnitude than in the previous event. In general, mean speeds increased lakeward across the landward slope of the outer bar from near zero (< +/- 0.03 m s^{-1}) at 60 m to 0.09 m s^{-1} at 70 m. The reduction in mean flow on the lakeward slope of the outer bar (110 m) suggests that the cross-shore mean flow was confined to the surf zone and was being driven by local forcing.

Coincident in time with the offshore mean flows was a large onshore directed skewness in the cross-shore velocity field. There does not appear to be a clear spatial pattern in the skewness, but rather a marked uniformity for a third order statistic which is highly susceptible to sampling variability. The positive skewness coincides well with the period in time when spilling breakers were

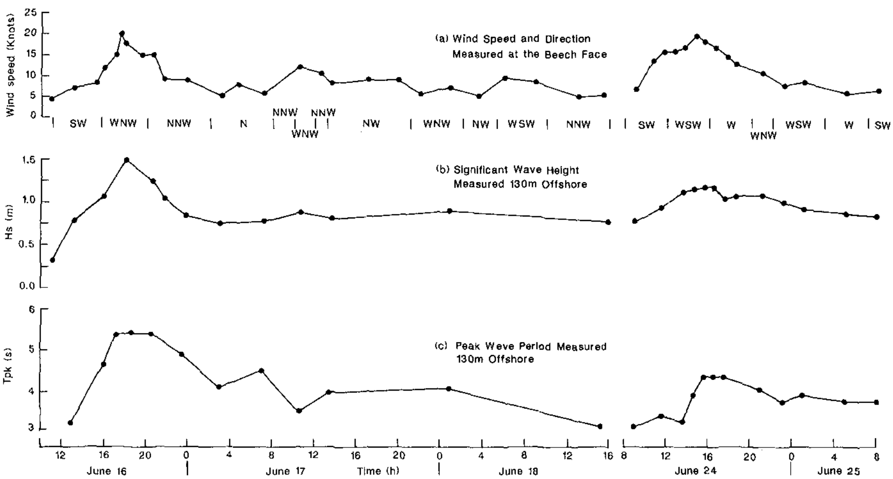

Figure 3. Wind and wave conditions, Wymbolwood Beach: June 16 to 18, 1986 (a); June 24 to 25, 1986 (b).

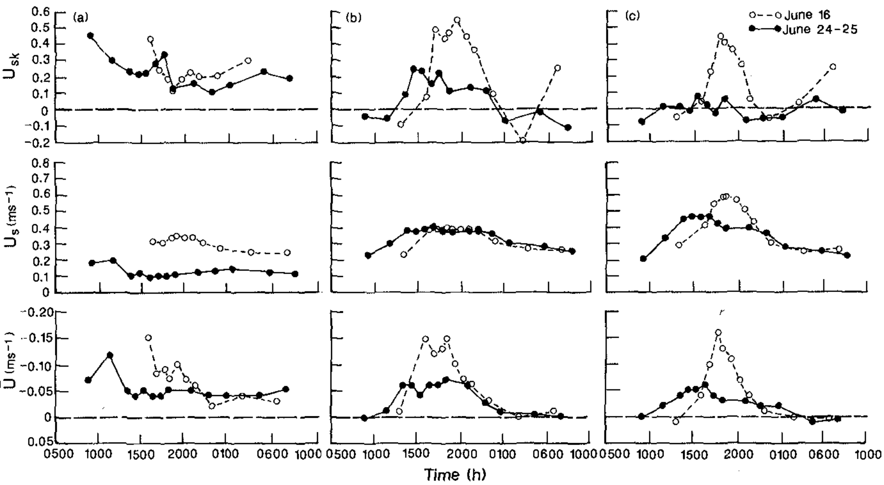

Figure 4. Temporal variation of near-bed (0.10 m) velocity parameters, $\bar{u}$, u_s, and u_{sk}, during the two storm events: 10 m offshore (a), 65 m offshore (b), and 110 m offshore (c). Note: positive values indicate onshore direction.

propagating through the tri-level sensor array, and this asymmetry was undoubtedly due to the non-linear nature of the surface waves. In the second storm, breaking waves were restricted landward of the outer bar crest, consistent with the near-zero skewness in velocity observed on the lakeward slope (Figure 4c).

CROSS-SHORE FLOW CHARACTERISTICS

Vertical variation in $\bar{u}$, u_s, and u_{sk} recorded on the landward slope of the outer bar (65 m) during both storms (1700 - 2030 h, June 16; 1500 -1730 h, June 24) is shown in Figure 5. The offshore mean flows exhibit a distinct vertical stratification; they were a maximum at the 0.1 m elevation and decreased in magnitude with elevation above the bed. At times, the mean flow exhibited a reversal, being directed onshore at the 1 m elevation, although these flows were small. In contrast, the wave-induced oscillatory motion was generally uniform in magnitude with elevation above the bed. Orbital speeds were similar during both storm events, indicative of the limiting velocity under wave breaking. Velocity skewness, on the other hand, exhibited more vertical variation, although it was almost always positive (directed onshore) at all elevations.

Figure 6 is an example of time-series of cross-shore velocities and water surface elevations under breaking waves during the storm peaks which illustrates that, even though a significant quasi-steady flow was present, the time-dependent, cross-shore flows were still dominated by oscillatory motion. The strongly non-linear nature of the water surface profile and the resulting velocity asymmetry associated with the spilling breakers is clearly displayed in these time-series; note also the "saw-toothed" water surface profile. Figure 7 illustrates a typical distribution of total velocity vector magnitude as a function of angle relative to the shore-normal during the storm peaks. It is evident that the vectors are distributed across all angles with the majority (greatest density of points) distributed about 200°, indicating that most flow vectors were associated with the offshore and alongshore currents. The distribution is also peaked at 0°/360° (the onshore direction); note that the magnitude of the relatively infrequent onshore directed vectors is similar to that of the offshore directed flows. This is in marked contrast with the signature of an active rip current recorded by Bowman et al. (1988).

In summary, the velocity field under spilling breakers was predominantly oscillatory, but with a well-defined offshore mean flow superimposed. The velocities exhibited a landward directed skewness, which was caused by the non-linear breaking waves. The spatial and temporal coherence

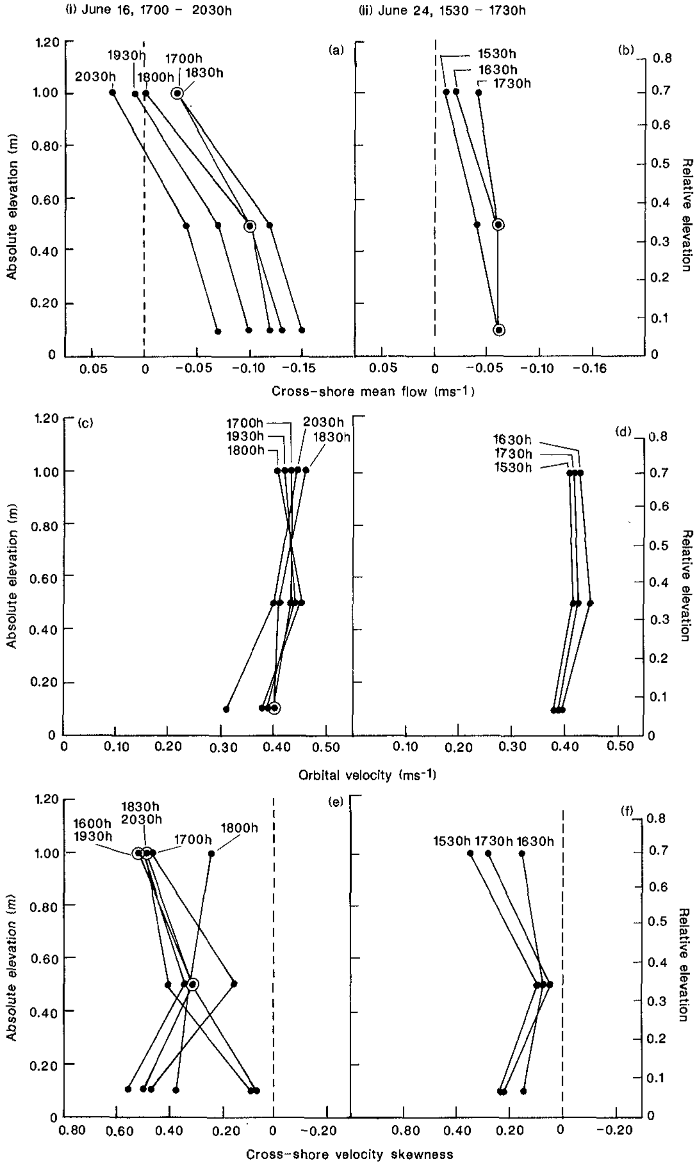

Figure 5. Vertical variation in the horizontal velocity field at 65 m offshore: i) 1700 - 2030 h on June 16; ii) 1500 - 1800 h on June 24; cross-shore mean velocity, $\bar{u}$, (a, b); cross-shore orbital velocity, u_s, (c, d); cross-shore velocity skewness, u_{sk}, (d, e). Note: positive values indicate onshore direction.

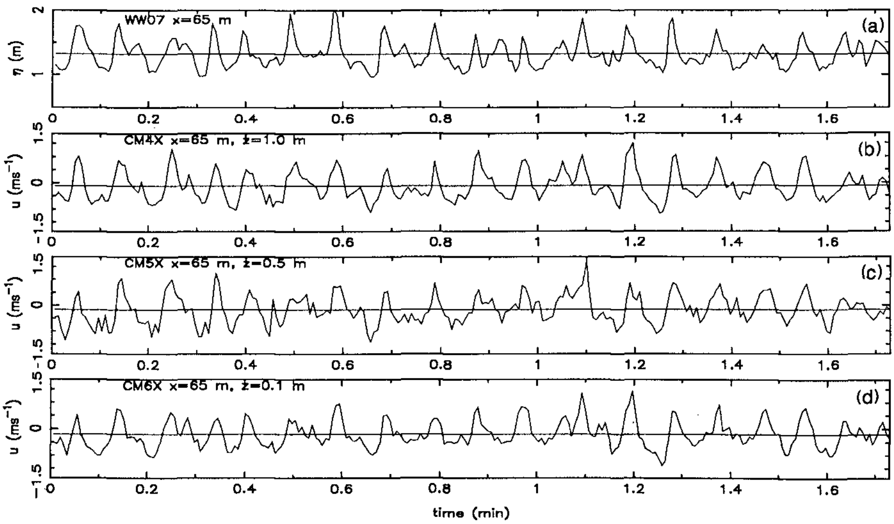

Figure 6. Time-series of: water surface elevation (a), and cross-shore velocities at 1.0 m (b), 0.5 m (c), and 0.1 m (d) elevation at 65 m offshore during the storm peak on June 16, 1800 h.

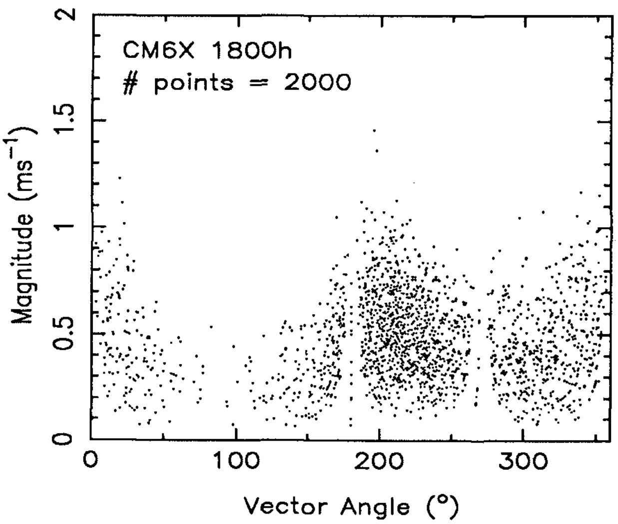

Figure 7. Velocity vector magnitude as a function of angle relative to shore normal (1800 h, June 16).

of the mean flow, with its maximum near the bed, has the characteristics of an undertow.

SPATIAL AND TEMPORAL VARIATION IN SET-UP AND WAVE HEIGHT

Temporal changes in the set-up of the mean water level in the inner part of the surf zone are shown in Figure 8. The set-up was well correlated with wave energy and also with the offshore mean flow. This is to be expected if the set-up is primarily wave-forced and the undertow is set-up driven.

In general, wave height decreased and set-up increased towards the shoreline during the storm peaks (1800 h, June 16; 1630 h June 24); however spatial variation in the wave height decay and elevation of the water level indicate a strong topographic influence induced by the bars (Figure 9). In both storms there was a rapid decay spatially in wave height across the upper lakeward slope and crest of the outer bar, the minimum height occurring just landward of the bar crest. The overall pattern for June 16 is consistent with the visual observation that breaking occurred by spilling across the whole experimental array and actually began well lakeward of the array. The wave height decay pattern also indicates that more intense breaking was associated with local decreases in water depth on the bar crests and at the shoreline. On June 24, the wave height decay across the lakeward slope of the outer bar (> 85 m) was less rapid than that observed during the June 16 storm owing to the smaller incident wave heights.

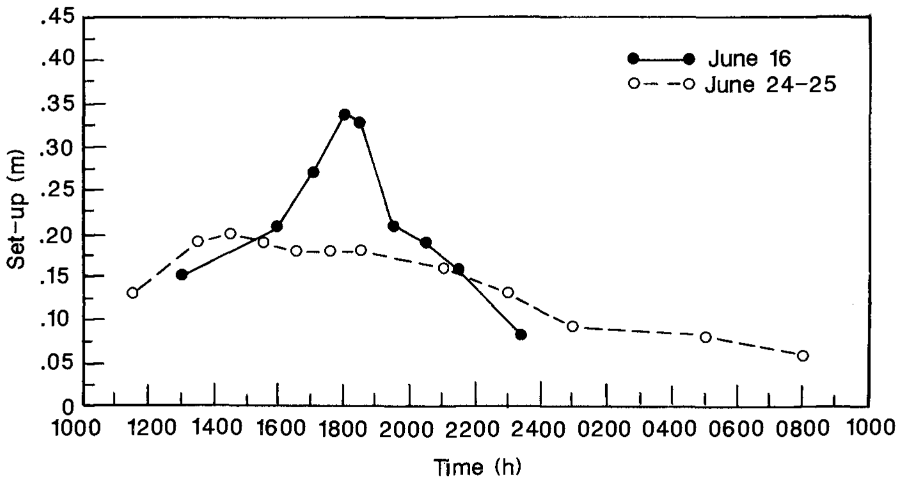

Figure 8. Temporal changes in the set-up of the mean water level measured at 10 m offshore.

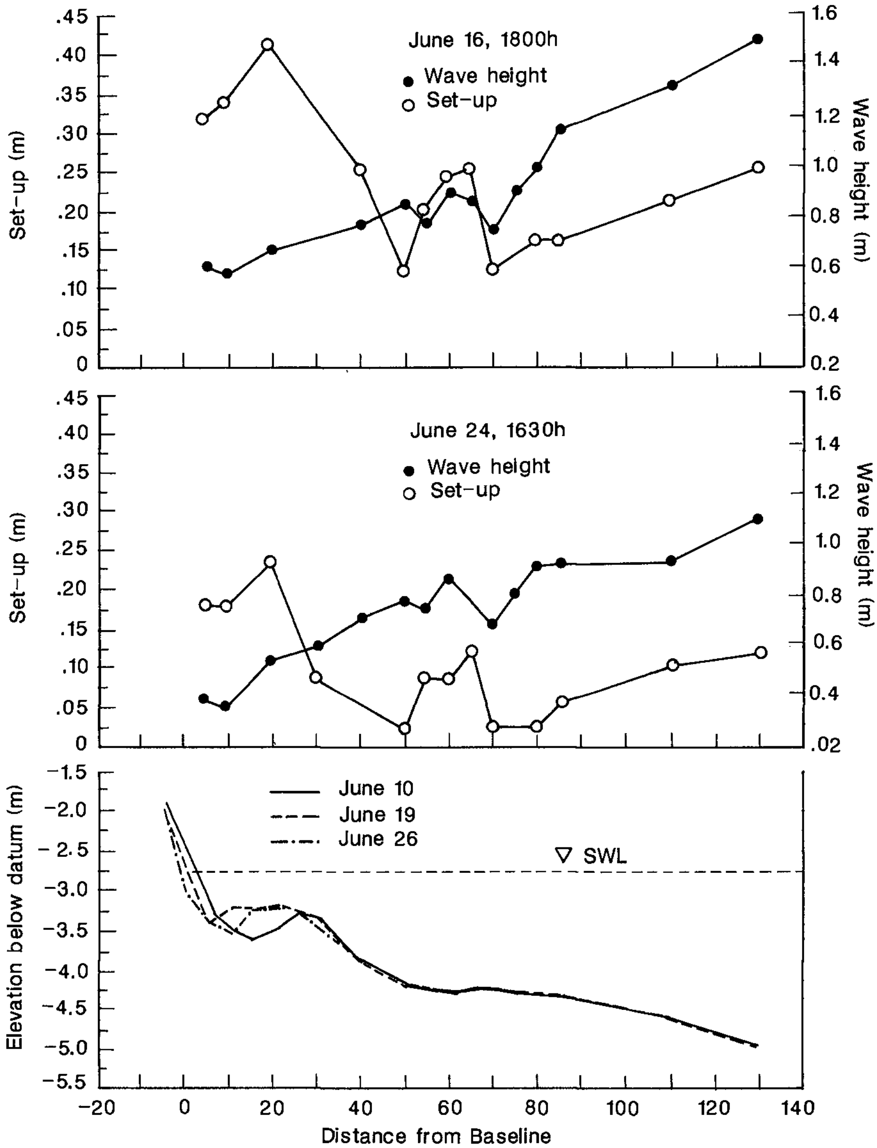

Figure 9. Shore-normal variations in the significant wave height and mean water surface set-up during the storm peaks: 1800 h June 16 (a); 1630 h June 24 (b).

The maximum local gradient in set-up occurred across the lakeward slope and crest of the inner bar, with maximum set-up in the trough to landward. There was a distinct decrease in the set-up landward of this local maximum. This pattern is consistent with the observed increase in local energy dissipation, often characterized by the presence of plunging breakers, which occurred over the crest and upper lakeward slope of the inner bar and again at the shoreline. No measurements of the water surface across the beach face were possible in this experiment to confirm the expected set-up due to the shoreline breakers, but visual observations confirmed an increase in the elevation of wave run-up during the storm peaks. A similar but less pronounced pattern in set-up is evident over the outer bar in association with the gradients in dissipation occurring in that region.

These observations provide strong evidence that topographic variations introduce spatial variability in both wave height and set-up, the former through enhanced shoaling, breaking and frictional effects as both theory and laboratory experiments suggest (Battjes and Janssen, 1978; Dally et al., 1985). However, the spatial gradients in set-up are significantly smaller than those expected for the measured wave height decay (Greenwood and Osborne, 1990b; Hazen et al., 1991).

DISCUSSION AND CONCLUSIONS

In this paper we illustrate the presence of an undertow on a natural barred beach which responds to both spatial and temporal variations in a wave-induced set-up. This distinctive two-dimensional cross-shore circulation pattern has been identified during two moderate storm events through detailed velocity and water surface elevation measurements.

During periods of breaking waves, the cross-shore velocity field was dominated by wave-induced flows with an average oscillatory speed of 0.40 m s^{-1}. A strong asymmetry in these oscillatory flows was evident in terms of large non-zero mean values (upto 0.20 m s^{-1}) directed offshore, and positive (onshore) directed skewness values. Vertical profiles of the wave-induced oscillatory velocity (u_s), the mean velocity ($\bar{u}$) and the velocity skewness (u_{sk}) indicate radically different structures. The oscillatory velocities were essentially uniform, perhaps increasing slightly with elevation above the bed, whereas the offshore mean flows generally decreased in speed with elevation, and in some cases flow reversals were present in the upper part of the water column. Velocity skewness was positive with considerable vertical variability, although a less distinct stratification than the mean and oscillatory components. These observations reveal a mean flow, which is separate and distinct, and imply the existence of a quasi-steady current superimposed on highly non-linear oscillatory motion.

The large positive skewness values together with the vertical structure of the oscillatory and mean flow components suggest a shoreward directed, depth-dependent momentum and mass flux which is greater near the surface as suggested by theory. The mass and momentum balance is achieved by the large offshore mean currents in the lower water column. A large number of vertical profiles with this distinctive vertical structure from across the outer part of a surf zone saturated with spilling waves, suggest a well-developed and spatially coherent undertow.

The undertow responds to changes in the set-up of the mean water level, which in turn is strongly correlated with the growth and decay of the incident wave height. This is consistent with the hypothesis of a two-dimensional circulation driven by the vertical differences in the water column between the depth-dependent radiation stress and a depth-uniform pressure gradient force associated with a sloping water surface.

Local variations in the set-up, wave height and cross-shore mean flow are topographically controlled on a barred beach (see also Hazen et al., 1991). Large set-up gradients on the steepest part of the beach (lakeward slope of the inner bar) are associated with large gradients in wave height decay over the outer bar crest. These observations together with the presence of vertically stratified flows lend support to the notion a two-dimensional circulation system, undertow, driven by wave set-up.

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