

CHAPTER FIFTY NINE

Is Surf Beat Forced or Free?

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Abstract

Although many field experiments have shown that surf beat motion, with periods longer than incident wave periods, becomes the dominant feature of the nearshore velocity field as the shoreline is approached, the nature of this motion is still not fully understood. This paper describes a field experiment on a sheltered beach which was designed to distinguish between long wave motion directly forced by the incident wave envelope (as suggested by Longuet-Higgins and Stewart, 1962), and wave motion which is only weakly coupled to the local incident waves and therefore essentially free.

The results for on/offshore flows show that low frequency surf beat (frequency less than 0.03 Hz) is strongly correlated with the wave envelope, suggesting the dominance of forced wave motion at these frequencies. In a higher frequency band, between 0.06 and 0.095 Hz, the correlation is generally much lower, suggesting that free wave motion, possibly subharmonic edge waves, is significant in this band.

The longshore flows are much more weakly correlated to the envelope of either the longshore or on/offshore components of the orbital velocity. This is consistent with previous observations that edge wave motion dominates the longshore surf beat motion.

Introduction

It is now clear that water motion with periods substantially longer than incident wave periods generally dominates the velocity field near the shore, and may be the controlling mechanism for changes in coastal morphology in response to waves (Bowen and Huntley, 1984). However, despite extensive field and theoretical work, the precise nature of this long period motion is still unclear.

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Figure 1 shows schematically the possible forms of low frequency motion which have been suggested for the nearshore zone. Broadly they fall into two categories, occurring either as forced waves or free waves.

Forced motion is generated directly by the incident waves. Longuet-Higgins and Stewart (1962) showed theoretically, using the radiation stress concept, that there should be a depression of the mean water level under high waves and a corresponding rise in mean water level under low waves. Hence if incident waves are "groupy", i.e. have an alternating sequence of high waves and low waves, they will carry with them a forced wave component at the frequency of the wave groups.

Free wave motion, on the other hand, is presumed to have an existence which is decoupled from the local incident waves. It can, in principle, take a number of different forms. Free edge waves are trapped to the coast and propagate parallel to the shoreline. Although such edge waves at surf beat periods are probably generated by the groupy structure of the incident waves, their growth rate is relatively slow and depends upon a spatial average of the incident wave structure, in contrast to the immediate and local response of the forced waves (Gallagher 1971, Bowen and Guza 1978). Free waves might also be "leaky" in the sense of being able to propagate towards or away from the shoreline. There is no evidence that significant free long wave energy propagates to the shoreline from deep water, but free wave motion may be generated within the nearshore zone itself. For example Symonds et al (1982) show how the varying position of the breakpoint for groupy incident waves can generate freely propagating long waves at the group period. They predict a shoreward propagating long wave which reflects at the shoreline to set up standing wave motion in the surf zone, and a seaward propagating free wave seawards of the breakpoint. It has also been suggested that the forced wave brought to the breakpoint by incident wave groups might be released at the breakpoint and travel seawards and perhaps shorewards as a free wave, though the mechanism for this is not clear (Tucker, 1950, Longuet-Higgins and Stewart, 1962).

Surprisingly little published data addresses the problem of distinguishing between these possible forms of long period motion in the field. A number of studies confirm that edge waves contribute to the long period energy (e.g. Holman, 1981; Huntley et al., 1981). For example, Huntley et al (1981) show unambiguous evidence that edge wave motion dominates in the alongshore components of velocity, though the on/offshore velocities

showed additional energy which could not be clearly related to edge wave motion.

This paper describes field measurements of nearshore velocities designed to distinguish between forced and free long wave motion. In order to measure significant incident wave groups the measurements were made just seawards of the breakpoint. The test of whether the long period motion is forced or free then becomes simply a question of the degree of correlation between the local incident wave envelope and the long period motion at a point; if forced motion dominates the correlation should be very high while if free wave motion is significant the correlation should be correspondingly low.

Theoretical considerations

Forced waves

Longuet-Higgins and Stewart (1962) showed theoretically that mean water level, ζ , under wave groups and the onshore component of radiation stress, S_{xx} , are related by

$$\zeta = - S_{xx} / \rho(gh - c_g^2) + \text{const} \quad (1)$$

where ρ is the density of water, g the gravitational acceleration, h the local water depth and c_g the incident wave group velocity. Equation 1 should be valid where the wave group wavelength is long compared to the water depth. Since S_{xx} is proportional to the square of the incident wave amplitude equation (1) predicts a relative depression of mean water level where the wave amplitude is high.

As the incident waves travel into shallow water their group velocity tends to the wave phase velocity and the denominator in equation 1 tends to zero, suggesting very large changes of mean water level. At small Ursell numbers the shallow water form of (1) can be written

$$\zeta \sim -3/4 \frac{ga^2}{\sigma^2 h^2} \quad (2)$$

where a is the wave amplitude and σ is the wave radian frequency. However the large mean water level changes predicted by this formula are clearly inappropriate in the nearshore zone. As Longuet-Higgins and Stewart (1962) pointed out, not only is the small Ursell number condition violated, but also the shallow water resonance implied by equation (1) must be properly treated.

Unfortunately, although there has been some theoretical work addressing this problem (e.g. Foda and

Mei 1981) there is as yet no accepted theoretical prediction of water level changes under wave groups in shallow water. Nevertheless, for the purposes of this study we assume that, although the forms of equations 1 and 2 are not valid where our measurements were made, the mean water level response in shallow water will still be proportional to the square of the incident wave amplitude since the varying radiation stress remains the agent driving the forced waves.

The measurements discussed in this paper are of velocities rather than sea level changes. The only change this might make to the discussion above is in the sign of the long wave response relative to the wave envelope. For elevations the depression of mean water level under high waves results in the negative sign on the right hand side of equations 1 and 2. Under such a depression the forced velocity is in the opposite direction to the group propagation direction. In the discussion below we take the positive x direction to be the seaward-pointing normal from the shoreline, so that offshore flows under shoreward propagating wave groups are positive. Hence, while for elevation measurements we would expect to find a negative correlation between wave envelope and mean sea level (assuming positive sea level changes to be upwards), for our current measurements we would expect a corresponding positive correlation.

Free waves

As we have shown in Figure 1 there are several different forms that free wave motion might take, but each is decoupled in some way from an immediate local response to incident wave groups.

Edge wave generation is generally considered to take one of two basic forms. Pairs of edge waves can be generated by the instability of a single incident wave component reflected at the shoreline, the most rapidly generated being zero mode edge waves at the subharmonic of the incident waves (Guza and Davis 1974; Guza and Bowen 1975). Edge waves can also be generated by the long period groupiness structure of the incident waves (Gallagher 1971, Bowen and Guza 1978). Theoretical and laboratory work on these generation mechanisms has been limited to monochromatic incident waves, but even in these studies edge wave growth rates have been found to be relatively slow (e.g. an e-folding time of 10 incident wave periods for the fastest growing subharmonic edge waves). On natural beaches with a stochastic spectrum of incident waves the growth rates should be substantially reduced below these monochromatic values and edge wave

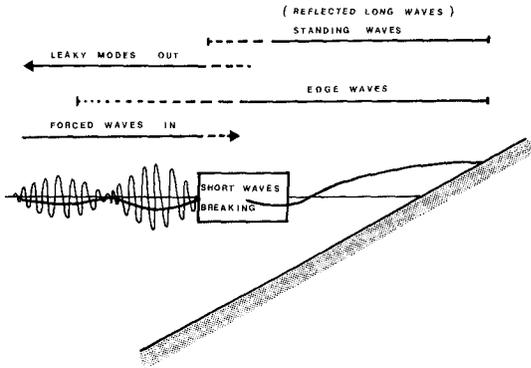


Figure 1. Possible forms of long waves on sloping beaches. The top three lines represent free wave modes and the bottom represents the forced wave.

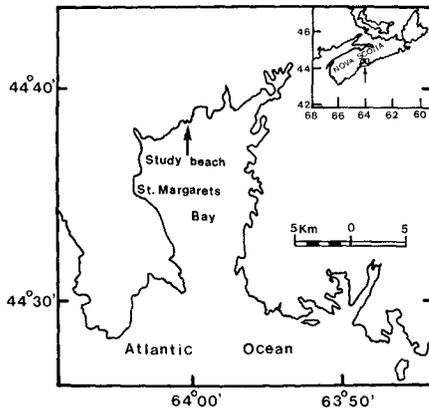


Figure 2. Location of Queensland beach.

amplitude is therefore expected to correspond to a time average of incident wave conditions rather than to the immediate local wave conditions. In addition, as Bowen and Guza (1978) point out, edge waves generated by incident wave groups will be linked only to that component of the groupiness whose spatial as well as temporal structure matches that of the edge wave. Again this suggests a low correlation between edge wave amplitude and local incident wave envelope.

Free waves generated by a time-varying breakpoint (Symonds et al. 1982) are clearly linked to the incident wave groupiness. However there are a number of reasons why correlation to incident wave amplitude may be small. The amplitude of the seaward propagating free waves is frequency dependent with free wave amplitude going to zero for some group frequency components. At each group frequency component, free waves at a range of harmonic frequencies are also predicted. In addition, for a sensor seawards of the breakpoint, there will be a time lag between the wave envelope and the long wave response corresponding to the travel time to the breakpoint and back. Without a more complete quantitative theory it is not possible to estimate the significance of the first two of these factors, and the third may be too small to detect in our data (see the discussion below). However a strong correlation over a broad frequency range would seem unlikely in this case.

Field Observations

Measurements of the nearshore velocity field were made at Queensland Beach in St. Margaret's Bay, Nova Scotia, on the 25th and 26th June, 1979. Queensland is a pocket beach with direct exposure to the Atlantic in only a very narrow range of directions around normal incidence to the beach (Figure 2). The shoreline is essentially straight, about 170 m long, and is terminated at one end by a headland and at the other by a reef of bedrock which extends several tens of meters offshore. The local beach slopes in the region where the currents were measured varied between 0.08 and 0.10.

The flow field was measured using Marsh-McBirney electromagnetic flowmeters mounted on the single tripod at three heights above the bed (10, 45 and 100 cm). Each sensor, measuring two orthogonal axes of flow with a response time of about 0.2 s, was aligned to measure the onshore and longshore components of flow. Figure 3 shows the position of the tripod on which flowmeters were mounted, the mean run-up position visually observed midway

through each data run and tidal variation during the measurements.

Winds during the experiment were generally mild and variable in direction. Near-normally incident waves approached the shoreline with noticeable groupiness. Generally the significant wave heights were between 40-60 cm near the tripod, which was located 10-25 m from the shoreline. Most of the waves broke inshore of the sensors.

Data Acquisition and Analysis

Spectra of the measured currents show two consistent spectral troughs. A trough near 0.095 Hz, present in all spectra, is taken to separate the incident wave energy, centered at 0.12 Hz, from the low frequency motion. A second spectral trough is found near 0.06 Hz, and its frequency is independent of offshore distance for the range of distances shown in Figure 3. This trough separates the low frequency band into a higher frequency band which we term "subharmonic" and a lower frequency band which we term "surf beat". For all segments of the data there is significant long period energy. Long wave energy varies from 2% to 11% of the total incident wave height, the largest values occurring nearest the breakpoint.

A Kaiser-Reed (1977) filter is used to separate time series of velocity into low- and high-passed components, with the division at 0.095 Hz. To obtain the wave envelope, the high-passed time series is squared and then low-passed through the same filter. Means of both the wave envelope and the long period time series are then calculated and removed.

Cross-spectra between wave envelope and low frequency wave motion were computed using the IEEE cross-spectral algorithm described by Carter and Ferrie (1979). Each time series of 4096 data points was partitioned into 7 segments of 1024 data points with a 50-percent overlap, giving a frequency resolution of 0.0029 Hz. Nuttal (1971) shows that the number of degrees of freedom, n , for 50% overlapped data segments is given by:

$$n = 3.82 N_d - 3.24$$

where N_d is the number of disjoint (non-overlapping) segments. For our data runs this gives $n = 12$.

Cross-correlations between the two series were also calculated for time lags up to ± 200 seconds, to determine

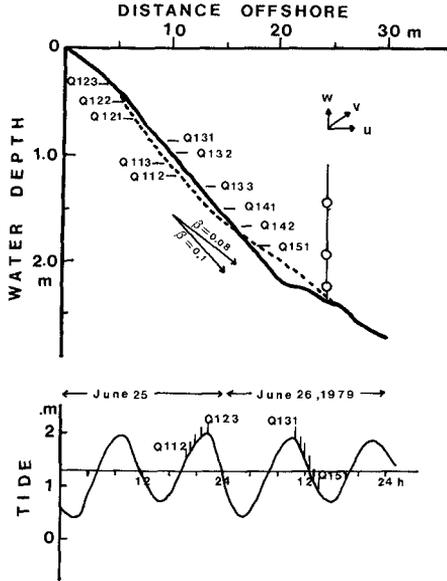


Figure 3. Tripod deployment and the variation of mean run-up positions with the tide.

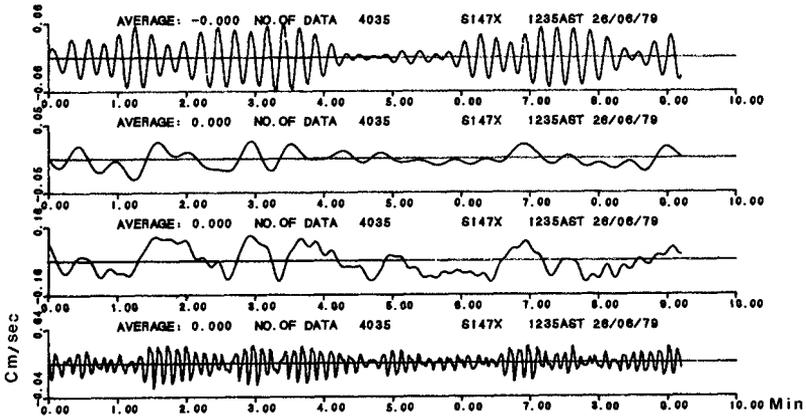


Figure 4. Sample segments of time series. From the bottom in ascending order the original data, the corresponding wave envelope, the very low frequency surf beat motion and, on top, the motion at sub-harmonic period.

any non-dispersive time lag between the series. The 95% significance level for cross-correlation is related to the effective number (N^*) of independent points within each series. The number of independent points can be estimated from the auto-correlation of the product of the two series by (Garrett and Toulany, 1981),

$$(N^*)^{-1} = (N)^{-1} + \sum_{j=1}^{N'} (N-j) R_{11}(j) \quad (3)$$

where N is the actual number of observation, $R_{11}(j)$ is the lagged auto-correlation of the product and N' is the number of lags up to the first zero crossing of R_{11} . Throughout our runs N^* lies in the range 150-600. The corresponding 95% confidence limits on zero correlation ranges between 0.18 to 0.10.

The On/Offshore Flow Response to Incident Wave Groups

The lowest plot of figure 4 is a segment of the time series of onshore velocity for run Q141, showing noticeable wave groupiness. Above this, in ascending order, are the corresponding wave envelope, the very low frequency surf beat motion and, on top, the wave motion at subharmonic periods. Clearly the surf beat energy is positively correlated with the wave envelope.

Figure 5 shows an example of the spectra, coherence and phase of wave envelope and long period motion. The cross spectra suggest that we can identify three spectral bands, a surf beat band (0.003 - 0.03 Hz), an intermediate band (0.03-0.06 Hz) and a subharmonic band (0.06-0.08 Hz).

In the surf beat band the coherence between the incident wave envelope and the long period motion is consistently above the 95% confidence level and the phase is close to zero degrees across the entire frequency band. These features occur in the surf beat band throughout the data set. They suggest that locally forced wave motion strongly dominates the on/offshore flow in this frequency band.

In the subharmonic band, on the other hand, the coherence is generally weak with a phase which, if not entirely random, varies significantly across the band. This suggests that free wave motion is significant in this band. This is not the case for all data runs, however. Where subharmonic energy occurs as a narrow high energy peak a corresponding narrow peak in coherence can occur, with again a phase close to zero degrees (Figure 6). Clearly this suggests that forced wave motions can occur

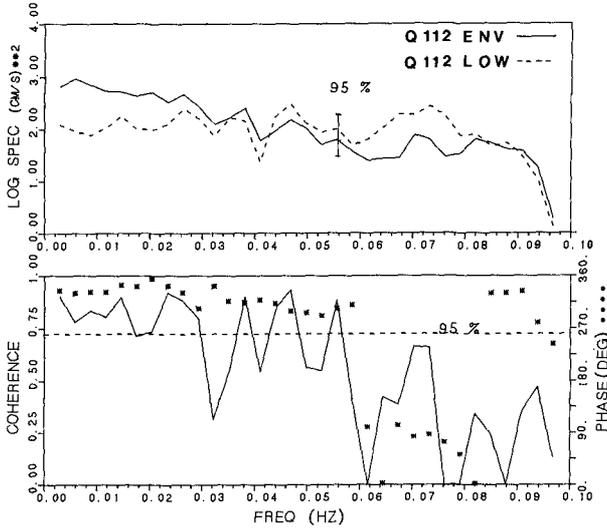


Figure 5. Cross-spectra between wave envelope and low frequency wave motion for Q112.

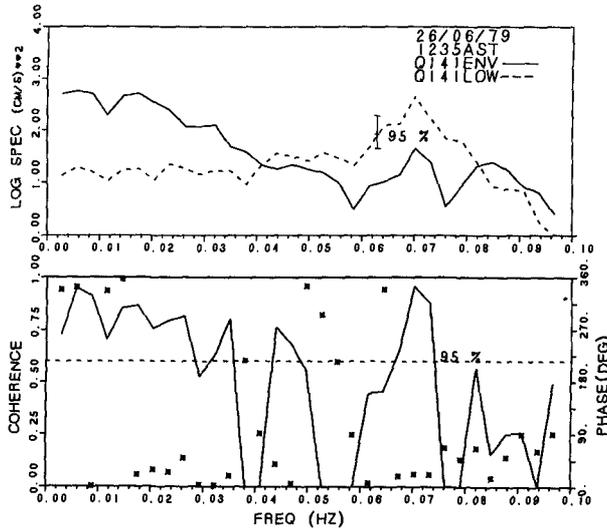


Figure 6. As Figure 5, but for Q141.

in a narrow frequency band within this "subharmonic" band, but the significance of this observation is not yet clear.

In the intermediate band between the lowest frequency band and the subharmonic band no consistent conclusion could be reached, the cross spectra suggesting the presence of both forced and free motion with neither dominating.

Figure 7 summarizes the band-averaged coherences and phases for the complete data set, for both the low frequency surf beat band and the subharmonic band. These confirm the conclusions discussed above. In the surf beat band the coherence averages about 0.8, suggesting that the long period energy is about 80% forced by the wave envelope. The phase, as expected from the Longuet-Higgins and Stewart (1962) theory, is very close to zero degrees. In contrast, the subharmonic band shows coherence values which, while sometimes above the 95% confidence level on zero coherence, are much lower, with an average value of around 0.55. The average phases are also scattered. Although definitive conclusions cannot be drawn from coherence values so close to the 95% level, it would appear that the forced wave motion can account for, at most, 55% of the long period energy present in this frequency band.

Cross-correlations between the incident wave envelope and the long period motion were also computed for the lowest frequency surf beat band to identify any time lags between the wave envelope and the long period response. Figure 8 shows the average cross-correlation function for the complete data set. The 95% confidence level is estimated as about 0.10. As expected, the largest correlation occurs at zero lag and the correlation drops rapidly for non-zero lags. In Figure 8 a positive lag implies that wave envelope leads the long period motion. In the case where the forced wave is released as a seaward propagating free wave at the breakpoint, the positive lag between wave envelope and long wave response was around 10 s for the present data set. This is too small to be clearly separated from the peak at zero lag, but the rapid decay of the peak at positive lag is suggestive of only a small seaward component, if any. The secondary, barely-significant peak at a positive lag of about 35 s is intriguing. It will be further mentioned in the following section.

The Longshore Flow Response

Huntley et al. (1981) used data from a California beach to show that the longshore component of flow was

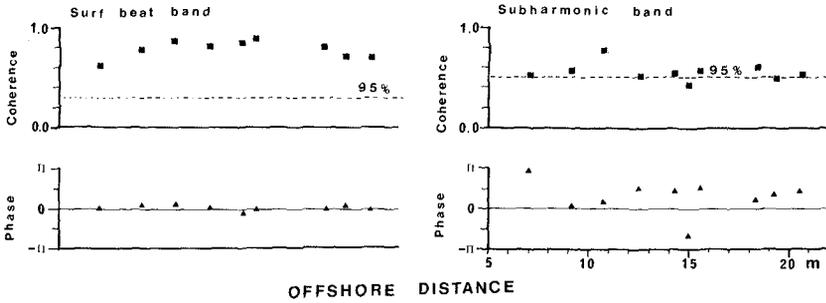


Figure 7. Band-averaged coherences and phases at surf beat and subharmonic frequencies.

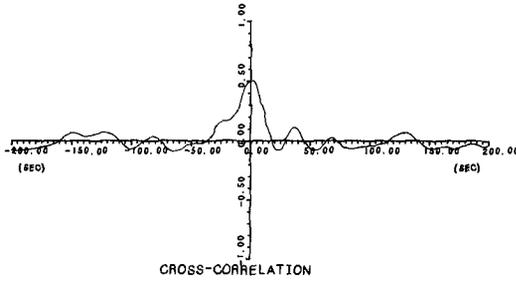


Figure 8. Cross-correlation between wave envelope and low frequency motion.

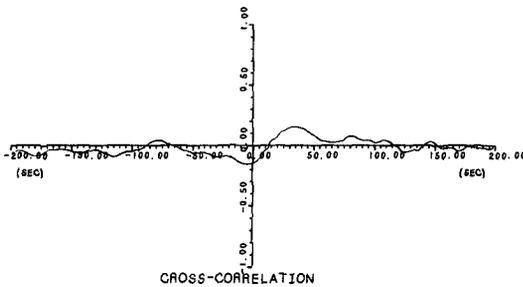


Figure 9. Cross-correlation between incident wave envelope and longshore surf beat energy.

dominated by free edge wave motion. It is therefore of some interest to ask whether the present data set is consistent with this observation or whether there is evidence for forced longshore motion correlated with incident wave groups.

Calculated cross-correlations between longshore current envelope and the longshore surf beat flow are low, below the 95% confidence level, for all time lags. Thus there is no evidence for longshore motion forced by longshore groupiness. However cross-correlation between the on/offshore envelope and the longshore surf beat flow does show a significant, though low, peak at a positive lag of around 35 s (Figure 9). This surprising result may be related to the peak at a similar lag observed in the on/offshore correlation (Figure 8). These observations and possible explanations for them will be the subject of a subsequent paper.

Discussion

This study clearly shows that, outside the surf zone, the long period surf beat motion at frequencies below 0.03 Hz is dominated by the locally forced response to the incident wave groupiness. This is contrary to the suggestion of Bowen and Guza (1978), based on laboratory and theoretical studies, that the free edge wave response should dominate.

Other studies of long period motion have emphasized its on/offshore structure, which is generally found to be consistent with shoreline-reflected standing waves or with edge waves (Suhayda, 1974; Huntley, 1976; Holman, 1981). The present data set cannot provide definitive evidence for or against the presence of a seaward propagating wave which could combine with the incoming forced wave to provide standing wave motion. The observed cross-correlation of figure 8 does not suggest the presence of an outgoing free wave at a lag expected for the wave envelope to travel to the breakpoint and a free wave to return to the sensor location, but the expected lag is within the peak centered at zero lag so no firm conclusions can be drawn. If there is a smaller seaward propagating component on Queensland Beach it may be related to the absence of long swell waves characteristic of many of the other sites studied.

The present data set is limited to measurements outside the surf zone, whilst many previous studies have concentrated on measurements within the surf zone. For data run Q151, when the sensor tripod was closest to the breakpoint, the cross-correlation between surf beat motion

and wave envelope was significantly lower than for runs further offshore. This is consistent with the observed saturation of wave amplitude on breaking, which reduces incident wave groupiness inside the surf zone. Thus previous measurements from within the surf zone which have emphasized the presence of edge waves will have been unable to identify forced wave motion by a direct correlation with the local wave envelope. It would be particularly interesting to correlate long period motion inside the surf zone with incident wave envelope just outside the breakpoint, to try to identify any free wave motion inside the surf zone released by wave breaking.

The lack of evidence for dominant free edge waves motion in the on/offshore flows on this relatively steep beach may require some modification of the hypothesis that edge waves are the most significant controlling factor for nearshore coastal geomorphology (Bowen and Huntley, 1984). However even small on/offshore standing wave components will be very significant in providing the mean flow divergences and convergences needed to create erosion and deposition. The observations of edge wave motion in the longshore flows (Huntley et al., 1981) is also consistent with the present data set and provides a further important component contributing to flow divergence and convergence.

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