CHAPTER 38

WAVE GROUPINESS AS A SOURCE OF NEARSHORE LONG WAVES

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Abstract

Data from a low energy swell-dominated surf zone are examined for indications that observed low frequency motions are simply group-forced bounded long waves. Time series of wave amplitude are compared to filtered long wave records through cross-spectral and cross-correlation analysis. These methods are found to have limited usefulness until long waves are separated into seaward and shoreward components. Then a clear picture of a rapidly shoaling bounded long wave emerges, with a minimum of nearly one fourth of the long wave amplitude being explainable by this type of motion close to shore. Through the zone in which waves were breaking, and incident wave amplitude variability decreased by 50%, the contribution from the bounded long wave continued to increase at a rate much greater than a simple shoaling effect. Also present are clear signs that this amplified bounded long wave is reflected from a position close to the shoreline, and is thus released from wave groups as a free, offshore-progressive wave.

Introduction

Numerous recent observations have shown that waves with periods much longer than the more visually apparent wind waves often dominate the spectrum in the inner surf zone, especially during storms. However, much less clear are the origins of these infragravity motions, though a number of theories and few observations exist. Most relate in some wave to the groupiness of the incident waves. Gallagher (1971) developed a theoretical model in which edge waves could be resonantly generated by obliquely incident wave groups; Bowen and Guza (1978) substantiated this concept in a laboratory experiment. Field observations of Huntley et al. (1981) showed that low mode edge waves can dominate the low frequency motion in the longshore currents and recently Oltman-Shay and Guza (1986) have shown that in some cases as much as 50% of the shoreline runup variance is due to low mode edge waves, the size of which can be predicted from offshore measurements of the wind wave variance and wavenumber-frequency distribution.

Still, much if not most of the cross-shore current variance in the low frequency band cannot be explained in this way and appears to be either high mode edge waves or simply leaky mode standing waves. Symonds et al. (1982) provide a model by which oscillations of this sort could be generated by long wave forcing at a time-varying breakpoint (produced by wave groupiness). However, as of yet there is no conclusive field evidence to support this model; most conspicuous is the absence of a separate standing wave zone landward of the breakpoint and a frequency dependent offshore progressive wave zone seaward of the breakpoint. Laboratory observations exist but seem conflicting. Kostense (1985) conducted a study in which changes in the wave group characteristics (wave difference frequencies, amplitude ratios, etc.) produced outgoing free waves with varying amplitudes qualitatively in accordance with the model of Symonds et al. However, in the experiment of Mansard and Barthel (1985) there seems to be a complete absence of an outgoing free wave generated at a time-varying breakpoint, although experimental conditions are largely the same except for the use of a Jonswap spectrum instead of bichromatic waves.

An alternate explanation of cross-shore surf beat motion is the direct forcing of long waves by radiation stress gradients in groupy waves. Longuet-Higgins and Stewart (1962,1964) showed that the mean water level, $\bar{\eta}$, is related to the component of radiation stress normal to wave crests, S_{xx}, by

$$\bar{\eta} = - \frac{Sxx}{\rho(gh-Cg^2)} + \text{const.} \tag{1}$$

where h is the mean water depth, ρ is the density, and C_g is the group velocity. The negative sign indicates, for example, that a group of large waves with high S_{xx} would produce a depression of the mean (averaged over several incident wave periods) sea level. Thus the correlation between wave amplitude and long wave time series should be negative, while the corresponding cross-spectrum should show a 180^0 phase difference. Unfortunately, both the shallow water approximation of equation (1) and the spectral approach of Ottesen Hansen (1978) predict unreasonably large values of $\bar{\eta}$ in very shallow water-exactly where the size of this bounded long wave (BLW) must be known to access its contribution to surf beat motion. Nevertheless, Longuet-Higgins and Stewart found support for their theory in Tucker's (1950) observation of a time-lagged negative correlation between wave groups and long waves at an offshore station. They speculated that group bound long waves are released as free waves when incident waves break, and then are radiated offshore after reflection. A substantial shallow water BLW amplification (landward of the measurement location) could explain Tucker's observation that groups are correlated with long waves only after a time sufficient for round-trip travel to the shoreline, and not with an incoming BLW at zero lag. However, in addition to inadequate theory for the shallow water BLW size, no mechanism has been proposed by which this forced response could be released from wave groups as a free wave.

Following the work of several previous Conference authors (Huntley and Kim, 1985, Guza et al., 1985) this study examines field data in an attempt to provide some guidelines for future theoretical investigations.

Data Collection

An experiment conducted in September, 1985 at the U.S. Army Corps of Engineers Field Research Facility in Duck, North Carolina provided the data for this study. (Please see acknowledgements.) Figure 1d shows the nearshore profile and measurement locations. The morphology was fairly 2-dimensional, although some irregularities existed. All bathymetric observations were collected by the Corps using the CRAB profiling system (see Mason et al., 1985 for description). At each of the 9 measurement locations pressure and bi-axial horizontal currents were sampled synchronously for 40 minutes at 2 Hz. Pressure sensors were of the diaphragm type and flows were measured by Marsh Mcbirney electromagnetic current meters.

Waves consisted of highly grouped swell with a fairly narrow spectral peak near T=12 seconds. The angle of incidence was nearly shore-normal, although wave crests and wave groups were not very continuous alongshore.

Processing

Cross-shore currents are defined as positive onshore in order that long waves in the flows and sea-surface show the same relation with wave groups. Fourier transforms of pressure records were converted to the sea-surface by applying linear theory to each coefficient and then back-transforming to the time domain. Time series of long waves in both the sea-surface (η_L) and cross-shore currents (u_L) were found by bandpassing the data using two low-pass least squares filters (Bloomfield, 1976). An incident/long wave band cutoff was chosen at 0.06 Hz based on offshore spectra, in which it was clear that the incident band energy was confined to higher frequencies. (Changes in the η and u cross-spectrum at this frequency also substantiate this cutoff.) Additionally, energy at very low frequencies (below 0.007 Hz) was removed because certain records contained red "wall climber" type energy that was uncorrelated with other records and tended to lower the association with wave groups. Thus the low frequency time series used here contain energy from 0.007 to 0.06 Hz.

Time series of wave amplitude, A_t, were found by low-pass filtering the modulus of the high-passed, incident band sea-surface time series. In order that this series truly follow the wave amplitude, each point was then divided by $\pi/2$ to compensate for the asymmetry of a sine wave modulus. As the size of the BLW is predicted by equation (1) to be proportional to the square of the incident wave height, an additional amplitude function was calculated as the lowpass-filtered square of the incident band waves.

A groupiness factor was found from the amplitude time series as

$$GF = \frac{\sqrt{2}\,\sigma A_t}{\ddot{A}_t} \tag{2}$$

where σA_t and A_t are the standard deviation and mean of A_t respectively. This groupiness factor has the advantage of being strictly confined between 0 (pure sine wave) and 1.0 (two beating sine waves), as opposed to factors using an amplitude function derived from the square of the incident wave (for example, see Sand, 1982).

All spectra and Cross-spectra presented here were smoothed to give 34 degrees of freedom, resulting in a 95% CI on zero coherence of approximately 0.41. Correlations between A_t and long waves were found at time lags separated by the sampling interval of 0.5 seconds to give a smooth cross-correlation function. As adjacent point in a wave time series are by no means independent, the 95% CI on zero coherence was found using a reduced number of points, N^*, given by Garret and Toulany (1981) as

$$N^{*-1} = N^{-1} + 2N^{-2} \sum_{j=1}^{N'} (N-j)\ R_{xy}(j) \tag{3}$$

where N is the original number of points, $R_{xy}(j)$ is the lagged auto-correlation of the product of the two series to be correlated, and N' is the number of lags until R_{xy} experiences a zero-crossing. Cross-correlations presented here generally have a 95% CI on r=0 below 0.15.

Some pressure channels showed a high energy, narrow band peak in the spectra that was judged to be some sort of electronic contamination. Gaps in the results presented below represent data that was not analyzed because of this problem.

Cross-shore Statistics

Figure 1 shows the cross-shore variations in significant wave height, H_s, standard deviation of the amplitude time series, σA_t, and groupiness factor, GF. While H_s does not decrease until station 2, it is evident from σA_t and GF that initial breaking of the largest waves must begin inshore of station 6. The waves groupiness in both the current and sea-surface incident band decreases from around 0.65 offshore, a fairly high value for natural waves, to 0.45 by station 1. More importantly, the wave height variability as measured by the standard deviation in A_t, decreases by a factor of 2 across the instrument array. If the size of the bounded long wave is proportional to variations in the wave height squared, as implied by equation (1), then the BLW size might be expected to be proportional to the square of σA_t, implying a four-fold decrease from station 6 to station 1. As it turns out, this does not seem to be the case.

Cross-spectra

The cross-spectra between A_t and η_L were found as a first step in assessing the degree to which long waves in the nearshore are directly forced by wave groups. Figure 2 shows the most coherent cross-spectrum of any calculated between co-located A_t and η_L. As seen in previous

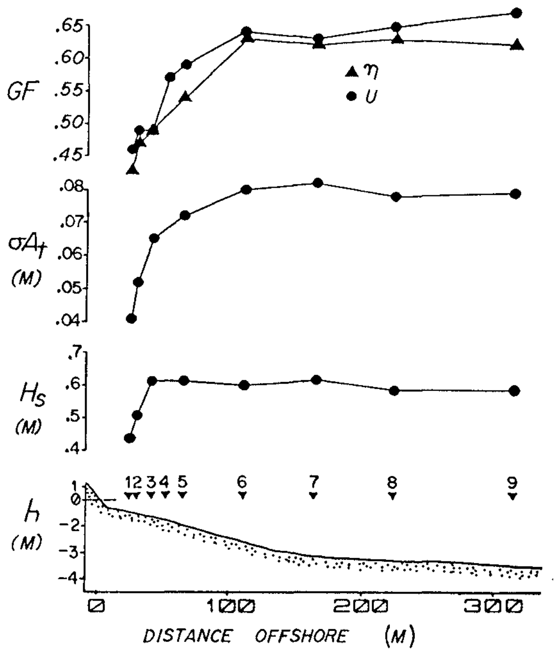

Figure 1 From top: Groupiness factor, standard deviation of amplitude time series, significant wave height (from incident band variance), nearshore profile with instrument stations.

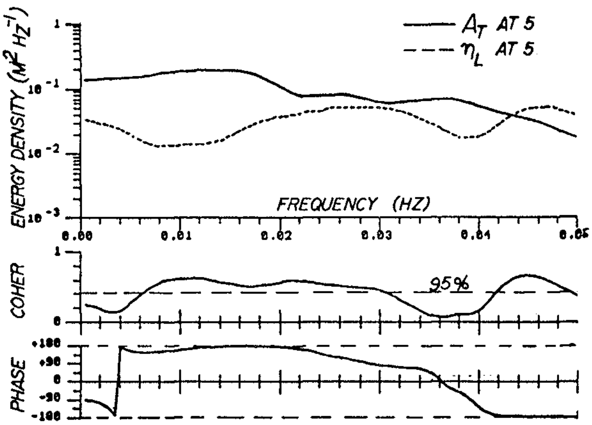

Figure 2 Cross-spectrum between amplitude time series and sea-surface long waves co-located at station 5.

studies (Huntley and Kim, 1985 and others) there is no significant frequency selection in the wave groupiness, precluding the possibility of identifying a groupiness-forced peak in the long waves. While there are some signs of the forced response (phase near 180^0 in bands of significant coherence) the relation is certainly less consistent and strong than presented by Huntley and Kim (1985). Since in addition to the incoming BLW, the nearshore long wave field may well consist of reflected long waves, waves generated at a time-varying breakpoint, and edge waves, it is not surprising Fig. 2 shows an unclear BLW signature. The Huntley and Kim measurements were taken very close to shore on a steep beach where the incoming and reflected waves would be virtually coexisting and other modes of long wave generation (other than the subharmonic) would likely be suppressed. The data presented here seems more representative of an open coast situation with waves breaking offshore and dissipating over a shallow surf zone.

Cross-correlations

In order to differentiate between group-related long wave components traveling shoreward and those either reflected or generated in the surf zone and traveling seaward, cross-correlations were calculated similar to those first presented by Tucker (1950). Figure 3a shows the cross-correlations between co-located A_t and longwaves (in both current and sea-surface) at 8 stations. The bounded long wave response is seen as a negative correlation near zero lag, which is marginally significant at station 9, strengthens to a maximum at station 3 and then decreases and disappears by station 1. That the group structure is forcing longwaves and not visa-versa is supported by a significant degree of correlation between the group structure offshore and inshore up to station 5--in other words the wave groupiness to a large extent is an original feature of the offshore waves through this zone, and is not being created by an interaction of short waves with long wave depth or current modulations. The disappearance of the zero-lag negative correlation landward of station 3 could be due to a decrease in the size of the BLW, but could also be due to this short wave/long wave effect (as has been observed by Abdelrahman and Thornton, 1985) causing a modification in the group structure and masking the ability of the cross-correlation to identify a forced response. To test this idea, the cross-correlations between the amplitude series at station 8 and long waves at 7 stations closer to shore were calculated and are shown in Figure 3b. The forced wave response, now at progressively greater time lags, appears to strengthen all the way to station 1. Solid dots in Figure 3b show the measured group travel time (from A_t cross-correlations), indicating that after waves begin breaking, the forced response tends to lag the wave groups by up to 10 seconds. The question of whether this group-correlated long wave component is still a bounded long wave or now a free wave will be addressed below.

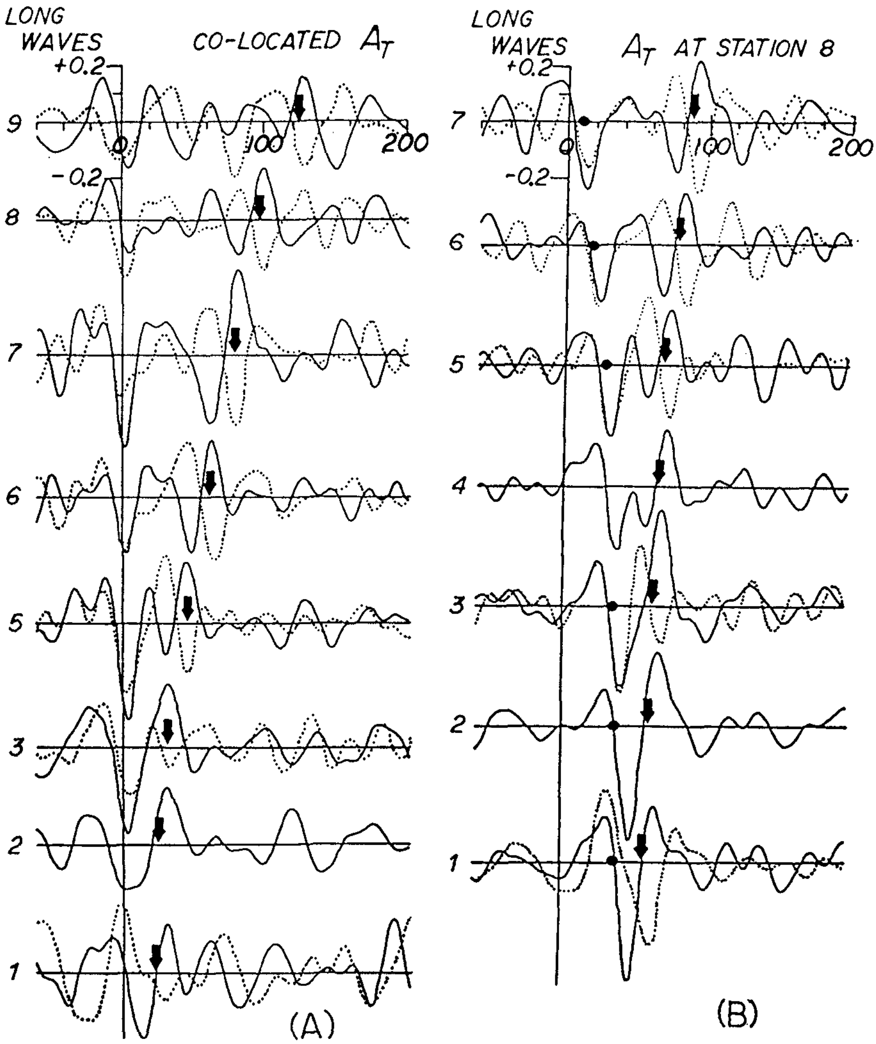

Figure 3 Cross-correlations between long wave (······· sea-surface, ——— cross-shore current) and amplitude time series. Horizontal scale is the time lag in seconds, vertical scale is the correlation coefficient. Positive lags indicate a leading group structure. 95% CI on zero correlation is a maximum of 0.15. (A): cross-correlations between co-located amplitude and long waves, (B): cross-correlations between amplitude at station 8 and long waves at 7 stations closer to shore.

Another interesting feature of both Figure 3a and 3b is a series of significant peaks occurring at lags nearly matching the long wave travel time given by

$$T = \int \frac{dx}{\sqrt{gh}} \tag{4}$$

from the point of A_t measurement, to the shore, and back to the point of long wave measurement (marked by solid arrows). The signs of the η_L and u_L correlations are opposite, confirming that this signal represents outgoing wave energy. Since the correlation is negative with η_L and positive with u_L, this signal satisfies the notion that the incoming BLW is released and simply reflected as a free wave, as suggested by Longuet-Higgins and Stewart (1962,1964).

Another sometimes significant signal, appearing mostly beyond the surf zone and having the opposite sign, occurs approximately 20 seconds earlier, corresponding to a point of origin near the outer limit of the breaker zone. (A similar feature is seen in Guza et al., 1985) As it is difficult to predict exactly how a wave generated by a breakpoint forcing model might affect the cross-correlations as calculated here (see Huntley and Kim, 1984), it can only be speculated that correlations at this time lag relate to this model. In a simplistic sense, however, it would seem that since larger waves are predicted to be associated with a higher setup, long waves generated by the model of Symonds et al. (1982) should have a sign of correlation with the wave groupiness structure opposite to that of the BLW (or a recently released long wave of BLW origin). The fact that most of the significant correlations in Figure 3 fit the idea of an incident, released and reflected BLW may indicate that the breakpoint forced waves were of lesser importance during this experiment.

Since the square of the correlation coefficient gives the percent of the variability in one channel that can be predicted by another, the correlations associated with the incoming BLW in Figure 3b could ideally be used to determine the fraction of long wave height attributable to group forcing at each station, resulting in a picture of the cross-shore changes in BLW size. Unfortunately, as shown by Sallenger and Holman (1984), the infragravity variance in η or u can be dependent on the sampling location's position relative to a standing wave structure, as seems to be the case in Figure 4a. Similarly, the correlations at lags for incoming and outgoing waves may merge close to shore, distorting the values in an unpredictable manner. A method of separating the landward and seaward long wave components (Guza et al., 1985) was used to circumvent these problems.

Onshore/Offshore Long Wave Components

After Guza et al. (1985), landward and seaward progressive long wave components in units of sea surface elevation were found as

$$\eta_L ON = \frac{\eta_L + \sqrt{h/g}\; u_L}{2}$$
$$\eta_L OFF = \frac{\eta_L - \sqrt{h/g}\; u_L}{2} \qquad (5)$$

where η_L and u_L represent each point in the η and u long wave time series and h is the average water depth. The components in units of velocity could be found similarly, but provide no additional information.

Equation (5) cannot be used with many data sets because of a number of restrictions. As noted by Guza et al., long waves must be shore normally oriented. An obliquely angled incident long wave would contaminate the offshore component and an angled outgoing long wave would contaminate the onshore component. Edge wave motions would put spurious energy into both η_L ON and η_LOFF, though probably to equal degrees. Also, long waves are assumed to follow the shallow water, linear dispersion relation, excluding bounded long waves associated with groups not in shallow water or long waves affected by steep bottom slopes.

Test showed that this data set must have largely met these conditions. For example, cross-spectra between two ON components at different stations (Figure 5a) show high coherence and the phase relations of an incoming progressive wave while cross-spectra between two OFF components (Figure 5b) show the reverse. Also, cross-correlations between separate components and A_t show a clear isolation of the incoming and outgoing long wave signals related to wave groupiness. Finally, that the ON/OFF separation has resolved problems with determining long wave heights in standing waves is evident in Figure 4b in which the H_s of ON and OFF components does not reflect the structure in the H_s of the total η_L (Figure 4a).

Cross-correlations: revisited

Correlations are now found between A_t and separate ON and OFF long wave components. The question of interest here is: how much of the long wave height at each station can be explained by a BLW type association? Thus the search is for the A_t series that can predict the most long wave variation at each station. For the onshore component stations 5,6,7,8, and 9 show the highest BLW correlations with co-located A_t; for stations 1 and 3 the highest correlations are with A_t at stations 5. For the offshore component the best correlations were always with the group structure near the maximum limit of wave breaking at station 5. Table 1 summarizes these relationships. The results differ from those presented by Guza et al. (1985) in that the maximum correlations remain negative to the most landward stations in both the ON and OFF components.

Correlations in Table 1a are squared and multiplied by the H_s of the corresponding onshore component (Figure 4b) to give estimates of

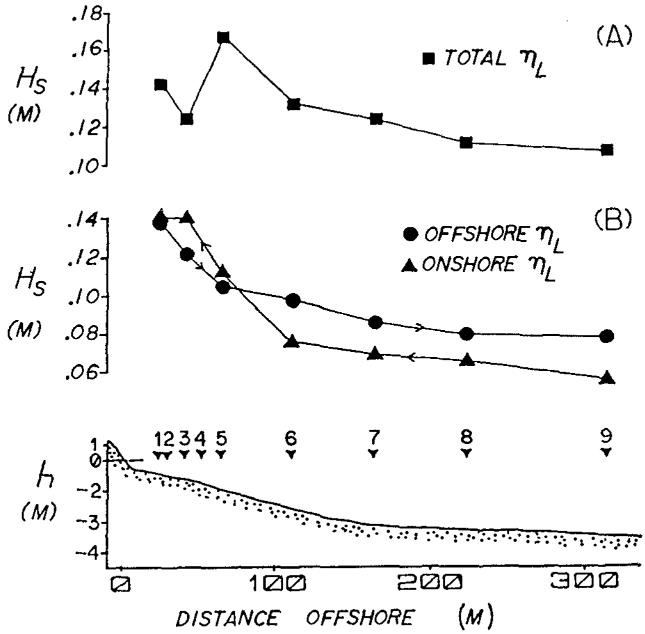

Figure 4 (A) Significant wave height from variance in sea-surface long wave band, (B) significant wave height from variance of separated onshore and offshore progressive long wave components.

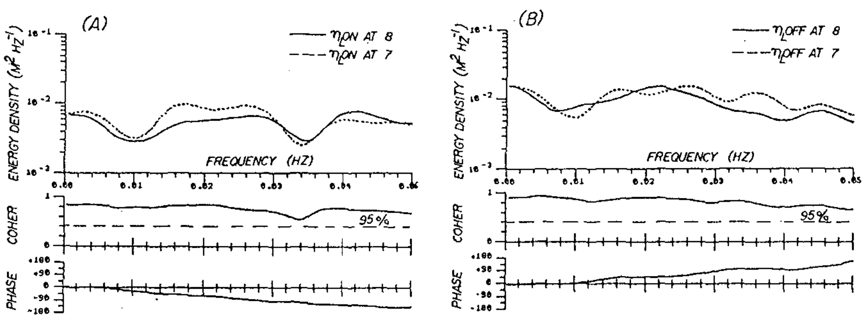

Figure 5 (A) Cross-spectrum between onshore progressive components at stations 8 and 7, (B) Cross-spectrum between offshore progressive components at stations 8 and 7.

BLW height at each station, shown in Figure 6. Values for BLW H_s found through use of the squared amplitude function are also plotted, and indicate that this method results in only a slight improvement in the analysis.

The values of BLW H_s in Figure 6 are extremely low, and probably not far from the limit of the instrument's measuring ability. However, every point is based on a correlation that is significantly different than zero at the 95% confidence level, and in most cases far better. In addition, cross-spectra calculated between the A_t and $\eta_L ON$ pairs in Table 1a show coherent relationships above the 95% CI. For example, Figure 7 shows that approximately 30% of the variance in $\eta_L ON$ at station 5 can be explained by the wave group structure. Thus it seems that the correlation values used in creating Figure 6 may underestimate the actual size of the BLW, since significant correlations seem to be predicting nearly insignificant wave heights.

Assuming that at least the relative changes in Figure 6 are real, it appears that the BLW undergoes rapid shoaling into shallow water, even through a zone in which waves are breaking. Specifically, between stations 6 and 1 the amplitude variability, σA_t, decreases by a factor of 2 (Figure 1), while at the same time the size of the estimated BLW increases four-fold. (The corresponding increase in A_t versus $\eta_L ON$ correlation is significant to the α=0.003 level.) Some investigators have implied that as incident waves break, the BLW also decays or is released to shoal toward shore as a free wave. However, the group-related long waves as observed here increase much more rapidly than predicted by a $(h_1/h_2)^{1/4}$ long wave shoaling, the rate being closer to $(h_1/h_2)^{5/2}$, the shallow water BLW shoaling predicted by Ottesen Hansen et al. (1981). Toward shore this group-correlated component is thus becoming a progressively larger piece of a progressively larger pie, which would not be the case for a free long wave progressing shoreward. This apparent increase in group forced long waves after incident waves have begun to break was also found by Mansard and Barthel (1985), who observed laboratory long waves increasing in size even through a constant depth zone.

The correlations with offshore components in Table 1b show that the outgoing long waves also contain a significant component related to wave groups. Close to shore these correlations are somewhat less than those for the incoming wave. This could indicate that to some degree the BLW is decreased in size before release and reflection, but could also simply be due to the greater spatial separation between the group structure and outgoing long waves. Not shown in Table 1b are positive correlations that were sometimes significant, and occurred at smaller lags than expected for a shoreline long wave reflection. While these correlations appear to be similar to those observed by Guza et al. (1985), they were never greater than the negative correlations, and were not present in the correlations with the onshore component.

A rapid shallow water increase in the forced response may explain the differences between the size of the incoming and outgoing components (Figure 4b) in the following manner. The onshore component increases rapidly past station 6 as the BLW shoals. At some point close to shore this forced wave is released and reflected as a free

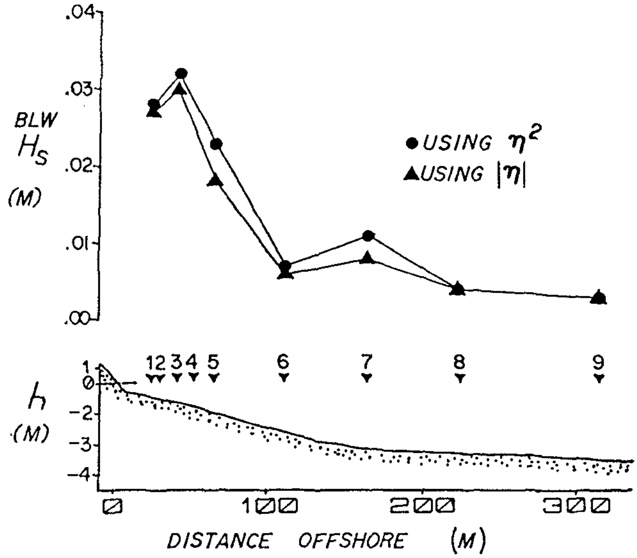

Figure 6 Significant wave height of bounded long wave inferred from correlations between amplitude time series and long waves (Table 1a). ● amplitude time series from square of incident waves, ▲ amplitude time series from modulus of incident waves.

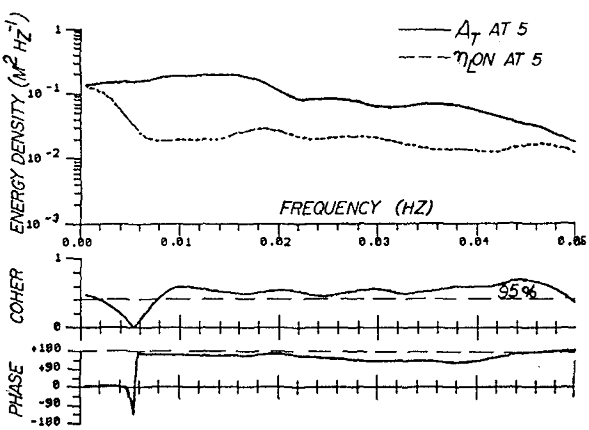

Figure 7 Cross-spectrum between amplitude time series and the onshore component of sea-surface long waves co-located at station 5. (Compare to Figure 2.)

wave which decreases in amplitude offshore at a smaller rate closer to $(h_1/h_2)^{1/4}$. Thus in deep water the offshore component is larger than the onshore component, which would explain why Tucker (1950) observed a forced response only after a large time lag. However, at the most landward stations the onshore component here is larger, implying that at least some of the incoming long wave energy decays in very shallow water with wave groups. Again the results here are different than those given by Guza et al. (1985), in which the onshore component was at all positions larger than the offshore component.

(A)

station η_{L} ON	station A_t	Max r
9	9	-0.23
8	8	-0.25
7	7	-0.36
6	6	-0.29
5	5	-0.40
3	5	-0.46
1	5	-0.44

(B)

station η_{L} OFF	station A_t	Max r
9	5	-0.25
8	5	-0.24
7	5	-0.31
6	5	-0.31
5	5	-0.29
3	5	-0.39
1	5	-0.37

Table 1 Maximum correlations between long wave components and amplitude time series. Integers are stations locations. Lags are at group or long wave travel time as in Fig. 3.

Discussion

Other studies of the BLW in the nearshore have exhibited a varying degree of evidence for the forced wave response. Guza et al. (1985) show that the incoming and outgoing long waves are clearly correlated to wave groups, but interestingly the negative sign of the BLW is overshadowed by positive correlations within the surf zone. Kim (1985) shows evidence of an incoming forced response, but little sign that outgoing long waves are correlated to wave groups. Huntley and Kim (1985) show nearshore long waves almost entirely forced by wave groups in a steep, reflective beach in which a separate outgoing wave cannot be distinguished. The results presented here are therefore not necessarily typical, but may represent an end member in the degree to which the BLW is clearly present in the incoming waves, and seems to be the source for at least part of the outgoing waves.

Evidence for long wave generation at a time-varying breakpoint may also exist to varying degrees throughout these studies of group-forced waves. However, it is still uncertain exactly what kind of relation these waves should show in cross-correlations or cross-spectra with wave groups. The laboratory study of Kostense (1985) showed frequency-dependent outgoing waves (never observed in the field), but this could also be an indication that the degree to which the BLW is released and reflected (instead of decayed with wave groups) is also dependent on the wave characteristics.

Certainly more theoretical work is needed to explain why the forced response seems so variable, and under what conditions the BLW becomes energetic in the nearshore, or could be released and reflected as a free wave. The observation of a BLW increase through a zone of wave breaking may find an explanation in a resonant interaction with residual wave grouping. Long waves may be released from wave groups if the BLW satisfies the free long wave dispersion relation before incident waves break. The Model of Symonds et al. (1982) must also be re-examined, with emphasis on possible interactions with group-bound waves, and on new methods of evaluating field data for this effect.

Conclusions

The following applies only to this study:

1. The bounded long wave, as measured by correlation coefficients with a squared wave group function, accounts for one-fourth of the incoming long wave height. This is probably a conservative estimate.

2. The bounded long wave increases in size even through a zone of wave breaking.

3. The outgoing long waves have a component correlated to wave groups with a sign and lag suggesting release and reflection of the BLW.

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