CHAPTER 63

INFRAGRAVITY-FREQUENCY (0.005-0.05 HZ) MOTIONS ON THE SHELF

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ABSTRACT

Extensive field observations in depths between 8-204 m are used to investigate the sources and variability of infragravity-frequency (nominally 0.005-0.05 Hz) motions on the shelf. The predicted local forcing of 'bound' infragravity motions by difference-frequency interactions of swell and sea (Hasselmann, 1962) is verified with array measurements of sea floor pressure in 13 m depth. Observed forced infragravity energy levels agree well with theoretical predictions, but are consistently much lower than the observed total infragravity energy. Wavenumber estimates show that free waves, obeying the surface gravity wave dispersion relation, are frequently the dominant source of energy in the infragravity band. The observed directional properties and cross-shore decay of free wave energy show that refractive trapping, neglected in many current infragravity wave generation models, is of O(1) importance. Both free and forced wave energy levels generally increase with both increasing swell energy and decreasing water depth, but the observed dependencies of free and forced waves are different. The relative contributions of free and forced waves to infragravity energy on the shelf are therefore highly variable. Comparisons of observations in the same water depth at different sites suggest that free wave radiation is relatively stronger from broad, sandy beaches than from rocky, cliffed coasts.

1. INTRODUCTION

Energy levels of surface elevation, velocity and pressure fluctuations at "infragravity" periods of 0.5-5 minutes, slightly longer than the 2-20 sec periods of typical wind-generated surface gravity waves, are generally weak in the deep ocean (Webb et al., 1991), but can be very energetic close to shore (surface elevation

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variances $O(10^3)\,\mathrm{cm}^2$; e.g., Wright et al., 1982; Guza and Thornton, 1985). Although numerous field observations have shown that infragravity and swell energy levels are highly correlated (e.g., Munk, 1949; Tucker, 1950; Holman et al., 1978; and many others), the generation mechanisms of infragravity motions on the shelf are not well understood. Nonlinear interaction of two surface waves theoretically excites a forced secondary wave with the difference frequency (e.g., Longuet-Higgins and Stewart, 1962; Hasselmann, 1962). Field observations often exhibit the phase-coupling theoretically expected between groups of swell and forced infragravity motions (e.g., Hasselmann et al., 1963; Elgar and Guza,1985; Okihiro et al., 1992; Elgar et al., 1992). However, qualitative comparisons of theoretically predicted and observed infragravity energy spectra show that forced waves may contribute significantly to infragravity energy when swell and sea are very energetic (Sand, 1982), but account for only a small fraction of the infragravity energy when swell-sea energy is low (Okihiro et al., 1992).

It has long been recognized that other contributions to the infragravity band may arise from the strong nonlinearities and wave breaking processes that occur close to shore. Based on early observations by Munk (1949) and Tucker (1950), Longuet-Higgins and Stewart (1962) suggested that, as the incident swells are dissipated in very shallow water through breaking, forced secondary waves may somehow be released as free waves and radiated from the nearshore. As these long-wavelength free waves travel seaward on a sloping beach refractive trapping may occur. Alongshore wavenumber spectra of infragravity motions in the surfzone show clear evidence of topographically trapped low-mode edge waves (Huntley et al., 1981; Oltman-Shay and Guza, 1987; and others). Observed variations in infragravity energy across the continental shelf (Webb et al., 1991; Okihiro et al., 1992) suggest that infragravity motions are predominantly trapped on the shelf with relatively weak radiation to the deep ocean. Various models have been developed that describe the generation of both leaky waves (radiating out to deep water) and edge waves at infragravity frequencies through nonlinear interactions and breaking of incident surface waves (e.g., Gallagher, 1971; Bowen and Guza, 1978; Foda and Mei, 1981; Symonds et al., 1982; Schäffer and Svendsen, 1988; Schäffer et al., 1990; List, 1992; Roelvink et al., 1992; Watson and Peregrine, 1992; and others).

In this paper, preliminary results are presented of a study of free and forced infragravity motions on the shelf, based on array measurements in 13 m depth and single-point measurements in depths ranging from 8-204 m. The field data are described in section 2. In section 3, bispectral analysis is used to decompose the observed infragravity energy in free and forced wave contributions, and the forced waves are compared to predictions of second-order nonlinear theory (Hasselmann, 1962). Wavenumbers and directional properties of free waves are discussed in section 4. The dependence of infragravity motions on water depth and incident wave conditions is examined in section 5, followed by a discussion and summary in section 6. A full account of the observations will be given in Herbers et al. (1992a,b).

2. FIELD DATA

The variability of infragravity motions on the shelf is investigated with single point pressure measurements at a variety of locations in both the Atlantic and Pacific oceans. Nine-months of bottom pressure data (September 1990-May 1991) were collected in 8 and 13 m depths, approximately 1 and 2 km offshore of Duck, North Carolina, respectively (Elgar et al., 1992). Three-month-long bottom pressure records were collected in 30-m depth during fall/winter of 1991/92 at 16 locations along the Southern California mainland coast and at 4 locations around Santa Rosa, an island in the Southern California Bight bordered with both steep vertical cliffs and shallow reefs (O'Reilly et al., 1992). Two representative coastal sites with gently sloping sandy beaches (Ventura and Redondo) and one of the Santa Rosa rocky island stations were selected for analysis here. Measurements in deeper water were obtained during a 6-month period in the fall/winter of 1991/92 from a pressure gauge mounted 16 m below the sea surface on Harvest Platform, located at the edge of the California shelf in 204 m depth (Seymour et al., 1985). More detailed results are based on data from a large aperture (250 x 250 m) array of 24 pressure sensors deployed in 13 m depth at Duck (Herbers et al., 1992a). The sample rates of the field data vary between 0.5 and 4 Hz. The data were divided into 170 minutes long records (137 minutes where longer continuous records were not available) for analysis.

The present study is focused on low frequency motions driven by surface waves. To exclude motions driven by other sources, the infragravity band was chosen to be the range in which spectral levels are strongly correlated with swell energy, 0.004-0.05 Hz for observations in the Atlantic and 0.004-0.04 Hz for observations in the Pacific (Herbers et al., 1992b). At frequencies below 0.004 Hz, weak correlations with swell energy suggest that the observed motions may be driven by atmospheric or other processes, not surface waves (e.g., Munk et al., 1956). The upper limit of the infragravity range was conservatively chosen to exclude contributions of low frequency swell.

3. FORCED WAVES

A perturbation expansion in weak nonlinearity shows that the interaction between two surface gravity waves with frequencies f and $f+\Delta f$ excites a forced secondary wave with the difference frequency Δf (e.g., Longuet-Higgins and Stewart, 1962; Hasselmann, 1962). Accurate predictions of forced wave energy at infragravity frequencies require accurate estimates of the surface wave frequency-directional spectrum $E(f,\theta)$, information unavailable in previous studies that used single-point (Hasselmann et al., 1963; Sand, 1982) or pitch-and-roll type (Okihiro et al., 1992) measurement systems. Detailed estimates of $E(f,\theta)$ for the dominant swell and sea (0.06 Hz $< f <$ 0.24 Hz), suitable for accurate predictions of forced wave energy, were extracted from the array measurements in 13 m depth at Duck. Predictions of the forced infragravity spectrum, based on Hasselmann's (1962) theory and the $E(f,\theta)$ estimates, were obtained for 15 data runs spanning a wide range of conditions (Herbers et al., 1992a). In all cases, predicted forced wave energy levels are much lower than observed infragravity energy levels (Figs. 1, 2a).

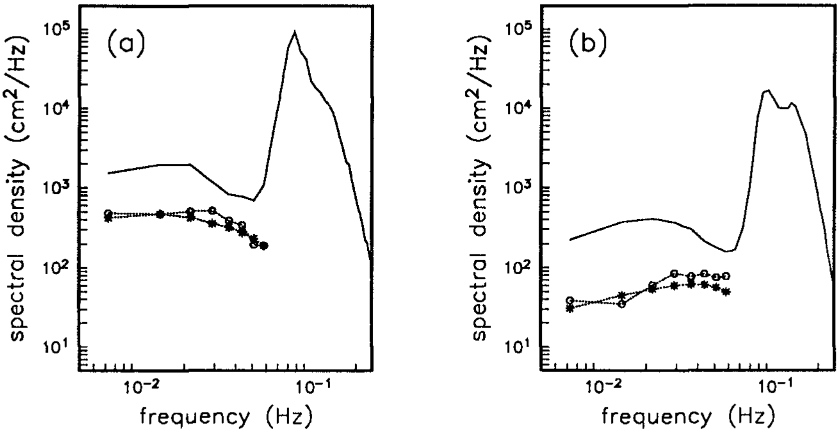

Fig. 1. Second-order nonlinear theory predictions (asterisks) and bispectrum-based estimates (circles) of the forced bottom pressure spectrum at infragravity frequencies. The observed (total) bottom pressure spectrum is indicated by a solid curve. (a) 26 October 1990. (b) 19 May 1991.

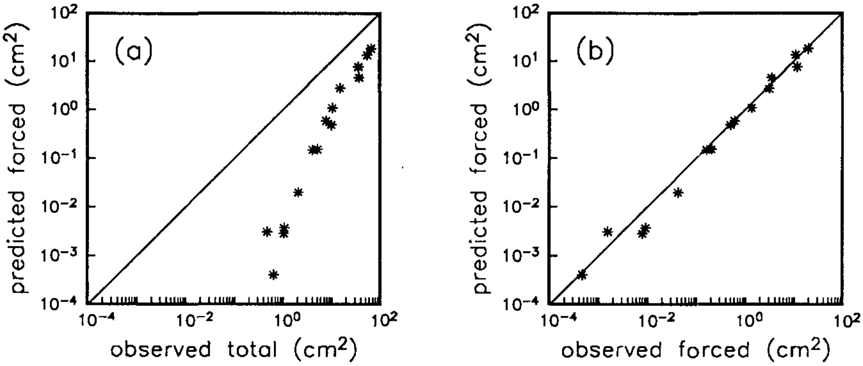

Fig. 2. (a) Predicted forced infragravity energy versus observed total infragravity energy. (b) Predicted versus observed (based on bispectral analysis) forced infragravity energy.

Bispectral analysis (frequency domain analysis of third-order statistics, Hasselmann et al., 1963) is used to estimate forced wave contributions to the infragravity band (Herbers et al., 1992a). Far from shore, free infragravity waves are statistically independent of the local swell-sea and thus do not contribute to the bispectrum. Nonzero bispectral values (i.e., nonGaussian statistics) result from phase-locking between forced waves and pairs of swell-sea components. Estimates of forced infragravity spectra, based on bispectral analysis, agree well with theoretical predictions, as illustrated in Fig. 1 (compare circles and asterisks) for two example cases with significant forced wave contributions to the infragravity band. For all 15 data runs, which span a variation of 10^5 in forced wave energy, (bispectrum-based) estimates and theoretical predictions of the total (integrated over the infragravity band) forced wave energy are in excellent agreement (typically within 30 %, Fig. 3b). The observed phase differences between forced waves and groups of swell are within a few degrees of the theoretical value 180^0 (Herbers et al., 1992a). Overall, the analysis shows that forced waves are accurately predicted by second-order nonlinear theory (Hasselmann, 1962), but their contribution to the infragravity band is relatively small (0.1-30 %, Fig. 2a).

4. FREE WAVES

It has been suggested (e.g., Longuet-Higgins and Stewart, 1962; Symonds et al., 1982; and many others) that the surf-zone radiates seaward-travelling free waves at infragravity frequencies. The observed wavenumbers do indeed show that the remaining, not locally nonlinearly forced, infragravity energy in 13 m depth is caused by freely propagating surface gravity waves. An average wavenumber magnitude $k_{rms}(f)$, defined as

$$k_{rms}(f) \equiv \left[\int_0^\infty dk \int_0^{2\pi} k\, d\theta\, k^2\, E(f,k,\theta) \Big/ \int_0^\infty dk \int_0^{2\pi} k\, d\theta\, E(f,k,\theta) \right]^{1/2} , \qquad (1)$$

with $E(f,k,\theta)$ the frequency-(vector) wavenumber spectrum of sea floor pressure, was estimated from the 13-m depth array measurements at Duck (the technique will be described in a subsequent publication). Estimates of $k_{rms}(f)$ are compared to the linear dispersion relation for surface gravity waves in Fig. 3 on three occasions with negligible forced wave contributions to the total infragravity energy (i.e., Fig. 2a). The observed wavenumbers in the infragravity band are in excellent agreement with the theoretical free-wave dispersion relation.

Both forced and free wave energies are expected to decrease with increasing water depth h owing to the weakening of nonlinearity and propagation effects, respectively. In shallow water forced infragravity energy is strongly amplified owing to near-resonances and approximately proportional to h^{-5} (Longuet-Higgins and Stewart, 1962). On the other hand, the energy of leaky (radiating to deep water), free infragravity waves is approximately proportional to $h^{-1/2}$ (e.g., Eckart, 1951; see also Elgar et al., 1992). In an earlier study, the observed ratio between total infragravity energy in 13 and 8 m depth at Duck was shown to be close to the theoretical value ($h^{-1/2}$) for leaky free waves when incident swell energy levels are low, and to decrease systematically with increasing swell energy (Fig. 3 in Elgar et al., 1992). This trend was attributed to increasingly large forced wave contributions to the infragravity band with increasing swell energy. The bispectrum-based estimates of forced infragravity energy (section 3) allow for a more quantitative assessment of free wave decay with increasing depth. Free infragravity energy was estimated by subtracting the forced wave energy estimates from the total observed infragravity energy. The ratio R between free infragravity energy in 13 and 8 m depth is approximately independent of swell energy (Fig. 4), confirming that the trend observed by Elgar et al. (1992) was indeed caused by forced wave contributions. The observed R vary between 0.4 and 1, with the majority of the observations in the range 0.5-0.7, significantly lower than the theoretical value 0.8 for leaky waves. The observed low values of R indicate that a significant fraction (typically 10-50 %) of the free infragravity energy observed in 8 m depth is refractively trapped (i.e., has a turning point) between 8 and 13 m depth. According to Snell's law, free long waves travelling seaward at oblique angles greater than 52° in 8 m depth are trapped between 8 and 13 m depth. Hence, the observed low values of R imply that a significant fraction of free infragravity energy observed close to shore in 8 m depth is travelling at large oblique angles relative to the beach.

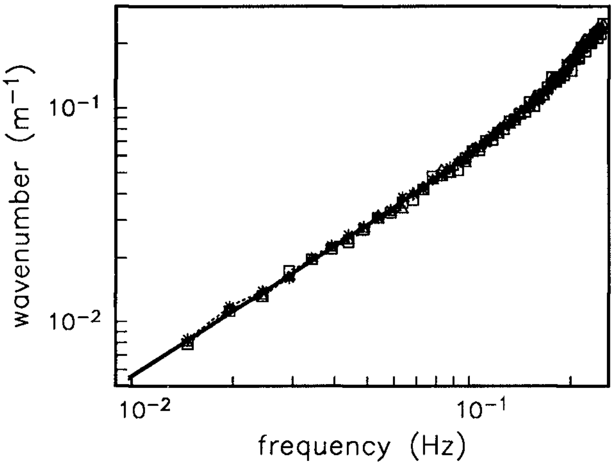

Fig. 3. Estimates of an average wavenumber magnitude $k_{rms}(f)$ as a function of frequency (Eq. 1), obtained from array measurements in 13 m depth at Duck on 7 September (squares), 26 September (triangles) and 8 October (asterisks), 1990. The linear dispersion relation for surface gravity waves is indicated by a solid curve.

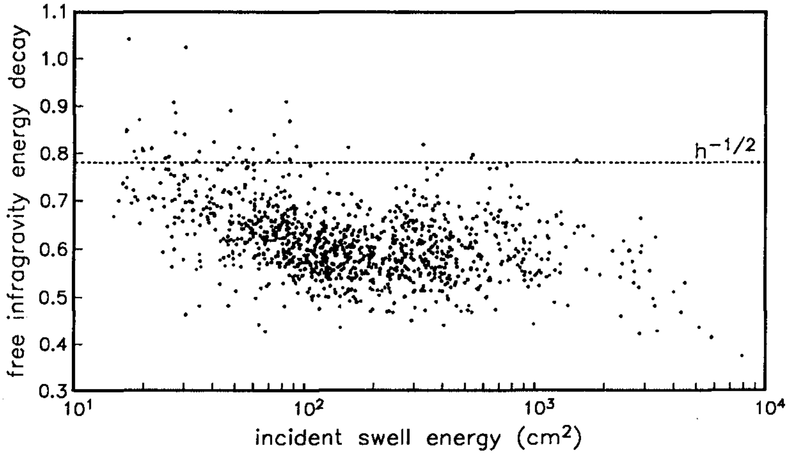

Fig. 4. Observed ratio R between free infragravity energy in 13 and 8 m depth at Duck versus incident swell energy (observed in 13 m depth). The dotted line labeled $h^{-1/2}$ indicates the theoretical decay for leaky waves.

For swell energies larger than about 50 cm^2, the observations do not suggest a dependence of R on swell energy, but the relatively few cases with very small amplitude swell (variances < 50 cm^2) show weaker decay, closer to the theoretical value $h^{-1/2}$ for leaky waves (Fig. 4). Possibly, these free infragravity motions are not generated at nearby shores but arrive from (and return to) the deep ocean. Observations by Webb et al. (1991) suggest that a small fraction of the free infragravity energy generated at coasts with energetic swell propagates off the shelf into deep water and radiates across ocean basins. These relatively weak background motions may be the dominant source of infragravity energy on the shelf when forcing by local swell is very weak.

Array measurements in 13 m depth confirm that free waves at infragravity frequencies are indeed directionally broad. Examples of estimates of directional distributions of energy at the infragravity (0.02 Hz) and swell (0.1 Hz) spectral peak frequencies, on a day with negligible forced wave contributions to the infragravity band, are shown in Fig. 5. In contrast to the directionally narrow, shoreward travelling swells, the directional distribution of infragravity energy is very broad with approximately equal amounts of energy travelling seaward and shoreward, and a maximum at 90°, corresponding to alongshore travelling waves. Note that although both swell and infragravity maxima correspond to waves travelling in the same upcoast direction there is significant infragravity energy travelling downcoast against the swell.

Consistent with earlier observations inside the surf-zone (e.g., Huntley et al., 1981, Oltman-Shay and Guza, 1987), the observed faster than $h^{-1/2}$ energy decay with increasing depth and directionally very broad spectra show that refractive trapping is of O(1) importance to infragravity motions on a natural beach. The

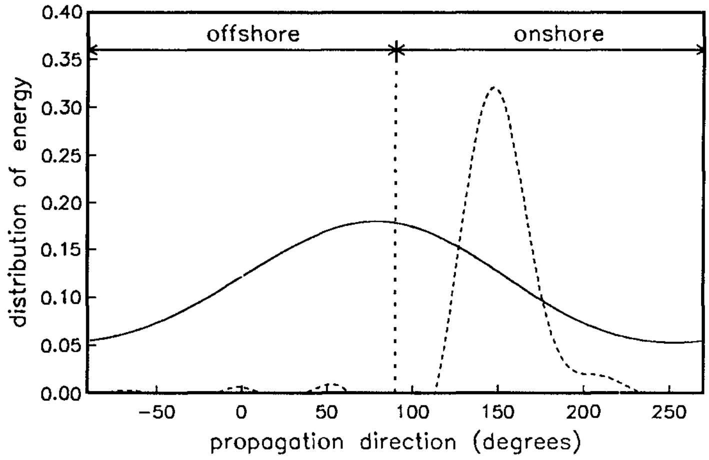

Fig. 5. Directional distributions of free infragravity energy (0.02 Hz; solid curve) and swell energy (0.1 Hz; dashed curve) observed in 13 m depth at Duck on 8 October 1990. The sector 90–270° corresponding to shoreward propagating waves, contains 98 % of the swell energy and 46 % of the infragravity energy.

assumption of uni-directional wave propagation used in current infragravity wave generation models (e.g., Symonds et al., 1982; Schäffer and Svendsen, 1988; Schäffer et al., 1990; List, 1992; Roelvink et al., 1992; Watson and Peregrine, 1992; and others) is inconsistent with the present observations.

5. SHELF-WIDE VARIABILITY

The mix of free and forced infragravity energy (Fig. 2a) observed on the inner North Carolina shelf (Duck) in 13 m depth is not necessarily representative of other sites, and is further investigated here using additional long-term bottom pressure measurements collected on the California shelf. Estimates of forced and free wave energy contributions to the infragravity band in 8, 30 and 204 m depth, based on bispectral analysis (section 3), are compared in Figs. 6a and 6b, respectively. Both free and forced infragravity energies are generally well correlated with swell energy (defined as the energy in the range 0.04-0.14 Hz for Pacific sites and 0.05-0.14 Hz for Atlantic sites). In all three depths forced wave energy is approximately proportional to the swell energy squared (Fig. 6a). This quadratic dependence is expected from second-order nonlinear theory because the amplitude of a forced secondary wave is proportional to the product of the amplitudes of the interacting swell components. Since the forced infragravity wave amplitude also depends on the frequencies and the difference in propagation direction of the interacting swell components, the scatter about the line with slope 2 is expected. As expected from theory, forced wave energies fall off rapidly with increasing depth. In 204 m depth

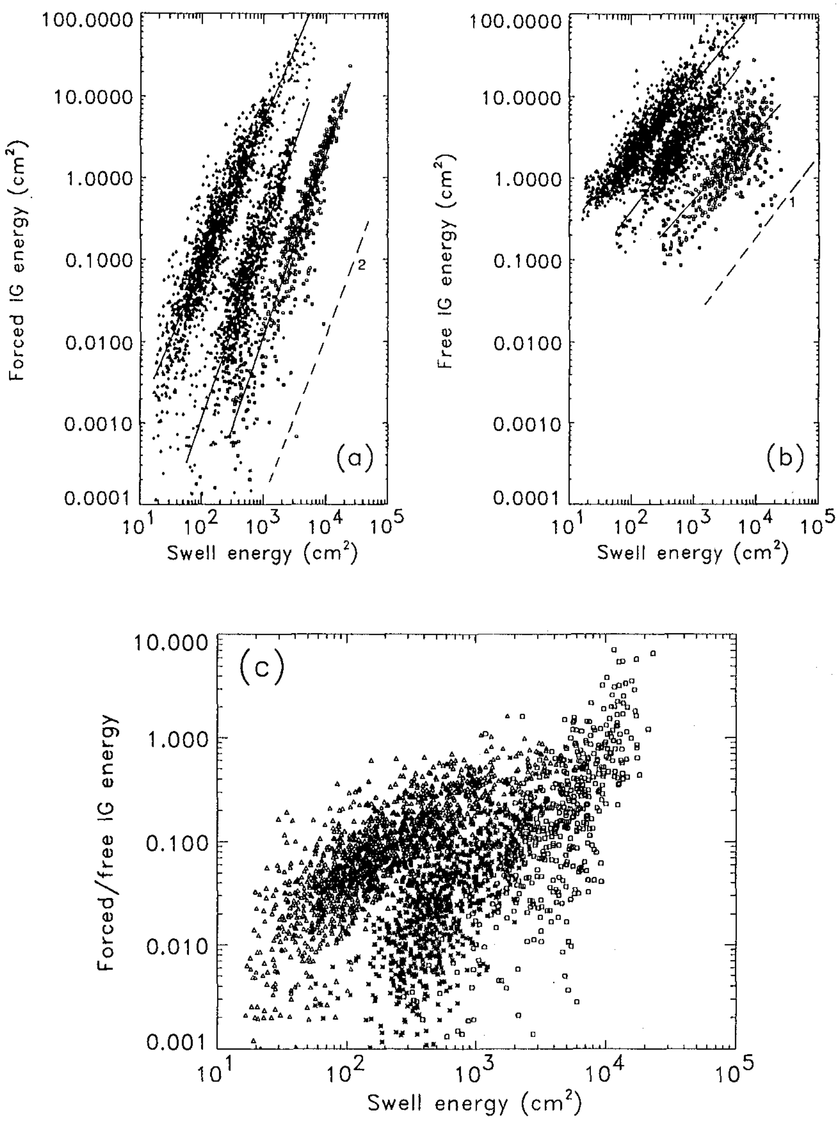

Fig. 6. Forced (a), free (b), and the ratio between forced and free (c) infragravity energies, observed in 8 m depth at Duck (triangles, upper clouds), in 30 m depth at Ventura (asterisks, middle clouds), and in 204 m depth at Harvest Platform (squares, lower clouds), are shown versus swell energy. Least-squares-fit curves to the logarithms of the observed energies are denoted by solid lines. Dashed lines labeled 1 and 2 indicate a linear and quadratic dependence, respectively.

the observed forced wave energy levels are typically smaller by a factor of 10^2-10^3 compared to 8 m depth for comparable swell energy (Fig. 6a). The depth dependence observed for free infragravity energy (Fig. 6b) is weaker than observed for forced waves, but stronger than the $h^{-1/2}$ dependence of leaky waves, consistent with significant refractive trapping of seaward propagating free waves.

In contrast to the strong (quadratic) dependence of forced wave energy on swell energy, in all three depths free wave energy is approximately linearly proportional to swell energy. The observed weak dependence of free infragravity energy on swell energy is not inconsistent with nonlinear generation and reflection at nearby shores, but suggests the importance of wave breaking in the generation process. If nonlinear transfer of energy from shoaling incident swell is the source of free infragravity motions, then the infragravity energy is expected to be roughly proportional to the square of the swell energy. However, the transfer of swell energy to lower frequencies may be arrested when the swell energy is dissipated through wave breaking. As larger amplitude swell break in deeper water farther from shore, the dependence of forced infragravity energy released in the surf-zone on incident swell energy is expected to be weaker than quadratic (Longuet-Higgins and Stewart, 1962). Alternative models (e.g., Symonds et al., 1982; and many others) assume that variations in set-up inside the surf-zone, rather than nonlinear interactions outside the surf-zone, drive free waves in the infragravity band. The solutions to these models (including standing waves within the surf-zone) are quite complicated, but since the driving set-up variations are linearly proportional to the incident swell amplitudes (Longuet-Higgins and Stewart, 1962), free infragravity energy generated inside the surf-zone is expected to be roughly linearly proportional to swell energy, qualitatively consistent with the present observations. A weaker than quadratic dependence of free infragravity energy on swell energy may also result from a nonlinear dependence of free wave damping (in the surf-zone or through bottom friction on the shelf) on swell energy.

The ratio of free to forced infragravity energy at the same three sites (Fig. 6c) is extremely variable, ranging from 10^{-3} to 10. Owing to the different dependencies of free and forced wave energies on incident swell energy and water depth (e.g., compare Figs. 6a and 6b) the relative contribution of forced wave energy to the infragravity band generally increases with both increasing swell energy and decreasing water depth. Overall the present observations (including the sites not shown in Fig. 6, see Herbers et al., 1992b for further discussion) indicate that free waves are the dominant source of infragravity energy on the shelf (well outside the surf-zone). However, forced wave contributions are significant with energetic swell and sometimes dominate the infragravity band even in 204 m depth (e.g., the forced/free wave energy ratios > 1 for swell energy > 10^4 cm^2 in Fig. 6c).

6. DISCUSSION AND CONCLUSIONS

Although differences in free infragravity energy levels measured in 8, 30 and 204 m depth (Fig. 6b) are qualitatively consistent with propagation (unshoaling and refractive trapping) effects, the observed energy levels may also depend on the detailed characteristics of the nonlinear shoaling/surf-zone processes close to shore where the free waves are generated. Comparable (within roughly ± a factor of 2) free wave energy levels observed in 30 m depth offshore of mildly sloping sandy beaches at various locations along the Southern California coast (not shown), do not indicate a strong sensitivity of the generation of free infragravity energy to the detailed, local beach morphology. However, free infragravity energy levels observed near rocky shores are much lower than observed near sandy beaches, as illustrated in Fig. 7 with comparisons of free and forced wave energy observed in 30 m depth offshore of a sandy beach at Redondo and in 30 m depth offshore of a rocky coast at Santa Rosa Island. The observed dependence of forced wave energy on swell energy is approximately the same at both sites, as expected for local nonlinear effects that depend only on the local water depth and wave conditions. However, for comparable incident swell conditions, free wave energy levels observed at Santa Rosa Island are typically an order of magnitude lower than observed at Redondo. Reflections of incident swell from steep cliffs and localized wave breaking on isolated reefs obviously affects the nonlinear shoaling and surf-zone processes at Santa Rosa Island, and may explain the observed low free infragravity energy levels. The dynamics are not understood but the observations strongly suggest that the generation and/or reflection of free infragravity motions is less efficient on rocky shores than on sandy beaches.

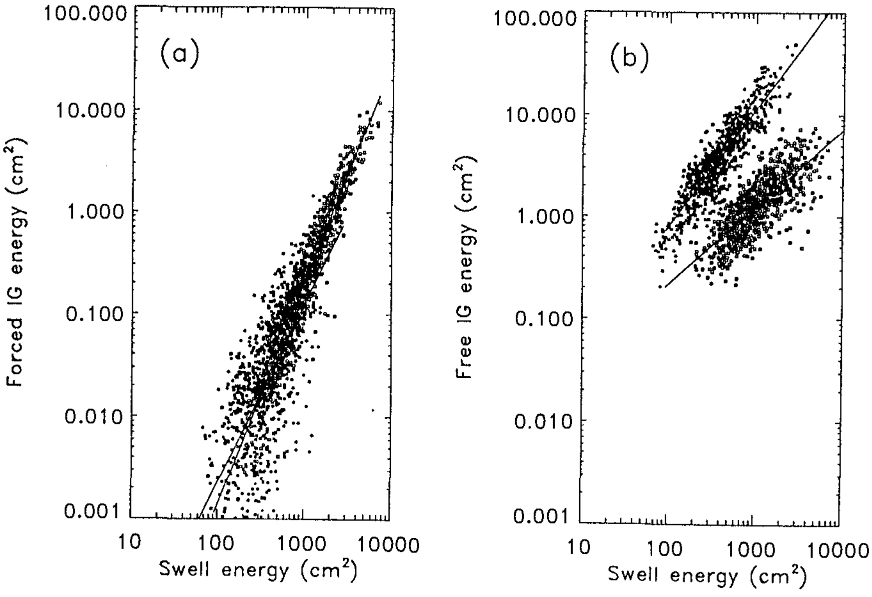

Fig. 7. Forced (a) and free (b) infragravity energies observed in 30 m depth, offshore of the sandy Redondo beach (asterisks, upper cloud in panel b) and offshore of the rocky Santa Rosa Island (squares, lower cloud in panel b), versus swell energy. Least-squares-fit curves to the logarithms of the observed energies are denoted by solid lines.

In summary, results of this study show that motions in the infragravity band (nominally 0.005-0.05 Hz) on the continental shelf are a mix of forced waves, phase-coupled to swell and sea, and free waves generated at nearby shores. The observed forced waves are accurately predicted by second-order nonlinear theory but the generation mechanism of free waves is not well understood. Both free and forced wave energies increase with increasing swell energy but, in contrast to the approximately quadratic dependence of forced wave energy on swell energy, the dependence of free wave energy on swell energy is approximately linear, qualitatively consistent with heuristic models of surf-zone dynamics (e.g., Longuet-Higgins and Stewart, 1962; Symonds et al., 1982; and others). Free and forced wave energies also decrease with increasing water depth owing to a weakening of local nonlinear effects and propagation effects, respectively. The observed free wave decay with increasing depth, although weak compared to the very strong forced wave decay, is much stronger than the decay theoretically predicted for leaky waves radiating to deep water. Refractive trapping of seaward travelling free waves, not included in many current infragravity wave generation models, is important on natural beaches. Very broad directional spectra at infragravity frequencies, with roughly comparable energy travelling seaward and shoreward, confirm that a large fraction of free wave energy radiating from the beach is refractively trapped on the shelf.

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References

Bowen, A. J., and R. T. Guza, 1978: Edge waves and surf beat. *J. Geophys. Res.*, *83*, 1913-1920.

Eckart, C., 1951: Surface waves on water of variable depth. *Wave Report 100*, 99 pp., Scripps Institution of Oceanography, Elgar, S., and R. T. Guza, 1985: Observations of bispectra of shoaling surface gravity waves. *J. Fluid Mech., 161*, 425-448.

Elgar, S., T. H. C. Herbers, M. Okihiro, J. Oltman-Shay, and R. T. Guza, 1992: Observations of infragravity waves. *J. Geophys. Res., 97*, 15573-15577.

Foda, M. A., and C. C. Mei, 1981: Nonlinear excitation of long-trapped waves by a group of short swells. *J. Fluid Mech., 111*, 319-345.

Gallagher, B., 1971: Generation of surf beat by non-linear wave interactions. *J. Fluid Mech., 49*, 1-20.

Guza, R. T., and E. B. Thornton, 1985: Observations of surf beat. *J. Geophys. Res., 90*, 3161-3172.

Hasselmann, K., 1962: On the non-linear energy transfer in a gravity-wave spectrum, Part 1. General theory. *J. Fluid Mech., 12*, 481-500.

Hasselmann, K., W. Munk and G. MacDonald, 1963: Bispectra of ocean waves, in *Times Series Analysis*, edited by M. Rosenblatt, pp. 125-139, John Wiley, New York. *J. Geophys. Res., 70*, 1415-1427.

Herbers, T. H. C., S. Elgar, and R. T. Guza, 1992a: Infragravity-frequency (0.005-0.05 Hz) motions on the shelf, Part 1. Local nonlinear forcing by surface waves. submitted to *J. Phys. Oceanogr.*

Herbers, T. H. C., S. Elgar, R. T. Guza, and W. C. O'Reilly, 1992b: Infragravity-frequency (0.005-0.05 Hz) motions on the shelf, Part 2. Free and forced waves. to be submitted to *J. Phys. Oceanogr.*

Holman, R. A., D. A. Huntley, and A. J. Bowen, 1978: Infragravity waves in storm conditions, in *Proceedings 16th Conference on Coastal Engineering*, American Society of Civil Engineers, New York, 268-284.

Huntley, D. A., R. T. Guza, and E. B. Thornton, 1981: Field observations of surf beat, Part 1. Progressive edge waves. *J. Geophys. Res., 86*, 6451-6466.

List, J. H., 1992: A model for the generation of two-dimensional surf beat. *J. Geophys. Res., 97*, 5623-5636.

Longuet-Higgins, M. S., and R. W. Stewart, 1962: Radiation stress and mass transport in surface gravity waves with application to 'surf beats.' *J. Fluid Mech., 13*, 481-504.

Munk, W. H., 1949: Surf beats. *Eos Trans. AGU, 30*, 849-854.

Munk, W., F. Snodgrass, and G. Carrier, 1956: Edge waves on the continental shelf. *Science, 123*, 127-132.

Okihiro, M., R. T. Guza, and R. J. Seymour, 1992: Bound infragravity waves. *J. Geophys. Res., 97*, 11453-11469.

Oltman-Shay, J., and R. T. Guza, 1987: Infragravity edge wave observations on two California beaches. *J. Phys. Oceanogr., 17*, 644-663.

O'Reilly, W. C., R. T. Guza, B. W. Waldorf, M. R. Kirk, W. A. Boyd, and M. C. Clifton, 1992: Data Report, Southern California Wave Experiment. Scripps Institution of Oceanography, Reference Series No 92-14.

Roelvink, J. A., H. A. H. Petit, and J. K. Kostense, 1992: Verification of a one-dimensional surfbeat model against laboratory data, to appear in *Proceedings 23rd Conference on Coastal Engineering*, American Society of Civil Engineers, New York.

Sand, S. E., 1982: Wave grouping described by bounded long waves. *Ocean Eng., 9*,(6), 567-580.

Schäffer, H. A., and I. A. Svendsen, 1988: Surf beat generation on a mild slope beach, in *Proceedings 21st Conference on Coastal Engineering*, American Society of Civil Engineers, New York.

Schäffer, H. A., I. G. Jonsson, and I. A. Svendsen, 1990: Free and forced cross-shore long waves, in *Water Wave Kinematics*, A. Torum and O. T. Gudmestad (eds.), 367-385.

Seymour, R. J., M. H. Sessions, and D. Castel, 1985: Automated remote recording and analysis of coastal data, *J. Waterw., Port, Coastal Ocean Eng., 111*, 388-400.

Symonds, G., D. A. Huntley, and A. J. Bowen, 1982: Two-dimensional surf beat: long wave generation by a time-varying breakpoint. *J. Geophys. Res., 87*, 492-498.

Tucker, M. J., 1950: Surf beats: Sea waves of 1 to 5 minute period. *Proc. Roy. Soc. Lon., A202*, 565-573.

Watson, G., and D. H. Peregrine, 1992: Low frequency waves in the surf zone, to appear in *Proceedings 23rd Conference on Coastal Engineering*, American Society of Civil Engineers, New York.

Webb, S. C., X. Zhang, and W. Crawford, 1991: Infragravity waves in the deep ocean. *J. Geophys. Res., 96*, 2723-2736.

Wright, L. D., R. T. Guza, and A. D. Short, 1982: Dynamics of a high-energy dissipative surf zone. *Mar. Geol., 45*, 41-62.