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Forcing of resonant modes on a fringing reef during tropical storm Man-Yi

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[1] Open basin resonant modes have been observed at tidal frequencies on coastal shelves, but their excitation on coral reef platforms has only been suggested. The topography of and water depth over most fringing reefs correspond to resonant periods that are the order of tens of minutes and fall outside of the energetic part of the wave spectrum. During tropical storm Man-Yi, low frequency near resonant oscillations dominated the variance of the sea surface elevation at the shoreline of Ipan reef, Guam. The excitation of the resonant modes resulted both from a large increase in water level over the reef due to wave setup, which increased the resonant frequencies, and the occurrence of wave group forcing with time scales commensurate with these increased resonant frequencies. **Citation:** Péquignet, A. C. N., J. M. Becker, M. A. Merrifield, and J. Aucan (2009), Forcing of resonant modes on a fringing reef during tropical storm Man-Yi, *Geophys. Res. Lett.*, 36, L03607, doi:10.1029/2008GL036259.

1. Introduction

[2] Fringing reefs provide natural protection for tropical island shorelines by efficiently dissipating sea and swell energy [Munk and Sargent, 1948; Hardy and Young, 1996; Hearn, 1999]. During large wave events, however, significant coastal inundation may occur. For example, large and variable wave overwash during typhoon Russ was reported by Jaffe and Richmond [1993] in Guam. While a variety of field studies have measured wave transformation over fringing reefs during moderate wave conditions [e.g., Young, 1989; Hardy and Young, 1996], few have captured the response of the reef to large wave events. The focus of the Pacific Island Land-Ocean Typhoon (PILOT) project is to assess the amount of wave energy reaching the shore of reef-fringed islands during large wave events. A cross-shore array of pressure sensors and current meters has been maintained at Ipan reef, Guam for more than three years, covering a variety of wave conditions. The focus of the present study is the response of the reef to the large wave event associated with tropical storm Man-Yi.

[3] Previous studies of wave transformation on fringing reefs have shown that the energy spectrum on reef flats is dominated by motions at infragravity frequencies [e.g., Young, 1989; Hardy and Young, 1996; Brander et al., 2004]. Lugo-Fernández et al. [1998] have suggested that part of the low frequency variability observed at Tague Reef,

St. Croix, USVI is related to the fundamental (1/4 wavelength) resonant mode. Open basin resonant modes at tidal frequencies have been well documented on coastal shelves [e.g., Huthnance, 1980; Giese et al., 1990]. For typical fringing reef topography [Steers and Stoddart, 1977] however, estimates of resonant periods are the order of tens of minutes and fall outside of the energetic part of the wave spectrum. For example, approximating the reef at Ipan as a step shelf with length $L = 450$ m and water depth $h = 0.5$ m, the fundamental resonant period $T_0 = 4L/\sqrt{gh}$ is approximately 13 minutes. During Man-Yi, however, wave setup increased the water level on the reef to $h = 2$ m reducing the resonant period by a factor of two.

[4] We report here field observations of the low frequency, near resonant oscillations that dominated the variance of sea surface elevation at the shoreline of Ipan reef at the peak of tropical storm Man-Yi and analyze the conditions that favored their excitation. In section 2, we describe the experimental setting and wave energy on the reef. In section 3, we compare the empirical orthogonal modes and the spectral structure of the oscillations observed on the reef with the theoretical spatial and temporal structure of open basin normal modes. In section 4, we demonstrate that the narrow bandedness of the swell generated by Man-Yi provided near resonant forcing for those normal modes. Finally, we summarize our results in section 5.

2. Field Site and Data

[5] The study site at Ipan (Figure 1a) is composed of a narrow sandy shore connected to a shallow (~ 0.5 m) wide (~ 450 m) fringing reef flat, which typifies the coastal morphology of many Pacific islands (Figure 1b). The rugose spur and groove reef face is very steep resulting in wave breaking typically confined to a narrow zone around the reef edge (Figure 1d). The deployment presented in this study consists of a bottom-mounted cross-shore array of 4 single pressure sensors and 2 collocated pressure sensors and acoustic current-meters (Figure 1b) sampling at 1 Hz, in bursts of 43180 seconds every 12 hours and 7200 seconds every 4 hours respectively. Sea surface elevations are derived from the pressure data and corrected for depth attenuation using linear wave theory. All spectral variables are estimated from two hour segments of de-trended and de-tided (least square fit using 5 dominant tidal constituents) time series, and are band averaged, yielding approximately 22 degrees of freedom and a spectral bandwidth of 0.0016 Hz. The data presented here were collected from June–July 2007 when offshore wave conditions at sensor 6 ranged from calm (significant wave height $H_s < 1$ m) to a typical moderate wave event ($H_s = 1$ –2 m with periods between 7 and 12 seconds, 20–23 June), to an energetic wave event ($H_s = 4$ m, 12 second

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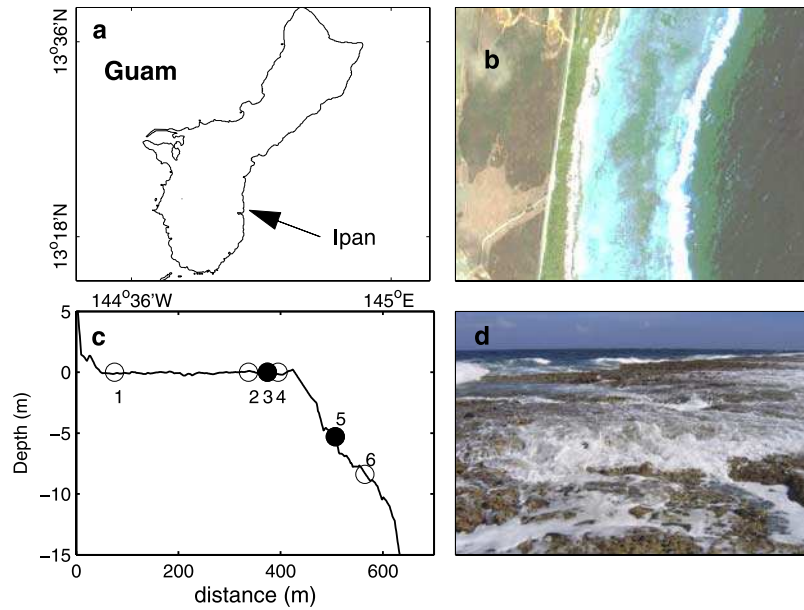


Figure 1. (a) Location of the study site at Ipan reef on the southeast coast of Guam. (b) Ikonos mosaic of Ipan reef, bounded at the shore with a narrow sandy beach and with white water marking the reef edge. (c) Topography along the across-shore transect at Ipan reef with the location and number of the pressure (open circles) and collocated pressure and current-meter (solid circle) sensors. (d) A view of the reef edge during weak wave and low water level conditions.

period, 9 July) when tropical storm (later upgraded to typhoon) Man-Yi passed 200 nm south of Guam. Although the direct impact of Man-Yi on Guam was not severe in terms of atmospheric pressure, winds and rain, significant wave-driven coastal inundation was observed along parts of the eastern side of the island. Consistent with in situ reports of inundation, the observed sea surface elevation near the

shoreline (sensor 1) peaked at 2.06 m (2% exceedance) during the event, which is nearly four times larger than the typical tidal range over the reef. The high water level at the shoreline is partially attributed to a 1.2 m rise in mean sea level caused by wave setup [Gourlay, 1996] (Figure 2a). This increase in water level across the reef, in turn, is

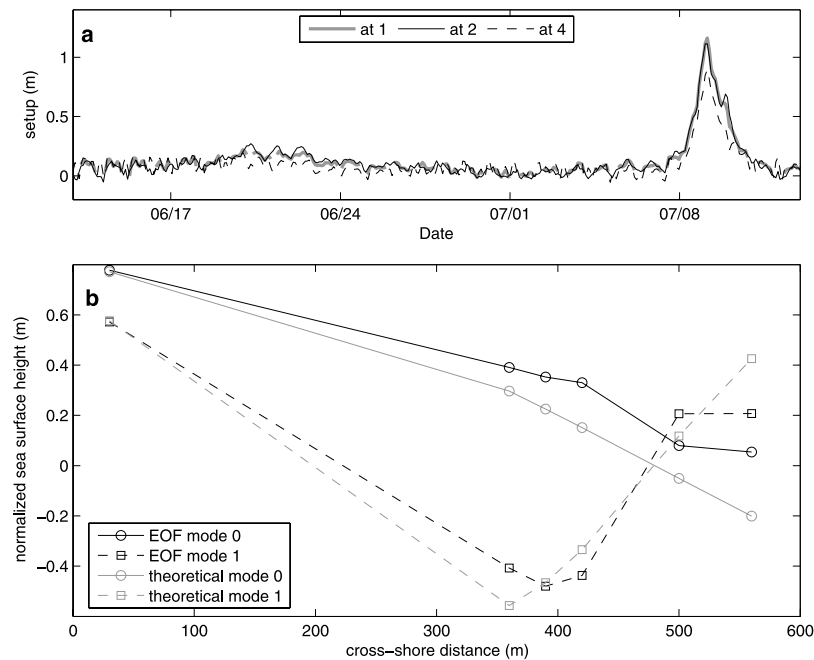


Figure 2. Temporal and spatial structure of the sea surface elevation on the reef. (a) Setup at sensor 1, 2 and 4 as a function of time (15 minutes average). (b) Cross-shore structure of the first two theoretical resonant modes from equation (3), with $n = 0, 1$, at the sensor locations (grey). EOF modes of the band pass filtered sea surface elevation across the reef during the peak of Man-Yi (black).

responsible for an increase in low frequency wave energy reaching the shore.

[6] During normal and storm conditions, waves at sea and swell periods (5 to 25 seconds) dominate the offshore energy spectrum, and largely dissipate at the reef face through breaking. Additional dissipation also is achieved on the reef flat through bottom friction [Lowe *et al.*, 2005]. Similar to dissipative sandy beaches [Guza *et al.*, 1984; Ruggiero *et al.*, 2004], shoreward of the surf zone at Ipan the water level fluctuations are dominated by low frequency waves (period of 25 to 1000 seconds). The amplitudes of the infragravity (0.005 to 0.04 Hz) and far infragravity [Oltman-Shay *et al.*, 1989] (fIG) (0.001 to 0.005 Hz) oscillations, although small in moderate wave conditions, increase both with the water level over the reef and the amplitude of the incident swell waves (not shown). During Man-Yi, the average amplitude of waves of periods ranging from minutes to tens of minutes reached approximately half a meter near the shore. While infragravity wave energy on the reef typically decays slightly in amplitude toward shore, presumably in part due to frictional effects, anomalous amplification of the longest waves (fIG, period 200 to 1000 seconds) is observed during Man-Yi with the largest amplitude occurring at the shore (sensor 1).

3. Reflection and Resonant Modes

[7] Infragravity energy reaching the shore must be either dissipated through breaking at the shoreline and friction or reflected [van Dongeren *et al.*, 2007]. We assess the reflection of IG waves on the reef flat by assuming normal incidence of shallow water waves and estimating the incoming (F^+) and outgoing (F^-) cross-shore energy fluxes [Sheremet *et al.*, 2002] at sensor 3 from the auto-spectra of surface elevation $S_{\eta\eta}$ and of cross-shore velocity u , S_{uu} , and from the co-spectrum of η and u , $S_{u\eta}$

$$F^\pm(f) = \frac{1}{4} \sqrt{gh} \left[S_{\eta\eta}(f) + (h/g) S_{uu}(f) \pm \left(2\sqrt{h/g} \right) S_{u\eta}(f) \right] \quad (1)$$

The frequency dependent reflection coefficient of waves on the reef is defined as F^-/F^+ . In general, we find that reflection (not shown) increases with increasing period and decreasing offshore wave height. fIG reflection is variable during calm to moderate wave conditions, and it reaches 100% during the peak of Man-Yi, indicating the presence of standing waves over the reef.

[8] We next demonstrate that the shallow reef flat at Ipan acts as a bounded open basin that supports resonant modes of oscillations with an antinode of surface elevation at the shore and a node at the reef edge. The resonant periods for a step shelf (reef) of width L , are given by

$$T_n = \frac{4L}{(2n+1)\sqrt{gh}} \quad n = 0, 1, 2, \dots \quad (2)$$

where h is the water depth on the shelf (assumed uniform) and g is the gravitational acceleration [Sorensen, 2005]. The cross-shore structure of the resonant modes of sea surface elevation is given by

$$A_n(x) = \cos \left[(2n+1) \frac{\pi}{2L} x \right] \quad n = 0, 1, 2, \dots \quad (3)$$

where x is the cross-shore distance from the shoreline. Using mean water depth at sensor 1 in equation (2), we find the period of the fundamental mode at Ipan reef ranges from more than 1000 seconds to 416 seconds at the peak of the storm.

[9] We perform an Empirical Orthogonal Function (EOF) analysis of the 2 hour segments of band pass filtered sea surface elevation time series across the reef. The band pass filter is designed to examine energy in the first 3 resonant frequencies (periods from 100 to 650 seconds during Man-Yi) as the spacing of the sensors on the reef is insufficient to resolve the spatial structure of higher modes. The cross shore structure of the first two empirical modes matches the structure of theoretical resonant modes (equation (3) $n = 0, 1$) during the storm (Figure 2b). These two EOF modes explain 75% and 23% of the fIG variance on the reef during Man-Yi but we emphasize that resonant modes are not observed during non storm conditions.

[10] We next estimate the coherence spectra between the sea level elevation at sensor 1 and sensor 2 (Figure 3a) in the fIG band. In this band, the timing error estimates associated with instrument clock drift and synchronization have a negligible effect on our coherence estimates. The theoretical resonant frequencies (inverse of equation (2)) of the first 3 modes ($n = 0, 1, 2$) are superimposed on the coherence and co-spectra. Motions at frequencies at or around the theoretical values are highly coherent on the reef. The central frequency of the bands of high coherence closely follows the shift of resonant frequencies associated with rise and fall of the mean water depth on the reef. High coherence is particularly pronounced during the large event when the absolute value of the co-spectrum (Figure 3b) between sensor 1 and 2 is high. The co-spectrum is organized in alternating bands of positive and negative values corresponding to phase shifts, from in phase (positive) to out of phase (negative), matching the theoretical phase of the corresponding resonant modes sampled between sensor 1 and sensor 2. The quadrature spectrum (not shown) at the resonant frequencies is near zero.

4. Near Resonant Forcing

[11] Although motions around the resonant frequencies (equation (2)) are highly coherent on the reef (Figure 3a), they are not necessarily energetic (Figure 3b) as forcing at or near the resonant frequencies is necessary to excite these modes. We next examine the forcing at sensor 6 and its relationship to the reef response.

[12] The excitation of motions at fIG frequencies may occur offshore [Herbers *et al.*, 1994, 1995] or in the surf zone by the breaking of modulated short-waves, or wave groups [Symonds *et al.*, 1982; Schäffer, 1993; Janssen *et al.*, 2003]. The former mechanism is unlikely as during Man-Yi, the peak fIG energy at a period of 416 seconds (frequency of 0.0024 Hz) is present in the spectrum of the inshore sea surface elevation S_{11} , but not in the spectrum of the offshore sea surface elevation S_{66} (Figure 4a), and energy in this band is not coherent between the two sensors (Figure 4b).

[13] To test that near resonance forcing occurs due to wave groups, we obtain the envelope of the offshore (sensor 6) sea surface elevation $\eta(t)$ by computing the slowly varying

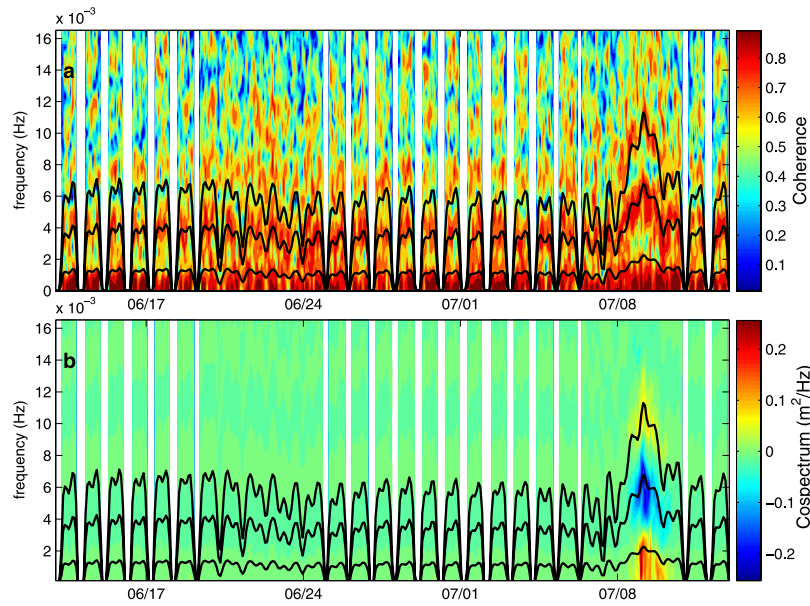


Figure 3. (a) The coherence spectrum and (b) the co-spectrum for sea surface elevation between the sensors closest to shore (1) and near the reef edge (2). Theoretical resonant mode frequencies based on equation (2) calculated from the mean water depth at sensor 1 (mode $n = 0, 1, 2$) are overlaid on the spectra.

(low frequency) envelope function $E(t)$ [Longuet-Higgins, 1984] as

$$E(t) = |\eta(t) + i \Gamma\{\eta(t)\}| \quad (4)$$

where $\Gamma\{\eta(t)\}$ denotes the Hilbert transform operator and $|\cdot|$ is the amplitude of the complex function. Figure 4a shows the spectrum of swell wave groups S_{env} , with modulation time scales commensurate with the frequencies of the resonant modes on the reef. In addition, a high coherence

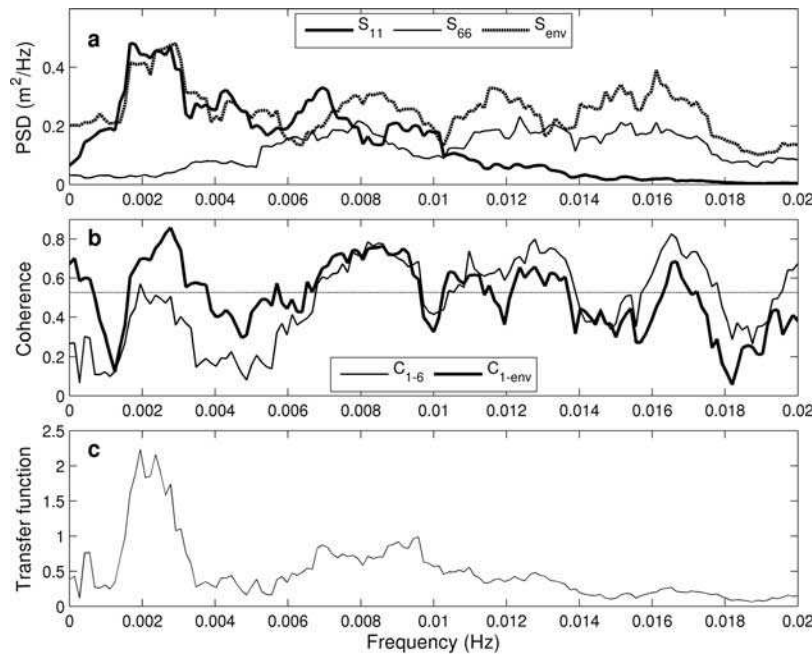


Figure 4. A comparison of auto and cross-spectra in the fIG and IG frequency bands during the peak of Man-Yi. (a) Autospectra of sea surface elevation at the most inshore sensor (S_{11}), the most offshore sensor (S_{66}) and the envelope of the swell band energy at sensor 6 (S_{env}). (b) The coherence spectra between sea surface elevation at sensors 1 and 6 (C_{1-6}), and between sea surface elevation at sensor 1 and the swell band envelope at sensor 6 (C_{1-env}). The dashed line is the 95% confidence level. (c) Transfer function between sea surface elevation at the most inshore (1) and offshore (6) sensors. The vertical dotted lines show the first 2 theoretical resonant frequencies.

between the inshore flG sea surface elevation S_{11} and the offshore swell wave envelope S_{env} exists (Figure 4b). We conclude that the flG oscillations on the reef are driven by the modulation of breaking swell waves at the reef edge, similar to a time-varying set-up. We also estimate the transfer function between the wave envelope and the inshore sea surface elevation (Figure 4c) as the ratio of the amplitude of the cross-spectrum between the two time-series, and the auto-spectra of the wave envelope [Emery and Thomson, 1998]. This transfer function shows a strong gain of energy near the fundamental resonant frequency, consistent with a near-resonant response on the reef to the envelope forcing.

5. Discussion

[14] The shelf topography of a fringing reef such as Ipan may support open basin normal modes. A cross-spectral analysis between sensors on the reef confirms that motions that match these normal modes retain high coherence and phase structure across the reef at very low wave energy. Forcing at the normal mode frequencies, however, is necessary to obtain resonant excitation and this condition of matching frequencies is rarely met at Ipan. During typical weak and moderate offshore wave conditions, the shallow water depth (~ 0.5 m) on the reef sets the gravest resonant period to >13 minutes, falling in a non-energetic band of the wave spectrum. During the large wave conditions generated by Man-Yi, however, wave setup elevates water levels on the reef, lowering the resonant period by approximately a factor of two. During a four hour period of the deployment, we demonstrate that near resonant forcing of the open basin resonant modes occurs from the envelope of the incident sea and swell waves.

[15] Previous studies have demonstrated that water level on the reef controls the frequency distribution and the amount of energy on the reef flat [e.g., Hardy and Young, 1996; Hearn, 1999; Brander et al., 2004]. We find that the water level on the reef also alters the dynamics of wave transformation, allowing here for a resonant response to occur on the reef, which significantly increases the amount of energy that reaches the shoreline. When the water depth at Ipan is within the usual tidal range, we find that the infragravity energy decays slightly shoreward. In contrast, the unusually large water depth observed during Man-Yi from large wave setup over the reef results in the excitation of resonant modes with an antinode (maximum energy) at the shore line.

[16] We conclude that any increase in water level on the reef will increase the resonant frequencies, which potentially will allow a wider range of wave conditions to excite reef resonant modes. With the prospect of sea level rise associated with global climate change [Intergovernmental Panel on Climate Change, 2007], we speculate that the excitation of reef resonances may become increasingly important in the dynamics of coral reefs.

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