1-1-2008

Nearshore wave environments around a sandy cay on a platform reef, Torres Strait, Australia

Colin D. Woodroffe
University of Wollongong, colin@uow.edu.au

Bongkoch Samosorn
University of Wollongong, bs95@uow.edu.au

Follow this and additional works at: <https://ro.uow.edu.au/scipapers>

Part of the [Life Sciences Commons](#), [Physical Sciences and Mathematics Commons](#), and the [Social and Behavioral Sciences Commons](#)

Recommended Citation

Woodroffe, Colin D. and Samosorn, Bongkoch: Nearshore wave environments around a sandy cay on a platform reef, Torres Strait, Australia 2008, 2257-2274.
<https://ro.uow.edu.au/scipapers/3544>

Nearshore wave environments around a sandy cay on a platform reef, Torres Strait, Australia

Abstract

Waves are the primary factor affecting reef-island morphology. This study examines spatial and temporal variations of wave characteristics in the nearshore around Warraber Island, a sandy cay on a platform reef in Torres Strait Australia, based on field measurements during the predominant southeasterly wind season. Water pressure was recorded simultaneously, and transformed to water surface wave spectra, at a location close to the reef edge and across the nearshore at different locations around the island. Wave environments off the reef were estimated based on wave characteristics measured at the reef-edge location and found to be primarily dominated by sea. Low and high wave-energy events were identified, based on wave energy level at the reef-edge location.

Analysis of measured data at locations around the island shows that in general, waves on the windward side were larger and shorter in comparison with those on the leeward side. This spatial pattern was found to be more evident during high wave-energy events. The spatial variation of wave characteristics is influenced by relative energy contribution from three main spectral components (incident short-period waves <2.5 s, incident wind waves <8 s and infragravity waves, the principal component >8 s). During low wave-energy conditions, incident short-period waves are dominant. During high wave-energy conditions, wave spectra clearly show triple peaks on the windward side, but have only two peaks at infragravity and incident wind wave components on the leeward side. Incident wind wave components around the island are primarily a function of incident waves in seas off the reef. Development of infragravity waves is directly related to that of the incident wind waves. Incident short-period waves are generated locally on the reef flat and increase towards the island, particularly on the broad windward reef flat, and their characteristics can be estimated using fetch-limited and depth-limited wave models.

Strong influence of water depth on wave characteristics was observed. Wave height and energy of the three wave components at all locations varied directly with changing water level on the reef, whereas wave periods show no clear trends, depending on location around the island. Wave conditions around the island during the northwesterly wind season were also estimated and are likely to be dominated by incident wind wave components.

Keywords

Nearshore, wave, environments, around, sandy, cay, platform, reef, Torres, Strait, Australia, GeoQUEST

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details

Samosorn, B. & Woodroffe, C. D. (2008). Nearshore wave environments around a sandy cay on a platform reef, Torres Strait, Australia. *Continental Shelf Research*, 28 2257-2274.

**Nearshore wave environments around a sandy cay on a platform reef,
Torres Strait, Australia**

Bongkoch Samosorn ^{1,2} and Colin D. Woodroffe ^{1 *}

¹ School of Earth and Environmental Sciences, University of Wollongong, Wollongong,
Northfield Avenue, NSW 2522, Australia

² Present address, Hydrographic Department, Royal Thai Navy, Bangna, Bangkok, 10260,
Thailand

* Corresponding author. Tel.: +61 2 4221 3359; fax +61 2 4221 4250

E-mail address: colin@uow.edu.au

Abstract

Waves are the primary factor affecting reef-island morphology. This study examines spatial and temporal variations of wave characteristics in the nearshore around Warraber Island, a sandy cay on a platform reef in Torres Strait Australia, based on field measurements during the predominant southeasterly wind season. Water pressure was recorded simultaneously, and transformed to water surface wave spectra, at a location close to the reef edge and across the nearshore at different locations around the island. Wave environments off the reef were estimated based on wave characteristics measured at the reef-edge location and found to be primarily dominated by sea. Low and high wave-energy events were identified, based on wave energy level at the reef-edge location.

Analysis of measured data at locations around the island shows that in general waves on the windward side were larger and shorter in comparison with those on the leeward side. This spatial pattern was found to be more evident during high wave-energy events. The spatial variation of wave characteristics is influenced by relative energy contribution from three main spectral components (incident short-period waves <2.5 s, incident wind waves <8 s and infragravity waves, the principal component >8 s). During low wave-energy conditions, incident short-period waves are dominant. During high wave-energy conditions, wave spectra clearly show triple peaks on the windward side, but have only two peaks at infragravity and incident wind wave components on the leeward side. Incident wind wave components around the island are primarily a function of incident waves in seas off the reef. Development of infragravity waves is directly related to that of the incident wind waves. Incident short-period waves are generated locally on the reef flat and increase towards the island, particularly on the broad windward reef flat, and their characteristics can be estimated using fetch-limited and depth-limited wave models.

Strong influence of water depth on wave characteristics was observed. Wave height and energy of the three wave components at all locations varied directly with changing water level on the reef, whereas wave periods show no clear trends, depending on location around the island. Wave conditions around the island during the northwesterly wind season were also estimated and likely to be dominated by incident wind wave components.

Keywords: Torres Strait, platform reef, wave transformation, Warraber, reef island,

1. Introduction

Sand cays, formed from skeletal carbonate sands on the surface of coral reefs, appear particularly vulnerable to erosion by waves, and there is concern that these islands, and the communities that depend on them, are threatened by the impacts of global climate and sea-level change (Hopley et al., 2007). Waves are the major driving force influencing sand-cay formation and stability; they transport sediments towards a focusing point, shape sand cays through patterns of wave convergence and determine sand-cay topography through wave run-up (Flood, 1986; Gourlay, 1988). Therefore, an understanding of the characteristic wave transformations on reefs and particularly wave environments around islands is necessary to explain the development and stability of sand cays.

In contrast to wave environments over a gradually-sloping, relatively smooth, sandy shoreface, wave characteristics in coral-reef environments are profoundly influenced by abrupt changes in reef morphology and the variable roughness of the reef surface. Two distinct wave environments are recognised in reef regions: waves off reefs and waves on reefs (Gourlay, 1990). Waves off reefs can be dominated by *seas* (e.g., inside the Great Barrier Reef (GBR); Wolanski, 1994), or *swell* (e.g., in Hawaii; Lee and Black, 1978), or a combination of *both* (e.g., in the Caribbean Sea; Roberts et al., 1992, and along the outer GBR; Wolanski, 1994). Five different zones have been described across reef platforms (Gourlay, 1990), based on the characteristics of waves, including: i) outer reef slopes where

waves are affected by propagation effects; ii) reef edges where wave breaking occurs; iii) reef rims where waves surge after breaking; iv) reef flats where waves reform; and v) beaches of either islands or mainland where reformed waves will break again.

Over recent decades, a great deal of information on wave characteristics on reefs has been derived from field observations, laboratory experiments and mathematical studies. These have been conducted over small reef-lagoon systems on fringing reefs of Hawaii (Lee and Black, 1978; Storlazzi et al., 2004), Seychelles (Sheppard et al., 2005), Grand Cayman Island (Roberts, 1989), St. Croix, US Virgin Islands (Lugo-Fernandez et al., 1998), Hayman Island, Australia (Gourlay, 1994), and the Japanese mainland and islands (Nakaza et al., 1990; Tsukayama and Nakaza, 2000). A few studies have also focused on wave transformation on reef platforms either across the reef edge (CERC, 1993; Gourlay, 1996a; Gourlay, 1996b; Hardy and Young, 1991; Hardy and Young, 1996; Massel and Gourlay, 2000; Young, 1989), or over transects across reef platforms and towards island beaches (Brander et al., 2004; Kench and Brander, 2006; Kench et al., 2006).

Warraber Island is an inhabited sand cay on a platform reef (Warraber Reef) in Torres Strait, Australia. A previous study by Brander et al. (2004) focused on wave transformation across the reef flat and deployed wave recorders along a transect from the Warraber island shoreline southeast across the Warraber reef platform to the reef rim. Although this demonstrated the reduction of wave energy as waves approached the island, it did not address the variation in wave conditions in the nearshore around the island, which is important to study sediment transport, and the morphodynamics and stability of sand cays. Data on variations in wave characteristics around sand cays is generally sparse.

The present study therefore focuses on spatial and temporal changes of nearshore wave environments around Warraber Island. Different configurations of instruments were deployed in the nearshore to examine the nearshore wave behaviour, and its implications for sediment

movement and shoreline dynamics around Warraber Island. The origins of the main wave spectral components are also examined in this study, which may have direct applications in assessing probable wave conditions and sediment transport processes in relation to the evolution of island morphology. In this paper, Sections 2 and 3 outline the field experiment and data analysis, respectively. Section 4 focuses on wave environments off the reef, which exert important influences on waves on the reef. Nearshore wave environments around the island are described in Sections 5 and the origin of the main spectral components is explored Section 6.

2. Field Experiment

A field experiment was undertaken between 24 and 29 November 2004 at Warraber Reef in Torres Strait. Torres Strait is a shallow shelf separating the northern tip of the Australian mainland at Cape York from Papua New Guinea (PNG), bounded on the west by the Arafura Sea and on the east by the Coral Sea (Figure 1a). It contains a dense network of various types of reefs and islands (Figure 1b). Warraber Reef is a planar reef, approximately 5.0 km long in the west-east orientation and approximately 2.5 km wide in the north-south orientation (Figure 1c).

Torres Strait is dominated primarily by southeasterly winds from April to November but is influenced by northwesterly winds from December to March (Hopley et al., 2007). During the experiment between 25 and 28 November 2004 wind directions were relatively stable from the East-South-East (ESE) (Figure 2a) while wind speed increased from approximately 8 m/s on the first day to around 10 m/s on 26/11/04, 11 m/s on 27/11/04, and 12 m/s, on 28/11/04, respectively (Figure 2b).

The reef-top topography of Warraber Reef can be divided into two main areas (Woodroffe et al., 2000; Hart, 2003): the elevated area on the east of the island, which is the main part of an emergent Holocene reef flat; and a deeper area on the west of the island (the

darker area in the aerial photograph, Figure 1c). Figure 2c shows tidal levels in the vicinity of Warraber Reef, based on tidal prediction for Poll Reef (Figure 1b). Tides are a mixed type with the highest high tide (HHT) reaching 4 m above lowest astronomical tide (LAT), and mean sea level (MSL) at 1.9 m above LAT (Hart, 2003). Elevations of the eastern area are approximately 2 m above LAT, and those of the deeper reef flat on the west of the island are about 0.5 – 1.0 m lower than the eastern area. Much of the elevated reef flat is exposed for approximately 50% of a tidal cycle whereas the western reef flat experiences continual submergence (Hart, 2003). During the experiment the reef platform was generally inundated during higher high tides (around noon) and lower high tides (around midnight) whereas during lower low tides (in the early morning) and most of higher low tides (in the afternoon) when tidal levels were below the major part of the reef platform, the reef platform was mostly exposed.

Warraber Island is a vegetated sand cay that has formed at the western, leeward end of the Warraber reef platform (Figure 1c) and has accreted incrementally along its southern margin over the past 3000 years (Woodroffe et al., 2007). It is oval in shape, approximately 1500 m long in the southwest-northeast orientation and approximately 920 m wide in the northwest-southeast orientation.

Wind data were measured twice a day on the windward side of the island during 25 – 28 November 2004. Wind speed was measured at a height of approximately 1.70 m above ground level, using a Kestrel 1000 pocket anemometer and converted to a standard 10 m level (based on CERC, 1984). Wind directions were estimated using a magnetic compass measuring the direction of the long ribbon attached to a wooden stick fixed on the beach. Atmospheric pressure was recorded using a baroTROLL installed at the airfield on the island and used for atmospheric-pressure correction of pressure data obtained from a miniTROLL and a Dobie pressure sensor.

Water pressure recorders were deployed on five transects within the nearshore zone around the island (RT4, RT6, RT5, RT1 and GZB) and one location on the reef flat close to the reef edge (RF) (Figure 1c). The pressure-type wave recorders included a NIWA Instrument System “Dobie”, an InterOcean S4DW wave-current meter, a Nortek Acoustic Doppler Velocimeter (ADV) “Vector”, two miniTROLL pressure sensors and a hardwired KPSI pressure recording system (Table 1). The KPSI includes three pressure sensors (KPSI01, KPSI02 and KPSI03) deployed together along a transect. All instruments are standalone units except the KPSI pressure sensors connected to the control unit on shore for power supply and data acquisition.

Due to the limited number of wave meters, different configurations of instrument deployments were chosen so that the distinct wave environments anticipated around the island were simultaneously recorded. In addition, more than one piece of equipment was deployed along a transect in order to investigate spatial variations of wave characteristics from the nearshore towards the island. An instrument position is indicated using a location code consisting of the transect number and distance of the instrument from the island shoreline. For example, the location code “RT6-30” means the instrument was installed at the transect RT6, approximately 30 m away from the island shoreline. Configurations of instrument deployments are illustrated in Figure 3 and details of the instrument locations are presented in Table 2.

Safety and accessibility issues precluded equipment deployment off the reef. Therefore, the Dobie pressure sensor was installed close to the eastern end of the reef flat (RF), about 100 m from the reef edge (Figure 1c), in order to capture the patterns of waves as close to those of the incident waves as possible. Derivation of the spectral peak of incident waves off the reef from the spectra of waves at RF is described in Section 4.

3. Data and Methods

The Dobie measured data in bursts of 1,024 s (~ 17 min) every 30 min at a sampling rate of 2 Hz. The S4, with a sampling rate of 5 Hz, collected data in bursts of 18 min every 30 min. The S4 5 Hz data were linearly decimated to 4 Hz (following procedures in Stearns and David, 1993), in order that in a 1024-s time series of data there were 2^n data points, as required for the algorithm used in wave spectral analysis. The Vector has a sampling rate of 8 Hz and recorded data in bursts of 18 min every 30 min. Only the first 1024-s component within a burst of the Vector data was used for analysis. The miniTROLL and the KPSI measured data continuously with a sampling rate of 2 Hz and 8 Hz, respectively. The miniTROLL and the KPSI data were subsequently separated into a 1024-s time series every 30 min. The data from the KPSI was only collected during daytime. A collection of 1024-s time series of water pressure obtained from the sensors every 30 min was used for subsequent wave spectral analysis. Time series of pressure signals from those sensors, that are characterised mainly by flat regions, generally occurring during very low water levels, were excluded from analysis.

FORTTRAN programs were developed for spectral analysis based on the fast Fourier transform (FFT) algorithm. The procedures adopted for spectral analysis are primarily those recommended by Bendat and Piersol (1986). A trend was observed, which is attributed to tide level, and a polynomial of degree 3 was deployed to detrend the records following Borse (1991). The 4-standard deviation criterion was used to remove outliers and resulting gaps were filled by interpolation using the data at both ends of the gaps. The segment-averaging technique with 50% overlapping was used in order to reduce the variance of the spectral estimates (Bendat and Piersol, 1986). With 50% overlap, the time series of 1,024 s were divided into 15 segments of 128 s, giving a spectrum having 30 degrees of freedom and a frequency resolution, Δf of 0.0078 Hz. Spectral leakage was suppressed using a Hanning

window. Fourier coefficients were computed from detrended and tapered data using the FFT algorithm (Swarztrauber and Pumphrey, 1985). A value of $(8/3)^{0.5}$ was applied to each coefficient to compensate for the loss of the variance due to the Hanning tapering. The spectral estimates were obtained from averaging the spectral components over 15 segments.

The energy spectrum obtained at this stage of the wave spectral analysis was the spectrum of water depth measured by a pressure transducer. A pressure-type wave recorder is normally subject to attenuation of wave action with depth. To compensate for this and to convert pressure records to surface waves, a transfer function, K_p , is applied and high-frequency cutoff is determined in order to prevent amplifying noise at high frequency regions (NortekUSA, 2002).

K_p based on linear wave theory is generally found to be reasonable except in shallow water where effects of nonlinear waves and currents become more dominant (Lee and Wang, 1984). An empirical correction factor, N , is generally applied to K_p to account for the difference between theory and observation (Bishop and Donelan, 1987). Bishop and Donelan (1987) indicate that N is normally greater than 1 for longer-period spectral components and less than 1 for shorter-period spectral components. Knowles (1983) recommended N derived by Grace (1978) for shallow and closed restricted-fetch estuaries or lagoons which are dominated by waves with periods generally less than 4 sec. In this study, N was not evaluated and consequently the equations of N determined by Grace (1978) were adopted here. According to visual inspection of the wave spectra, NK_p with its maximum value of 10 was appropriately applied to convert pressure spectra to surface wave spectra. The frequency cut-off was determined at the value of the relative depth of 0.7. Areas between the cutoff frequency and 1.0 Hz were extrapolated using a high-frequency f^5 tail (Young and Verhagen, 1996).

Wave parameters were calculated from the wave energy spectra, including the significant wave height H_{mo} , the peak wave period T_p and the mean wave period T_1 . They are defined as (Tucker, 1991):

$$H_{mo} = 4\sqrt{m_0} ; \quad T_1 = \frac{m_0}{m_1} ; \quad \text{Where } m_p = \sum f^p S(f) df$$

The spectral peak T_p was derived from $T_p = 1/f_p$ where f_p is defined as (Mansard and Funke, 1991):

$$f_p = \frac{\int f S^5(f) df}{\int S^5(f) df}$$

A wave spectrum is divided into 4 different frequency ranges: i) incident short-period wave frequencies of 0.4-1.0 Hz (2.5-1.0 s); ii) incident wind wave frequencies of 0.125-0.4 Hz (8.0-2.5 s); iii) incident swell wave frequencies of 0.05-0.125 Hz (20.0-8.0 s); and iv) infragravity wave frequencies of less than 0.05 Hz (greater than 20 s). The calculation of wave energy was also done from wave spectra for both the whole spectral components and each frequency range defined above.

4. Wave Environments off the Reef

Studies of wave transformation on a coral reef on the Great Barrier Reef (Hardy and Young, 1996), in Hawaii (Lee and Black, 1978) and at sites in the Caribbean Sea (Lugo-Fernandez et al., 1998; Roberts et al., 1975) indicated that the frequency of the spectral peak of waves on a reef maintains that of waves off the reef, even when wave spectra become broader as a result of energy dissipation and energy transfer. Hardy and Young (1996) found that when T_p of incident waves is less than 5.0 s, there is close similarity between T_p both off and on the reef, and when T_p of incident waves is greater than 5.0 s, T_p of waves on the reef flat is slightly shorter. In addition, at Tague Reef, St. Croix, in the US Virgin Islands, Roberts (1989) found that the reef is a more efficient filter for high-frequency waves and only the low-frequency peaks of the forereef spectra persist in the backreef. Therefore, T_p of waves off

Warraber Reef could be deduced from T_p derived from wave data at RF, during high tides when water depth has less influence on waves on the reef.

The plot of T_p in Figure 4b indicates that waves at RF were generally dominated by incident wind-wave frequencies except during low water level when infragravity wave frequencies were dominant. Accordingly, wave environments off Warraber Reef during the experiment were predominantly characterised by seas, which are wind waves under the influence of local wind conditions. According to the variation of H_{mo} and T_p in Figure 4, two events related to wave energy are arbitrarily identified, a low wave-energy event during 24-25/11/04 and a high wave-energy event during 26-29/11/04. Therefore, T_p was approximately 4.0 s during low wave-energy events and 6.0 s during high wave-energy events. These energy events are also used to describe wave environments around the island.

The relationship between wind speeds and variations of wave characteristics at RF, as illustrated in Figure 5, also suggests that such sea conditions predominate off Warraber Reef. In Figure 5, at the same water depth over the period of the experiment, values of H_{mo} and T_p were not constant but tended to increase and peak approximately between 27-28/11/04, similar to a trend of wind-speed variations. This supports the finding above that wave conditions at RF are primarily influenced by seas which are directly driven by local wind patterns.

In areas where seas are dominant, swell is more likely to be apparent when the energy of seas is small. Therefore, a good time to check if swell is present is when wind is light and water level is high. Figure 6 shows wave spectra at a higher high tide during low wave energy. During the low wave-energy event at a higher high tide, very low swell energy was observed with periods of approximately 8.0 s which persisted until water depth was below approximately 0.5 m (Figure 6a). It is also noted that as wave energy increased, swell wave components were less clear and infragravity wave components became more obvious (Figure

6b). During the high wave-energy event, a swell component was not evident. Therefore, it can be concluded that the influence of swell waves on the wave environment off the reef is negligible, particularly during high wave-energy events.

Most energy found within a swell frequency range in Figure 6b is probably not contributed by incident swell waves but rather energy transferred across the spectrum from spectral peaks (incident wind wave components) to infragravity wave components which develop during the time that incident waves move onto the reef (Gerritsen, 1980). At RF, energy transfer to lower frequency components is observable particularly during low water level, causing the spectra to become broader and increasing T_p (Figure 4b).

5. Wave Environments around the Island

In Section 4, the swell wave components were found to be very small and only discernible during low wave-energy events. Most energy contained within a swell frequency range, in particular during high wave-energy events, is likely attributed to energy transferred from incident wind waves to infragravity waves. Therefore, it is reasonable in this study to extend the higher frequency limit for infragravity waves. A previous study by Bauer (1990) suggested higher frequencies for the higher frequency limit of infragravity waves for areas where incident waves are fetch-limited and their frequencies are short. As described above, sea, not swell, dominated the wave environment off Warraber Reef during the experiment. In addition, the physiography of the reefs that occur throughout Torres Strait (Figure 1b) and persistent ESE winds during the experiment imply probable fetch-limited conditions for sea generation in this region. In this section, therefore, energy occurring within a swell wave frequency range is included as part of the infragravity wave range.

5.1 Low Wave-Energy Events

On 24/11/04 wave information was obtained from 4 locations along transect RT4 (RT4-80, RT4-44, RT4-20 and RT4-6), 2 locations along transect RT5 (RT5-114 and RT5-34) and

one location on transect RT6 (RT6-27) (Figure 3a). The maximum values of H_{mo} occurred at RT4-80 which was more exposed to the ESE wind occurring during the experiment (Figure 7a). Smaller values of H_{mo} were observed at three shoreward locations along transect RT4 (RT4-44, RT4-20 and RT4-6). Values of H_{mo} along transect RT5 (from RT5-114 to RT5-34), located on the leeward side, were relatively constant and very close to those at RT4-44, RT4-20 and RT4-6. The lowest values of H_{mo} occurred on the leeward side at RT6-27, with a maximum value of approximately 0.08 m.

On 25/11/04, the instruments on transects RT5 and RT6 remained in the same positions whereas the 4 pressure sensors were moved from transect RT4 to record data along transect RT1, which is on the windward side; they were placed at about 144, 44, 14 and 3 m from the island (Figure 3b). According to values of H_{mo} on transects RT5 and RT6, waves on 25/11/04 were slightly higher than those on 24/11/04. Relatively constant values of H_{mo} occurred along transects RT1 and RT5 (Figure 8a). Waves on transect RT1 were higher than those on transect RT5, with the highest value of approximately 0.25 m, and waves on transect RT6 were found to be the smallest with a maximum value of approximately 0.12 m.

Waves at all locations on the windward side (RT4) on 24/11/04 had a similar value of T_l (Figure 7b). Values of T_l across the leeward locations (RT5) were also found to be relatively constant, equivalent to those on transect RT6 and slightly greater than those at RT4. For example, a value of T_l of approximately 2.0 s occurred on transects RT5 and RT6 whereas values of approximately 1.7 s were observed along transect RT4. Waves on 25/11/04 had a similar pattern of spatial variations of T_l (Figure 8b). T_l of around 2.0 – 2.5 s on transects RT5 and RT6 was slightly longer than that on transect RT1 (approximately 1.5 s).

In summary, during low wave-energy events, wave characteristics varied little across the nearshore, but waves were shorter and larger at locations exposed to wind (RT4 and RT1) than at locations on the leeward sides (RT5 and RT6). This spatial variation of wave

characteristics is attributed to the different magnitude of energy contribution from different wave frequency ranges. At the windward locations (RT4 and RT1), wave energy was dominated by the incident short-period wave range (80-90%) (Figures 7h and 8h). This relative energy contribution was found to remain almost constant across the nearshore. Sample spectra on transects RT4 and RT1 show prominent peaks over the incident short-period wave range (Figures 9a, b, c and d, and 10d, e, f and g). At the leeward locations (RT5 and RT6), waves contained less of the incident short-period wave energy (50-80%) (Figures 7h and 8h), and greater percentages of the incident wind wave energy (20-50%) (Figures 7f and 8f). Sample spectra on transects RT5 and RT6 indicate less pronounced peaks over the incident short-period wave components (Figures 9e, f and g, and 10a, b and c). During these low wave-energy events, the infragravity wave energy was very small, less than 5% of total wave energy (Figures 7d and 8d).

5.2 High Wave-Energy Events

On 26/11/04, the deployment of instruments was the same as that on 25/11/04, except that no data were recorded from the most seaward location on transect RT1 (RT1-114). During this higher energy event, H_{mo} varied slightly (less than 0.05 m) across the windward (RT1) and the leeward (RT5) transects (Figure 11a). Waves at all locations on transect RT1 were greater than those on transect RT5, and waves were smallest on transect RT6 (Figure 11a). On the other hand, T_I showed an increase along both the windward and leeward transects (Figure 11b). T_I on the windward side during the peak of a higher high tide increased from approximately 2.2 s at RT1-44 to approximately 2.3 s at RT1-14 and to approximately 2.6 s at RT1-3, and on the leeward side increased from around 2.7 s at RT5-114 to around 3.0 s at RT5-34 which was equal to that at RT6-27 (Figure 12).

The increase in H_{mo} and T_I on 26/11/04 was attributed to an increase in wave energy not only over the incident short-period wave components that were dominant during the low

wave-energy events, but also over the incident wind wave and infragravity wave components. This is clearly seen on the spectra, particularly at the windward locations (RT1), which exhibit three clearly separated peaks representing the infragravity wave, incident wind wave, and incident short-period wave components (Figure 12).

During this high wave-energy event, the relative energy of the incident wind waves at the windward locations (RT1) (Figure 11f) was comparable to that of the incident short-period waves (Figure 11h). Both wave ranges contributed up to 80% of wave energy. However, the relative energy of these two wave components altered along the transect towards the island. The relative energy of the incident wind waves increased approximately 10% along the transect whereas a decrease of approximately 20% was observed in the incident short-period waves. On the other hand, incident wind wave energy was dominant at the leeward locations (RT5 and RT6), accounting for relative energy of approximately 50 – 60%, and increased slightly shoreward (Figure 11f). The relative energy contributed by infragravity waves increased from less than 5% on 25/11/04 to around 10 – 20% on 26/11/04 and showed a shoreward increase, which was more evident at the windward locations (Figure 11d).

On 27/11/04, the 3 sensors deployed on transect RT1 (RT1-44, RT1-14 and RT1-3) were relocated to transect GZB which was also on the windward side. The sensors were positioned on the mid beach (GZB-B), and at about 4 m (GZB-4) and 35 m (GZB-35) from the shoreline. The instrument at RT5-34 was relocated to RT5-14 and the instrument at RT6-27 was installed on the mid beach on transect RT5 (RT5-B) (Figure 3c). This configuration of instruments was deployed for two days (27-28/11/04) to examine the spectral characteristics of these two different wave environments. According to visual observations, waves on transect GZB on the windward side of the island were steeper and larger, and broke with greater intensity whereas waves on transect RT5 which is on the leeward side of the island were calmer and characterised by more regular shape and smaller size.

Wave characteristics on 27/11/04 and 28/11/04 showed a similar pattern of variation. Values of H_{mo} at the windward locations (GZB) were almost constant across the nearshore, with approximately 0.40 m around the peak of a higher high tide (Figures 13a and 14a). On the other hand, values of H_{mo} at the leeward locations (RT5) reduced between RT5-114 and RT5-14, and remained stable from RT5-14 to RT5-B. During the peak of a higher high tide, H_{mo} decreased from approximately 0.3 m at RT5-114 to about 0.2 m at RT5-14 and RT5-B (Figures 15a, b and c). Generally, H_{mo} on transect GZB was higher than that on transect RT5 (Figures 13a and 14a).

During these high wave-energy events, an increase in T_I towards the island occurred on both the windward (GZB) and leeward (RT5) sides but was more evident on the leeward side (Figures 13b and 14b). These patterns of T_I variations were attributed primarily to a combination of increased infragravity wave energy (Figures 13d and 14d) and decreased incident short-period wave energy (Figures 13h and 14h) towards the island. In general the relative energy contribution from the incident wind waves and the incident short-period waves was comparable on the windward side (GZB) but the relative energy contribution from the incident wind wave energy on the leeward side (RT5) was greater and increased towards the island (Figures 13f and 14f). This distinction in relative energy from different frequency ranges was recognised on spectra, with clear peaks evident in incident short-period frequency at locations on the windward side (RT1 and GZB) (Figures 15d, e and f, and 16d, e, f and g) but almost absent in incident short-period frequency at the leeward locations (RT5-14 and RT5-B) (Figures 15a and b, and 16a and b).

It can be clearly seen that wave characteristics around Warraber Island were strongly related to water depth on the reef. H_{mo} at all locations increased with depth. At low tide the reef flat was exposed, whereas H_{mo} at all locations was small and tended to exhibit similar values during shallow water depths. In contrast, different patterns of T_I variation over a tidal

cycle were observed. T_1 exhibited a slight change, particularly on transects RT4 and RT5 during low wave-energy events (Figures 7b and 8b), a decrease with depth, such as those on the beach on the leeward side (RT5-B in Figures 13b and 14b), or an increase with depth, like those at seaward locations (GZB-35 and RT5-114 in Figures 13b and 14b).

In summary, wave environments around the island can be broadly divided into the windward and leeward sides. Waves at windward locations are shorter and larger while waves at leeward locations are longer and smaller. Spatial variations in wave characteristics across the nearshore are negligible during the low wave-energy events but became more pronounced during the high wave-energy events. An increase in wave period towards the island is recognised and more evident on the leeward side. In contrast, wave height on the windward side changes slightly towards the island whereas a significant reduction in wave height occurs towards the island on the leeward side.

6. Development of Spectral Components around the Island

6.1 Incident Wind Wave Components

Results presented in the previous section demonstrated that incident wind waves are one of the main components of waves around the island. The results showed that their magnitude is strongly related to water depth on the reef (Figures 7e, 8e, 11e, 13e and 14e) and appeared to increase with the total wave energy, being prominent during the high wave-energy events (Figures 11f, 13f and 14f). However, their origin has not been determined. The origin of this wave range can be investigated by comparing wave spectra at locations around the island with those at RF which represented the wave environment off the reef (Figure 17). In Figure 17, it can be seen that peaks over incident wind wave frequencies at locations around the island correspond with spectral peaks at RF on the windward reef crest, implying that the energy of the incident wind waves around the island was primarily driven by incident waves from off Warraber Reef.

As demonstrated in Section 4, wave fields off the reef were dominated by seas, suggesting that their directions of propagation primarily follow the local wind directions which were persistent from the ESE during the experiment. However, wave analysis results shown in Figures 7e, 8e, 11e, 13e and 14e indicated that there was incident wind wave energy at all measurement locations around the island and higher energy of this wave range was even observed at the leeward locations (RT5) during the low wave-energy events (Figures 7e and 8e). In addition, comparison of the incident wind wave energy at RF and at the leeward location (RT5-114) shown in Figure 18a indicated that the relative energy at the leeward location increased with a decreased water depth and the relative energy at the leeward location rose to more than 100% during very low water depth. This higher relative energy at RT5-114 means that there is more incident wind wave energy reaching this location than reaching RF and is attributable to the fact that the reef flat at transect RT5 is lower than the eastern reef flat, where the Dobie pressure sensor was installed (RF). When the eastern part of the reef flat is emerged during the lower tides, waves can still propagate across the western side of the reef flat, which is still submerged. This relative energy at RT5-114 implies that incident wind wave components reach the leeward side of the island by wave refraction and diffraction on the western reef rim. Wave refraction along the northern reef rim is also shown in a georeferenced aerial photograph taken on 02/08/1981 (Figure 19) when ESE and SE winds were prevalent, according to wind data from a meteorological station on Thursday Island (its location indicated in Figure 1b). These results confirmed the influence of waves from off reefs on reef-island morphodynamics through wave refraction and diffraction, which has been inferred in the scientific literature, but rarely demonstrated.

As waves propagate across the reef platform from the reef rims to the island, their energy is likely to be attenuated as a result of bottom friction as shown by Brander et al. (2004). The attenuation of wave energy influenced by incident waves off Warraber Reef can

be estimated based on a reduction in incident wind wave energy from RF to the locations on the windward side of the island (GZB in Figure 18b and RT1 in Figure 18c). The attenuation of incident wind wave energy was approximately 70-80% increasing to 90% when water depth decreased.

A reduction in the incident wind wave energy across the nearshore toward the island was evident during high wave energy (Figures 11e, 13e and 14e). As mentioned above, the energy of these frequency ranges is strongly influenced by water depth on the reef. The energy reduction of the incident wind waves across the nearshore can be attributed to both the bottom friction and decreased water depth towards the island (Table 2). However, an increase in the incident wind wave energy was also observed, particularly at the most shoreward locations (GZB-B, RT1-3 and RT5-B). This increased energy was probably accentuated by the shoaling effect as waves moved to shallower water.

6.2 Infragravity Wave Components

Normally, infragravity waves develop as a result of energy transferred from spectral peaks when waves shoal (Kofoed-Hansen and Rasmussen, 1998). The results of island wave analysis in the previous section have indicated that the magnitude of the infragravity wave energy at locations around the island increased with the incident wind wave energy and total wave energy.

During the low wave-energy events (24-25/11/04) when the incident short-period wave energy was dominant, no infragravity wave components have amplitudes comparable to those of the spectral peaks in the incident short-period waves (Figures 9 and 10). On the other hand, during the high wave-energy events (26-28/11/04), peaks over the incident wind wave components were pronounced and amplitudes of infragravity wave components were similar to those of the incident wind wave and incident short-period wave components (Figures 12, 15 and 16). In addition, the infragravity wave components at the windward locations (RT4,

RT1 and GZB) contained more energy than those at the leeward locations (RT5 and RT6) (Figures 7c, 8c, 11c, 13c and 14c). This direct relationship between infragravity waves and incident wind waves is similar to that found on coastal beaches where infragravity waves grow with offshore wave height (Komar, 1998).

The infragravity wave components also exhibited an increase in amplitude across the nearshore towards the island which was more evident at the windward locations (RT4, RT1 and GZB) (Figures 7c, 8c, 11c, 13c and 14c). The increase in infragravity energy across the nearshore is similar to that occurring across a sandy mainland shoreface where it may be attributed to the presence of edge waves which are a type of infragravity wave (Komar, 1998; Ruessink, 1998).

6.3 Incident Short-Period Wave Components

The main components of waves in the open ocean and coastal areas are sea, swell, or a combination of both. However, incident short-period waves were found in this study to be the important components of waves around the island on this reef platform. They were particularly prominent at locations that were exposed to winds. In addition, their energy exhibited an increase when water depth increases (Figures 7g, 8g, 11g, 13g and 14g). Based on their spectral peaks, together with relationships between their energy and winds, and water depth on the reef, these waves are likely generated locally on the reef platform in response to local wind conditions. The origin and development of the waves can be investigated using data measured at locations in the nearshore around the island.

Development of wind waves in shallow water is fundamentally a function of fetch, wind speed, wind duration and water depth (CERC, 1984). The focus of this paper is on the development of incident short-period waves at specific locations around the island, so the role of fetch across the reef flat is not central to this investigation. It is also reasonable to assume that the wind duration was not a limiting factor based on wind data recorded during the

experiment. Therefore, development of the incident short-period waves was investigated compared against wind speed and water depth. Data used for the investigation were selected from the windward locations (RT1 and GZB) of the island in order to correctly estimate wave characteristics under the influence of the southeasterly wind on the reef.

Development of incident short-period wave portions of the spectra at the windward side of the island was found to be dependent on water depth on the reef flat (Figure 20a) and wind speed (Figure 20b). At constant mean wind speed, the energy of incident short-period waves increases as water depth increases, with a shift of peak frequencies to lower ones. At constant water depth, an increase in wind speed gives rise to an increase in incident short-period wave energy and a decrease in peak frequencies as well.

Further analysis was carried out to examine whether the development of the incident short-period wave characteristics (H_{mo} and T_p) derived from incident short-period wave portions of the spectra at the windward side of the island can be estimated by simplified wave models. The equations of Young and Verhagen (1996) are adopted here for comparing with the field data because they have been developed based on the comprehensive study of fetch-limited and finite depth wave growth. In addition, the equations use U_{10} , which is wind speed measured at a standard height of 10 m above ground and generally available from meteorological stations, instead of wind-stress factor, U_A , that requires the information on air-sea temperature differences for conversion from U_{10} .

Curves of H_{mo} and T_p according to the equations of Young and Verhagen (1996) are presented in Figure 21 in conjunction with H_{mo} and T_p derived from the field data. A curve of H_{mo} was calculated from their equation of non-dimensional wave energy, ε , according to $\varepsilon = g^2 E / U_{10}^4$ and $H_{mo} = 4(E)^{0.5}$ where E is dimensional wave energy. A curve of T_p was calculated from their equation of non-dimensional peak frequency, v , which equals $f_p U_{10} / g$ where f_p is a peak frequency.

In calculating non-dimensional wave energy, ϵ , and peak frequency, ν , U_{10} has been converted from mean wind speed measured in the field on that day, water depth is averaged depth at the site at the time of calculation, assuming the reef elevation along the fetch is flat, and fetch, estimated distance from the Dobie pressure sensor measured in the ESE direction to the island, is treated as constant at 3,500 m. As mentioned above, the wind duration was assumed to be not limited, lasting long enough for waves to grow along the fetch. Therefore, the fetch is constant for all cases, values of U_{10} change daily and water depth is depth at the time of calculation.

The results shown in Figure 21 indicated that in general the Young and Verhagen's equation overestimates the values of H_{mo} at lower water level and underestimates the values of H_{mo} at higher water level, particularly during low-energy events. The Young and Verhagen's equation and the data show similar values of T_p during low wave-energy events (Figure 21b1). However, during high-energy events the equation overestimates the values of T_p , and T_p from the equation and from field data during flooding showed a similar trend (Figures 21b2, b3 and b4). In general, their equations are in a better agreement with H_{mo} than T_p .

The discrepancy between the curves of Young and Verhagen (1996), and the field data probably results from tidal currents, reef-flat topography and bottom friction. The equations were developed based on data from a confined lake with relatively uniform depth and having little bottom friction as on natural beaches. Therefore, no effect of tidal currents was incorporated into equation development. The reef flat across Warraber Reef is actually not flat; the eastern reef flat basically consists of lower backreef areas behind the reef rim and higher emergent areas towards the centre of the platform. Compared to water depth, the difference in elevations on the reef flat may be less significant during high tides but can exert more influence on fetch determination during lower tides, causing fetch to be shorter.

Subsequently, a combination of shorter fetch and shallower water leads to smaller H_{mo} and T_p during low water level. The bottom friction in the reef environment is approximately one order of magnitude greater than that existing on natural beaches, due to a combination of a very rough bottom and very shallow water (Hardy and Young, 1991). More energy is therefore dissipated, causing waves to have smaller H_{mo} and T_p than those calculated using the equations.

As suggested in Section 5, incident waves off Warraber Reef are dominated by seas. These incident waves have been shown in this section to be the main driving force for incident wind wave components on the reef flat. They undergo attenuation as they move across the reef flat towards the island. Therefore, incident wind wave energy becomes smaller from the reef rim towards the island. Growth of infragravity waves around the island is found in the present study to be related to incident wind wave energy on the reef flat. Incident short-period waves that are the main component of wave spectra, especially at windward locations, were demonstrated to be locally generated on the reef platform by the local wind system and their energy probably increases along their fetch across the reef platform. These patterns of wave-component development are depicted in Figure 22. Therefore, it can be concluded that growth of all three wave frequency ranges is related to a local wind system but their magnitude occurs differently around the island depending on locations around the island in relation to the main directional influence of wind, the magnitude of wind speed and reef-top topography, resulting in distinct wave characteristics around the island with potential for differing patterns of sediment movement.

It has generally been assumed that development of sand cays and their stability on platform reefs were determined primarily by the residual energy of waves breaking at the reef crest (Gourlay, 1988). On large reef platforms such waves may lose their capacity to transport sediments before reaching a focusing points towards the leeward of the platform.

However, the findings in this study indicate that on the large Warraber reef platform there are significant proportions of wave energy developed on the reef platform in response to local wind conditions, suggesting that wave capacity to entrain and transport sediments may be maintained both on the reef flat and around the island.

Water depth over the reefs has been suggested as the primary factor influencing wave characteristics on the reef (Hardy and Young, 1996; Lugo-Fernandez et al., 1998; Young, 1989). The influence of water depth on wave characteristics was also observed around Warraber Island, particularly for H_{mo} and energy of the three wave components which increased with depth. This changing pattern of wave characteristics with depth implies that a more energetic wave field can be anticipated in this reef setting under conditions of higher sea level that may occur over longer time scales as a result of global warming. Some studies have suggested that an increase in wave energy due to deeper water over the reef can generate greater erosion, for example on reef islands on atolls (Yamano, 2000) and beaches behind fringing reefs (Sheppard et al., 2005). However, on large reef platforms such as Warraber Reef the ability of waves to transport sediments to sand cays is of far more concern than the effect of waves on erosion (Gourlay, 1988; Hopley, 1992; Hopley et al., 2007).

This study presents the results of wave characteristic examination undertaken during the influence of southeasterly winds. Between December and March this region is dominated by northwesterly winds which are more variable both in direction and speed (Hart, 2003; Hopley et al., 2007). According to primary wind directions during the northwesterly winds, therefore, windward and leeward sides of the island are reversed (RT4, RT6 and RT5 on the windward side, and RT1 and GZB on the leeward side). The windward side of the island over this period is characterised by a submerged reef flat with deeper water and shorter fetch. The short distance and deeper reef flat are likely to result in only a small reduction in wave height across the reef from reef crest towards the island. Little information exists on swell waves in

Torres Strait. The location of Warraber Reef in central Torres Strait, bounded in all directions by reefs, islands and the mainland suggests that any swell waves that may be present in this region at any time of year are likely to be very small. It seems likely that sea dominates the wave environment off Warraber Reef all year round. Incident short-period waves that are generated on the reef flat and important during the southeasterly season, may be negligible on the western reef flat due to the very short fetch and high variation in wind patterns. During the northwesterly season infragravity wave components may contribute significant portions of energy to the wave field around the island due to prominent incident wind waves. Therefore, different combinations of the three main wave components can occur during the northwesterly winds. Waves generated by the northwesterly winds are likely to have significant effects on the sand cay, and their role in influencing island morphodynamics requires further study.

7. Conclusion

A field experiment was conducted at Warraber in order to gain more insight into wave characteristics around a sand cay on a reef platform. Subsurface pressure signals were measured using pressure-type wave recorders at one location on the reef flat close to the reef edge and at 5 locations around the island. Surface wave energy spectra were estimated from subsurface pressure data using FORTRAN programs developed for wave analysis, based on the fast Fourier transform algorithm.

Sea, influenced by local weather conditions, was found to be the primary wave condition in this reef setting. The reef flat is exposed at low tide, but during the upper part of the tidal cycle, two main wave environments were identified around the island: shorter and larger waves on the windward side and longer and smaller waves on the leeward side. Spatial variations of wave characteristics across the nearshore are negligible during low wave-energy events but pronounced during high wave-energy events. This finding indicates that different

parts of the island shore have been modified by distinct wave characteristics, and implies that changes in sand-cay morphology can be related to local environmental influences.

Three main wave components were recognised in this study. Incident short-period wave components, which have not been examined in previous wave-transformation studies on reefs, were found to be very significant. These appear to develop across extensive reef platforms as fetch-limited and depth-limited wind waves, which can be reasonably approximated by simplified wave models. On the other hand, incident waves generated off reef, which have been suggested as the primary force on the reef platforms, have undergone energy attenuation across the reef platform and reach the island as incident wind wave components. Significant infragravity wave components develop across the nearshore towards the island, similar to wave transformations on the sandy shorefaces to mainland beaches, and are related to an increase in incident wind wave energy. These differing patterns of wave-component development imply that waves on large reef platforms may be capable of entraining and transporting sediments both on the reef flat and around the island.

Wave characteristics around Warraber Island were directly controlled by water depth on the reef. Wave height and energy of the three wave components increase with water depth, although wave period showed greater spatial variability. This direct relation between wave energy and water depth suggests that under anticipated higher sea-level conditions in the future more sediment will be entrained and moved, and sand cays on a large platform reef like Warraber Reef are more likely to gain than lose sediment.

Southeasterly winds occurring during the study dominate for much of the year, but there is a period in summer when northwesterly winds are typical and when considerably different wave environments will influence the reef with implications for sediment movement and island shoreline response. This study implies that morphology of sand cays on platform reefs such as those in Torres Strait is influenced by local environmental factors. These findings

also provide significant foundations for further research to examine sediment transport processes and in turn changes in sand-cay morphology.

Acknowledgement

This research was funded by the Australian Research Council (A00103066). Research on Warraber Island was supported by the Warraber Island Council. We thank Kevin Parnell, Deirdre Hart and Kristy van Putten for assistance in the field.

References

- Bauer, B.O., 1990. Assessing the relative energetics of infragravity motions in lakes and seas. *Journal of Coastal Research* 6, 853-865.
- Bendat, J.S., Piersol, A.G., 1986. Random data: analysis and measurement procedures. John Wiley & Sons, Inc., Canada, 566 pp.
- Bishop, C.T., Donelan, M.A., 1987. Measuring waves with pressure transducers. *Coastal Engineering* 11, 309-328.
- Borse, G.J., 1991. FORTRAN 77 and numerical methods for engineers. PWS-KENT Pub. Co., Boston, 722 pp.
- Brander, R.W., Kench, P.S., Hart, D., 2004. Spatial and temporal variation in wave characteristics across a reef platform, Warraber Island, Torres Strait, Australia. *Marine Geology* 207, 169-184.
- CERC, 1984. Shore Protection Manual v.1, U.S. Army Coastal Engineering Research Center, Vicksburg.
- CERC, 1993. Wave attenuation over reefs. CETN I-56, U S Army Engineer Waterways Experiment Station, Vicksburg.
- Flood, P.G., 1986. Sensitivity of coral cays to climatic variations, southern Great Barrier Reef, Australia. *Coral Reefs* 5, 13-18.

- Gerritsen, F., 1980. Wave attenuation and wave set-up on a coastal reef. Proceedings of the 17th International Coastal Engineering Conference, Sydney, Australia, pp. 444-461.
- Gourlay, M.R., 1988. Coral cays: products of wave action and geological processes in a biogenic environment. Proceedings of the 6th International Coral Reef Symposium, Townsville, Australia, pp. 491-496.
- Gourlay, M.R., 1990. Waves, set-up and currents on reefs cay formation and stability. Engineering in Coral Reef Regions Conference, Magnetic Island, Townsville, pp. 163-178.
- Gourlay, M.R., 1994. Wave transformation on a coral reef. *Coastal Engineering* 23, 17-42.
- Gourlay, M.R., 1996a. Wave set-up on coral reefs. 1. Set-up and wave-generated flow on an idealised two dimensional horizontal reef. *Coastal Engineering* 27, 161-193.
- Gourlay, M.R., 1996b. Wave set-up on coral reefs. 2. Set-up on reefs with various profiles. *Coastal Engineering* 28, 17-55.
- Grace, R.A., 1978. Surface wave heights from pressure records. *Coastal Engineering* 2, 55-67.
- Hardy, T.A., Young, I.R., 1991. Modelling spectral wave transformation on a coral reef flat. 10th Australasian Conference on Coastal and Ocean Engineering, Auckland, New Zealand, pp. 345-350.
- Hardy, T.A., Young, I.R., 1996. Field study of wave attenuation on an offshore coral reef. *Journal of Geophysical Research-Oceans* 101, 14311-14326.
- Hart, D.E., 2003. Eco-sedimentological environments of an inter-tidal reef platform, Warraber Island, Torres Strait. Unpublished PhD Thesis, University of New South Wales, Australia, 210 pp.
- Hopley, D., Smithers, S.G., Parnell, K.E., 2007. The geomorphology of the Great Barrier Reef: development, diversity and change, Cambridge University Press, Cambridge, 532 pp.

- Hopley, D., 1992. Coral reef islands in a period of global sea level rise, *Recent Advances in Marine Science and Technology* 92, pp. 453-462.
- Kench, P.S., Brander, R.W., 2006. Wave processes on coral reef flats: implications for reef geomorphology using Australian case studies. *Journal of Coastal Research* 22, 209-223.
- Kench, P.S., Brander, R.W., Parnell, K.E., McLean, R.F., 2006. Wave energy gradients across a Maldivian atoll: Implications for island geomorphology. *Geomorphology* 81, 1-17.
- Knowles, C.E., 1983. On the estimation of surface gravity waves from subsurface pressure records for estuarine basins. *Estuarine Coastal and Shelf Science* 17, 395-404.
- Kofoed-Hansen, H., Rasmussen, J.H., 1998. Modelling of nonlinear shoaling based on stochastic evolution equations. *Coastal Engineering* 33, 203-232.
- Komar, P.D., 1998. Beach processes and sedimentation. Prentice-Hall, Inc., New Jersey, 544 pp.
- Lee, D.Y., Wang, H., 1984. Measurement of surface waves from subsurface gauge. Proceedings of 19th Coastal Engineering Conference, Houston, Texas. ASCE, New York.
- Lee, T.T., Black, K.P., 1978. The energy spectra of surf waves on a coral reef. Proceedings of 16th International Coastal Engineering Conference, Hamburg, Germany, pp 588-608.
- Lugo-Fernandez, A., Roberts, H.H., Suhayda, J.N., 1998. Wave transformations across a Caribbean fringing-barrier Coral Reef. *Continental Shelf Research* 18, 1099-1124.
- Mansard, E.P.D., Funke, E.R., 1991. On fitting of JONSWAP spectra to measured sea states. Proceedings of the 22nd Coastal Engineering Conference, New York.
- Massel, S.R., Gourlay, M.R., 2000. On the modelling of wave breaking and set-up on coral reefs. *Coastal Engineering* 39, 1-27.
- Nakaza, E., Tsukayama, S., Hino, M., 1990. Bore-like surf beat on reef coasts. Proceedings of 22nd International Conference Coastal Engineering, Delf, Netherland.

- Roberts, H.H., 1989. Physical processes as agents of sediment transport in carbonate systems: Examples from St. Croix, U.S.V.I. 12th Caribbean Geological Conference, Teague Bay, St. Croix: West Indies Library.
- Roberts, H.H., Murray, S.P., Suhayda, J.N., 1975. Physical processes in a fringing reef system. *Journal of Marine Research* 33, 233-260.
- Roberts, H.H., Wilson, P.A., Lugo-Fernandez, A., 1992. Biologic and geologic responses to physical processes: examples from modern reef systems of the Caribbean-Atlantic region. *Continental Shelf Research* 12, 809-834.
- Ruessink, B.G., 1998. The temporal and spatial variability of infragravity energy in a barred nearshore zone. *Continental Shelf Research* 18, 585-605.
- Sheppard, C.R.C., Dixon, D.J., Gourlay, M.R., Sheppard, A., Payet, R., 2005. Coral mortality increases wave energy reaching shores protected by reef flats: examples from the Seychelles. *Estuarine Coastal and Shelf Science* 64, 223-234.
- Stearns, S.D., David, R.A., 1993. Signal processing algorithms using Fortran and C. P T R Prentice-Hall, Inc., New Jersey, 331 pp.
- Storlazzi, C.D., Ogston, A.S., Bothner, M.H., Field, M.E., Presto, M.K., 2004. Wave- and tidally-driven flow and sediment flux across a fringing coral reefs: Southern Molokai, Hawaii. *Continental Shelf Research* 24, 1397-1419.
- Swarztrauber, P.N., Pumphrey, H.C., 1985. DFFTPACK V1.0. <http://ftp.netlib.org/fftpack/dp.tgz>.
- Tsukayama, S., Nakaza, E., 2000. Wave transformations on coral reefs. Proceedings of 27th International Coastal Engineering Conference, Sydney, Australia.
- Tucker, M.J., 1991. Waves in ocean engineering: measurement, analysis, interpretation. Ellis Horwood, Chichester.

- Wolanski, E., 1994. Physical oceanographic processes of the Great Barrier Reef. CRC Marine Science. CRC Press, Inc., Boca Raton, 194 pp.
- Woodroffe, C.D., Kennedy, D.M., Hopley, D., Rasmussen, C.E., Smithers, S.G., 2000. Holocene reef growth in Torres Strait. *Marine Geology*, 170, 331-346.
- Woodroffe, C.D., Samosorn, B., Hua, Q., Hart, D.E., 2007. Incremental accretion of a sandy reef island over the past 3000 years indicated by component-specific radiocarbon dating. *Geophysical Research Letters* 34, L03602, doi:10.1029/2006GL028875.
- Yamano, H., 2000. Sensitivity of reef flats and reef islands to sea-level change. Proceedings of 9th International Coral Reef Symposium, Bali, Indonesia, pp. 1193-1198.
- Young, I.R., 1989. Wave transformation over coral reefs. *Journal of Geophysical Research-Oceans* 94, 9779-9789.
- Young, I.R., Verhagen, L.A., 1996. The growth of fetch limited waves in water of finite depth .2. Spectral evolution. *Coastal Engineering* 29, 79-99.

Figure captions

Figure 1. Locations of: a) Torres Strait; b) Warraber Reef in Torres Strait; and c) Warraber Island on the leeward end of Warraber reef platform, and locations of wave measurements around the island (RT4, RT6, RT5, RT1 and GZB) and on the reef flat close to the reef edge (RF).

Figure 2. Temporal changes in wind, tides and water depth on the reef during the experiment: a) wind direction; b) wind speed; and c) water depth (h) (—) at RF and tides (---) at Poll Reef (its location shown in Figure 1b).

Figure 3. Configurations of instrument deployments around the island on: a) 24/11/04 0900 – 25/11/04 0700; b) 25/11/04 0900 – 27/11/04 0700; and c) 27/11/04 0900 – 29/11/04 0700. An arrow indicates wind direction during the experiment.

Figure 4. Temporal variations of: a) significant wave height (H_{mo}); and b) peak period (T_p) at RF (--●--); shown together with those of water depth (h) (—) at RF.

Figure 5. Temporal variations of: a) H_{mo} ; and b) T_p , for equivalent water depth at RF, compared with variations of wind speeds (—). Data on H_{mo} and T_p on each line are from the same water depth and only some lines are labelled with water depth due to a limited space. Values of wind speeds are equally reduced so that they can be displayed in the same range of values of H_{mo} and T_p .

Figure 6. Wave spectra at a higher high tide during low wave energy on: a) 24/11/04; and b) 25/11/04, indicating peaks at swell frequencies. Values of wave spectral energy density are plotted using a logarithmic scale so that peaks of swell wave frequencies, which are very small when compared to wind wave components, can be seen.

Figure 7. Temporal variations of: a) H_{mo} ; b) T_I ; c) energy of the infragravity waves; d) relative energy of the infragravity waves; e) energy of the incident wind waves; f) relative energy of the incident wind waves; g) energy of the incident short-period waves; and h) relative energy of the incident short-period waves, at different locations around the island between 24/11/04 0600 (24.25) - 25/11/04 0600 (25.25). Water levels on the reef at RT5-114 (—) are also given in (a). Y-axes in (c), (e) and (g) indicate energy density with a unit of m^2s x 10, and in (d), (f) and (h) indicate percentage of energy (%).

Figure 8. Temporal variations of: a) H_{mo} ; b) T_I ; c) energy of the infragravity waves; d) relative energy of the infragravity waves; e) energy of the incident wind waves; f) relative energy of the incident wind waves; g) energy of the incident short-period waves; and h) relative energy of the incident short-period waves, at different locations around the island between 25/11/04 0600 (25.25) - 26/11/04 0600 (26.25). Water levels on the reef at RT5-114 (—) are also given in (a). Y-axes in (c), (e) and (g) indicate energy density with a unit of m^2s x 10, and in (d), (f) and (h) indicate percentage of energy (%).

Figure 9. Wave spectra at a higher high tide (1100am) on 24/11/04 at: a) RT4-80; b) RT4-44; c) RT4-20; d) RT4-6; e) RT6-27; f) RT5-114; and g) RT5-34. The y-axis indicates energy density with a unit of m^2s .

Figure 10. Wave spectra at a higher high tide (1100am) on 25/11/04 at: a) RT6-27; b) RT5-34; c) RT5-114; d) RT1-3; e) RT1-14; f) RT1-44; and g) RT1-144. The y-axis indicates energy density with a unit of m^2s .

Figure 11. Temporal variations of: a) H_{mo} ; b) T_I ; c) energy of the infragravity waves; d) relative energy of the infragravity waves; e) energy of the incident wind waves; f) relative energy of the incident wind waves; g) energy of the incident short-period waves; and h) relative energy of the incident short-period waves, at different locations around the island between 26/11/04 0600 (26.25) - 27/11/04 0600 (27.25). Water levels on the reef at RT5-114 (—) are also given in (a). No vector data were available on 26/11/04. Y-axes in (c), (e) and (g) indicate energy density with a unit of m^2s x 10, and in (d), (f) and (h) indicate percentage of energy (%).

Figure 12. Wave spectra at a higher high tide (1130am) on 26/11/04 at: a) RT6-27; b) RT5-34; c) RT5-114; d) RT1-3; e) RT1-14; and f) RT1-44. No vector data were available on 26/11/04. The y-axis indicates energy density with a unit of m^2s

Figure 13. Temporal variations of: a) H_{mo} ; b) T_I ; c) energy of the infragravity waves; d) relative energy of the infragravity waves; e) energy of the incident wind waves; f) relative energy of the incident wind waves; g) energy of the incident short-period waves; and h) relative energy of the incident short-period waves, at different locations around the island between 27/11/04 0600 (27.25) - 28/11/04 0600 (28.25). Water levels on the reef at RT5-114 (—) are also given in (a). No vector data were available on 27/11/04. Y-axes in (c), (e) and (g) indicate energy density with a unit of $\text{m}^2\text{s} \times 10$, and in (d), (f) and (h) indicate percentage of energy (%).

Figure 14. Temporal variations of: a) H_{mo} ; b) T_I ; c) energy of the infragravity waves; d) relative energy of the infragravity waves; e) energy of the incident wind waves; f) relative energy of the incident wind waves; g) energy of the incident short-period waves; and h) relative energy of the incident short-period waves, at different locations around the island between 28/11/04 0600 (28.25) - 29/11/04 0600 (29.25). Water levels on the reef at RT5-114 (—) are also given in (a). Y-axes in (c), (e) and (g) indicate energy density with a unit of $\text{m}^2\text{s} \times 10$, and in (d), (f) and (h) indicate percentage of energy (%).

Figure 15. Wave spectra at a higher high tide (1200am) on 27/11/04 at: a) RT5-B; b) RT5-14; c) RT5-114; d) GZB-B; e) GZB-4; and f) GZB-35. No vector data were available on 27/11/04. The y-axis indicates energy density with a unit of m^2s

Figure 16. Wave spectra at a higher high tide (1200am) on 28/11/04 at: a) RT5-B; b) RT5-14; c) RT5-114; d) RT1-144; e) GZB-B; f) GZB-4; and g) GZB-35. The y-axis indicates energy density with a unit of m^2s

Figure 17. Comparison between wave spectra (—) at the peak of a higher high tide (1100am) on 26/11/04 at: a) RT6-27; b) RT5-34; c) RT5-114; d) RT1-3; and e) RT1-44 with a spectrum from the Dobie pressure sensor (—) on the reef flat at RF. The y-axis indicates energy density with a unit of m^2s . Values of wave energy density are plotted using a logarithmic scale due to significant difference in the magnitude between the spectra at RF and those from locations around the island.

Figure 18. Energy of an incident wind wave range ($2.5\text{sec} < T < 8.0\text{sec}$) at: a) RT5; b) GZB; and c) RT1, relative to that of an incident wind wave range at RF.

Figure 19. Georeferenced aerial photograph taken on 02/08/1981, showing wave refraction along the northern reef rim. The location of RT4 is shown.

Figure 20. Spectral growth of incident short-period wave frequencies: a) the same mean wind speed of 8.8 m/s with different water depths (0.55 m (—), 0.72 m (—), 0.95 m (----) and 1.18 m (—)); and b) the same water depth of 1.28 m with different mean wind speed (6.0 m/s (----) and 8.0 m/s (—)). Data are obtained from GZB-35 on 27/11/04 for (a), RT1-44 on 25/11/04 1100 for (b) 6.0 m/s and RT1-44 on 26/11/04 1030 for (b) 8.0 m/s.

Figure 21. Relationships between water depth and H_{mo} (a) and T_p (b) (a1 and b1 at RT1-44 on 25/11/04, a2 and b2 at RT1-44 on 26/11/04, a3 and b3 at GZB-35 on 27/11/04, and a4 and b4

at GZB-35 on 28/11/04) (x=flood, ▲=peak and □=ebb). Also curves of H_{mo} and T_p (—) according to Young and Verhagen (1996) are presented based on fetch = 3500m, and $U_{10}=7.7\text{m/s}$ (a1 and b1), $U_{10}=10.3\text{m/s}$ (a2 and b2), $U_{10}=11.3\text{m/s}$ (a3 and b3) and $U_{10}=11.9\text{m/s}$ (a4 and b4).

Figure 22. Schematic diagram of development of: a) incident short-period waves; b) incident wind waves; and c) infragravity waves, on the reef platform during southeasterly winds.

Tables

Table 1 Instrument deployment during the experiment

Instrument	Sensor type	Number of instruments	Sampling
Kestrel 1000 pocket wind meter	Wind speed	1	-
BaroTROLL	Atmospheric pressure	1	300sec continuous
MiniTROLL pressure sensor (MN)	Water pressure	2	2 Hz continuous
NIWA Instrument Systems “Dobie” (DB)	Water pressure	1	2 Hz, 17.1 min/30 min
Hardwired KPSI pressure recording system (KPSI)	Water pressure	1	8 Hz continuous
Nortek Acoustic Doppler Velocimeter “Vector” (VT)	Water pressure and current	1	8 Hz, 18 min/30 min
InterOcean S4 integrated pressure and current meter (S4)	Water pressure and current	1	5 Hz, 18 min/30 min

Table 2 Details of the instrument locations

Date	Transect	Distance* (m)	Relative depth ** (m)	Location code	Instrument
24-25/11/04	RT4	80	0.61	RT4-80	VT
		44	0.29	RT4-44	KPSI01
		20	0.10	RT4-20	KPSI02
		6	0.00	RT4-6	KPSI03
	RT5	114	0.70	RT5-114	S4
		34	0.55	RT5-34	MN162
	RT6	27	0.57	RT6-27	MN158
25-27/11/04	RT1	144	0.22	RT1-144	VT
		44	0.10	RT1-44	KPSI01
		14	0.05	RT1-14	KPSI02
		3	0.00	RT1-3	KPSI03
	RT5	114	1.18	RT5-114	S4
		34	1.03	RT5-34	MN162
	RT6	27	1.09	RT6-27	MN158
27-29/11/04	GZB	35	0.89	GZB-35	KPSI01
		4	0.76	GZB-4	KPSI02
		On the beach	0.00	GZB-B	KPSI03
	RT1	144	1.01	RT1-144	VT
	RT5	114	1.95	RT5-114	S4
		14	1.52	RT5-14	MN162
		On the beach	0.38	RT5-B	MN158

* from the island shoreline

** based on the shallowest location on that day

Figures

Figure 1. Locations of: a) Torres Strait; b) Warraber Reef in Torres Strait; and c) Warraber Island on the leeward end of Warraber reef platform, and locations of wave measurements around the island (RT4, RT6, RT5, RT1 and GZB) and on the reef flat close to the reef edge (RF).

Figure 2. Temporal changes in wind, tides and water depth on the reef during the experiment: a) wind direction; b) wind speed; and c) water depth (h) (—) at RF and tides (---) at Poll Reef (its location shown in Figure 1b).

Figure 3. Configurations of instrument deployments around the island on: a) 24/11/04 0900 – 25/11/04 0700; b) 25/11/04 0900 – 27/11/04 0700; and c) 27/11/04 0900 – 29/11/04 0700. An arrow indicates wind direction during the experiment.

Figure 4. Temporal variations of: a) significant wave height (H_{mo}); and b) peak period (T_p) at RF (--●--); shown together with those of water depth (h) (—) at RF.

Figure 5. Temporal variations of: a) H_{mo} ; and b) T_p , for equivalent water depth at RF, compared with variations of wind speeds (—). Data on H_{mo} and T_p on each line are from the same water depth and only some lines are labelled with water depth due to a limited space. Values of wind speeds are equally reduced so that they can be displayed in the same range of values of H_{mo} and T_p .

Figure 6. Wave spectra at a higher high tide during low wave energy on: a) 24/11/04; and b) 25/11/04, indicating peaks at swell frequencies. Values of wave spectral energy density are plotted using a logarithmic scale so that peaks of swell wave frequencies, which are very small when compared to wind wave components, can be seen.

Figure 7. Temporal variations of: a) H_{mo} ; b) T_1 ; c) energy of the infragravity waves; d) relative energy of the infragravity waves; e) energy of the incident wind waves; f) relative energy of the incident wind waves; g) energy of the incident short-period waves; and h) relative energy of the incident short-period waves, at different locations around the island between 24/11/04 0600 (24.25) - 25/11/04 0600 (25.25). Water levels on the reef at RT5-114 (—) are also given in (a). Y-axes in (c), (e) and (g) indicate energy density with a unit of $\text{m}^2\text{s}^{-1} \times 10$, and in (d), (f) and (h) indicate percentage of energy (%).

Figure 8. Temporal variations of: a) H_{mo} ; b) T_l ; c) energy of the infragravity waves; d) relative energy of the infragravity waves; e) energy of the incident wind waves; f) relative energy of the incident wind waves; g) energy of the incident short-period waves; and h) relative energy of the incident short-period waves, at different locations around the island between 25/11/04 0600 (25.25) - 26/11/04 0600 (26.25). Water levels on the reef at RT5-114 (—) are also given in (a). Y-axes in (c), (e) and (g) indicate energy density with a unit of $m^2s \times 10$, and in (d), (f) and (h) indicate percentage of energy (%).

Figure 9. Wave spectra at a higher high tide (1100am) on 24/11/04 at: a) RT4-80; b) RT4-44; c) RT4-20; d) RT4-6; e) RT6-27; f) RT5-114; and g) RT5-34. The y-axis indicates energy density with a unit of m^2s .

Figure 10. Wave spectra at a higher high tide (1100am) on 25/11/04 at: a) RT6-27; b) RT5-34; c) RT5-114; d) RT1-3; e) RT1-14; f) RT1-44; and g) RT1-144. The y-axis indicates energy density with a unit of m^2s

Figure 11. Temporal variations of: a) H_{mo} ; b) T_1 ; c) energy of the infragravity waves; d) relative energy of the infragravity waves; e) energy of the incident wind waves; f) relative energy of the incident wind waves; g) energy of the incident short-period waves; and h) relative energy of the incident short-period waves, at different locations around the island between 26/11/04 0600 (26.25) - 27/11/04 0600 (27.25). Water levels on the reef at RT5-114 (—) are also given in (a). No vector data were available on 26/11/04. Y-axes in (c), (e) and (—) are also given in (a). No vector data were available on 26/11/04. Y-axes in (c), (e) and

(g) indicate energy density with a unit of $\text{m}^2\text{s} \times 10$, and in (d), (f) and (h) indicate percentage of energy (%).

Figure 12. Wave spectra at a higher high tide (1130am) on 26/11/04 at: a) RT6-27; b) RT5-34; c) RT5-114; d) RT1-3; e) RT1-14; and f) RT1-44. No vector data were available on 26/11/04. The y-axis indicates energy density with a unit of m^2s .

Figure 13. Temporal variations of: a) H_{mo} ; b) T_l ; c) energy of the infragravity waves; d) relative energy of the infragravity waves; e) energy of the incident wind waves; f) relative energy of the incident wind waves; g) energy of the incident short-period waves; and h) relative energy of the incident short-period waves, at different locations around the island between 27/11/04 0600 (27.25) - 28/11/04 0600 (28.25). Water levels on the reef at RT5-114 (—) are also given in (a). No vector data were available on 27/11/04. Y-axes in (c), (e) and

(g) indicate energy density with a unit of $\text{m}^2\text{s} \times 10$, and in (d), (f) and (h) indicate percentage of energy (%).

Figure 14. Temporal variations of: a) H_{mo} ; b) T_i ; c) energy of the infragravity waves; d) relative energy of the infragravity waves; e) energy of the incident wind waves; f) relative energy of the incident wind waves; g) energy of the incident short-period waves; and h) relative energy of the incident short-period waves, at different locations around the island between 28/11/04 0600 (28.25) - 29/11/04 0600 (29.25). Water levels on the reef at RT5-114

(—) are also given in (a). Y-axes in (c), (e) and (g) indicate energy density with a unit of m^2s x 10, and in (d), (f) and (h) indicate percentage of energy (%).

Figure 15. Wave spectra at a higher high tide (1200am) on 27/11/04 at: a) RT5-B; b) RT5-14; c) RT5-114; d) GZB-B; e) GZB-4; and f) GZB-35. No vector data were available on 27/11/04. The y-axis indicates energy density with a unit of m^2s

Figure 16. Wave spectra at a higher high tide (1200am) on 28/11/04 at: a) RT5-B; b) RT5-14; c) RT5-114; d) RT1-144; e) GZB-B; f) GZB-4; and g) GZB-35. The y-axis indicates energy density with a unit of m^2/s

Figure 17. Comparison between wave spectra (—) at the peak of a higher high tide (1100am) on 26/11/04 at: a) RT6-27; b) RT5-34; c) RT5-114; d) RT1-3; and e) RT1-44 with a spectrum from the Dobie pressure sensor (---) on the reef flat at RF. The y-axis indicates energy density with a unit of m^2s . Values of wave energy density are plotted using a logarithmic scale due to significant difference in the magnitude between the spectra at RF and those from locations around the island.

Figure 18. Energy of an incident wind wave range ($2.5\text{sec} < T < 8.0\text{sec}$) at: a) RT5; b) GZB; and c) RT1, relative to that of an incident wind wave range at RF.

Figure 19. Georeferenced aerial photograph taken on 02/08/1981, showing wave refraction along the northern reef rim. The location of RT4 is shown.

Figure 20. Spectral growth of incident short-period wave frequencies: a) the same mean wind speed of 8.8 m/s with different water depths (0.55 m (—), 0.72 m (—), 0.95 m (----) and 1.18 m (—)); and b) the same water depth of 1.28 m with different mean wind speed (6.0 m/s (----) and 8.0 m/s (—)). Data are obtained from GZB-35 on 27/11/04 for (a), RT1-44 on 25/11/04 1100 for (b) 6.0 m/s and RT1-44 on 26/11/04 1030 for (b) 8.0 m/s.

Figure 21. Relationships between water depth and H_{mo} (a) and T_p (b) (a1 and b1 at RT1-44 on 25/11/04, a2 and b2 at RT1-44 on 26/11/04, a3 and b3 at GZB-35 on 27/11/04, and a4 and b4 at GZB-35 on 28/11/04) (x=flood, ▲=peak and □=ebb). Also curves of H_{mo} and T_p (—) according to Young and Verhagen (1996) are presented based on fetch = 3500m, and $U_{10}=7.7\text{m/s}$ (a1 and b1), $U_{10}=10.3\text{m/s}$ (a2 and b2), $U_{10}=11.3\text{m/s}$ (a3 and b3) and $U_{10}=11.9\text{m/s}$ (a4 and b4).

Figure 22. Schematic diagram of development of: a) incident short-period waves; b) incident wind waves; and c) infragravity waves, on the reef platform during southeasterly winds.