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Geomorphological impacts of high-latitude storm waves on low-latitude reef islands — Observations of the December 2008 event on Nukutoa, Takuu, Papua New Guinea

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ABSTRACT

Low-latitude reefs and reef islands usually experience relatively benign climatic and hydrodynamic conditions due to their location near to the equator, outside of the major storm belts, and they typically exhibit geomorphological traits that reflect the prevailing low-energy conditions. For example, algal ridges are poorly developed, reef flat boulder zones are modest or lacking, rubble banks are rare, and reef islands tend to be low and dominated by sand. Nukutoa is a low-lying triangular-shaped reef island of ~6 ha located on the eastern rim of Takuu atoll (4°45′S, 157°2′E), Papua New Guinea, approximately 300 km northeast of Bougainville. The approximately 450 residents of Takuu all live on Nukutoa. In December 2008 Takuu was struck by several days of very high water levels and waves, which washed completely over approximately 50% of Nukutoa. GPS shoreline mapping and topographic surveys of the island were undertaken in the days immediately prior to the event, and were repeated immediately after. Homes and village infrastructure were damaged during this event, which eroded around 60% of the shoreline, and deposited a sand sheet averaging around 50 mm thick over approximately 13% of the island. This event was generated by two distant storms — one located >6000 km away near 50°N, and affected a wide area of the Western Pacific. Oral histories record at least five similar events since the 1940s. In this paper we document the geomorphic impacts of the December 2008 event and discuss the possible significance of similar events in the past, and in the future.

1. Introduction

Coral reef islands are composed largely of unconsolidated or weakly lithified carbonate sands and gravels produced on adjacent reefs (Stoddart and Steers, 1977; Perry et al., 2011). Most are also low and relatively flat, rising just a few metres above sea level (Woodroffe, 2008; Webb and Kench, 2010). These traits, together with numerous accounts documenting the dynamic nature of reef island shorelines over historical timescales (e.g. Flood, 1986; Kench and Brander, 2006; Rankey, 2011), underpin the widespread perception that they are particularly vulnerable to projected climate and sea-level changes (Nicholls et al., 2007; Simpson et al., 2009; Becker et al., 2012). As sea levels rise and climate and oceanographic regimes change, including the frequency and intensity of cyclones (Bender et al., 2010; Knutson et al., 2010), shoreline erosion, seawater inundation, and salinization of freshwater lenses will be key challenges for reef island ecosystems and inhabitants (Mimura, 1999; Yamano et al., 2007; Woodroffe, 2008). Many reef islands are undoubtedly vulnerable to these impacts. However, differences in elevation, topography, relative sea-level history, and the extent of shoreline modification and or vegetation removal confer varied degrees of resilience (Nunn and Mimura, 1997; Smithers et al., 2007; Woodroffe, 2008). Various researchers stress that reef islands are not static features that will simply drown as sea levels rise but are instead dynamic landforms able to morphologically adjust to changed sea level and climatic regimes (Woodroffe, 2008; Dawson and Smithers, 2010; Webb and Kench, 2010). The diversity of reef island morphologies developed under different hydrodynamic and sediment supply regimes documents their capacity to adjust to a wide range of environmental conditions. The tempo of reef island formation and morphodynamics is similarly a function of varied sediment supply and hydrodynamic regimes, as demonstrated by shifts in shoreline position driven by seasonal monsoon reversals on Maldivian reef islands (Kench and Brander, 2006) and El Niño-Southern Oscillation (ENSO) cycles in Kiribati (Solomon and Forbes, 1999; Rankey, 2011). Although reef islands may morphologically adjust to changing environmental conditions, it must be acknowledged that island habitability may be compromised, especially where sustained reef productivity and modest rates of change are unlikely.

Erosion and deposition normally occur on reef islands under 'average' weather conditions but the often-conspicuous geomorphological impacts of storms on both reefs and reef islands have received particular attention in the literature (e.g. Stoddart, 1962; Maragos et al., 1973; Scoffin, 1993). Although high-energy storms may be destructive in the short term, their

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role in delivering sediment onto the reef flat to be worked shoreward over time, and their importance for reef island construction and maintenance in the storm belts are widely recognised (Maragos et al., 1973; Baines and McLean, 1976). These relationships are incorporated within conceptual models that link reef island geomorphologies and morphodynamics to storm frequency and intensity (Bayliss-Smith, 1988; McLean and Woodroffe, 1994). Significantly, these models portray very different geomorphological development and responses for reef islands exposed frequent high-energy events compared with those rarely affected by severe storms. A key difference is that leeward sand cays tend to erode during storms and recover between events, whereas windward motu dominated by coarser sediments accrete during (or in the years after) storms through the addition of storm-transported clasts and erode during intervening quiescent periods when sediment supply is low. These models are usually based on observations of particular storms passing over or near to affected reef islands (Bayliss-Smith, 1988), or less frequently the influence of unusually persistent and strong trade winds (McLean and Woodroffe, 1994).

The ability of long-wavelength wind-waves or 'swell' generated by extreme mid and high-latitude storms to propagate across entire ocean basins has been long-known (Munk et al., 1963; Collard et al., 2009; Delpey et al., 2010), but the influence of swells generated by distant storms on tropical reefs and islands has received scant attention (see Solomon and Forbes, 1999; Khan et al., 2002 and Hoeke et al., 2013 for rare examples). This is especially true for near-equatorial (between 5°N and 5°S) reef islands located outside the tropical storm belts. Severe storms are rare near the equator, but at decade to century timescales high-energy waves produced by distant extreme events may reach

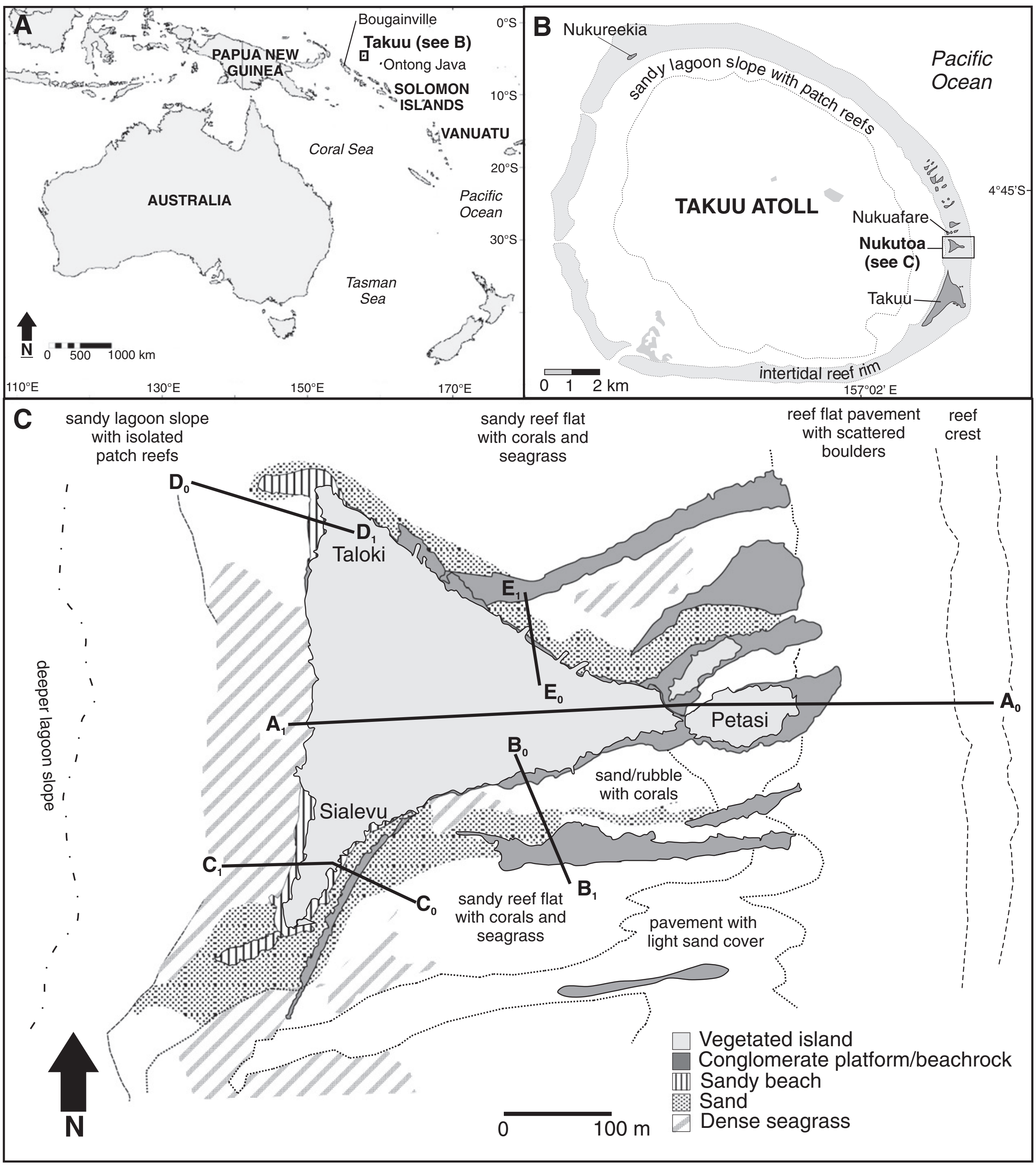

Fig. 1. A) Location of Takuu Atoll; B) Nukutoa on Takuu; C) geomorphological features and locations of topographic transects.

reef islands in this usually low-energy setting. Here we document the geomorphological impacts of several days of large waves affecting Nukutoa, a reef island on Takuu atoll, Papua New Guinea (Fig. 1). Due to its latitude (4°45′S, 157°2′E), tropical cyclones rarely strike Takuu directly. Occurring in early December 2008, this scarcely reported wave event inundated low reef islands and coasts across a broad swath of the western Pacific causing significant shoreline erosion, destruction of crops and water supplies, and infrastructure damage (Fletcher and Richmond, 2010; Hoeke et al., 2013). We conclude that the geomorphological influence of waves generated by distant storms deserves greater consideration in interpretations of reef island formation, and in projections of reef island resilience.

2. Study site

Nukutoa is a reef island on the eastern rim of Takuu (4°45′S, 157°2′E), an isolated atoll located approximately 300 km northeast of Bougainville, Papua New Guinea (Fig. 1). Takuu atoll (also known as the Mortlock Islands, Tauu, and Marqueen) is roughly circular in shape, with the lagoon approximately 12 km from north to south and 14 km from east to west. Nukutoa is one of 15 named islands, with all except Nukureekia located on the east–southeast quadrant of the atoll rim. Nukutoa is triangular in shape and approximately 6 ha in size. Maximum elevation is around 1 m above Highest Astronomical Tide (HAT) but most of the island is less than 0.5 m above HAT (Fig. 2). Observations of erosion scarps, wells and surficial deposits indicate that Nukutoa is predominantly composed of sands with minor gravels. Gravels through to boulders are more abundant on berms on the seaward margin of Petasi, a small islet located only metres off Nukutoa's eastern point (considered part of Nukutoa). As discussed below, natural sedimentary processes and deposits on Nukutoa have been anthropogenically modified, and caution is necessary when interpreting sedimentary features on this and other islands on the atoll. Nukutoa is the only inhabited island on Takuu, with the population increasing from around 100 in the mid-1800s (Moyle, 2003) to 491 in September 2002 (Bourke and Betitis, 2003). This is relevant to the geomorphology of Nukutoa as population increase has caused land shortages, and led islanders to create new land by building seawalls over beaches and backfilling with rubbish, sand and coral gravels collected (mostly) from the adjacent reef flat. Almost everywhere that seawalls have been built the beach in front has been lost or substantially diminished. In November 2008 45% of the Nukutoa's shoreline was protected by seawalls of different types or armoured with vegetative debris (Fig. 3). Of the remaining 55%, approximately one third was on Petasi (where no one lives), and one third was conspicuously eroded or scarped. Just over 13% of the entire shoreline comprised 'natural' (but probably retreating) beaches that extend from the vegetation line to reef flat. These beaches are restricted to the northern (Taloki) and southern (Sialevu) lagoonward ends of the island.

The reef crest is 180 m east of the most seaward part of Nukutoa (Petasi), and consists of a broad algal surface at about the same elevation

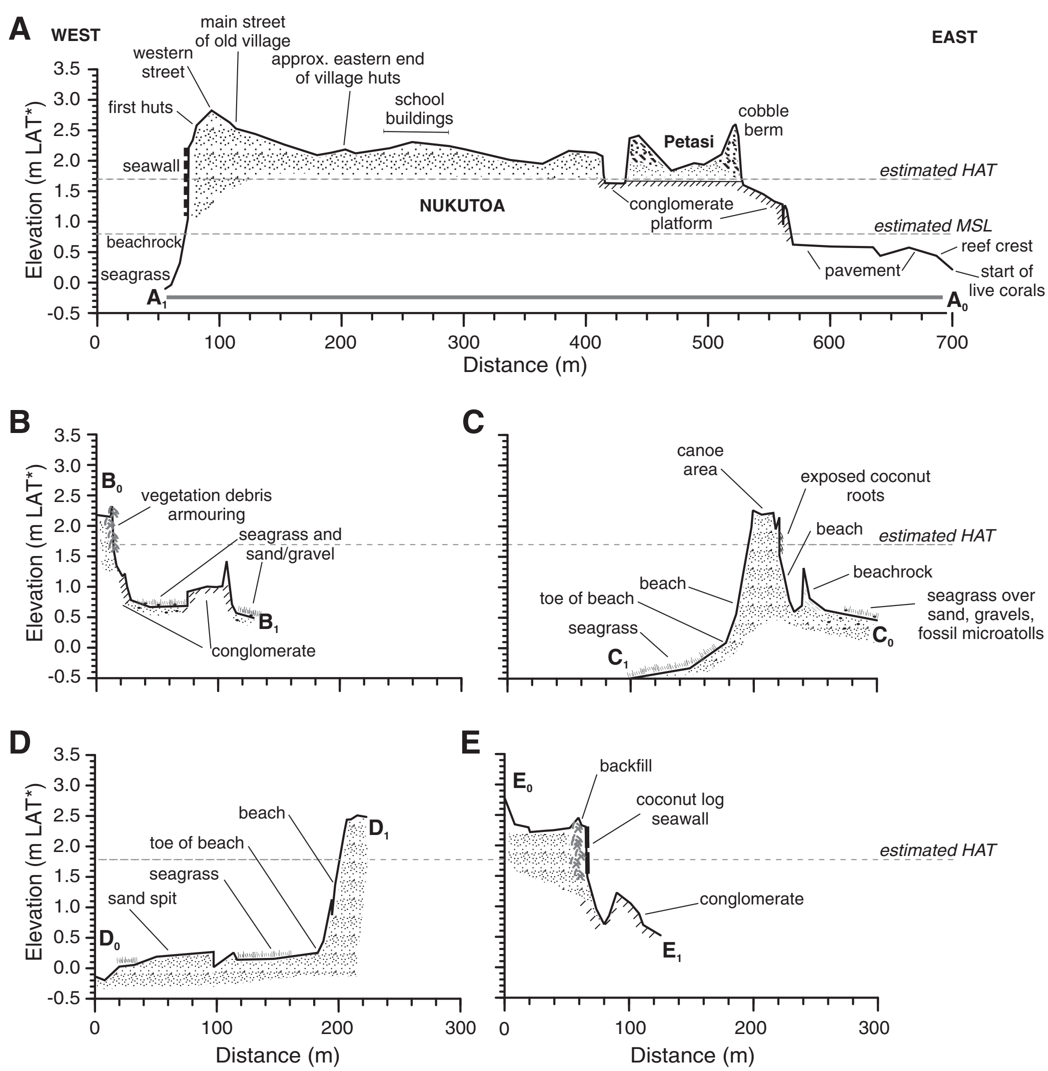

Fig. 2. Shoreline topographic cross-sections. Transect locations are shown in Fig. 1C.

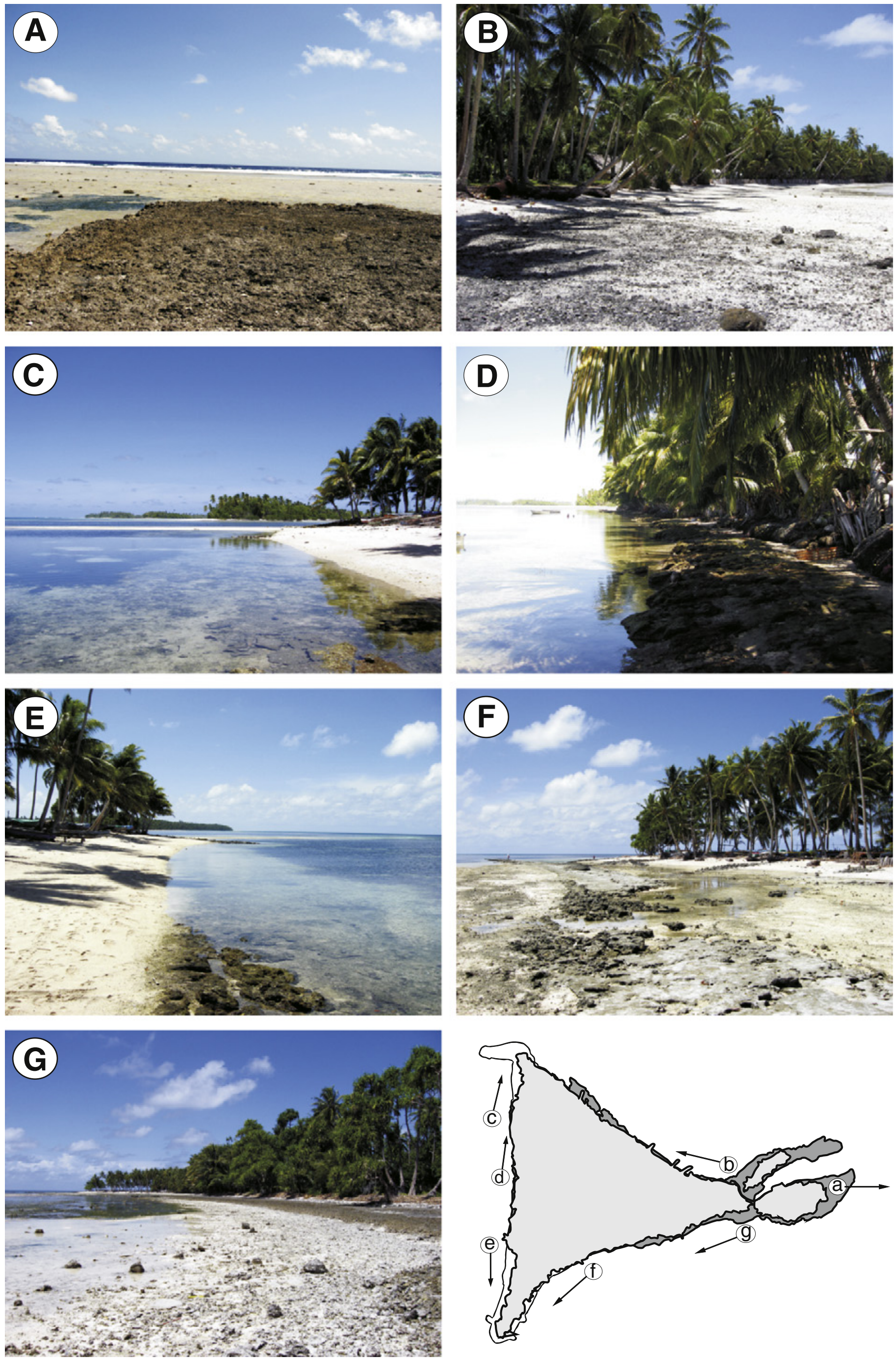

Fig. 3. Shoreline at Nukutoa before the December 2008 wave event. Camera positions and direction of view are shown in map at lower left. (A) View across elevated conglomerate seaward of Petasi in foreground then across reef flat pavement toward reef edge; (B) northeastern shoreline showing scarping over conglomerate in foreground and log palisade wall with truncated beach below in distance; (C) beach at Taloki; (D) gabion seawall over beachrock on lagoon shore; (E) lagoon beach at Sialevu; (F) east-facing beach at Sialevu; (G) southern shoreline of Nukutoa looking back toward Sialevu. Note conglomerate platform, sandy rubble and seagrass.

as the adjacent reef flat but separated from it by a shallow (0.2 m) moat (Fig. 2A). To seaward, the upper reef slope gently falls a metre or so over a distance of around 50 m. Rudimentary spurs built mainly of massive corals are developed over this zone. The reef flat between the reef crest and the eastern point of Nukutoa is a planar coralline pavement, with boulders generally less than 0.6 m on their longest axis scattered across it (Fig. 3A). Many of these boulders are eroded from elevated (variably 0.2–0.6 m above the pavement) conglomerate outcrops (locally referred to as '*hatupa*') that form prominent linear features aligned seaward to lagoon across the reef flat. These outcrops include in situ fossil corals suggesting that they are remnants of a former, higher reef flat and not storm deposits. A similar cemented and comparably elevated deposit is exposed around much of the eastern half of Nukutoa, including directly seaward of Petasi. Although in situ corals could not be found to confirm its origin, fossil microatolls on a spur attached to Nukutoa's northwestern flank suggest it is also an emergent reef flat. Modern corals are rare across the contemporary reef flat seaward of the islands, restricted to very scattered low-profile (2–5 cm high) *Porites* and *Favid* microatolls growing in shallow depressions within the pavement surface. Lagoonward of the pavement and roughly in line with the islands is a zone of a sand and rubble substrate, with scattered living and dead corals of both massive (microatoll) and branching forms, and patches of dense seagrass (*Thalassia* sp.). Villagers report that seagrass coverage and density have increased in recent decades. Sparse seagrass adjacent to other (uninhabited) islands around the atoll supports speculation that eutrophication associated with increased population may be responsible. A broad intertidal and shallow subtidal sandflat heavily vegetated with *Thalassia* seagrass extends around 120 m lagoonward from Nukutoa. Some large (~50 m^2) patches of *Montipora digitata* occur within this zone, and massive *Porites* corals, some of which exhibit microatoll morphology, become more common over the sandy substrate as the water deepens to a metre or so below LAT. As the steep sandy lagoon slope further deepens to around 5–8 m below LAT, larger patch reefs to 50 m across occur, some of which approach the water surface. Sand spits extend lagoonward off the northern and southern ends of Nukutoa (Fig. 3C). A large beachrock outcrop just east of Sialevu documents a former shoreline position (Fig. 3F), and the toe of the seawall along the lagoonward shore presently sits over exposed beachrock at approximately 0.4 m above LAT level (Figs. 2B, 3D).

No formal climate data exist for Takuu, but the climate may be described as wet tropical and normally dominated by southeast trade winds from May to October and a northwest monsoon from December to April. Tropical depressions and cyclones occasionally affect the atoll, usually during northwest monsoon. When close to Takuu these systems rarely produce cyclonic winds, but they may strengthen as they track south. Bayliss-Smith's (1988) account of major storms affecting the southern islands of Ontong Java atoll (5°16′S 159°21′E), to the east and slightly south of Takuu, is a valuable record of relatively rare cyclonic storms near Nukutoa. Bayliss-Smith (1988) reported that villagers who endured Tropical Cyclone (TC) Annie (November 1967) considered it unprecedented, suggesting no major storms between 1910 and 1967. Just two storms strong enough to blow down trees (occurring around 1820 and 1850) are captured in oral histories. Based on eye-witness accounts Bayliss-Smith (1988) estimated winds during TC Annie exceeded 215 km·hr^{-1}, with significant island overwash and heavy surf. Radford and Blong (1992) concluded that most damage during TC Annie was caused by storm surge.

The spring tide range at Takuu is approximately 1.75 m, estimated from a tide gauge deployed in the lagoon for 26 days during our visit. Following barometric correction, this record was calibrated against timed water level readings on a tide staff and compared with tidal predictions at Anewa Bay (6°13′S 155°38′E), the nearest tide gauge, to estimate HAT and LAT levels. Topographic survey elevations were reduced to this LAT estimate. Sea-surface elevations in the western Pacific are modulated by ENSO and other phenomena (e.g. Pacific Decadal Oscillation (PDO)) at sub-decadal and multi-decadal frequencies, causing sea-surface elevations to fluctuate by around ±0.2–0.3 m (Becker et al., 2012; Walsh et al., 2012). The elevation of the island relative to the ocean surface therefore varies depending on ENSO phase and strength. ENSO conditions in late 2008 were weakly La Niña (Monthly multivariate ENSO Index (MEI) of −0.67 (Wolter and Timlin, 1998)), meaning sea level was higher than average at Takuu at that time (Becker et al., 2012; Hoeke et al., 2013).

3. The December 2008 wave event

The wave event described here occurred between 7 and 11 December 2008, and affected a broad area of the central to western Pacific. Hoeke et al. (2013) provide an excellent description of the nature, timing and reported damage associated with this event, which inundated low islands and coasts extending from as far north as Wake Island (19°18′N, 166°38′E) and as far east as Marakei atoll (2°00′N, 173°17′E) in Kiribati, through Micronesia to the offshore islands and northern coasts of Papua New Guinea (3°34′S, 143°39′E) and the Solomon Islands (8°18′S, 160°42′E). Analysis of peak wave period and direction associated with the arrival of the peak wave energy at affected locations identifies two mid-latitude storms as sources of the damaging swells (Hoeke et al., 2013). Climate Forecast System Reanalysis (CFSR) reveals the presence of two systems on December 3, a large Aleutian Low centred around 50°N with an extremely large area of storm force winds, and a smaller system centred further to the west around 30°N. It is difficult to distinguish two separate low pressure systems by December 6, with the CFSR locating a single low pressure centre northeast of Wake Island, around 23°N, 170°E (Fig. 4A). The large Aleutian Low reached a minimum pressure of 957.7 hPa and the system active on December 6 a minimum pressure of 990.9 hPa. CSFR analyses indicate both systems produced hurricane force winds (Hoeke et al., 2013). We emphasise that the storms identified on December 3 were located more than 6000 km (Aleutian Low) and 3800 km (smaller system) away from Nukutoa respectively, and the system active on December 6 was still >3000 km northeast of Takuu. Following is a day-by-day account of the event at Nukutoa, which experienced clear skies and calm winds during all but the final day. December 11 was overcast and a stiff wind from the north–northwest developed in the afternoon.

a) *December 7*

The first waves arrived at Nukutoa on the evening high tide of December 7, when the water level was 1.01 m above LAT at the tide gauge. At 11 pm breaking waves surged across the reef flat into the lagoon. Amplitudes of 0.7 m were established for these surges on the northern shoreline of Nukutoa by referencing minimum and maximum depths to features surveyed on transect 5 (Fig. 2). Between 11 and 11.30 pm these surges had periods of 6–8 min. Lower amplitude water level fluctuations were observed on the lagoon shore between midnight and 12.30 am (drawdown was approximately 10–15 cm below the predicted tide), and the waves in the lagoon had a slightly shorter period (5 min).

b) *December 8*

As the tide rose to its predicted peak of 1.2 m LAT around midday on December 8 waves surged through the interisland passages to the north and south of Nukutoa as bores, with variable amplitudes and periods (the period of one wave was timed at 8 min 26 s). The peak water level at the tide gauge was 1.35 m LAT, 0.15 m above the predicted maximum, but peak heights of waves passing through the interisland passages were estimated at >0.5 m. From the shoreline at Petasi waves outside the reef appeared to approach from the northeast, and large breaking waves were observed around the north and northeastern rim of the atoll. No overwash of the island occurred on December 8.

c) *December 9*

The account for December 9 is reconstructed from the observations of villagers; we were surveying the adjacent island of Takuu for most of this day. Between about 10 am and 3 pm, but peaking around the midday high tide (predicted 1.4 m LAT; measured 1.58 m LAT), waves began to periodically wash across the lagoonward corners of the island, and swash over the seawalls on the northern shore, causing significant alarm and some erosion. Overwashing abated as the tide fell.

d) *December 10*

From mid-morning surges of broken water moved across the reef flat toward the lagoon (Fig. 4B), with larger waves every 7–10 min. The amplitude of waves passing through the passage averaged around 0.8–1.1 m. Around the top of the tide (predicted 1.5 m LAT at 1258; measured 1.70 m LAT at 1304), waves surged over shorelines and seawalls to inundate a large part of the island (Figs. 4C, 5). Waves overwashed the island for around 4 h. The northern shoreline was particularly affected. Approximately 20–30 dwellings were rendered uninhabitable, and the school and other government buildings, churches, and water tanks were severely damaged. Many seawalls were damaged or destroyed, and backfill emplaced behind these structures was scoured out. Water surging across the reef was very turbid, with plumes extending into the lagoon. Standing waves

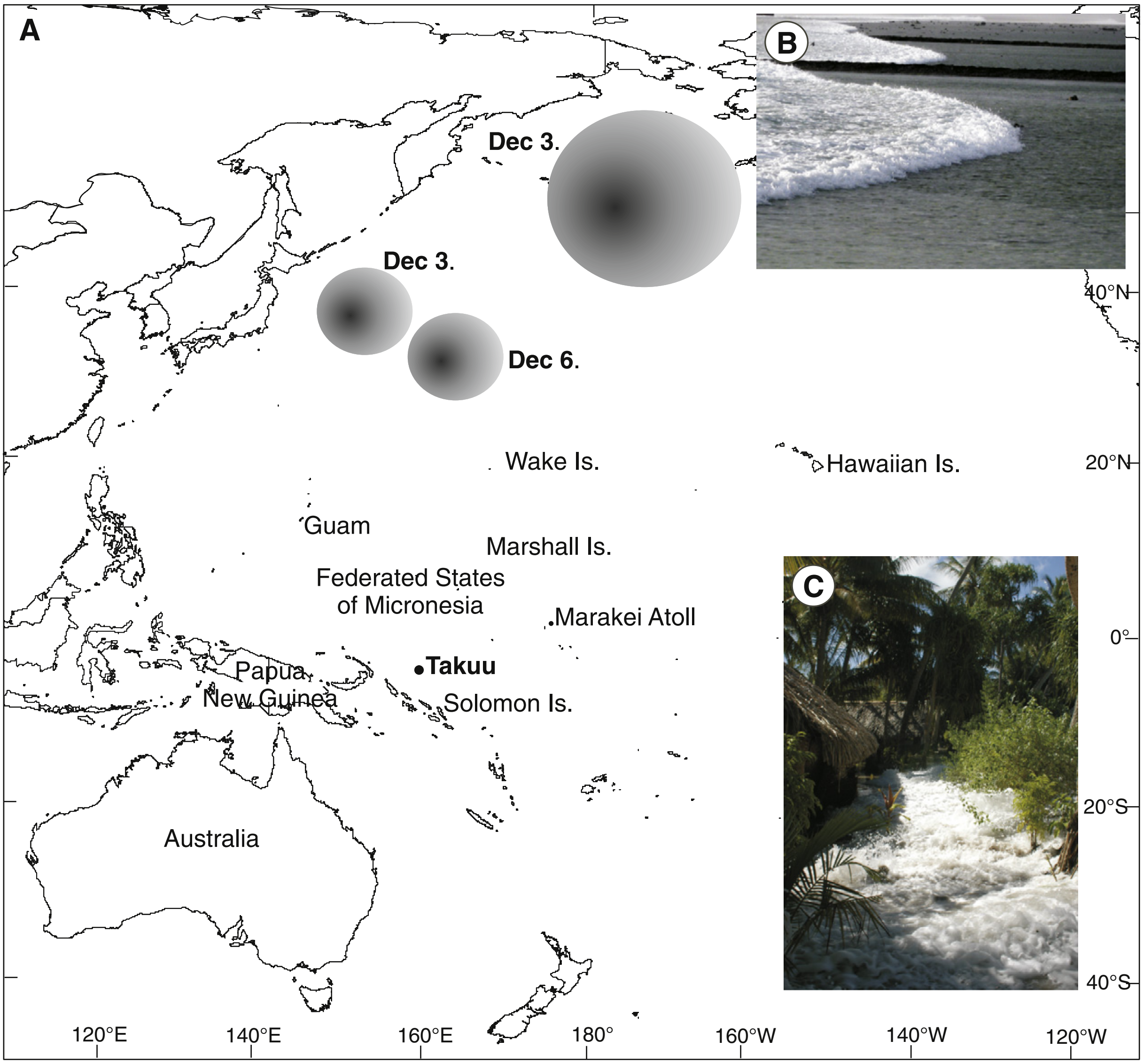

Fig. 4. (A) Locations of storms inferred to have generated the waves experienced at Nukutoa between December 7–11, 2008. Size of system is approximate only. (B) Waves surging over reef flat between Nukutoa and Takuu Island December 8; (C) wave overwashing the island and into village on northeast shore.

occasionally formed as the surges pulsed into the lagoon at the western end of the interisland passages. Waves 0.5–1.0 m in height approached the western shoreline of Nukutoa from across the lagoon at irregular intervals. These waves tended to swash onto the island edges rather than surge across it.

e) *December 11*

The swell abated significantly, but occasional surges occurred around the high tide. Flooding was far less severe and frequent than the previous day, even though the predicted tide (1.7 m LAT) was 0.2 m higher (the measured tide was still 0.08 m higher than the predicted, but the elevation above the predicted was also lower than on the previous few days). Waves washing onto the island swashed up and back rather than surging across the island.

The Honiara SEAFRAME tide gauge indicates a positive ~0.1 m sea-level anomaly for December 2008, after tides, seasonal cycles and sea-level trends are filtered (www.bom.gov.au), and Hoeke et al. (2013) calculated an anomaly of 0.171 m at Takuu using the AVISO delayed-time gridded sea-level anomaly (SLA) product (www.aviso.oceanobs.com), indicating sea level was slightly above average at the time of the event. These estimations accord well with the sea-surface anomaly derived from the surveyed upper limits to coral growth on lagoonal *Porites* microatolls that were around 0.25 m below the MLLW–MLWS tidal datum at which upward coral growth is normally constrained in similar settings (Smithers and Woodroffe, 2000). Based on surveys of debris wrack lines we estimate that the maximum inundation depth was approximately 0.45 m above HAT (on December 10) and that more than 50% of the island was flooded during this event (Fig. 5).

4. Methods

Takuu was visited over 4 weeks in November and December 2008 to assess the vulnerability of the atoll to climate-change impacts. The shoreline and other geomorphological features on Nukutoa were planimetrically mapped with a Trimble GeoExplorer 3 global positioning system (GPS) for this assessment. A full survey was completed before the December wave event, and major features were surveyed again after it. The instrument was used in rover mode for mapping, set to record a line feature at 1 Hz whilst the operator walked the perimeter of the feature of interest. A single operator conducted all surveys to ensure consistency of feature interpretation. A mean horizontal positioning

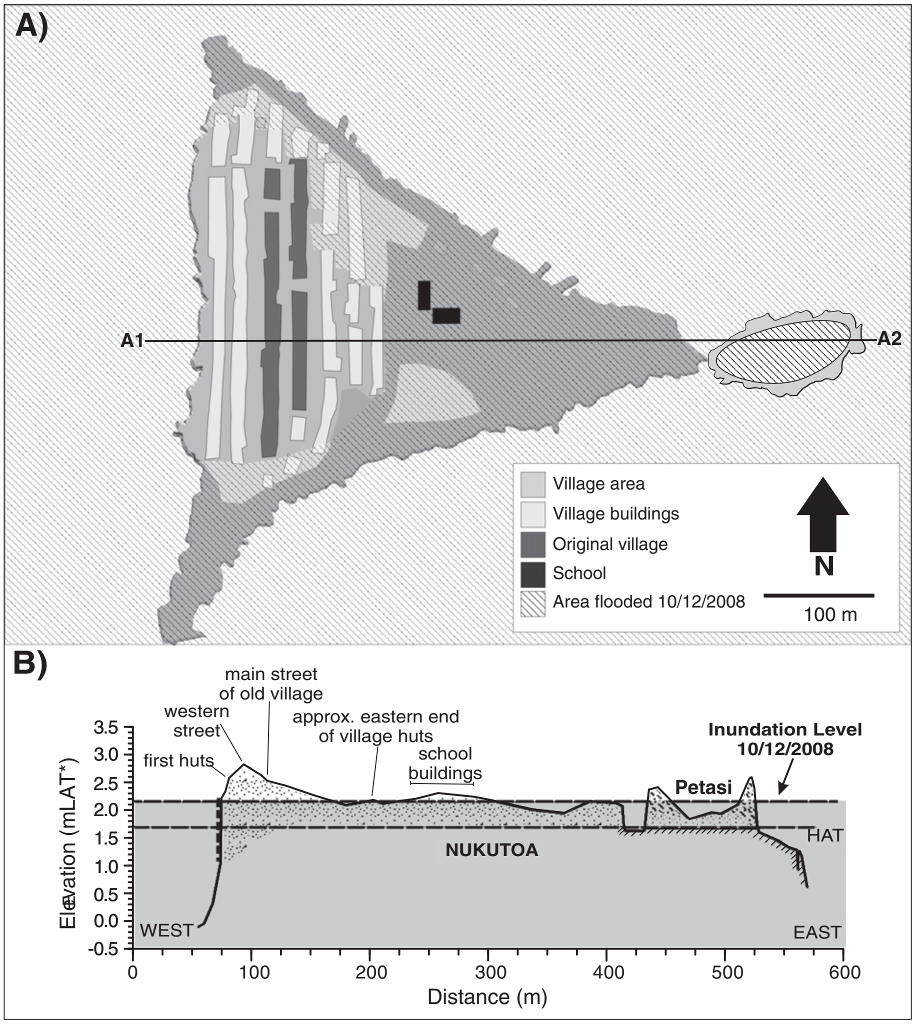

Fig. 5. (A) Map showing areas of island inundated by waves during the event. (B) Topographic cross-section approximately across the centre of the island showing areas inundated during the event.

error of ± 0.75 m is estimated based on surveys of features with measured relative positions, for example, opposite sides of the main street.

Two major boundaries were always mapped: i) the vegetation line (VL); and ii) the 'toe of beach' (TOB). The vegetation line (VL) is the seaward edge of vegetation that would be visible on an aerial photograph or satellite image. This approach allows comparison with historical aerial photographs if available, but may overestimate island size where tree canopies substantially overhang the shoreline. The TOB is where the sandy beach meets the reef flat or other substrate. It is usually marked by a distinct break in slope where the beach meets the sub-horizontal reef flat, or by a change to finer rippled sand where the beach merges onto a sandy reef flat. As discussed in Section 2, natural sandy beach is unusual around Nukutoa, with much of the shoreline composed of seawalls or erosion scarps above conglomerate platform or beachrock, sometimes with minor sand deposits perched over them on the lower shoreface (see Fig. 3). These features were also mapped as above, as were sand spit boundaries and the landward limits of the sand sheet deposited on the island by the December 2008 event.

Topographic surveys were completed using standard dumpy-levelling techniques. Reported elevations are reduced to the LAT datum estimated from the tide-gauge data (see Section 3). We acknowledge that our LAT datum is unlikely to be the true long-term LAT, but it provides a practical benchmark against which to interpret the geomorphology of Nukutoa and the impacts of the December 2008 waves.

In addition to post-event shoreline surveys, we collected GPS locations for debris wrack lines and damage sites for which elevations were later surveyed, completed photo-circuits and descriptions of the shoreline, and measured the extent, thickness, and composition of surficial deposits — including the sand sheet deposited on the northeastern part of the island. The latter task was undertaken by excavating small pits across three transects aligned normal to the shoreline (Fig. 6), and measuring the depth of 'fresh' sand deposited over the buried island surface which was distinctly firm and/or organic.

5. Results

A total of 646 m of the 1393 m of the vegetation line surveyed prior to the wave event was eroded (retreated landward), equivalent to 46% of Nukutoa's shoreline. However, another 200 m of eroded shoreline occurred beneath stable overhanging vegetation canopy, which when included increases the proportion of Nukutoa's shoreline eroded during the event to ~60%. No significant shoreline progradation occurred anywhere on Nukutoa, but a sand sheet was deposited over the island surface adjacent to the northeastern margin, and sand spits at Taloki and Sialevu increased in size and elevation. The nature and distribution of these geomorphological changes are shown in Figs. 6–8 and are detailed further below.

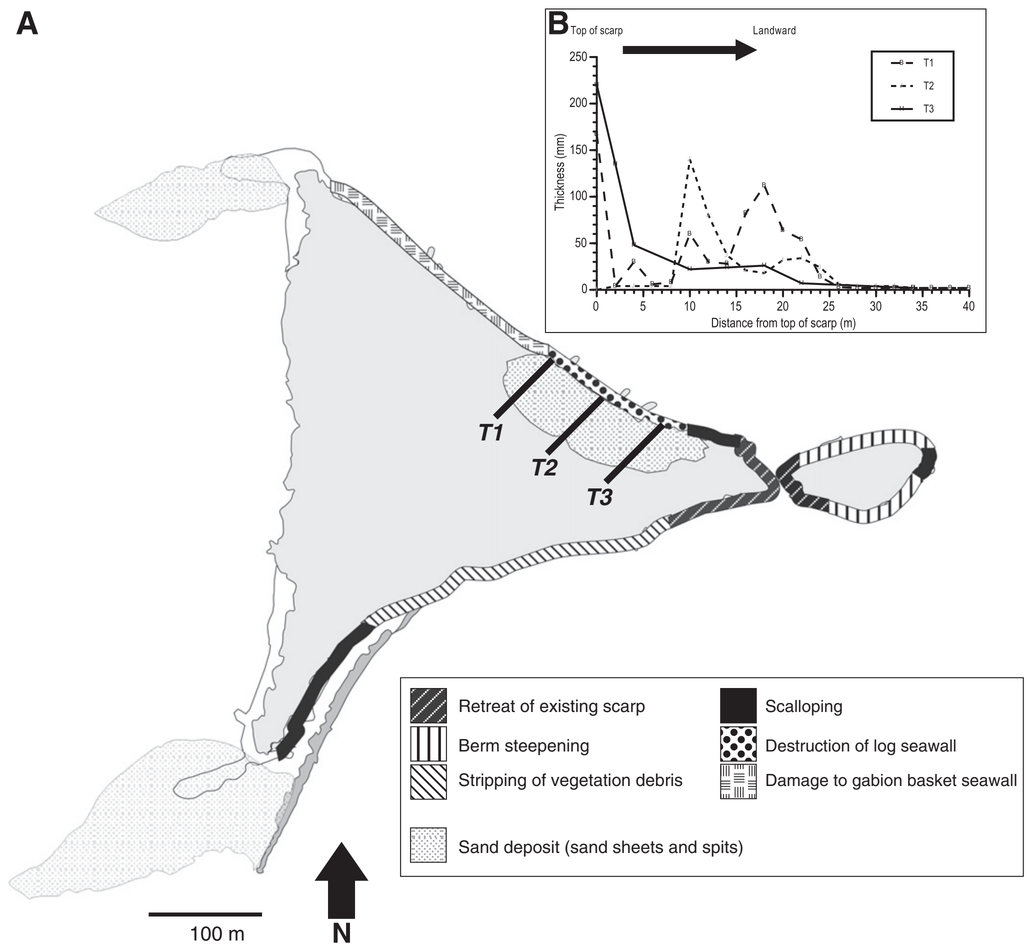

Fig. 6. Map showing major geomorphological changes and locations of sand sheet transects. See text for detailed descriptions of shoreline classes; B) sand sheet thickness along transections 1–3.

5.1. Erosional impacts

Six different types of shoreline erosion occurred during the event:

i) *Retreat of existing erosional scarps*. This occurred where existing but previously stable scarps, usually developed in partly indurated sandy sediments held together with vegetation roots, were cut back. Both before and after the event these scarps were around 0.4 m high and developed above a conglomerate platform elevated around 1.3 m above LAT. Previous stability was inferred from algal staining over the conglomerate right up to the base of the scarp. Scarp retreat during the event exposed ‘fresh’ conglomerate without algal staining. This type of erosion mainly occurred on the western end of Petasi and the eastern end of Nukutoa, with maximum scarp retreat of 2.4 m measured at the southeastern end of Nukutoa (Fig. 7A).

ii) *Berm steepening and migration*. Coarse sediments (gravels to boulders) derived from the conglomerate form berms around Petasi rising to 0.9 m above HAT (the conglomerate is at 1.3 to 1.7 m LAT). Berms in place before the event were clearly reworked. Overturned clasts exposed ‘fresh’ surfaces unstained by algae or pitted by karstic solution (Fig. 7B), seaward berm slopes were steepened, and splays of reworked clasts spilled toward the island interior. At the east–northeast corner of Petasi the toe of the berm at the conglomerate retreated by up to 1.4 m. A few fragments (a-axis to 0.35 m) of recently living corals (with tissue still present) were transported to the berms during the event; a reef edge provenance is assumed as only very flat and thin colonies were seen over the seaward reef flat during surveys. The recently living coral fragments confirms the delivery of some new material to the island during the event, but the majority of larger clasts were reworked conglomerate fragments from the pre-existing berm. Berm deposits exhibit an imbricated fabric, and a-axis alignment of clasts normal to the shoreline is common.

iii) *Stripping of vegetation debris, minor scarping and retreat*. The mid-section of the southern coast of Nukutoa experienced only very minor erosion ($<$0.5 m retreat) and localised scarping (Fig. 7C), with vegetation debris emplaced to protect the shore largely removed from above the conglomerate platform but not from above the scarp. This suggests shore-parallel rather than shore-normal current flows and waves, an interpretation supported by the orientation of clasts stripped from the conglomerate which had a-axes aligned obliquely to the shore.

iv) ‘*Scalloping*’ *of the upper shore between coconuts*. A distinctive pattern of erosion was observed where coconuts grew directly at the shoreline, such as at the northeastern end of Nukutoa and on the seaward beach at Sialevu. At these locations the upper shore was ‘scalloped’ as sandy sediments were eroded from between and behind resistant coconut root masses to form scallop-shaped embayments, often with scarped margins (Fig. 7D). At the northeastern end of Nukutoa these scallops extended an average of 1–3 m landward of the coconut roots. Gravels and coarser sediments accumulated at the head scallops soon after the event, grading to the conglomerate platform exposed by the scarp retreat. Coconut spacing controlled scallop width, with no consistent relationship between width and cut back extent. Some scallops were partially formed before the December 2008 event, but all appeared to have been reactivated by it. On the

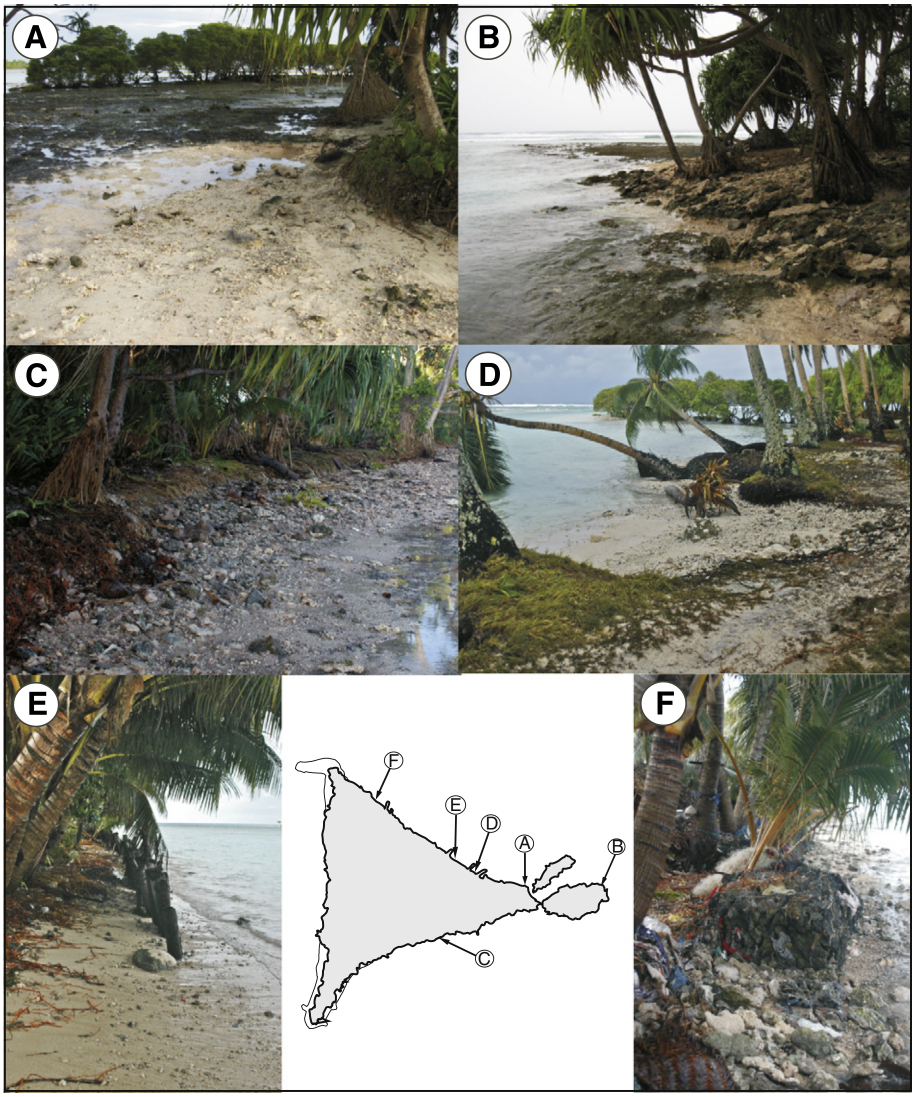

Fig. 7. Shoreline at Nukutoa after the December 2008 wave event. Camera positions and direction of view are shown in map at centre left. (A) Scarp retreat and conglomerate exposure at northeastern point of Nukutoa; (B) rubble and boulder berms and berm retreat at Petasi; (C) root protected scarp over conglomerate on southern shoreline; (D) scalloping between coconuts on northeastern shoreline; (E) beach developed where log palisade seawall removed and damaged — note remaining logs mid-beach and removal of backfill; (F) damaged gabion basket seawall on north western shoreline. Note exposed roots and sediment stripping from above the wall.

seaward side of Sialevu some minor scalloping occurred between coconuts on the upper beach, with fresh splays of eroded sand extending from the scallop heads back into the canoe resting area. These splays were up to 25 mm thick and extended up to 8 m landward. On the seaward shore at Sialevu, a beachrock outcrop was partly exposed near the toe of beach with a more north–south alignment than the existing shoreline. The cross-sectional profile of the lagoon beach at Sialevu was not significantly altered.

v) *Log seawall destruction and retreat of upper beach*. The section of Nukutoa's northeastern coast formerly protected by coconut log palisade walls was significantly modified during the event. Approximately 35% of the wall length was destroyed, and the backfill behind eroded. The toe of beach did not retreat markedly, but where the seawall was removed the grade of the beach extended landward repositioning the top of the beach ~4 m inland of the previous edge of island (defined by the top of the wall). Remnants of the wall left standing were located mid-beach after the event (Fig. 7E).

vi) *Gabion basket seawall destruction*. Before the event a seawall of rubble and boulder-filled wire gabion baskets or locally manufactured equivalents fashioned from washed-ashore fishing nets filled with rubble protected a small section of the northwestern coast of Nukutoa. After the event large sections of this shoreline were covered in rubble and boulders, and the top of the beach had retreated, generally by 1–2 m. Many gabion baskets were damaged, making it difficult to distinguish whether rubble and boulders strewn over the shore spilled from the damaged seawall or included new material delivered during the event (Fig. 7F). Backfill behind the wall was scoured out, exposing the roots of coconuts planted to stabilise the reclamation.

Minor erosion also occurred over the island. Soil was stripped to expose roots along the island edge immediately behind the northern shore, forming a stripped belt similar to Kench et al.'s (2008) ‘bypass zone’. Scouring and ‘halo’ development also occurred around the bases of some coconut palms and house footings in the same location. Waves from across the lagoon episodically washed a short distance (~5 m maximum) up onto Nukutoa's western (seawall protected) shore. These caused minor erosion of sediments from reclaimed land as they drained back to the lagoon.

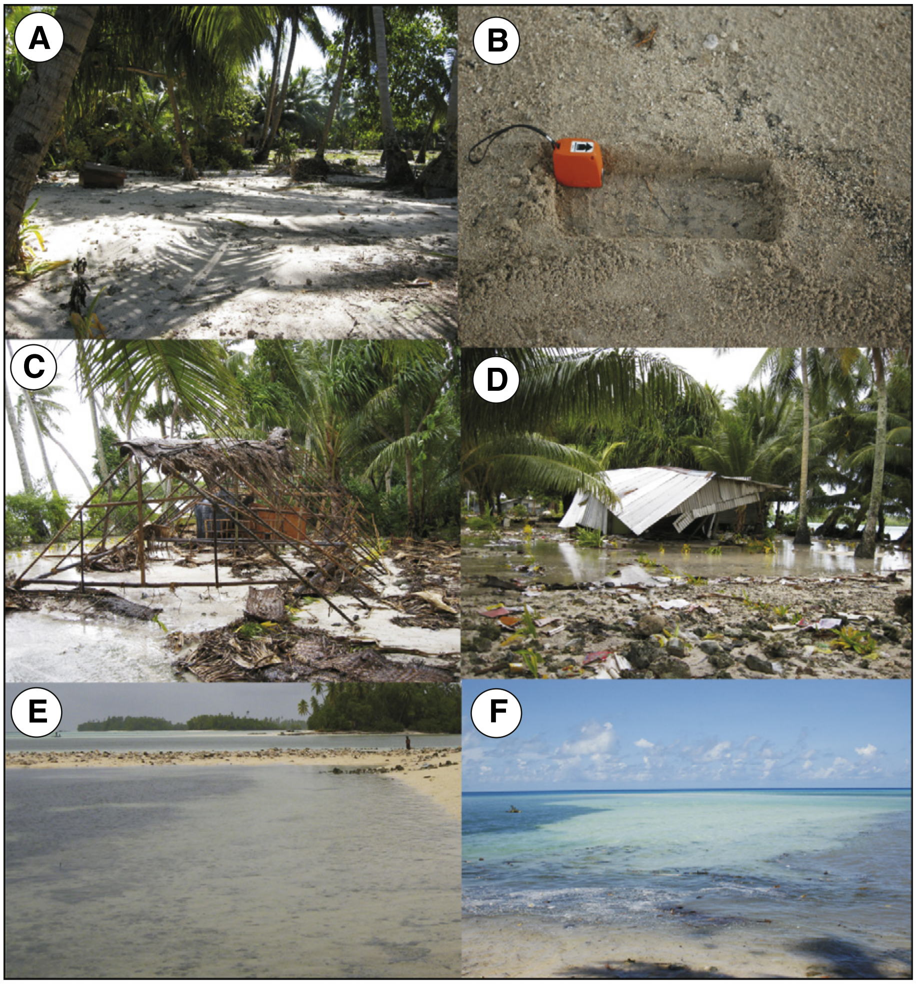

Fig. 8. Depositional impacts associated with the December 2008 wave event. (A) Sand sheet near landward end of transect 2; (B) sand sheet at 15 m on transect 3 — tape measure for scale approximately 50 mm across; (C) sand sheet at transect 1; (D) sand sheet and debris looking from transect 2 toward transect 3; (E) sand spit extending lagoonward from Taloki. Note abundant coarse material deposited over upper surface; (F) sand spit extending lagoonward from Sialevu.

5.2. Depositional impacts

The major depositional features formed during the event were the sand sheet deposited over the northeastern section of the island and the sand spits extending lagoonward from Taloki and Sialevu. Spreading inland from the shoreline formerly protected by the log seawall, the sand sheet is lobe-shaped in plan view and covers approximately 0.8 ha or 13% of the island (Figs. 6, 8A–D). The orientation of the deposit accords with the direction of wave approach; although waves surged through the interisland passages, waves and erosion tended to be higher on the northeastern side of Nukutoa (see Section 5.1 above). Unfortunately, difficulties shipping samples to Australia have to date prohibited any quantitative sedimentological description of the sand sheet. However, visual assessment indicates medium to coarse bioclastic sands dominate (Fig. 8D). We infer that these sediments were mostly eroded from the reef flat and beach bordering the deposit, and from backfill placed behind the log seawalls by villagers (harvested from the adjoining reef flat and beach). The location of the sand sheet adjacent to these sources, and its absence away from them, support this conclusion. Conglomerate outcrops that extend back toward Nukutoa's northern shore (see Fig. 1) act like groynes and trap sediments on the reef flat that were available for transport onshore during the event.

Sand sheet thickness varied from the shoreline landward and from east to west (Fig. 6B). It was thickest (220 mm) at the seaward end of the easternmost transect (Transect 3), where sand accumulated against vegetation debris. Where undergrowth was absent the first 5–10 m across the sand sheet was often thin and deposited over or around exposed root mats scoured by erosion that occurred earlier in the event. Thicker deposits, such as the initial sample on transect 1 are clearly deposited over exposed roots and were likely swashed onshore later in the event. The sand sheet is generally best developed from around 8 to 25 m landward of the island edge, where thicknesses of 50 mm are typical. Further landward a thin 1–2 mm veneer of sediment extends to around 40 m inland, although wrack lines of vegetative debris indicate surge penetrated much further across the island (Fig. 5). The sand sheet was relatively homogenous, with no visible grading, structures or laminae.

Sand spit extension and augmentation also occurred during the event (Fig. 6A). At Taloki the sand spit extended from 50 m to 160 m offshore of the beach, and the footprint of the spit increased from 1250 m^2 to 6810 m^2. The sand spit at Sialevu increased its lagoonward limit from 64 m to 166 m offshore of the beach and enlarged from 710 m^2 to 10,375 m^2. Slip faces could be distinguished around the margins of both spits, dipping down onto seagrass that had obviously been buried by spit encroachment. The upper surface of these deposits was up to 40 cm above the surrounding seagrass at both ends of the island, with the greatest relief generally occurring approximately half way along the spit's length.

Sand spit extension at both ends of Nukutoa clearly indicates active sediment transport into the lagoon during the event. Most of the sand deposited was visually assessed as coarse to medium texture, but particularly at Taloki, cobble and occasionally larger-sized clasts were also included and scattered over the spit surface (Figs. 8E–F). At Taloki it is probable that some of this coarser material was eroded from damaged gabion baskets on Nukutoa's northwestern shore, but some may also have been transported from the reef flat or interisland passages.

6. Discussion

Severe storms rarely pass near to Takuu, but the December 2008 wave event clearly demonstrates the influence of distant storms on equatorial and other reefs; 4 days of high waves generated by storms between 6000 and 3000 km away inundated nearly 50% of Nukatoa, eroded approximately 60% of its shoreline, and deposited a sand sheet covering 13% of its surface. Below we discuss the geomorphological significance of this event on Nukutoa, and reflect on the broader significance of similar events on reef island geomorphology more generally.

6.1. Geomorphological impacts on Nukutoa

Observations and GPS mapping pre and post event indicate that the most severe erosion occurred along Nukutoa's eastern and northeastern coast. This shoreline was most exposed to waves which approached the outer reef from the northeast, but the geomorphology of the reef to the north of Nukutoa and pre-existing shoreline condition may also have contributed to the severity of impacts. The interisland passage north of Nukutoa toward Nukuafare is narrow compared to the passage to the south, and constricts lagoonward due to Nukutoa's triangular shape (Fig. 1B). This may have amplified wave set-up (Gourlay, 2011a) and wave penetration through this area on higher tides, increasing erosion and overwashing. Conglomerate spurs that extend obliquely across the passage may also have directed waves and currents against this shoreline (Fig. 1C). Although ~60% of Nukutoa's shoreline was eroded, it was generally relatively minor (<1 m) around most of the island, with more severe erosion isolated to sites such as 'scallop' heads and where the log seawall was damaged. We note that exposed scarps and seawalls indicate that shoreline erosion was widespread around Nukutoa prior to the wave event, although some seawalls were installed to reclaim land rather than control erosion.

It is unknown if the erosion is temporary and a steady-state equilibrium shoreline will be re-established, or whether an erosionary disequilibrium trajectory better describes the situation at Nukutoa. However, the vegetated area of Nukutoa (calculated by digitising the 1943 aerial photograph and the 2005 DigitalGlobe satellite image from Google Earth) decreased by approximately 4.8% between 1943 and 2005 (neighbouring Takuu island showed no significant difference), and contracted a further 2–3% by late 2008. Changes in the morphology and position of Taloki and particularly Sialevu account for most of the above reduction, with the remaining shoreline remarkably static. The position and structure of these sedimentary promontories, and their exposure to seasonally shifting waves and currents, are typical of particularly dynamic parts of reef islands elsewhere (Flood, 1986; Webb and Kench, 2010), and it is thus premature to suggest a significant erosionary trend for Nukutoa prior to the 2008 event based on mapping data alone. We note, however, that shorelines unprotected by seawalls but apparently relatively stable since 1943 from the aerial photograph analysis (they may have been eroded but cannot be detected due to canopy obscuration or image resolution) were eroded during the December 2008 event, and that shoreline progradation occurred nowhere around the island.

Although 50% of Nukutoa was inundated, the deposited sand sheet is modest in size and thickness (Figs. 6, 8A–D), reflecting the limited distribution and volume of sediment available for transport onto the island by waves. Debris wrack lines beyond the distal margins of the sand sheet indicate that sand sheet development was sediment supply rather than energy limited. The location and composition of the sand sheet strongly suggest that it is predominantly composed of sands eroded from the truncated beach that existed below the log seawall and sediments used to backfill behind it, with minor additions scoured from the island surface immediately behind the erosion scarp. The sand sheet contains 110–140 m^3 of sand and averages around 50 mm thick over a band approximately 8–25 m landward of the vegetation line where it is most uniformly developed, thinning further landward. Despite its restricted extent and thickness, the sand sheet deposited in the few days of wave inundation contributes significantly to land building on Nukutoa; a 50 mm deposit vertically accretes the island surface and increases its elevation by 10% of the average height above HAT. Although the sand sheet sediments were eroded from the shoreline, the process constitutes a spatial transfer of sediment rather than a net loss from the island sediment budget (Kench and Cowell, 2002; Perry et al., 2011). Waves overwashing an island and depositing sediments are problematic for residents but comprise a critical geomorphic process required for reef island adjustment to higher sea levels (Kench and Cowell, 2002; Kench et al., 2009). In contrast, turbid plumes discharging into the lagoon and the enlargement of sand spits during the event document significant sand loss from Nukutoa's sediment budget. The terminal ends of both spits extend to the lagoon slope, from where sediments are unlikely to return onshore. Seasonal reversals in winds and waves redistribute sediments on other reef islands (Kench and Brander, 2006; Dawson and Smithers, 2010), but shoreward transport from the sand spits at Nukutoa is likely to be limited by low hydrodynamic energy and trapping by dense seagrass (Hopley et al., 2007).

The importance of sediment supply for reef island growth and maintenance is well established, with sediment budget disruptions and deficits shown to influence reef island geomorphology and stability (e.g. Barry et al., 2007; Kench et al., 2009; Perry et al., 2011). Although Nukutoa is mostly composed of sand, little sand is produced or stored on the seaward reef flat at present. This probably reflects the turn-off of primary carbonate production over the reef flat associated with late Holocene emergence; sea level fall of ~0.9 m is indicated by the elevation range separating modern microatolls and the highest fossil microatolls preserved on the conglomerate. Declines in carbonate productivity associated with late Holocene emergence are commonly inferred (e.g. Perry and Smithers, 2010), and given the mid-ocean setting and relatively low population pressure it is difficult to identify other likely factors. Recent seagrass expansion behind Nukutoa may reflect higher population and nutrient loads, but it is difficult to attribute any sediment deficit to reduced foraminiferan production due to pollution (Osawa et al., 2010) because seawater arriving from the seaward reef flat is essentially oceanic. Stratigraphy exposed at erosion scarps reveals a relatively thin (0.5–1.0 m) sandy unit perched on conglomerate (Fig. 2), suggesting sand accumulated over the higher mid-Holocene reef flat. Data are not yet available to determine whether island accumulation began before or following relative sea-level fall as proposed for other Pacific reef islands (Dickinson, 2004). Sediments eroded from the elevated mid-Holocene reef flat may have contributed to Nukutoa, but lagoonal infill suggest that most probably bypassed the island to be deposited in the lagoon, as established at other atolls where sea level fell after the mid-Holocene (Smithers et al., 1994).

Although image analysis suggests that Nukutoa has only marginally contracted since 1943, beachrock exposures and pre-existing erosion scarps – often in cay sandstones formed in stable island interior deposits – are geomorphic features indicative of shoreline retreat. As outlined above, at Nukutoa this may be symptomatic of chronic sediment deficit driven by sediment production shutdown due to late Holocene reef flat emergence. Wave-deposited ridges to 3–4 m high are characteristic of the seaward shores of many reef islands (termed 'ridge crests' by Woodroffe, 2008) but are absent on Nukutoa except at Petasi, where they are small features (rising just 0.7 m above the island interior) composed of coarse clasts eroded from the proximal conglomerate. This again suggests sediment supply not wave energy limits berm development. Waves easily inundated

Nukutoa's low-lying interior (mostly <0.5 m HAT) during the 2008 wave event without ridge crests to provide some protection from erosion and overwash (Nukutoa is of comparable elevation to Maldivian reef islands described by Woodroffe (2008) as 'particularly low-lying' and 'precariously' above sea level). As noted previously, the paucity of available sediment, both on the reef flat and shoreline, also restricted the development of onshore accretionary deposits such as the sand sheet, and seagrass expansion in recent decades may have intensified sediment budget deficits by trapping sediment on the lagoonal reef flat. A prolonged deficit in sediment supply is, however, suggested by Nukutoa's contemporary morphology, with former ridges – if they existed – simply being eroded away rather than rolled up onto the island. The existing topography preserves no evidence of dynamic adjustment by rollover or migration sensu Woodroffe et al. (1999) or Kench and Cowell (2002).

Curiously, the highest elevation on Nukutoa occurs along a ridge parallel to but 40–120 m landward of the lagoon shore (Figs. 2A, 5A). Typically the highest point on most reef islands is the seaward ridge crest. However, higher ridges can occur on the lagoonward shore where fetch and inshore depth allow waves formed in the lagoon by seasonally reversed winds to swash onshore higher than on the seaward shore where wave energy is filtered by the reef flat before reaching the island (Woodroffe, 2008). The high ridge at Nukutoa may have formed this way at the peak of the mid-Holocene highstand, with the slope to the present beach developing as the shore prograded lagoonward as sea level fell to present. An alternative hypothesis with equal merit is that the higher ridge is the result of anthropogenic augmentation; it is occupied by the older parts of the village and was not significantly inundated by the December 2008 waves. It is cultural practice to regularly add clean sand and gravel to hut floors to maintain a clean and practical surface. Using the maximum elevation of approximately 1 m above HAT and the widely accepted length of occupation at Takuu of around 600 years (Bourke and Betitis, 2003) additions equivalent to a net annual accretion of just 0.8 $\mathrm{mm \cdot yr^{-1}}$ would be necessary to develop the ridge above the general island elevation. The colossal network of taro pits on neighbouring Takuu Island proves the capacity and willingness of Nukutoan ancestors to significantly modify island topography and redistribute enormous volumes of sediment. These pits are so large that customary belief is that they were excavated by beings with powers beyond humans. The detailed chronostratigraphic analyses required to test these hypotheses are beyond the scope of this paper, but it is relevant to note that however formed, this higher ground was not catastrophically flooded during the 2008 wave event.

Nukutoa's sandy construction and geomorphology largely conform to morphodynamic expectations given its latitude and low-energy setting (Bayliss-Smith, 1988; McLean and Woodroffe, 1994). In this model sandy reef islands progressively build up between storms, and are eroded by episodic high-energy events (Fig. 9A). Boulders scattered across the reef flat at Nukutoa document occasional storms (of unknown magnitude), and villagers offered oral accounts of erosion associated with these events. However, in contrast to the generalised model where recovery follows erosion to maintain an equilibrium island form, in recent decades at least and perhaps for much longer, recovery between events has not occurred. As a result, Nukutoa is currently a relict deposit in a phase of punctuated but progressive erosion, with intervening periods of stability but not recovery (Fig. 9A). Erosion mainly occurs during infrequent storms and episodic swell events, with stability between incidents improved by weakly indurated cay sandstone, root bound sediments, or seawalls at the shoreline. However, as observed during the 2008 wave event, these shorelines cannot withstand higher-energy events, including those generated by distant systems. The geomorphic impact of the 2008 wave event is compared to tropical cyclones and tsunami in Section 6.3, but we note here that despite 4 days of heavy surf at the reef edge and surging waves across the reef rim, neither a rubble rampart nor conspicuous boulder tract formed, the two main depositional signatures of tropical cyclone waves (Scoffin, 1993). Although the geomorphic impacts of tropical cyclones on reefs are notoriously patchy (Harmelin-Vivien, 1994; Etienne and Terry, 2012), in the case of rubble ramparts, the

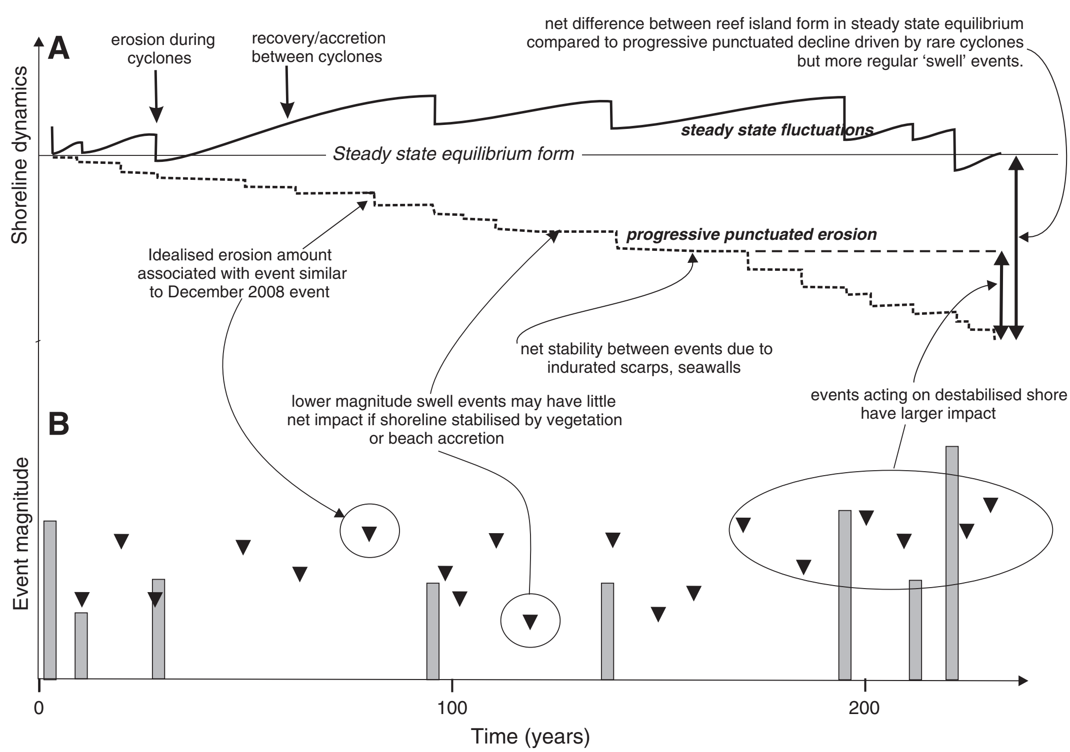

Fig. 9. Conceptual model of shoreline dynamics in response to rare cyclones and episodic swell events at Nukutoa. (A) Comparison of steady-state equilibrium model (after Bayliss-Smith (1988)) with progressive punctuated erosion model driven by combination of high(er) energy events at this usually low-energy reef setting combined with a chronic sediment budget deficit due to late Holocene reef flat emergence; (B) schematic showing idealised relationship between the frequency and magnitude of tropical cyclones and swell events produced by distant storms at Nukutoa.

general absence of pre-existing ridges at Nukutoa may be instructive. Rubble ridges occur on other reefs where storms are rare, such as the East Indies (Umbgrove, 1947), making it difficult to attribute the lack of recent and older ridges at Nukutoa to available energy. This again suggests sediment supply is constraining; the reef slope may be too steep to support dense coral cover and/or store rubble (Scoffin, 1993; Etienne, 2012) for reworking onto the reef during storms (Maragos et al., 1973; Baines and McLean, 1976). The importance of these ridges for reef island accretion is well documented (Cloud, 1952; McLean, 1993), and they can also dissipate wave energy and protect sandy islands in their lee (Scoffin, 1993). Their absence on Nukutoa is thus significant from both a constructional and erosion mitigation perspective. The longer-term geomorphological trajectory for Nukutoa at present appears similar to the progressively contracting remnant island envisaged by Woodroffe et al. (1999).

6.2. Was the December 2008 wave event unusual?

Villagers were obviously distressed by waves overwashing 50% of Nukutoa, but interviews with elders revealed memories of at least five similar incidents extending back to the 1940s. Prior inundations recalled by the elders include one in the 1940s, another in the 1950s, one in 1962 or 1963, another in 1973, and one in the 1980s. A more precise record of when these events occurred would be preferred, but villager accounts suggest their frequency has not increased in recent decades, a perception supported by swell-influenced sea-level anomalies at Midway atoll determined to be a reliable proxy index of North Pacific storminess (Aucan et al., 2012). We note that there is no memory of inundation associated with severe TC Annie in 1967 that generated large seas and damaging surge at Ontong Java (Bayliss-Smith, 1988; Rasmussen et al., 2009), approximately 300 km east–southeast of Takuu. This is likely due to TC Annie's rapid west southwest path, which puts the largest swells to the south of the cyclone track (Nott, 2006), and increasingly distant from Takuu.

Modelling by Hoeke et al. (2013) indicates 4–5 m swells reached Takuu during the December 2008 event. Waves of 4–5 m have a return interval of around 5 years at Takuu and are thus not uncommon. However, the concurrence of such waves and La Nina (MEI < -0.5; Wolter and Timlin, 1998) elevated sea levels as occurred during December 2008 extends the return interval to around 32 years (Hoeke et al., 2013). We emphasise that the largest waves arrived 4 days before the highest high tide for that lunar period, which may have raised water levels a further 0.3 m and enabled more and larger waves to propagate across the reef (Gourlay, 2011b; Pequignet et al., 2011). The 0.171 m sea-level anomaly associated with the La Niña was also not extreme. Neither the wave height nor parameters influencing sea level (ENSO phase, tidal stage) were exceptional during the 2008 wave event. Nonetheless, because wave energy over reef flats is strongly depth limited (Gourlay, 2011b; Pequignet et al., 2011), the coincidence of seasonally higher spring tides (Walsh et al., 2012) and phenomena such as ENSO that can periodically elevate sea level (Church et al., 2006; Merrifield et al., 2012) tend to increase the probability of damaging swell-induced surges and inundations on reef islands (Woodroffe, 2008). Even though the tidal range at Takuu is less than 2 m, tidal modulation of water depth and wave propagation across the reef flat during the December 2008 event was clear; waves surged across the reef flat and over Nukutoa for a few hours either side of the higher daytime tides but were less active at lower tidal levels, including the lower evening high tides which peaked up to 0.7 m below the daytime counterparts.

Inundations comparable to the December 2008 flooding at Nukutoa have been reported from reef islands across both equatorial and storm belt latitudes, with mid-latitude storms commonly implicated. Solomon and Forbes (1999) reported damaging inundation at Tarawa (173°00′E; 1°30′N) associated with swells and generated by distant storms, and attributed erosion and destruction in the Cook Islands to 'energetic swell' generated in the North Pacific and Southern Oceans. They provide a detailed account of the July 1996 inundation at Manihiki Atoll, Cook Islands (161°00′W; 10°25′S) when 5 m swells (>3 m above normal height) outside the atoll raised lagoonal water levels by around 1 m. Inundations are reported from the Republic of the Marshall Islands (events in November and December 1979 (Ginoza, 1979) and December 2007, September and December 2008 (Chowdhury et al., 2010; Fletcher and Richmond, 2010); the Maldives (events in April 1987 (Khan et al., 2002), 1988 (Woodroffe, 2008), May 2007 (United Nations Office for the Co-ordination of Humanitarian Affairs); and Ontong Java (flooded in early 2006 (Rasmussen et al., 2009)). Hoeke et al. (2013) provide a comprehensive list of reported inundations. The number of inundations generated by distant storms and their influence on atoll geomorphology and populations has undoubtedly been under-reported (or misreported as tsunami), and we support recent calls to better understand these events (Walsh et al., 2012).

6.3. Broader implications

Our observations of the December 2008 wave event on Nukutoa have broader implications for reef islands more generally, and for assessments of vulnerability to projected climate-change impacts. Generated by storms more than 3000 km away, this event caused erosion on more than 60% Nukutoa's shoreline and inundated more than 50% the island. The 4–5 m waves at the reef edge on Takuu were comparable to wave heights associated with Severe TC Tomas which tracked within 30 km of Taveuni, Fiji in 2010, producing geomorphological changes that were spatially patchy due local factors such as coral community composition, reef edge morphology and the nature of existing sediment deposits (Etienne and Terry, 2012). Others have also noted the patchiness of cyclone impacts (e.g. Harmelin-Vivien, 1994; Etienne, 2012), but most describe the formation of reef flat storm ridges and lobes composed of both newly fractured and/or reworked material as well as erosion impacts (e.g. Blumenstock, 1958; Stoddart, 1962; Bayliss-Smith, 1988; Scoffin, 1993; Etienne and Terry, 2012). However, severe cyclones do not always storm produce ridges (Richmond and Morton, 2007; Etienne, 2012), and it probable that the geomorphic impacts of inundation events may be equally as patchy. If material was available at Takuu a rubble ridge may have formed; stripping of beach sediments from the shoreline, damage to seawalls, and extension of the sand spits into the lagoon confirm that waves and wave-generated currents were competent to entrain and transport sediments to at least small boulder size several hundred metres back from the reef edge (Fig. 8E).

The geomorphological impacts of severe tropical cyclones and swells generated by distant storms may, however, differ due to different wave and hydrodynamic conditions over the reef rim. Cyclone waves within a few hundred kilometres of a storm typically have maximum periods between 10 and 20 s (e.g. Young and Hardy, 1993; Lugo-Fernandez and Gravois, 2010), comparable with the hindcast peak wave period of 17.2 s calculated for waves offshore at Takuu during the 2008 event (Hoeke et al., 2013). However, wave energy over the reef flat is largely limited by depth (Gourlay, 2011a). Where intense tropical cyclones pass close to a reef the depth and wave size over the reef flat can be increased by storm surge. For example, flood depths (storm surge and waves) above 7 m occurred during Severe TC Tomas (Etienne and Terry, 2012), and many records exist of storm surge increasing depth over reef flats enabling damaging waves to wash across atoll reef flats and islands (Blumenstock, 1958; Stoddart, 1962; Bayliss-Smith, 1988). In contrast, swells generated by distant storms have propagated beyond the wind fields where significant storm surge can develop. Wave set-up may increase depth over the reef flat during swell events allowing waves to travel further across the reef than tidal depths alone, but the magnitude of this set-up is rarely more than 20% of breaking wave height (Gourlay, 2011a). Maximum set-up calculated for the December 2008 event was just 0.84 m (Hoeke et al., 2013).

Waves propagating across the reef near Nukutoa during the December 2008 event were conspicuously long period (averaging around 7 min) and bore-like infragravity waves (Baldock, 2012) (Fig. 4B), surging through the interisland passages rather breaking and reforming as storm waves typically do (Gourlay, 2011b). The formation of these surges requires an understanding of complex wave transformations at the reef edge not possible here (and as far as we are aware, not resolved for infragravity waves), and thus the following assessment may be overly simplistic. However, as surging waves across the reef flat were restricted to a few hours around the higher daytime high tides between December 7 and 10 (around 4 h for 4 days), approximately 140–160 such waves propagated over the reef during the event. In contrast, the same number of 20-second period cyclone waves would break across the reef flat in just 45 min, demonstrating a fundamental difference between the hydrodynamics of each type of event. Similarly, in contrast to wave run-up and swash associated with wind-waves that build ridges and berms (Gourlay, 2011b), waves during the December 2008 event surged across the island surface, with sediment deposits and debris suggesting without backflow.

Although the Sumatran tsunami arrived at the Maldives as a series of rising tidal surges rather than the bore-like surge at Nukutoa, similar patterns of inundation and subtle topographic control of flow paths were reported (Kench et al., 2008). Geomorphological changes during the December 2008 event at Nukutoa also have many affinities with those of the December 2004 tsunami on Maldivian reef islands, where sediments were stripped from exposed beaches and transported leeward, and where sand sheets similar to the one at Nukutoa formed (Kench et al., 2008). Indeed, the homogenous structure of the Nukutoa sand sheet is more typical of tsunami deposition (Kench et al., 2006); those deposited by cyclones typically include discrete laminations deposited by successive overwashing waves (Morton et al., 2007; Etienne and Terry, 2012). The homogeneity of the Nukutoa sand sheet may be a function of the well-sorted beach sediments of which it is composed, or alternatively suggest that the limited sand supply was exhausted by the first overwashing wave. Recognition that far-field storms may periodically leave sedimentary and geomorphological signatures very similar to tsunami deposits on low-latitude reef islands has implications for researchers attempting to interpret palaeo-histories of tsunami (Morton et al., 2007; Goff et al., 2011), especially where low-latitude reef islands are targeted to avoid the confounding influence of storms.

A recurrence interval exceeding 100 years may be reasonably estimated for a severe cyclone passing close to Takuu based on historical accounts from Ontong Java (Bayliss-Smith, 1988). Swell-driven inundations of a magnitude comparable to the December 2008 event have a calculated average return interval of around 30 years (Hoeke et al., 2013) and are thus far more frequent, with 'memorable' events recalled by elders on Takuu even more common, occurring roughly once a decade (Fig. 9B). If the geomorphic impacts observed at Takuu are typical, shorelines at low-latitude reef islands like Nukutoa will be eroded without any of the immediate (event) or ensuing (post-event) constructional legacies normally associated with proximal cyclone impact. Swells produced by mid- and high-latitude storms will also affect reefs and reef islands in the storm belts, but those regularly affected by cyclones are likely to be more robust (Massel and Done, 1993; Harmelin-Vivien, 1994). Indeed on storm-adapted reefs far-field swells may contribute to the shoreward transport of cyclone-generated sediment deposits. In contrast, where cyclones and sediment delivery by storms are less frequent, the accretionary benefits of cyclones may not persist through the extended inter-storm period. Reef islands may transition to an erosional phase once the storm-supplied sediments are exhausted, and it is during this part of the cycle that far-field swells can worsen reef island erosion. This sequence is validated by observations at Ontong Java, where the accretionary redistribution of cyclone ridges onshore takes approximately 20 years, but the average recurrence interval for severe storms is 60–100 years (Bayliss-Smith, 1988). Villagers report a shift from island accretion after TC Annie in 1967 to erosion now as a sediment budget deficit has developed in the absence of storm-delivered replenishment (Rasmussen et al., 2009). The number of intense cyclones is projected to increase over the next century (Knutson et al., 2010), potentially generating more swell events capable of impacting distant reefs. The future behaviour of mid-latitude storms is less certain (Booth et al., 2012), but the number and strength of high-latitude storms is confidently projected to grow (Solomon et al., 2007). An important implication is that low-latitude reef islands geographically isolated from heavy direct storm impacts and known to be less resilient to them may in the future experience more storm waves generated by distant storms.

In addition to short-term and dynamic effects related to tides, storm surge, and set-up that may influence water depth over reef flats, sea-level fluctuations associated with ENSO phase may modulate the geomorphic influence of swell events, with inundation and wave related geomorphological impacts highest when coincident with positive sea-level anomalies. The ENSO phase during which sea levels are elevated varies geographically (Becker et al., 2012); at Takuu the largest positive sea-level anomalies accompany strong La Nina conditions. Changes in the spatial development and tempo of ENSO cycles detected over the past half century are expected to continue into the future (Becker et al., 2012), modifying both the frequency and intensity of storms (Donnelly and Woodruff, 2007) and the generation of sea-level anomalies, changing the exposure of low-latitude reef islands to distant-source swells. As sea levels rise through the next century, the exposure of reef islands may increase where they are unable to keep pace, or where they structurally compromised (Sheppard et al., 2005). Critically for people living on reef islands, episodic inundations and the damage and disruptions they cause present the biggest and most immediate challenge to continued habitability — not the gradual increase in sea levels.

Finally, the influence of shoreline management activities and structures on the geomorphological response of Nukutoa to the December 2008 event must be acknowledged. Even on this remote island where access to sophisticated technology is limited, 45% of the shoreline was behind seawalls at the time of the event. Seawalls interfere with natural shoreline processes, modifying sediment distribution and shoreline condition prior to events, as well as the morphodynamic response to them. Although the seawalled shoreline on Nukutoa experienced limited serious damage during the December 2008 event, where seawalls occur sand volumes stored in beaches available for transport onshore by waves was reduced, and wave run-up onto the island margin was impeded. Both these conditions diminish prospects of morphodynamic adjustment and autonomous adaptation argued to accommodate to future changes in climate and sea level (e.g. Webb and Kench, 2010). Natural morphodynamic adjustment will occur on reef islands with shorelines unmodified by anthropogenic activities, but cannot progress where humans reacting to shoreline change construct seawalls. Although this is well recognised for urbanised reef islands (Ford, 2012), the extent to which traditional reef island shores have been modified and/or managed and the implications of this for future shoreline trajectories remains poorly understood. It is possible that even on remote Nukutoa anthropogenic modifications of the coastline to reclaim land and slow erosion have and will continue to override any geomorphic trajectory. We note that the older parts of the village located on higher ground were not inundated during the December 2008 event, whereas housing and infrastructure later constructed nearer the shoreline was. Since 1943 the population on Nukutoa has roughly doubled (Bourke and Betitis, 2003) and the area of the village increased by 450%. Most of the village expansion has been onto lower and sometimes reclaimed land nearer the shore, where exposure to inundation is increased. The situation at Nukutoa parallels that reported at Funufuti where village expansion onto low-lying land has increased the vulnerability of some in the community to flooding (Yamano et al., 2007), and is likely to be replicated on many other reef islands with limited space where population growth has occurred. Conversely, we emphasise that the impacts of the December 2008 wave event on Nukutoa – with its high degree of anthropogenically modified shoreline – may not be representative of the behaviour of completely unmodified islands. However the beach, conglomerate and scarped shorelines unprotected by seawalls (and comprising 55% of Nukutoa's coastline) were typical of those we have observed on a large number of reef islands, and the seawalls were typical of many we have seen constructed on remote inhabited islands. We are confident that the observations reported and discussed above are relevant to both unmodified reef islands and to many with anthropogenically modified coasts.

7. Conclusions

Nukutoa is located close to the equator and outside of the storm belt, and is rarely affected by severe storms. In December 2008, Nukutoa experienced 4 days of very high water levels and waves, which washed completely over approximately 50% of the island, and caused mostly minor erosion to approximately 60% of the shoreline. These waves were generated by weather systems more than 3000 km distant from the atoll. Six different erosionary impacts were observed. Accretion was limited to the deposition of a sand sheet covering 13% of the island surface, and marked expansion of the lagoonward sand spits. Although the geomorphic impact of this event was modest, historical accounts and statistical analyses confirm they are not infrequent events, occurring on average every 30 years, and thus their cumulative impacts over the longer term requires consideration. The implication is that these under-reported events affect both 'low-energy' and high-energy settings more frequently than currently acknowledged, and their geomorphological role (and significance in terms of current sea level rise and reef island habitability concerns) needs further examination. Recognising that both the factors that generate the initiating storms and those that amplify the impacts of resultant swells on any reef will vary spatially and through time in response to phenomena including tides and ENSO phase, a priority goal should be to construct joint probability models (Caldwell et al., 2009) that examine the frequency with which combinations of the contributing factors are likely to be exceeded at particularly vulnerable reefs and reef islands.

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