Sedimentary Geology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Special Issue Contribution: SEDIMENTARY EVIDENCE OF GEOHAZARDS

Magnitudes of nearshore waves generated by tropical cyclone Winston, the strongest landfalling cyclone in South Pacific records. Unprecedented or unremarkable?

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ARTICLE INFO

Article history:
Received 10 May 2017
Received in revised form 11 October 2017
Accepted 13 October 2017
Available online xxxx

Editor: Dr. J. Knight

Keywords:
Coastal boulders
Extreme waves
Wave magnitude
Cyclone Winston
South Pacific
Tropical cyclones

ABSTRACT

We delimit nearshore storm waves generated by category-5 Tropical Cyclone Winston in February 2016 on the northern Fijian island of Taveuni. Wave magnitudes (heights and flow velocities) are hindcast by inverse modelling, based on the characteristics of large carbonate boulders (maximum 33.8 m^3, 60.9 metric tons) that were quarried from reef-front sources, transported and deposited on coral reef platforms during Winston and older extreme events. Results indicate that Winston's storm waves on the seaward-margin of reefs fringing the south-eastern coasts of Taveuni reached over 10 m in height and generated flow velocities of 14 m s^{-1}, thus coinciding with the scale of the biggest ancient storms as estimated from pre-existing boulder evidence. We conclude that although Winston tracked an uncommon path and was described as the most powerful storm on record to make landfall in the Fiji Islands, its coastal wave characteristics were not unprecedented on centennial timescales. At least seven events of comparable magnitude have occurred over the last 400 years.

1. Introduction

1.1. Understanding disaster risk from tropical cyclones

The Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR, 2015), adopted by the United Nations in 2015, places 'understanding disaster risk' as the first priority in the global task of substantially reducing the human cost of disasters over the coming decades. Embedded in the first priority is the need to understand the characteristics of hazards. In the tropical South Pacific basin, tropical cyclones are one of the main natural hazards that occur with an annual frequency. Much has undeniably been learnt concerning the patterns and behaviour of tropical cyclones in the South Pacific (e.g., Basher and Zheng, 1995; Kuleshov et al., 2008; Terry and Gienko, 2010; Dowdy et al., 2012; Diamond et al., 2013). Dealing with cyclones nonetheless remains a great challenge for Pacific Islands nations (Magee et al., 2016).

Over recent years, a number of particularly devastating tropical cyclones has impacted various island nations, including Heta, Pam and Winston that struck Niue, Vanuatu, and Fiji respectively in 2004, 2015 and 2016. These cyclones surpassed previous records for their widespread destruction in the islands they afflicted. This paper focuses on Cyclone Winston, currently ranked third most intense cyclone to form in the South Pacific basin and one of the most powerful systems ever recorded in the southern hemisphere (FMS, 2016b). Winston is remarkable for making history by becoming the first cyclone to make landfall in the Fiji Islands as a category-5 system and is the most severe cyclone to make landfall in the South Pacific (FMS, 2016c; WMO, 2016) (Fig. 1). A state of emergency was declared after extensive ruin was inflicted across Fiji, with 40,000 houses damaged or destroyed. Costs of damage have been estimated at FJD 2.98 billion (USD 1.4 billion); Winston was therefore the costliest ever cyclone for the Fiji Islands. Close to 40% of the nation's population (350,000 people) was impacted in a significant way (WMO, 2016). Fatalities numbered 44.

High-magnitude but low-frequency cyclone events pose a concern for coastal vulnerability. An important question in the aftermath of Winston is whether such a storm represents the upper limit of cyclone intensity to be anticipated in Fiji, or have events of greater magnitude been experienced in the past? Such questions are not easy to answer. Satellite observations of tropical cyclones only stretch back to the 1970s. This provides a limited dataset for empirical analysis. Unknown stronger storms may have occurred before the modern satellite record began. In addition, little information on wave height and power is

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https://doi.org/10.1016/j.sedgeo.2017.10.009
0037-0738/

Please cite this article as: Terry, J.P., Lau, A.Y.A., Magnitudes of nearshore waves generated by tropical cyclone Winston, the strongest landfalling cyclone in South Pacific records. Unprecedented or unremarkable? Sedimentary Geology (2017), https://doi.org/10.1016/j.sedgeo.2017.10.009

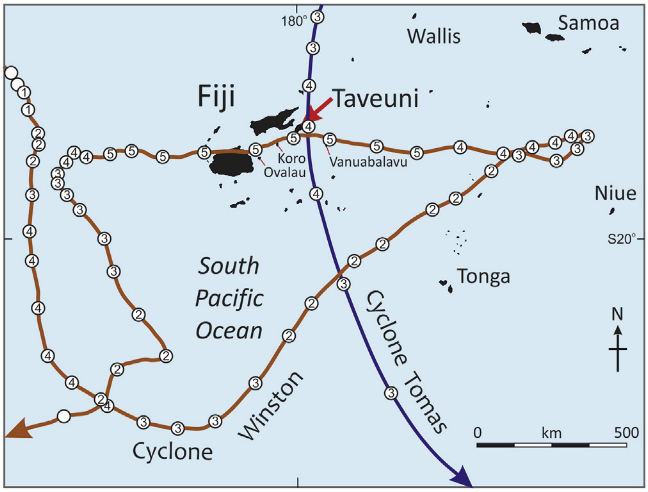

Fig. 1. Track map for cyclones Winston in February 2016 (orange line) and Tomas in March 2010 (blue line), showing positions at 6-hourly intervals. Numbers in the round position markers denote the intensity according to the Australian Tropical Cyclone Intensity Scale, which uses a five-category system based on maximum 10-min sustained winds. Category 1: 34–47 knots (63–87 km/h), Category 2: 48–63 knots (89–117 km/h), Category 3: 64–85 knots (119–157 km/h), Category 4: 86–107 knots (159–198 km/h), Category 5: ≥108 knots (≥200 km/h). For categories 3–5, a system is classified as a 'severe tropical cyclone'. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

available. But the majority of the Pacific Island populations lives on the coast, and is therefore especially at risk from marine flooding. Although a combination of satellite altimetry and modelling provides a way to hindcast wave data for individual cyclones (Bosserelle, 2015; Cruz-Castro, 2016), derived wave data are more representative of offshore conditions rather than wave characteristics experienced directly along affected coastlines. Moreover, such methods cannot be applied to palaeo-cyclones. For this, other methods are needed. One technique available is inverse modelling of wave heights and flow velocities from the characteristics of wave-transported coastal boulders (Nandasena et al., 2011, 2013; Nakamura et al., 2014; Weiss and Diplas, 2015).

1.2. Study aims

The principal aim of this study is to delineate the characteristics of nearshore storm waves generated by Winston on the northern Fiji island of Taveuni (N16°50′, 180°). Findings are then compared with the magnitude of storm waves generated by earlier cyclones, both recent and prehistorical. This work is carried out to determine whether Winston was the most powerful storm to have struck Fiji over past decadal to centennial timescales. Such knowledge deduced from comparisons of cyclone-generated extreme wave magnitudes will be a useful guide in future endeavours pertaining to coastal hazard perceptions across Fiji and beyond. The task is accomplished using geomorphic proxy methods to interpret wave characteristics, namely wave heights at breaking and resulting water flow velocities induced at the coastline. Methods are based on the analysis of large reef-derived carbonate boulders that were transported and deposited on Taveuni's eastern coastline during Winston and older extreme events.

Taveuni Island is selected as the study site because it lay adjacent on the north side of Winston's track and was therefore heavily impacted by storm waves. Furthermore, Taveuni's coastal storm deposits have previously been investigated following an earlier cyclone strike by Tomas in 2010 (Fig. 1), for which data are available allowing useful comparison (Etienne and Terry, 2012; Terry and Etienne, 2014). Tomas had a contrasting track to Winston, approaching Taveuni from the north rather than the east. On 15 March 2010, Tomas passed 30 km east of Taveuni (Fig. 1); this track orientation meant that winds of 100 knots (185 km hr^{-1}) and gusts up to 140 knots (259 km hr^{-1}) were directed onshore along the eastern coast of Taveuni as the storm approached. Consequently, heavy swells of 4 m or more offshore were generated (FMS, 2010). Unconfirmed media reports mentioned floods (storm waves and storm surge combined) over 7 m at the coast, causing inundation of low-lying areas by Tomas.

1.3. Coastal boulder investigations

1.3.1. Boulder proxies for storm events

First described in the early 20th Century as a potential proxy for high-magnitude storms (Hedley and Taylor, 1907), coastal boulder analysis is now a well-established field in (palaeo)geomorphological research, and has been applied across a range of tropical and extra-tropical regimes (Etienne and Paris, 2010; Goto et al., 2010; Terry et al., 2013; Lau et al., 2015). Coastal boulder deposits have been used to characterise the nature of palaeo-storms (and tsunamis), enabling comparisons with recent events, and permitting approximations of the temporal frequencies of the strongest events experienced over centennial to millennial timescales on specific coastlines. Measuring the position, orientation and size of coastal boulders reveals clues concerning the characteristics (e.g., height, direction, power) of the storm waves that deposited them (Goto et al., 2009; Etienne, 2012; May et al., 2015; Terry et al., 2015). Tropical coasts behave differently from mid- and high-latitude coasts because the interaction of storm waves with fringing coral reefs produce and transport low-density boulders of carbonate lithology that may be distributed in boulder fields across reef platforms. Carbonate boulders sourced from living reefs fringing a coastline may yield information on the timing of palaeo-cyclone events through the cautious application of laboratory age-dating of boulder coral fabric (Hearty, 1997; Zhao et al., 2009; Yu et al., 2009, 2012; Atwater et al., 2017).

1.3.2. Boulder movement by waves

Understanding the hydrodynamic mechanisms responsible for boulder dislodgement by causative waves, their subsequent movement, and the interaction of physical influences, are complex problems. Boulders normally possess irregular shapes, which interact in a non-linear fashion with the turbulent water flow around them (Weiss and Diplas, 2015). The pre-transport setting, i.e., whether boulders are bounded by, or free of, their parent rock mass (Nott, 2003), rock-platform geomorphic features such as boulder traps and topographic irregularities (Naylor et al., 2016), and bed slope and roughness in the vicinity of boulders (Weiss and Diplas, 2015), are all crucial factors in both initial boulder dislodgement and total wave transport.

A principal pursuit has been to determine whether any boulder evidence can be used to distinguish between storm and tsunami waves (e.g., Nott, 1997; Noormets et al., 2004; Switzer and Burston, 2010; Atwater et al., 2017). One observation has been that the numerous waves impinging on coasts during storms can organise boulders in landward-fining trends (although this is not always the case, e.g., Naylor et al., 2016), whereas more powerful but individual tsunami waves are more likely to leave erratic and disorganised boulder distributions (e.g., Goto et al., 2010; Weiss, 2012). However, recent work is challenging earlier ideas that storm-driven waves are less competent than tsunamis at large boulder transport. Detailed investigation of coastal conditions during 2013 Supertyphoon Haiyan in The Philippines, through wave modelling and observations caught on film, combined with examination of resulting coastal deposits, has shown that surf beat and long-period infragravity waves can produce tsunami-like bores, capable of quarrying and redistributing very large clasts and lifting boulders to elevations up to 10 m (May et al., 2015; Roeber and Bricker, 2015). In consequence, Kennedy et al. (2017) reach the conclusion that the largest blocks transported by storm waves overlap much of the tsunami transport range.

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