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Short communication

A relationship to describe the cumulative impact of storm clusters on beach erosion

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ABSTRACT

Estimation of erosion volumes for adequate dry beach buffer zones is commonly estimated on the basis of a single extreme event, such as the 1 in 100 year storm. However, the cumulative impact of several smaller, closely spaced storms can lead to equal, if not more, dry beach loss, but this is often not quantified. Here we use a calibrated model for dune erosion, XBeach, to hindcast the cumulative erosion impact of a series of historical storms that impacted the Gold Coast, Queensland region in 1967. Over a 6-month period, four named cyclones (Dinah, Barbara, Elaine, and Glenda) and three East Coast Lows caused a cumulative erosion volume greater than the predicted 1 in 100 year event. Results presented here show that XBeach was capable of reproducing the measured dry beach erosion volume to within 21% and shoreline retreat to within 10%. The storms were then run in 17 different sequences to determine if sequencing influenced final modeled erosion volumes. It is shown that storm sequencing did not significantly affect the total eroded volumes. However, individual storm volumes were influenced by the antecedent state of the beach (i.e. prior cumulative erosion). Power-law relationships between cumulative energy density ($\sum E$) and eroded volume (ΔV) as well as cumulative wave power (($\sum P$)) and eroded volume (ΔV) both explained more than 94% of the modeled dry beach erosion for the 1967 storm sequences. When the relationship was compared with observed and modeled erosion volumes for similar beaches but different storm forcing, the inclusion of pre-storm beach swash slope (β_{swash}) in the parameterization was found to increase the applicability of the power-law relationship over a broader range of conditions.

1. Introduction

While sandy coastlines are observed to be highly dynamic on timescales from days to years, the impact of storms on beaches can cause dramatic erosion over a very short time period. Storm waves determine the destructive potential of a storm, while the range in water levels (tides and surge) also influences the erosion potential, particularly on the upper beach, in the presence of spring tides and large surge. Notable examples of large erosion events include the impact of hurricanes and Nor'easters along the east coast of the USA, such as the 2013 'Super Storm Sandy', as well as tropical cyclones and East Coast Lows along the east coast of Australia, such as the 2007 'Pasha Bulker Storm'.

While typically we design for the impact of these extreme individual storms (i.e. the 1 in 100 year event, which signifies a storm that has a 1% chance of occurring every year), the cumulative impact of smaller closely-spaced storms (i.e. storm sequencing, or clusters) can far outweigh the erosion potential of a single much larger storm (Birkemeier et al., 1999; Callaghan et al., 2009; Carley and Cox, 2003; Castelle et al., 2008; Cox and Pirrello, 2001; Ferreira, 2002, 2005; Thom and Hall, 1991). Examination of almost 20 years of Duck, North Carolina data by Birkemeier et al. (1999) showed that the largest integrated wave power associated with a storm group had an average return interval of occurrence (ARI) of 20 years. However, for an individual storm of equivalent wave power, this equated to greater than a 1 in 1000 year event (i.e. 1000 year ARI). As such, it is critical for coastal engineers and managers alike to be able to predict erosion volumes for both single storms and the cumulative impact of smaller storms in order to protect the coastline and adjacent infrastructure.

This communication focuses on the sequence of storms that impacted the Gold Coast, Queensland, Australia region during the first half of 1967 and summarized in McGrath (1968) and Allen and Callaghan (1999). It is estimated that nearly 8 million cubic meters of sand was lost from the subaerial beach (above mean sea level, MSL) during this 6-month period of above average wave conditions (Delft, 1970). As a consequence, this sequence of storms is often used as the design storm for the region.

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The calibrated model, XBeach (Roelvink et al., 2009), is used to first predict the erosion for the 6-month period in 1967 and then assess if storm sequence may have impacted the total observed beach erosion. This communication then utilizes these results to examine more generally the relationship between cumulative storm forcing (measured as wave power or wave energy density) and total erosion volumes along a micro-tidal, exposed open coastline.

2. Methodology

2.1. Data

2.1.1. Storm selection

Based on McGrath (1968) three named cyclones (Dinah, Elaine, and Glenda) and three East Coast Lows (ECLs) had deep-water H_s over 2 m and were used to estimate the impact of storm sequence on overall beach erosion at the Gold Coast (Table 1). Along the Gold Coast, $H_s =$ 2 m approximates the 95% exceedance value and the threshold of $H_s > 2$ m to define a storm wave is commonly used along the South-East coast of Australia (e.g. Shand et al., 2011). A storm start and finish was defined when H_s first exceeded this threshold (start) and the last successive time before H_s fell below the threshold (end).

Storm clusters are often characterized by recurring high wave events in close succession such that the beach does not have adequate time to recover significantly between events. The definition of a storm group depends on the recovery timescale of the specific beach. Typically 1 to 2 months is used as a threshold between storms to define a storm cluster (Birkemeier et al., 1999). However, along the Portugal coast, Ferreira (2005) utilized 3 weeks between storm peaks or 2 weeks between the end of one storm and the start of the next to define a storm group. Spacing between the 1967 storms ranged from a few days to just over 2 months (1). For the sequence of storms considered here, McGrath (1968) stated that for the first six months of 1967 the swell was generally heavy and that conditions conducive to beach recovery did not return until September 1967, and as such, is considered a single event (storm group).

2.1.2. Available bathymetry

Bathymetry data for the northern Gold Coast (Narrowneck) were generated from digitized profiles shown in McGrath (1968), Delft (1970), and available Gold Coast City Council surveys. Pre-storm surveys were from October 1966 and post-storm surveys were dated July 1967. It is noted that the inner surf zone/bar was not surveyed for the pre-storm survey and the gap in the data was linearly interpolated. The two most landward points from the 1967 survey were used to extend the 1966 profile backwards to allow for additional erosion.

2.1.3. Waves

No wave buoys were located in the area in 1967 such that wave statistics were taken from the global wind-wave model of the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year wave Re-Analysis with the wave height correction applied by Caires and Sterl (2005) (corrected ERA-40) for grid point coordinates (28.5°S, 154.5°E) located approximately 122 km southeast of the Gold Coast. Modeled directional wave data included spectral significant wave height (H_s), mean wave period based on the 2nd moment (T_{02}), and wave direction measured from degrees North (θ). Mean wave period was transformed to peak wave period (T_p) based on the method of Paik and Thayamballi (2007), p.107 assuming a JONSWAP ($\gamma = 3.3$) spectrum (Hasselmann et al., 1976). These were used as offshore boundary conditions in a calibrated MIKE-21 spectral wave model (Splinter et al., 2012). Modeled wave statistics (H_s, T_p, θ) in 25 m of water directly offshore of Narrowneck were extracted from the MIKE-21 spectral wave model and used as input into XBeach.

Table 1
Storm duration (denoted as hrs where $H_s > 2$ m), integrated wave energy density, E (Eq. (2)) and wave power, P (Eq. (3)).

Storm	Start date	Duration (hrs)	$\sum E$ (MJh/m^2)	$\sum P$ (MWh/m)
Dinah	28-01-1967	48	0.25	1.92
Elaine	12-03-1967	126	0.39	2.79
Glenda	31-03-1967	138	0.54	4.30
ECL1	11-06-1967	120	0.51	3.95
ECL2	21-06-1967	54	0.19	1.36
ECL3	26-06-1967	108	0.42	3.64

2.1.4. Total water levels

Total water levels can also play an important role in the erosion potential of a storm (e.g. Dean, 1991) when it lasts several tidal cycles or makes impact during spring high tides (particularly important on large tidal range beaches). These elevated water levels further expose the upper beach and dune system to direct wave impact. To include this forcing mechanism, water levels were derived from the superposition of tides and surge information detailed in McGrath (1968). Maximum surge recorded was of the order of 1 m and occurred on June 27th during ECL3. Total water levels (excluding wave setup and runup) for all six storms considered never exceeded 2 m above mean sea level (MSL). This is of the same order of magnitude as the mean spring tide range for the Gold Coast(~1.5 m) as reported by Turner et al. (2006) and as such, was not considered to be the principal driver of beach erosion during these storms. Additionally, as peak surge frequently occurred during the peak of the storm (when wave heights and periods were also at their largest), simple relationships correlating wave height to erosion may also capture some effect of total water levels.

2.2. Model

XBeach (Roelvink et al., 2009) is a process-based numerical model designed to estimate eXtreme Beach erosion under storm events. The reader is referred to Splinter and Palmsten (2012), Roelvink et al. (2009) and the XBeach user's manual (www.xbeach.org) for a complete description of the model. Model inputs included a time series of 3-hourly offshore significant wave heights (H_s), spectral peak wave period (T_p), and wave direction (θ, degrees North) as well as hourly total water elevation (tide + surge) as described above.

For the results presented here, XBeach (version 18) was run in profile mode and calibrated using the Narrowneck pre- and post-storm surveys from the May 2009 East Coast Low as detailed in Splinter and Palmsten (2012). Good model agreement between the observed dry beach erosion and modeled erosion for the May 2009 ECL was found using default values except γ_{ua} (best-fit = 0.15), which defines the influence of short wave skewness and asymmetry on sediment transport, and wave dissipation (best-fit = Roelvink (1993), Eq. 2). Observed shoreline retreat was 28 m and was modeled to within 1 m. Observed dry beach erosion volume (measured above 0 m AHD (Australian Height Datum) and roughly equal to MSL) was 66 m^3/m and was over-estimated by 11 m^3/m (17%). Detailed sensitivity analysis to both errors in the pre-storm profile and model free parameters is presented in Splinter et al. (2011) and Splinter and Palmsten (2012).

2.3. Assumptions and simplifications

Several simplifications have been made in order to run the 1967 storm sequence. First, the model was run in profile mode (no alongshore gradients in transport) and this was assumed as an acceptable simplification given that the focus here is on the modeled dune erosion (a cross-shore process) and limited survey data was available. Longshore transport is of order 500,000 m^3/year (e.g. Patterson, 2007; Splinter et al., 2012), however, alongshore gradients in longshore transport are not the dominant mode of shoreline variability at the seasonal to annual scale (Davidson and Turner, 2009; Davidson et al., 2013). Second, the