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Widespread inundation of Pacific islands triggered by distant-source wind-waves ☆

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ABSTRACT

It is essential to understand the causes of sea level extremes in order to anticipate and respond to coastal flooding (inundation), and to adapt to sea level rise. We investigate a series of inundation events which occurred across the western Pacific over several consecutive days during December 2008, causing severe impacts to five Pacific Island nations. These events were not associated with commonly identified causes: tropical cyclones or unusually large astronomical tides. Instead, the dissipation of wind-waves generated by distant extra-tropical cyclones (swell) was the main cause, although regional sea level variability, including recent accelerated rise, significantly contributed to the severity of impact experienced at many locations. The implication of recent sea level rise in the severity of these events suggests that episodic swell will increasingly cause major impacts of the nature described herein, although such impacts will continue to be modulated by El Niño/Southern Oscillation (ENSO) variability in the region. Significantly, tide gauges recorded little evidence of extreme sea levels during the event, implying that causes of extreme sea levels inferred from tide gauge analysis are unlikely to include this important cause of inundation. Therefore, any assessment of inundation risk predicated on tide gauge information (as well as larger scale sea level information such as satellite altimetry) may fail at many locations in the Pacific. To be accurate, such efforts must include information on the relationship between wave climate, wave forecasts and local extreme water levels. Further development of related early warning systems will become more pertinent as modern SLR continues to add to the magnitude of extremes.

1. Introduction

More frequent and severe inundation associated with climate-change related sea level rise (SLR) is one of the biggest threats to coastal communities and particularly island nations (Nicholls et al., 2007; Seneviratne et al., 2012). Inundation events can significantly change shorelines, damage infrastructure, contaminate freshwater reserves, destroy food crops, and in the severest of cases, take human lives (Barnett, 2011). Higher mean sea levels will exacerbate the impacts of extreme sea levels caused by a range of other processes. Understanding the processes that cause extreme sea levels and subsequent inundation is of paramount importance to climate change adaptation strategies of island nations.

It has long been recognized that long-wavelength wind-waves (swell) produced by mid-latitude storms can propagate across entire ocean basins, sometimes to distances greater than 20,000 km (Munk et al., 1963; Delpey et al., 2010). Wave set-up, or the elevation of the mean still water surface due to the breaking (dissipation) of wind waves (Longuet-Higgins and Stewart, 1964), can reach approximately 1/3 of incident wave height along coasts typical of tropical and sub-tropical islands (Munk and Sargent, 1948; Tait, 1972; Vetter et al., 2010), and therefore has the potential to be a significant driver of extreme sea levels along these coastlines. Additionally, swell dissipation typically generates infra-gravity waves (e.g. Pomeroy et al., 2012) and causes uprush of individual waves at the shoreline (wave run-up), which may have considerable coastal impact. This suggests that the arrival of such swells may be a trigger of inundation events along such coasts. However, despite some evidence that this is the case (Harangozo, 1992), peer-reviewed literature on swell-driven

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contributions to extreme sea levels and associated coastal impacts is extremely limited: more commonly cited causes are astronomical tides, tropical cyclone storm surges and regional sea level variability such as that due to El Niño/Southern Oscillation (ENSO), e.g. Church et al. (2006), Lowe et al. (2010), Menèndez and Woodworth (2010) and Walsh et al. (2012). Contributing reasons for the scant literature addressing swell as a cause of extreme sea level events likely include the relative remoteness of island communities, relatively poor reporting networks (OCHA, 2011; Kruke and Olsen, 2012), and the low density of in situ observations of coastal sea level and surface waves (Lowe et al., 2010). The greater importance of wind set-up and inverse barometric pressure (collectively referred to as storm surge) relative to wave set-up along better studied (and instrumented) continental shelves (Kennedy et al., 2012; Walsh et al., 2012) may also have led to the (mis)conception that coastal inundation processes are relatively well predicted and well understood for island communities. Another significant factor, as we show here, is that the tide gauge network, which is the primary data source for extreme sea level analysis (e.g. Menéndez and Woodworth, 2010), may completely miss or at least under-represent the contribution of swell to extreme sea levels.

Here, we document the environmental context and impacts surrounding a series of major inundation events, which occurred in the western Pacific during December 2008. We draw on data from a variety of sources, including newspaper articles, regional humanitarian situation reports and available meteorological and oceanographic data and reanalysis products. Most reports suggest that significant inundation occurred over several consecutive days at high tide, with several reports indicating additional impacts due to wave run-up and infra-gravity bores “surging” across low-lying islands. The reports indicate widespread and severe damage to infrastructure and key natural resources such as soils and freshwater at islands in Micronesia, the Marshall Islands, Kiribati, Papua New Guinea and the Solomon Islands. We show that a large, though not unique, swell generated in the mid-latitude regions of the northern Pacific Ocean, more than 4000 km from the furthest affected island, was the main cause of these damaging events, but that regionally elevated sea level, due to both La Nina conditions and non-ENSO SLR, also played an important role.

2. Data sources and derived information

2.1. Inundation reports

Reports of inundation were collated from a variety of sources including; the United Nations Office for the Coordination of Humanitarian Affairs (http://www.unocha.org/) Situation Reports database, the International Federation of Red Cross and Red Crescent Societies (http://www.ifrc.org/) Disaster Management Information System (DMIS) database, the Pacific Disaster Net database (http://www.pacificdisaster.net/), the U.S. Federal Emergency Management Agency (http://www.fema.gov/), as well as reports from disaster management and meteorological agencies of the island countries and personal interviews (see Supplementary Table S1 for a summary of all reports). Information contained within the reports varied widely and significant interpretation was required, e.g. level of impact was sometimes difficult to ascertain and actual inundation may have occurred somewhat earlier than reported, given the remote location of the events (Kruke and Olsen, 2012). Despite these challenges, the date, time, maximum water level and overall damage of the inundation reported at each location were ascertained as objectively as possible and converted to UTC time to allow comparison with geophysical data. We classified the reported inundation impacts (or lack thereof) as following:

(1) None: no reported damage
(2) Minor: some reported damage to homes and/or limited evacuation
(3) Major: reported crop losses up to 50% and/or damage to infrastructure and/or more widespread damage to homes and some degree of community displacement
(4) Severe: reported crop losses greater than 50% and/or significant overtopping/overwashing of islands and/or displacement of large portions of entire communities.

Inundation and coastal impacts were often reported for multiple locations within single reports, sometimes encompassing vast areas (for instance, all of West Sepik, New Ireland and Bougainville provinces in Papua New Guinea (PNG), the east–west extent of which is approximately 1700 km). For simplicity, however, we report wave, sea level and meteorological information for a smaller number of “representative” locations, based primarily on proximity to geophysical data (e.g. tide gauges). These representative locations are not always in the immediate vicinity of affected locations. For instance, at locations such as Wake, Kwajalein and Majuro atolls, a tide gauge is located within the lagoon of the affected islands. In the Solomon Islands (SI) however, the Honiara tide gauge is the closest gauge to the affected atolls of Ontong Java and Sikaiana, which are several hundred kilometers north east, respectively; we therefore use Honiara as a “representative” location, despite Honiara itself being unaffected (this is something of an extreme case in the analysis). For conciseness then, we use the place or country name or acronym when discussing general reported inundation impacts, but use the representative location (based on proximity to geophysical data) or its 4-letter code when discussing actual geophysical values. For example, we use Papua New Guinea (or PNG) when discussing the event's impact on the country, but use Takuu (TAKU) or Lombrum (LOMB) when discussing or plotting tidal or wave height values for two representative locations within in PNG. See Table 1 for further clarification.

2.2. Tides

Hourly tide gauge data from the University of Hawaii Sea Level Center (http://uhslc.soest.hawaii.edu/) and the Australian Bureau of Meteorology's South Pacific Sea Level and Climate Monitoring Project (http://www.bom.gov.au/pacificsealevel/) were sourced for most locations listed in Table 1. Prior to analysis, tide gauge water levels were adjusted to a zero bias with respect to a global sea-surface height reconstruction (*SSHR*, see next section) at each location. A common datum of zero mean between the years 1990 and 1995 (a period with relatively minimal ENSO extremes) was used for both tide gauge water levels and *SSHR*. Harmonic analysis and prediction using exact nodal/satellite corrections were carried out using Utide software (Codiga, 2011). Non-tidal residuals were calculated by subtracting the resulting predicted tidal time-series from the (datum adjusted) observations. Predicted tidal heights in Table 1 are given relative to a Mean Higher High Water (MHHW) datum, defined as the mean of the highest daily tide for an 18.6-year period at each location. This makes comparison with other water level drivers easier, as the predicted highest tides are relative to an average high tide.

Water level observations for Takuu Atoll (PNG) were derived from a pressure sensor deployed in the lagoon for 22 days, fortuitously during the inundation event. The water level observations' datum was adjusted by minimizing bias between predicted tides and the observations when sea level anomaly and wave heights were at a minimum during the observation period. Tidal predictions for Takuu and for Kosrae (FSM) were made using the most current version available of the TPXO global tidal model (Egbert and Erofeeva, 2002); version 7.2 (http://volkov.oce.orst.edu/tides/).

2.3. Regional sea level, pressure and winds

A monthly gridded (1° × 1°) sea-surface height reconstruction (*SSHR*) for years 1950–2010 (Church et al., 2004; Church and White,