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Changes to extreme wave climates of islands within the Western Tropical Pacific throughout the 21st century under RCP 4.5 and RCP 8.5, with implications for island vulnerability and sustainability

James B. Shope [a,*], Curt D. Storlazzi [b], Li H. Erikson [b], Christie A. Hegermiller [c]

[a] University of California at Santa Cruz, Earth and Planetary Sciences, 1156 High Street, Santa Cruz, CA 95065, USA
[b] US Geological Survey, Pacific Coastal and Marine Science Center, 400 Natural Bridges Drive, Santa Cruz, CA 95060, USA
[c] University of California at Santa Cruz, Ocean Sciences, 1156 High Street, Santa Cruz, CA 95065, USA

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ABSTRACT

Waves are the dominant influence on coastal morphology and ecosystem structure of tropical Pacific islands. Wave heights, periods, and directions for the 21st century were projected using near-surface wind fields from four atmosphere–ocean coupled global climate models (GCM) under representative concentration pathways (RCP) 4.5 and 8.5. GCM-derived wind fields forced the global WAVEWATCH-III wave model to generate hourly time series of bulk wave parameters around 25 islands in the mid to western tropical Pacific Ocean for historical (1976–2005), mid-century, and end-century time periods for the December–February and June–August seasons. The December–February regional wave climate is dominated by strong winds and large swell from extratropical cyclones in the north Pacific while the June–August season brings smaller waves generated by the trade winds and swell from Southern Hemisphere extratropical storms. Extreme significant wave heights decreased (~10.0%) throughout the 21st century under both climate scenarios compared to historical wave conditions and the higher radiative forcing RCP 8.5 scenario displayed a greater and more widespread decrease in extreme significant wave heights compared to the lower forcing RCP 4.5 scenario. An exception was for the end-century June–August season. Offshore of islands in the central equatorial Pacific, extreme significant wave heights displayed the largest changes from historical values. The frequency of extreme events during December–February decreased under RCP 8.5, whereas the frequency increased under RCP 4.5. Mean wave directions rotated more than 30° clockwise at several locations during June–August, which could indicate a weakening of the trade winds' influence on extreme wave directions and increasing dominance of Southern Ocean swell. The results of this study underscore that December–February large wave events will become smaller and less frequent in most regions, reducing the likelihood and magnitude of wave-driven flooding at these island locations over the 21st century. However, relatively large increases in the mean of the top 5% of significant wave heights and large changes to the mean direction of these waves in the June–August season at several islands within 150–180° E will drive greater flooding and island morphological change along previously more stable shorelines. The reported results herein project large changes to tropical Pacific island wave climates that will be necessary for assessing island vulnerability under climate change in future studies.

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1. Introduction

Large wave events generated from tropical and extratropical cyclones pose a significant threat to low-lying Pacific island nations. Flooding from these events can damage infrastructure, salinate groundwater, and ruin crops; the waves can induce large morphological changes to island coastlines (Terry and Falkland, 2010; Aucan et al., 2012; Hoeke et al., 2013; Smithers and Hoeke, 2014). It is anticipated that sea-level rise (SLR) will increase the severity of flooding events, as more wave energy will reach the shoreline (Nicholls et al., 2007; Storlazzi et al., 2011; Seneviratne et al., 2012). However, these SLR projections do not take changing wave climates into account. Understanding how the magnitude and frequency of large wave events will change over the next century is critical to anticipate hazards to island communities and changes to island morphology.

Previous research projecting the stability and sustainability of tropical Pacific islands (Dickinson, 1999; Woodroffe, 2008; Webb and Kench, 2010) has predominantly focused on inundation from SLR. Sea level in the western tropical Pacific (WTP) rose at a rate of 4.3 mm/yr over 1993–2001, which is significantly faster than the global average of approximately 3.0 mm/yr (Church et al., 2006, 2013). Increased SLR rates in the WTP are associated with increased regional trade wind intensity (Merrifield, 2011; Merrifield and Maltrud, 2011). If SLR in the

* Corresponding author.
E-mail address: jshope@ucsc.edu (J.B. Shope).

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WTP continues at a fast rate, the region will likely experience more extensive inundation in the near future. However, extreme wave events coupled with SLR will threaten island communities before inundation by SLR alone, as increased sea level will contribute to extreme high water levels along coasts, allowing nearshore waves to be larger and more damaging (Seneviratne et al., 2012).

Global (Hemer et al., 2013; Mori et al., 2013) and regional (Semedo et al., 2013) projections of future WTP wave conditions show general decreases in boreal winter (December–February) and summer (June–August) significant wave heights (H_s) by the end of the 21st century. These projections, however, focus on mean wave parameters instead of extreme events. There has been limited exploration of global extreme wave conditions, but recent studies forecast decreases in Pacific extreme H_s (Fan et al., 2013; Wang et al., 2014). Regional-scale projected extremes are still uncertain, yet Pacific island nations are increasingly threatened by SLR and depend on these projections as extreme events deliver the most devastating impacts to insular communities and island morphologies (Fletcher and Richmond, 2010; Hoeke et al., 2013).

Many extreme wave events within the WTP are dominated by swell waves generated by extratropical cyclones (Hoeke et al., 2013). In December 2008, an extreme event inundated five island nations in the tropical Pacific over a period of several days, resulting in significant damage to community infrastructure and large-scale coastal erosion (Fletcher and Richmond, 2010; Smithers and Hoeke, 2014). However, there have been few studies projecting how waves from extratropical storms within the WTP will change over the 21st century and how these changes may affect island nations in the region. Combined with King tides (maximum annual spring high tides), El Niño Southern Oscillation (ENSO)–induced seasonal sea level anomalies, and/or tropical cyclone storm surge, extratropical cyclone waves can deliver even more energy to island shorelines via reduced depth-limited breaking (Storlazzi et al., 2011; Seneviratne et al., 2012; Hoeke et al., 2013). Therefore, extratropical swell has the potential to cause significant flooding events along low-elevation Pacific island coastlines throughout the WTP.

In this paper, we present results derived from near-surface wind fields from four Coupled Model Intercomparison Project, phase 5 (CMIP5) global climate models (GCMs) used to force WAVEWATCH-III (WW3) to project wave conditions in the WTP. Projections of December–February (DJF) and June–August (JJA) parameters of the mean of the top 5% of significant wave heights were developed for historical (1976–2005), mid-century (2026–2045), and end-century (2081–2100) time periods. This study focused primarily on waves generated in extratropical regions. These extratropical-generated swell waves, although likely smaller than typhoon-generated waves, will pose a hazard to these islands throughout the 21st century as SLR enables more extensive flooding. A description of the study area's wave climatology and island vulnerability is given in Section 2. Section 3 details the GCM and WW3 input parameters and analysis methods. Section 4 presents the model skill analysis, changes in wind speed conditions, and extreme wave parameters (heights, directions, and frequencies) relative to historical values. Wave parameter changes during DJF and JJA for the mid- and end-century are presented separately. A discussion of implications to island vulnerability from these changes is presented in Section 5 and conclusions in Section 6.

2. Study area

2.1. Wave and Wind Climate

This study focused on 25 island locations in the tropical Pacific west of 150° W (Fig. 1a) that were divided into six regions based on proximity and similarity of general atmospheric patterns (Australian Bureau of Meteorology and CSIRO, 2014): Western, Marianas, Central, Northeast, Eastern Equatorial, and Southern (Fig. 1b). WTP H_s are generally larger and more energetic during boreal winter than during other seasons (Young, 1999; Bromirski et al., 2013). Swell generated by northern hemisphere extratropical cyclones dominates the extreme wave climate of the WTP during boreal winters and summers. Boreal winter waves are generally the largest in the region each year, except for the Southern Hemisphere islands, where waves are largest during the boreal summer (Young, 1999). These waves can traverse more than 4000 km within the basin, delivering energy from mid-latitude cyclones to islands near the equator (Hoeke et al., 2013). During boreal summer, waves generated by easterly trade winds dominate the swell wave spectrum in the eastern half of the study area. Waves generated in the Southern Hemisphere characterize larger swell waves in the western half of the region during the boreal summer (Young, 1999; Australian Bureau of Meteorology and CSIRO, 2014).

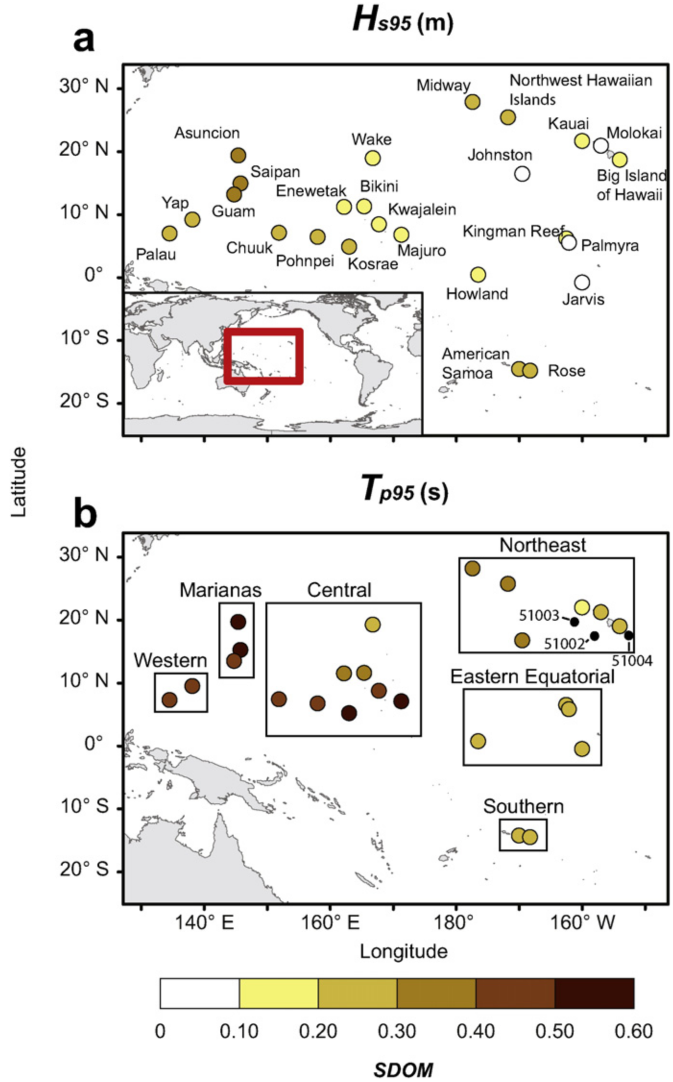

Fig. 1. Extent map of the study area displaying model coherence over the hindcasted period (1976–2005). (a) H_{s95} and (b) T_{p95}. The colors represent the magnitude of the standard deviation of the mean (SDOM) for (a.) H_{s95} and (b.) T_p of H_{s95} values. The red box in (a) indicates the study area within the global map. Black boxes in (b) represent regional groupings of output points based on proximity and similar variation. Black points in (b) represent National Data Buoy Center station names and locations near the Hawaiian Islands.

Easterly trade winds dominate atmospheric circulation and surface winds within the region throughout most of the year (Australian Bureau of Meteorology and CSIRO, 2014). However, the strongest winds in the region are the result of tropical cyclones and other storm systems. The northeast quadrant of the study area receives strong winds and large waves from mid-latitude storms during boreal winter, despite the