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Using local knowledge to project sea level rise impacts on wave resources in California

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ABSTRACT

Sea level rise will have significant impacts on many coastal resources. Waves are an important resource in California, where they support the recreation of 1.1 million surfers who inject millions of dollars into local economies. The impacts of sea level rise on wave resource quality, however, are unknown. By examining the local knowledge of more than one thousand California surfers collected through an online survey, this study extrapolates their evaluations to estimate the susceptibility of California surf-spots to sea level rise based on the principle of tidal extrapolation. Vulnerability classifications are derived from the relationship between wave quality, tide effects, and sea floor conditions. Applying these classifications to 105 surf-spots in California evaluated by multiple respondents, we project that as a result of sea level rise by 2100: 16% of surf-spots are Endangered due to drowning; 18% are Threatened, but could adapt if natural shoreline processes are not impeded; and 5% might improve as rising sea levels increase the likelihood they will experience optimal conditions. These projections are significant not only for the many surfers who depend on surf-spots, but also for the coastal communities who rely on the availability of high quality wave resources. Results from this study also have important implications for when and how managers might take surf-spot quality and vulnerability into consideration through coastal adaptation. Lastly, this study establishes a baseline of wave resource quality in California and suggests that this baseline will shift as wave quality changes over the coming century.

1. Introduction

Sea level rise is affecting coastal communities worldwide and the severity of these impacts is projected to increase in the coming century as the rate of sea level rise increases (Church et al., 2013; National Research Council, 2012). The results include growing threats to critical infrastructure, private property, human populations, cultural and economic resources, and entire island nations (Caldwell et al., 2013; Hanak and Moreno, 2012; Langridge et al., 2014; Marzeion and Levermann, 2014). In coastal California, dense development and a large, rapidly growing population are both susceptible to sea level rise; Heberger et al. (2009) estimate that the replacement cost of coastal property at risk from inundation by 1.4 m of sea level rise could be nearly $100 billion. These estimates, however, exclude the effects of impacts to the quality of breaking waves, which are valuable and potentially vulnerable resources in California. Breaking waves are a key element of California's intertidal ecosystems, are central to the viewshed and experiences of many tens of millions of people who live on and visit the California coastline each year, and enable surfing—one of the most iconic, as well as culturally and recreationally significant, activities in coastal California. Surfers rely on carefully honed knowledge of the behavior of ocean waves that informs their ability to catch and ride waves (Reineman, 2016). This study draws on an assessment of this local knowledge among California surfers to estimate how sea level rise will impact California's wave resources and discusses the implications of these impacts in the context of coastal management and climate change adaptation.

Waves drive surfing and, in turn, the character of coastal communities. In 2006, the surfing industry was valued at more than $7.4 billion in the US alone (Lazarow et al., 2008) and is projected to reach $13.2 billion globally by 2017 (Global Industry Analysts, 2014). The 1.1 million surfers in California, roughly one-third of

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the nation's total, contribute substantially to the estimated $2 to $5 billion national, annual economic impact from US surfers (Leeworthy and Wiley, 2001; Wagner et al., 2011; the number of surfers has likely increased in the 1.5 decades since these participation data were collected). The geology and bathymetry of California's active coastline (Griggs et al., 2005) lead to a high diversity of wave types, including those well suited to all surfing ability levels, from beginner to expert (Guisado and Klaas, 2005), and to a full range of oceanic swell conditions (Espejo et al., 2014). Surfers are central to California's beach image and coastal cities in California have been home to some of surfing's most seminal moments, which have in turn shaped the identities of many coastal communities (Warshaw, 2010; Westwick and Neushul, 2013). Huntington Beach, CA, for example, proclaims itself “Surf City, USA,” an exclusive title for which it vied bitterly with the city Santa Cruz, CA (Carcamo, 2008).

Along these coastlines, surfers rely on specific coastal locations, “surf-spots,” where depth and bottom contours interact with incoming ocean swells to produce waves that break in a way that favors riding (Butt et al., 2004). The characteristics of any surf-spot vary with the tide, swell, wind, and other conditions, as does the sensitivity of a surf-spot to changes in these conditions. For example, an ebbing tide could reduce wave quality at one surf-spot and improve it at another surf-spot, or have little effect at either depending on the size of the swell. These variations are predictable with differing levels of accuracy and precision and the general features of individual surf-spots remain fairly constant over time allowing surfers to predict with some certainty the quality of the waves at any given time. This predictive capability enables the surf forecasting industry to help surfers choose where to surf given the day's current and expected conditions (see *e.g.*, Surfline Inc. or Magicseaweed Ltd.). While these services may offer global coverage, forecasting and daily wave quality reporting are often conducted on a surf-spot-by-surf-spot basis, which is important given the amount of potential variability between surf-spots and also given that many surfers surf both frequently and close to home (Nelsen et al., 2007; Wagner et al., 2011).

Despite the cultural and economic importance of surfing and the relative predictability of wave quality in the short term via oceanographic and meteorological forecasting, little is known about the potential long-term impacts of sea level rise on surf-spots in California, or elsewhere. Speculation within the surf media, however, is common. Surfer Magazine, for example, asks:

> Sea level is expected to increase by about three feet. Many of us surfers get pretty picky about the volume of water overlaying our surfing topography. Three extra feet at any given time means that your favorite high-tide spots will be your everyday spots. You may find new high-tide favorites, but you might not see your low tide favorites… like, ever… Where are you going to surf? (Taylor, 2013)

This question as posed also emphasizes the individual nature of wave-quality preference among surfers, who develop knowledge about (Reineman, 2016) and affinities for specific surf-spots (Reineman and Ardoin, In Review). Thus, the focus of surfers' concerns is not only global—that is, how will ocean waves change—but highly local—how will each specific surf-spot change.

Impacts of changing global climate on the ocean's waves have been projected, primarily through numerical modeling-based approaches. Hemer et al. (2013) project ocean basin-scale changes in wave size resulting from changes to ocean water temperature and storm frequency and intensity (among other factors). Espejo et al. (2014) developed a Wave Quality Index and modeled wave quality at roughly 100 km resolution for all the world's coastlines. These efforts, while valuable, do not address wave quality and variability at scales relevant to individual surfers or to the communities vested with coastal management authority. Other investigators have applied numerical modeling techniques at the scale of individual surf-spots (see, *e.g.*, Feddersen, 2007; Spydell and Feddersen, 2009), but these data and computationally intense techniques are challenging to implement at the scale of entire coastlines.

The objective of this study is to fill this gap by recording the local ecological knowledge of more than 1000 California surfers via a survey-based approach and to use this knowledge to evaluate the potential impacts of sea level rise on individual surf-spots across the California coast.

2. Methods

This study primarily relies on data for conditions at California surf-spots collected through a survey of California surfers that was disseminated online in the spring of 2014. Surf-spots evaluated by respondents were verified against a dataset of surf-spot descriptions assembled and curated by a surf forecasting company. A projection of sea level rise impacts is generated based on today's tidal range through tidal extrapolation.

2.1. Tidal extrapolation

Breaking waves have very specific relationships with water depth: wave shoaling (first interaction with the seafloor) begins when the water depth is one-half of wave length and wave breaking occurs when the wave height is three fourths the water depth (Garrison, 2001). The depth over a given location on the seafloor fluctuates daily as the tide rises and falls and this has significant impacts on breaking wave quality at many surf-spots (Butt et al., 2004). Tidal extrapolation capitalizes on the overlap between current (*i.e.*, present day) tide ranges and those projected when sea level has risen (Fig. 1). Climate change-induced sea level rise is a vertical translation, not only of sea level, but also of tide range such that in the future at a given location, high tide and low tide will be higher than at present. (The mean tide range between high and low tides has increased at most West Coast tide stations over the preceding century (Flick et al., 2003), but these range changes are minor compared to projected increases in mean sea level.) Until the point when a future tide range, centered around a higher mean sea level, no longer overlaps with today's tide range, the current-day and future tide ranges will share a set of sea surface levels across those portions of their ranges that overlap (Fig. 1). Therefore, a portion of current tide levels are not merely representative of future tide conditions, but are instances when the water depth at a surf-spot is the same today as it will be in the future. The exact date of a future sea level embodied in a current-day tide level depends on a variety of factors, including tide range, isostatic adjustment, and rates of sea level rise, processes that vary locally and each change slowly and continuously. Table 1 displays current-day tide ranges and project increases in sea level for two regions of the California coast.

This study relies on a characterization of current-day conditions within the zone of overlapping depths and extrapolation outside this zone to understand how California's surf-spots will potentially behave under a higher sea level regime in the future. This approach is conceptually similar to that employed by the California Coastal Commission's “King Tides Initiative” (Papendick, 2013), which seeks to highlight future threats from sea level rise to coastal property and infrastructure by providing visual documentations of present day inundation events during extreme high tides.