SUPPLEMENTAL ONLINE MATERIALS:

The impacts of climate change on surfing resources

By

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I. THE DYNAMIC PHYSICAL BASIS OF SURFING WAVES

For the purposes of this review, we only discuss and consider impacts to wind-generated surface gravity waves on the ocean breaking in nearshore waters.[1] The following non-technical summary of these processes is drawn from several sources, including (Garrison 2001, Hutt *et al.* 2001, Mead and Black 2001a, 2001b, Cool 2003, Scarfe *et al.* 2003, Butt *et al.* 2004, Espejo *et al.* 2014, Meldahl 2019). We divide the overview to focus separately on swell generation and wave breaking, and also briefly summarize a variety of other factors relevant to breaking wave quality for surfing.

A. Swell generation, propagation, and transformation

Initially, wind perturbs the ocean's surface generating surface displacement of water, counteracted by gravity.[2] Three factors, the wind's speed, duration, and distance over which it blows (its "fetch"), control the eventual size of the waves generated, though the exact processes by which wind leads to waves are still not perfectly understood (Pizzo *et al.* 2021). Waves are dispersive in deep water and two key characteristics — wavelength (distance between individual wave crests) and period (time between passing crests) — determine the speed at which waves propagate away from their source such that like-sized waves group together in "wave trains" and travel outward as swells. Wave power, also called wave energy flux, is the rate of transfer of wave energy through a fixed point.

[1] As participation in surfing has grown, surfers now ride waves of various other types in pelagic, lake, river, and completely humanmade settings; surfing originated in the nearshore ocean (see Warshaw 2010).

[2] Though at extremely small scales, this counteracting ("restorative") force is surface tension.

In deep water, waves do not interact with and are not affected by the sea floor and therefore can travel for great distances, with longer wavelength waves traveling faster than smaller waves. Upon reaching shallower water, waves begin to "shoal" (interact with the bottom, i.e. touch or "feel" bottom) and their wavelength and speed decrease. The conservation of energy then leads to an increase in their amplitude (or height: the vertical distance between trough and crest). In shallow water, wave speed is determined by depth, rather than wavelength and period. Refraction is the change of direction of wave propagation based on depth and differential areas of shoaling (and associated decrease of wave speed) along a wave crest's lateral extent. Refraction results in parallel, incoming lines of swell "wrapping" or bending around bathymetric features to break in directions potentially different from their direction of origination.travel perpendicularly to the decreasing depth approaching a shoreline. Reflection is precisely that: a reflection of wave energy and direction of propagation off a rigid structure (natural or anthropogenic) in its path. In sum, key factors in the generation of swells, from a surfing perspective, include (1) origin location of generation (and thus their "direction" of origination from the perspective of the coasts where they eventually arrive), (2) wave power, derived from the intensity of the weather systems that create them, and, though not discussed above, (3) frequency of swell generating storm events, as from the surfing resource perspective, more frequently occurring rideable waves are preferred to fewer. Local to regional winds can also result in rideable waves at surf breaks, referred to as "wind swell" in contrast to "groundswell" that is more distantly generated by storm events.

B. Wave breaking

Waves begin to break when the wave height-to-wavelength ratio exceeds a critical threshold such that the wave becomes steeper to the point of instability. Generally, the seafloor slope (change in water depth over distance) determines how quickly a wave shoals and breaks: steep slopes (rapidly decreasing depth) yield high energy "plunging" waves; gentle slopes (gradually decreasing depth) yield lower energy "spilling" waves; other situations resulting from wave-wave interactions can likewise generate these break characteristics. Surfing occurs when a surfer maneuvers themself (usually paddling "by hand," though wind or mechanical power sources can also be used) into a breaking wave (or nearly breaking) and harvests energy from the moving water to move with along it. Lateral motion of the surfer along the wave face is likewise determined by the relative angle ("peel angle") that the wave breaks relative to the incoming wave crest, with lower peel angles generating faster rides, but a peel angle of zero representing a "close-out" in which the whole wave breaks at once (Walker *et al.* 1972, Hutt *et al.* 2001). Along with offshore bathymetry, the relative orientation of the coastline to incoming swells delineates the surf break's "swell corridor," the range of angles of incoming swell direction that generate waves at the break. A break with a wide swell corridor receives swell originating from broader range of directions versus a break with a narrow corridor (Atkin and Greer 2019).

C. Additional factors

Other surfing-relevant aspects of breaking waves include local wind patterns that alter a wave's rideability based upon the wind's strength and direction; this can either favorably groom a wave for riding (e.g. offshore wind assisting plunging breakers to hold their shape and become more "hollow") or degrade waves (e.g. onshore wind accumulates surface chop along the shoreline and disrupts the consistency of the breakers).

Each of the physical factors described above are dynamic in space and time (see Figure 1 in main manuscript) and each influences the manner in which an individual wave breaks, as well as the type and quality of the summation of individual waves at a surf break. The factors shaping open ocean swells (wind speed, direction, fetch, and location in an ocean basin) vary in time and space according to season. The depth of water on the coast varies according to the tide cycle, lunar cycle, and other factors (*e.g.*, seasonal thermal expansion trends). Depth at any specific location on the coast varies further based on the composition of the seafloor on that coast, which derives from its geographic, geologic, and geomorphic setting, including basic composition of the coast itself (based on tectonics, continental margins, and plate boundary processes) and its proximity to sediment sources (e.g. rivers, creeks, calcifying organisms, coastal dunes, bluffs, and estuaries) and sinks (e.g. submarine canyons, offshore flow from headlands). Differences in seafloor composition within or between coastal locations are further shaped by water motion (itself influenced by wave action), which depending on its energy can accrete, erode, and transport sediment and thereby alter seafloor shape and water depth, with attendant implications for breaking wave quality.

Local biota can also play a role, by either creating the seafloor itself (e.g. as by a coral reef), anchoring sediment in place (e.g. as by mangroves on the perimeter of shorelines, coastal dune vegetation onshore, or potentially seagrass meadows offshore (de Boer 2007), dampening surface chop (e.g. as by kelp forest canopies), or adding to the supply of sediment (e.g. through the lifecycle of calcifying microorganisms or the breakdown of calcifying organisms by digestion in herbivores or predators or by physical processes). Various internal and external factors, including seasonality and general ecosystem health, can alter the rate or strength of these processes.

Many of these dynamic, interacting processes are subject to influences of climate change, others can be altered by human activities that, themselves, may be carried out in direct response to climate change impacts. The main manuscript (Section III) provides an overview of these influences and their potential positive and negative effects for surf breaks and surfing.

II. NUMERICAL MODELS AND OCEAN WAVES

Models are built using historic, "hindcast" observations, collected through remotely sensed data, coupled with *in situ* measurement instruments, such as buoy arrays and drifter networks (O'Reilly *et al.* 2016). Wave models generate information on key wave parameters (including, significant wave height, wave power, wave period, and wave direction of propagation). This information is compiled, calibrated, "trained," and validated using subsets of historically measured observations. Inputs of near-term future atmospheric conditions can force these models to produce short-term (accurate to several days) forecast models for swell heights, which have seen pronounced improvement in recent decades (e.g. the Coastal Data Information Program, https://cdip.ucsd.edu; last accessed 26 February 2023). Publicly available, government-supported efforts (e.g. WaveWatch III, https://polar.ncep.noaa.gov/waves/wavewatch; last accessed 26 February 2023) have been incorporated into various private and commercial platforms specifically targeting surfing and coastal user communities (e.g. https://www.surfline.com, http://www.stormsurf.com, and others; last accessed 26 February 2023).

Global climate models are comprehensive efforts to combine the mathematical descriptions and relationships of many physical variables and include ocean surface gravity waves, as detailed above, since these result from energy transfer from wind to water. Such models now enable projections of a variety of future environmental factors and conditions, including trends of future wave climate (SOM Table 1). For more details on global climate modeling, see, among others: Christensen *et al.* 2013, Wang *et al.* 2014, Erikson *et al.* 2015, Morim *et al.* 2018, 2019, Collins

Table 1.

Climate model projection for key wave characteristics by ocean basin. Projected ▼ decreases and ▲ increases in key wave parameter with significant findings indicated with *. Sub-basin level trends indicated by N (north), E (east), W (west), S (south), T (tropical) or combinations thereof (*e.g.*, EN = eastern north).

Ocean Basin	Significant Wave Height H_s	Average Period T_m	Average Direction θ_m	Wave Power (WP)
Southern Ocean	▲ mean[a,b,c]; ▲ extreme[c,o,*l]	▲[c]	Shift in swell propagation to tropics[a, b, c,f, g,n]; clockwise shift[c]	▲* [a,m]
Pacific	**N:** ▼ mean ~10% under RCP 8.5[c] **EN:** ▲ mean S Alaska and NE Hawai'i[i] ▼ mean much of EN[i,o] ▼ in extreme south of ~50°N[i] ▲ in extreme north of ~50°N Gulf of Alaska[i] **W:** ▼* (pronounced in Boreal Winter)[a] **TE:** ▲ mean[a,b,c,d,k] ▲* maximum[k] **ES:** ▲ average and extreme[c]	**EN:** ▲ and peak ▲* for southwest facing coasts[l] **W:** ▼[a] **ES:** ▲[c]	**EN:** extreme shift counterclockwise at ~53°N, slight change 30-50°N; confidence in northward and/or westward displacement of major storm tracks [i] **WN:** poleward migration of maximum tropical cyclone intensity [d]	**N:** ▲* mid-high latitudes; ▼mid-latitudes[a] **W:** *▼[a]
Atlantic	No consensus mean[b] **N:** ▼ of mean[b,c,d, *o,*l] ~10% RCP 8.5 2019[c] **NW:** ▼ mean[a] **S:** ▲* extreme[l]	**N:** ▼[a] **NW:** ▼[a]	-	**N:** ▲* high latitudes; ▼ mid-latitudes[a]
Indian Ocean	**TN:** ▲[a] **S:** ▼* (Austral Summer), ▲* (Austral Winter)[a], ▲* extreme[l]	-	-	▼* [a]
Global	▲ overall, but not regionally homogeneous. Certain ocean basins will increase more than others[e] ▲ extreme at 59% of global coastlines[l] ▼ mean over ~26% global ocean [g]	▲[e] over ~44% global ocean[c], over ~30% global ocean[f] ▲* most Southern Hemisphere ▲* for the eastern portions of Northern Hemisphere sub-basins, consistent with enhanced Southern Ocean swell propagation[a]	Clockwise shift over tropical Pacific/Atlantic (~32% of globe) and counterclockwise shift elsewhere[c] Poleward shift storm tracks and jet stream, widening of tropical belt, contraction of northern polar vortex and Southern Ocean westerly wind belt[d,n]	▲[e]

Superscript references are as follows*: a.* Lemos et al. 2019*; b.* Morim et al. 2018*; c.* Morim et al. 2019*; d.* Collins et al. 2019*; e.* Reguero et al. 2019*; f.* Hemer et al. 2013*; g.* Hemer and Trenham 2016*; h.* Christensen et al. 2013*; i.* Erikson et al. 2015*; j.* Odériz et al. 2021*; k.* Wang et al. 2015*; l.* Meucci et al. 2020*; m.* Wang et al. 2014*; n.* Sigmond et al. 2011*; o.* Lobeto et al. 2021*. For detailed scenarios and graphical visuals of these data, see individual references, such as the supplemental materials available for* Morim et al. 2019*.*

et al. 2019, Lemos *et al.* 2019, Oppenheimer *et al.* 2019. Here we limit our review to how these efforts intersect and can provide outputs relevant for wave modeling.

Many academic and international governmental collaborative efforts have been established to perturb parameters of different climate models to simulate climate change scenarios. The production of global circulation, global climate, and eventual climatological global mean wave field modeling efforts are driven using representative concentration pathways (RCPs) of global greenhouse gas concentrations. Two scenarios are commonly used: RCP 4.5 representing a medium and RCP 8.5 representing a high emission scenario. Outputs of interest (from a surfing perspective) from these modeling efforts are mean significant wave height, mean wave period, direction and propagation of swell, wave energy flux, and extreme/maximum wave conditions. The model outputs under different future RCP scenarios can be compared to historic observations to determine potential changes in these parameters from climate change. While these global climate-modeling efforts are large and complex in nature, they can be downscaled for and utilized to generate information of future global wave climate conditions. As swell production is critical for rideable surfing waves, these modeling efforts provide insight on how the surfing resources of the future may be altered by a changing climate.

III. MULTI-PURPOSE REEFS AND ARTIFICIAL SURFING REEFS

Multi-Purpose Reefs (MPRs) are a shoreline management strategy that could dampen storm surge and incoming swell energy and thus protect shorelines and mitigate coastal erosion while simultaneously generating surfing waves (Black and Mead 2001, Ettinger 2005, do Carmo and Neves 2009, ten Voorde *et al.* 2009, Kang and An 2018). Additional proposed benefits include reduction of coastal flooding, increasing longevity of beach nourishment, and provision of habitat for marine species with associated recreational/commercial activities (Black and Mead 2001, Turner *et al.* 2001b, Pattiaratchi 2007, Black and Mead 2009, Jackson *et al.* 2012, Rendle and Rodwell 2014). Prior attempts to engineer artificial surfing reefs (ASRs) for explicitly surfing-focused benefits exist (though *unintentional* creation of surf breaks resulting from other shoreline or sediment management activities is more typical[3]). Several MPRs have been implemented, monitored, and evaluated to determine if they achieved their intended goals,[4] including: in Australia, Palm Beach[5], Narrowneck (Turner *et al.* 2001a, Jackson *et al.* 2005, 2012), Neilson's Park, Burkitts Reef, and Cables Reef; in the United States, Hoppy's Reef and Pratte's Reef (Borrero and Nelsen 2003), in New Zealand, Mount Maunganui (Scarfe *et al.* 2009)[6]; in the United Kingdom, Boscombe (Atkin 2010, Fletcher *et al.* 2011, Rendle and Davidson 2012); and in India, Kovalam[7].

With advancements in hydrodynamic modeling and coastal engineering, as well as the need for increased shoreline protection, several ventures are in the conceptual phase to design and implement MPRs (e.g. Webber Reefs[7]), and ASRs (e.g. Airwave[8]). These have generated additional momentum to understand the feasibility of MPRs with surfing amenities in Western Australia (Albany Reef and Bunbury Airwave) and California (Oceanside[9]). While these technologies are still in the research, feasibility, and design phase, pilot and demonstration projects suggest benefits for coastal communities experiencing erosion and preparing for future impacts. In summary, there is a small but global distribution of artificial and multipurpose surf breaks, but there is limited evaluation of the long-term success of purpose-built ASRs and MPRs (though some investigations do exist: see Mead and Borrero 2017 for review). The feasibility and desire for effective and efficient MPRs is growing in coastal communities including investigations of other features offshore that can influence wave preconditioning (Atkin *et al.*

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[3] These byproducts where a rideable wave is enhanced or created due to an engineered feature include such notable surf breaks as: in the United States, Mannesquin (New Jersey), Sandspit and the Wedge (California), Pumphouse and Sebastian Inlet (Florida); in South Africa, New Pier (Durban); and in Brazil, Barrinha Saquarema (Rio de Janeiro); among many others.

[4] For a review of these, see artificial surfing reef profiles curated at https://raisedwaterresearch.com (last accessed 26 February 2023).

[5] See https://stabmag.com/news/this-artificial-reef-on-the-gold-coast-is-showing-serious-potential (last accessed 26 February 2023).

[6] See https://www.surfer.com/features/pipe-dreams-artificial-reef (last accessed 26 February 2023).

[7] See https://webber-reefs.com (last accessed 26 February 2023).

[8] See https://www.surfer.com/features/western-australia-inflatable-artificial-reef (last accessed 26 February 2023).

[9] See https://www.ci.oceanside.ca.us/government/public-works/beaches-pier/coastal-management (last accessed 26 February 2023).

2019). As investments in coastal resilience and adaption continue, it seems likely that more MPRs will be proposed and implemented.

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