**Incident Wave Swath Method: Formulation and Limitations**

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**Introduction**

Wave forcing is a known driver of community structure on coral reefs (Gove et al 2013; Gove et al 2015; Richards et al 2012). To examine the effect of wave forcing, however, in the absence of direct observations at the site level, proxies for wave exposure must be developed utilizing satellite data, numerical models, or a combination of the two. Numerical models, while the most accurate, are computationally expensive and require complete, high resolution bathymetry data, which is not always available.

In the absence of the ability to run a numerical model, methods have been developed for estimating wave exposure using a combination of fetch length and exposure angles. Commonly, the wave directions that a site is exposed to are calculated using coastline data and geoprocessing software. Fetch is estimated by calculating the distance between a site and wave blocking objects within its wave-exposure swath. Wind data are then incorporated to calculate a wave exposure metric based on a combination of wave direction exposure, fetch, and local wind conditions (Burrows et al, 2008; Malhotra and Fonesca, 2007; Pepper and Puotinen, 2009; Puotinen 2005). This method can be useful and relatively accurate in regions where locally generated wind-swell is the dominant form of wave energy. However, remotely generated swell can account for a large portion of wave energy a site experiences in some regions, such as areas that are exposed to swells coming from the mid-latitude regions of the Atlantic and Pacific oceans.

The Coral Reef Ecosystem Program does long term ecological monitoring at more than 40 remote islands in the Pacific. These islands fall within four main regions, the Hawaiian archipelago, Guam and the Commonwealth of the Northern Marianas, the Pacific Remote Island Area, and American Samoa. Given the number of islands and lack of sufficient bathymetry data at many of them, running numerical models at each island is not feasible. Using the output for a global wave model such as Wave Watch III (WW3) is also not ideal, since the resolution of this model is 0.4 degrees, and most islands are substantially smaller than a single grid cell. Because all islands are exposed, to some degree, to remotely generated swell, using local wind as a proxy for wave exposure is not likely to be accurate. Therefore, here we describe a method utilizing both WW3 data and coastline analysis of wave exposure to derive a wave metric relevant to ecological studies at near-shore sites around islands in the Pacific.

**Procedure**

In order to calculate a wave exposure metric for a specific site at an island, first that site’s incident wave swath must be determined. This incident wave swath consists of all wave directions a site is exposed to without a wave blocking object, such as a headland or another island, in the way. To determine a site’s incident wave swath, a radial plot of 360, 100km long lines is created. Where these lines intersect land, whether it is on the island itself or a neighboring island, that degree bin is removed from the radial plot, leaving only the angles open to exposure in the incident wave swath. A visualization of the incident wave swaths for four sites on Maui is shown in Figure 1.

Many islands of interest for CREP are low lying atolls with very little land area above sea-level, but still with large, shallow shoals where waves break. Because of this, during coastline analysis the contour used to derive incident wave swaths is not consistent between islands. The contour used is the one that best represents the shape of the wave-affecting (ie shallow enough for most waves to break on) region. In some cases, the choice of contour is limited by the amount of bathymetry data available. Table 1 shows a list of bathymetric contours used for each island and the sources of bathymetry data.

Next, the closest WW3 data pixel is selected and the time-series of significant wave height, peak period, and peak direction are extracted. The WW3 model used is model version 4.08 forced with Climate Forecast System Reanalysis surface winds, developed by the Commonwealth Scientific and Industrial Research Organisation (Durant et al, 2013). Wave power is then calculated from the significant wave height and peak period by the following equation:

*Ef* = (*ρ* *g2*/ 64*π*) × *Hs*­­­2 × *Tp / 1000*

Where *ρ* is the density of seawater (1024 kg m-3) *g* is the acceleration of gravity (9.8 m s-2), *Hs* is offshore significant wave height, and *Tp* is the dominant wave period, (1/wavelength).  Units are in kilowatts per meter of wave front(kW m-1). The annual wave power data are then sorted into degree bins according to the peak direction. Then, data that do not fall within the incident wave swath are removed. The remaining wave power data are then summed to give a single number for wave power at that site. Because this number is quite large, it is reported in units of MW m-1. This number represents the cumulative wave power a site is exposed to over the course of one year.



Figure 1: Incident wave swaths for four sites on Maui.

Although the WW3 grid size is not large enough to resolve most islands, it is large enough to account for the main Hawaiian Islands archipelago. This makes the pixel choice to represent the islands an important one, since a pixel north of the islands will be blocked from South swell by the archipelago, and vice-versa. To solve this problem, a combination of the North and South pixels surrounding the main Hawaiian Islands is created by taking the maximum wave power between the two pixels for each time-step.

**Table 1. Bathymetric contour used for each island/atoll to derive Incident Wave Swaths**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Region Code | Island/Atoll Code | Depth of Contour(m) | Source |  | Region Code | Island/Atoll Code | Depth of Contour(m) | Source |
| MHI | NII | 0 | 1 |  | NWHI | FFS | -10 | 6 |
| MHI | OAH | 0 | 1 |  | NWHI | GAR | 0 | 7 |
| MHI | MOL | 0 | 1 |  | NWHI | KUR | -10 | 8 |
| MHI | MOI | 0 | 1 |  | NWHI | LAY | -10 | 9 |
| MHI | MAI | 0 | 1 |  | NWHI | MID | -10 | 10 |
| MHI | HAW | 0 | 1 |  | NWHI | NEC | 0 | 9 |
| MHI | KAH | 0 | 1 |  | NWHI | NIH | 0 | 9 |
| MHI | KAU | 0 | 1 |  | NWHI | PHR | -10 | 11 |
| MHI | LAN | 0 | 1 |  | NWHI | MAR | -10 | 12 |
| AMSM | OFU | 0 | 2 |  | NWHI | LIS | -5 | 13 |
| AMSM | OLO | 0 | 2 |  | PRIA | BAK | 0 | 14 |
| AMSM | ROS | -5 | 3 |  | PRIA | HOW | 0 | 14 |
| AMSM | SWA | 0 | 1 |  | PRIA | JAR | 0 | 14 |
| AMSM | TAU | 0 | 1 |  | PRIA | JOH | -10 | 15 |
| AMSM | TUT | 0 | 1 |  | PRIA | KIN | -10 | 16 |
| CNMI | AGR | 0 | 4 |  | PRIA | PAL | -10 | 17 |
| CNMI | AGU | 0 | 4 |  | PRIA | WAK | -5 | 7 |
| CNMI | ALA | 0 | 4 |  | CNMI | GUG | 0 | 4 |
| CNMI | ANA | 0 | 4 |  | CNMI | MAU | 0 | 4 |
| CNMI | ASC | 0 | 4 |  | CNMI | PAG | 0 | 4 |
| CNMI | FDP | 0 | 4 |  | CNMI | ROT | 0 | 4 |
| CNMI | GUA | -1 | 5 |  | CNMI | SAI | -5 | 4 |
| CNMI | TIN | 0 | 4 |  | CNMI | SAR | 0 | 4 |

1. Benthic Habitats of the Main Hawaiian Islands prepared form IKONOS and Quick Bird (2007), Center for Coastal Monitoring and Assessment (CCMA), Biogeography Branch
2. Benthic Habitats of American Samoa Derived from IKONOS Imagery, 2001-2003, Center for Coastal Monitoring and Assessment (CCMA), Biogeography Branch
3. Mosaic of gridded multibeam bathymetry and bathymetry derived from multispectral IKONOS satellite imagery of Rose Atoll, American Samoa, USA. NOAA PIFSC CRED, the Pacific Islands Benthic Habitat Mapping Center and Davey Jones Locker GIS Laboratory Oregon State University
4. Benthic Habitats of Northern Mariana Archipelago Derived from IKONOS Imagery, 2001-2003, Center for Coastal Monitoring and Assessment (CCMA), Biogeography Branch
5. Chamberlin, C., 2008. A digital elevation model of Guam for tsunami inundation modelling, NOAA Pacific Marine Environmental Laboratory technical report, Seattle, WA, 7pp.
6. Gridded bathymetry of French Frigate Shoals, Hawaii, USA. NOAA PIFSC CRED, the Pacific Islands Benthic Habitat Mapping Center. Bathymetry derived from multispectral IKONOS satellite imagery of French Frigate Shoals, Hawaii, USA. NOAA NOS NCCOS CCMA Remote Sensing Team.
7. Island shapefile digitized from IKONOS collected in 2003
8. Gridded bathymetry and IKONOS estimated depths of Kure Atoll, Hawaii, USA. NOAA PIFSC CRED, the Pacific Islands Benthic Habitat Mapping Center
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11. Gridded bathymetry and IKONOS estimated depths of Pearl and Hermes Atoll, Hawaii, USA. NOAA PIFSC CRED, the Pacific Islands Benthic Habitat Mapping Center
12. Gridded bathymetry and IKONOS estimated depths of Maro Reef, Hawaii, USA (2007). NOAA PIFSC CRED, the Pacific Islands Benthic Habitat Mapping Center
13. Gridded bathymetry and IKONOS estimated depths of Lisianski Island, Hawaii, USA. NOAA PIFSC CRED, the Pacific Islands Benthic Habitat Mapping Center
14. Island shapefile digitized from IKONOS collected in 2000
15. Mosaic of gridded multibeam bathymetry and bathymetry derived from multispectral IKONOS satellite imagery of Johnston Atoll, Pacific Remote Island Area, USA (2009). NOAA PIFSC CRED, the Pacific Islands Benthic Habitat Mapping Center and Davey Jones Locker GIS Laboratory Oregon State University
16. Mosaic of gridded multibeam bathymetry and bathymetry derived from multispectral IKONOS satellite imagery of Kingman Reef, Pacific Remote Island Area, USA (2009). NOAA PIFSC CRED, the Pacific Islands Benthic Habitat Mapping Center and Davey Jones Locker GIS Laboratory Oregon State University
17. Mosaic of gridded multibeam bathymetry and bathymetry derived from multispectral IKONOS satellite imagery of Palmyra Atoll, Pacific Remote Island Area, USA (2009). NOAA PIFSC CRED, the Pacific Islands Benthic Habitat Mapping Center and Davey Jones Locker GIS Laboratory Oregon State University

**Limitations**

There are several unavoidable limitations and biases that arise when using this method. This method is not meant to replace nearshore wave modeling or equal it in accuracy; it is meant to provide an improved site-level estimation of wave exposure in regions where remotely generated swells are known to contribute to local wave energy.

The first, and most significant limitation, is that this metric can underestimate the true wave power at a site because it does not utilize spectral data. WW3 data outputs the peak period swell, so even though at any given time there may be multiple swell directions, WW3 output will only reflect the swell with the longest period. For example, if a long period south swell and a short period northeast wind swell coexist, the WW3 output will only reflect the south swell. Therefore, for a site only exposed to northeast swells, by this method, the wave power will be zero at that time-step, despite being exposed to a small swell. Unfortunately, although it is clear that the incident wave swath method can underestimate wave power, the underestimation is not easily predictable without full spectral data.

The second major limitation of this method is that it does not include shallow water processes such as refraction or shoaling. This becomes important in some areas where offshore shoals can reduce wave energy. Since this shoaling is not reflected in the wave power metric, the energy on the south shore of Tutuila, for example, is overestimated relative to other areas of the island. Due to the combination of this in addition to the limitations induced by not using spectral data, it is difficult to predict whether wave exposure is likely to be over or under-estimated at a site. Although model validation exists in the form of high-resolution SWAN runs in the main Hawaiian Islands and Tutuila, validation at other islands is impossible without running a complete model.

Finally, although WW3 is a very accurate model, its coarse spatial resolution can cause it to miss important wave events, such as typhoons. Because typhoons are smaller than the resolution of the model, in particular the direction of the waves from typhoons is represented poorly, resulting in poor representation of these episodic events in the final wave metric. Despite these limitations, the incident wave swath exposure metric can be a useful tool in studies where site-specific wave exposure is expected to be an important variable, but numerical modeling is not an option.

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