Time Series and Climatological Information Provided to the Pacific Islands Climate Change Cooperative

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Introduction:

Coral reef ecosystems are exposed to a diverse suite of environmental forcing. Waves, wind, currents, temperature, irradiance, salinity, nutrients, turbidity, aragonite saturation state, and planktonic productivity each influence coral reefs to varying degrees, fluctuating on daily, seasonal and interannual time scales and across spatial scales spanning reefs, islands and archipelagos [1-3]. Environmental forcing is highly influential to reef ecosystem process and function, including coral reef extent and growth rates and the abundance, diversity, and morphology of reef organisms [1, 4]. Through time, coral reef ecosystems have adapted to exist within a particular climatological setting; a finite range in long-term physical, chemical and biological environmental forcing that is region specific and governed by a reef's geographic location [2]. Regional variability (100s-1000s of kilometers) in the climatological setting is a major determinant for spatial differences in coral reef ecosystems [3].

Environmental forcing that exceeds the climatological setting can be considered beyond a reef ecosystem's 'normal' or adapted range of environmental conditions [1]. For example, ENSO related forcing can drive variations in ocean temperatures, salinity, and ocean waves not observed on a reef ecosystem for years to decades. Depending on the magnitude and duration of exceedance forcing, considerable ecological consequences to coral reef ecosystem can result [5-7].

In recent decades it has become abundantly clear that coral reef communities are not only structured by natural environmental forcing, but also by human related activities [8]. Local human impacts include habitat and water quality degradation associated with land clearing, improper waste water treatment, and coastal urbanization [9, 10], as well as destructive and over fishing practices [11-13]. In addition, human-induced climate change is driving global-scale changes in environmental forcing, including ocean warming, ocean acidification, sea-level rise, and increased storminess, each of which have profound implications to the future of coral reef ecosystems [1, 8, 14-17].

Coral reefs are among the most diverse and productive marine ecosystems on earth and provide economic benefits to millions of people as sources of food, employment, natural products, coastal protection and recreation [17, 18]. Despite this societal importance, the interplay between coral reef ecosystem dynamics and the environmental conditions in which they exist are not fully understood. Further confounding this knowledge-gap is our ability to discern human versus natural induced perturbations in reef ecosystem health, which can act synergistically and be difficult to ascertain [1]. Now, more than any other time in our history, effective ecosystem-based management and successful strategies to mitigate anthropogenic impacts to coral reef ecosystems require proper characterization of environmental conditions to help assess the underlying abiotic-biotic interactions determining coral reef ecosystem function and health.

CRED has provided climatological and time series information for the following parameters to characterize environmental conditions on coral reef ecosystems across the Pacific; wind, waves, sea surface temperature (SST), chlorophyll-a, irradiance, sea surface height, ocean currents, dissolved inorganic carbon (DIC), total alkalinity (TA) and precipitation. These environmental parameters were chosen as they represent the primary drivers of coral reef ecosystem variability (through space and time) and/or serve as a proxy for other pertinent environmental variables to reef ecosystems. Ideally, additional environmental parameters would be included (e.g. salinity, dissolved inorganic nutrients, etc) to provide a more comprehensive assessment of environmental conditions; however, there are limits to the availability of science-quality information at the appropriate spatial and temporal resolution required for climatological and time series calculations.

Below is a brief description of the methodological approach for calculating the climatological and time series data products. Where possible, we provided existing peer-reviewed climatological data products. Many of the data products provided; however, were derived for the purpose of the Pacific Islands Climate Change Cooperative, as existing climatological information both at the basin scale and at the spatial scale of individual islands and atolls are not currently available. More detailed information related to the environmental data sets can be found in the metadata documents provided with each parameter.

Wind: Island-specific and basin-scale climatological wind data were obtained from NASA's Quick Scatterometer (QuickSCAT); a microwave satellite that measures near-surface wind speed and direction at 0.125° spatial resolution over the Earth's oceans (*http://winds.jpl.nasa.gov/missions/quikscat/index.cfm*). Monthly climatological information was extracted using 1° spatial box centered at each island location, calculated over the time period from 1999 - 2010. Island-scale time-series data were obtained from NOAA's National Center for Environmental Prediction (NCEP) Global Forecast System (*http://www.emc.ncep.noaa.gov/GFS/*). These data are available at 3 hr intervals at a 1° spatial resolution and are the same data used in NOAA's Wave Watch III global wave model. Wind magnitude is expressed in units of meters per second ($m\ s^{-1}$) and direction is represented by compass bearing degrees (0-360°) from which the wind originated.

Waves: Wave time-series and climatological data for each of the islands and atolls of interest were derived using NOAA's Wave Watch III (WWIII); a global, full spectral wave model output every 3 hours from January 1997 - 2011 (*http://polar.ncep.noaha.gov/waves*). Wave data presented here utilize WWIII's 1° spatial resolution output of mean significant wave height, dominant period and direction, centered at each island location. Time series data were calculated by averaging the 3-hour output over a 5-day period. This time period was chosen because it captures the episodic nature of wave events and avoids averaging out the signal of potentially heterogeneous data. Monthly climatological data were calculated by averaging all 3-hour time steps within each calendar month, and then averaging the same calendar month over all years.

Time series and climatological data are presented as significant wave height (H_s), output directly from WWIIII, and wave energy flux ($kW\ m^{-2}$). Although wave height is often easier to contextualize and frequently used in ecological research, we find that wave energy flux (given its dependence upon wave period and wave height) is a more realistic estimate of the effects of waves on coral reef ecosystems, and therefore a more ecologically relevant parameter with which to quantify wave-induced forcing [19].

SST: Sea Surface Temperature time-series and climatologies were derived from Pathfinder Version 5.0 SST; a global, twice-weekly SST data set from 1981 - 2009, at a spatial resolution of 4.63 km (0.417°) (*http://pathfinder.nodc.noaa.gov*). Data utilized were from nighttime SST retrievals in units of degrees centigrade (˚C).

SST data sets and climatologies were developed specifically for each island location. The island-specific data sets were produced by taking the mean of all SST data pixels within a set distance from an island, defined as 0.25° from the 30 m bathymetric contour.

Chlorophyll-a: Remotely sensed ocean color data are derived for optically-deep waters, where the signal received by the satellite sensor originates from the water column without any bottom signal contribution. In the region of interest, optically-deep waters are typically deeper than 25 m. Optically-shallow water encompasses lagoonal areas, regions within atolls and most reef-building environments. In optically-shallow waters bottom substrate properties and/or suspended sediment affect light propagation, which increase marine reflectance and data quality issues when quantifying in-water constituents, such as chlorophyll-a.

Chlorophyll-a climatological and time series data sets were derived taking into account the above data-quality constraints. Using 8-day, 4.63 km (0.0417°) resolution time-series of chlorophyll-a data from 2002 – 20011 obtained from the Moderate Resolution Imaging Spectroradiometer (*http://modis.gsfc.nasa.gov/*), island-specific data sets were calculated by taking all data pixels within an area bounded by 0.25° from the 30 m isobath. A complex multi-step masking routine was employed to remove contaminated data pixels within this area. Using the 30 m contour as the cut-off for data pixel inclusion, all pixels within the 30 m isobath were identified and removed from the analysis [20]. This step; however, is not sufficient to ensure an error-free chlorophyll-*a* data set because pixels that reside outside the 30 m isobath may still contain biased information associated with optically-shallow waters [21]. This occurs because data pixels can be considered box-like in shape and are georeferenced at their center point; information contributing to any single pixel value is collected ≤ ½ a pixel's diagonal distance away. To address this bias, we created a data exclusion contour set at ½ a pixel's diagonal length , perpendicular to the 30 m isobath, with all pixels on or within this area removed from the final data set. Chlorophyll-a (Chl-a) data are presented in milligrams per meter cubed (mg m^{-3}).

***Irradiance**:* Satellite derived photosynthetically available radiation (PAR), defined as downwelling irradiance between 400-700 nm averaged over an entire day, is subjected to similar data quality concerns associated with nearshore shallow water environments. The data production algorithm [22], in addition to a number of other quality control steps, incorporates irradiance attenuation in the overall calculation of PAR. Attenuation sources include the absorption and scattering of irradiance in the atmosphere due to concentrations of ozone, water vapor and aerosols, and at the air-sea interface due to reflection, associated with surface properties such as sea-surface roughness, levels sea-foam and sea-ice. Areas of strong bottom reflectance and shallow water environments, such as lagoonal areas, regions within atolls and most reef-building areas; however, are wrongly interpreted as irradiance attenuation sources, thereby leading to spuriously low PAR values.

Climatological and time series data sets were derived taking into account the above data-quality constraints. Using 8-day, 4.63 km (0.0417°) resolution time-series of PAR data from 2002 - 2011 obtained from the Moderate Resolution Imaging Spectroradiometer (*http://modis.gsfc.nasa.gov/*), island-specific data sets were derived by taking all data pixels within an area bounded by 0.25° perpendicular to an island or atoll's 30 m isobath. The same complex multi-step masking routine as employed above (see *chlorophyll-a*) was used to remove contaminated data pixels for this parameter. PAR data are presented in units of Einsteins per meter squared per day (E m^{-2} day^{-1}).

Sea Surface Height: Basin-scale climatological sea surface height (SSH) deviation data was obtained from AVISO; a global, 27.75 km (0.25°) spatial resolution sea surface height (SSH) altimetry data set available from 1992 - 2010 (*http://www.aviso.oceanobs.com/*). The Aviso SSH data product is a blend of multiple altimetry satellites, including TOPEX/Poseidon, ERS-1, ERS-2, Geosat Follow-On, Envisat, and Jason-1. SSH deviation is the deviation from the mean geoid as measured from 1992 – 1995. Sea surface height deviation is presented in meters (m).

Ocean Currents: Ocean surface currents were obtained from NOAA's Ocean Surface Currents Analyses, Real-Time (OSCAR; *http://www.oscar.noaa.gov/*); a global, 1° spatial resolution 5-day averaged data set of geostrophic vector currents derived from satellite altimetry and vector wind data from 1992 – 2011 [23]. Data were obtained for each location using the center point of each island. Basin-scale and island-specific climatological current magnitude and direction were calculated using monthly current data. Ocean currents are presented in the direction of flow with the magnitude represented in meters per second (m s^{-1}).

Dissolved Inorganic Carbon and Total Alkalinity: Basin-scale Dissolved Inorganic Carbon (DIC) and Total Alkalinity (TA) data were developed from surface ocean measurements compiled by the Global Ocean Data Analysis Project (GLODAP). GLODAP originated from a collaboration of scientists interested in water sample data collected during three ocean research expeditions in the 1990's: 1) The World Ocean Circulation Experiment (WOCE), 2) The Joint Global Ocean Flux Study (JGOFS), and 3) The Ocean Atmosphere Carbon Exchange Study (OACES). The GLODAP data set is a calibrated synthesis for numerous water column properties available at 1° spatial resolution and 33 different depth surfaces [24]. The DIC and TA products produced by CRED are surface values only. DIC and TA information were obtained from the Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory (*http://cdiac3.ornl.gov/las/servlets/dataset/*). Data are presented in units of micromole per kilogram (µmol kg^{-1}), and the overall accuracy of the DIC and TA information is approximately 3 µmol kg^{-1} and 5 µmol kg^{-1}, respectively [25].

Precipitation: Basin-scale climatological precipitation data were calculated using information obtained from NOAA's CPC (Climate Prediction Center) Merged Analysis of Precipitation (CMAP); a global, 2.5 degree spatial resolution monthly data set of precipitation from 1979 - 2011 (*http://www.cpc.ncep.noaa.gov/products/global_precip/html/wpage.cmap.html*). Precipitation data were derived from rain gauges and information from precipitation estimates based on several satellite-based algorithms [26]. Precipitation data are presented in millimeters of rainfall per day (mm day^{-1}).

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