Physics and connectivity informing reef conservation: an interdisciplinary study of coastal oceanography of the eastern tropical Pacific

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Overview

Coral reefs are succumbing rapidly to rising ocean temperatures, and will continue to decline absent effective greenhouse gas mitigation. Even if the Paris Agreement is achieved, 70–90% of reef-building corals will disappear [1]. Coral reef conservation has thus adopted strategies that incorporate three main actions to maximize coral survival into the future: (1) strengthening protections on reefs to reduce pollution and overfishing; (2) increasing coral resilience through reef restoration and interventions that improve their capacity to adapt; and (3) maximizing these efforts within reef networks that capitalize on coral larval dispersal patterns.

The goal of coral reef restoration (active repopulation of reefs with corals) is to create self-sustaining reefs whereby coral populations can produce sufficient coral larvae to sustainably generate both local recruitment and “downstream” recruitment via larval dispersal. Because it is economically infeasible to conduct reef restoration everywhere, it is urgent that we identify optimal sites for these activities: (a) sites that will be least impacted by continuing climate change and (b) sites that are the most valuable for reseeding coral reefs across a reef network.

The primary objective of this research is to optimize coral conservation and restoration through characterization of the oceanographic environment within a new, high-resolution modeling framework. This proposed research aims to build on newly-available state-of-the-art simulation capabilities at NCAR (CESM-MOM6, MPAS) and apply them to the societally-urgent issue of marine habitat restoration in the eastern tropical Pacific (ETP). NCAR’s scientific and computing resources will enable this research to be conducted at unprecedented spatial resolution (1 km, and over the entire coastal Pacific of Central America) and to employ cutting-edge data analysis techniques (Lagrangian internal wave-filtering, larval connectivity) that would not be possible elsewhere. This project both embodies and paves the way toward further transformative science at NCAR, as it builds upon new modeling capabilities, establishes new branches of scientific research within the institution, and establishes a link to new funding streams and collaborations.

Explanation of the scientific merit of the proposal

Coral reef science naturally encompasses oceanography, biology, and ecology. Reefs are also limited to shallow environments that are strongly affected by coastal oceanographic processes. Here we describe how this research represents transformative science both at the intersection of these fields and within each field individually.

Coral reef restoration efforts are small relative to the spatial extent of coral populations. In the ETP, coral reefs occur in a number of locations along the coastline as well as on several offshore islands. ETP reefs are smaller and less continuous than those of barrier reef systems, because coastal upwelling causes strong temperature and pH fluctuations that slow $CaCO_3$ accretion (“reef building”). However, ETP corals have evolved to live in these extreme conditions, mostly in genetic isolation from western Pacific corals, which marks them as resilient to climate change [2] and thus good candidates for coral restoration.

Maximizing the geographic scope of restoration depends on designing a network of restoration sites that considers where (1) environmental conditions favor coral resilience, and (2) where restoration takes advantage of larval connectivity to maximize recruitment potential. A summary of the few coral genetics studies in the ETP [3] highlights the oceanographic isolation from coral reefs elsewhere in the Pacific, and the relatively high connectivity amongst coastal reefs. These observations are broadly supported by a connectivity study based on a 9-year ROMS simulation with 9-km spatial resolution [4], which indicated the importance of coastal reefs in maintaining overall resilience of ETP reefs, but also noted the need for higher-resolution modeling to resolve a number of biases associated with a coarser resolution model.

From a purely physical perspective, the ETP is dynamically complex and offers a number of research opportunities. The upward tilting of the thermocline in the ETP brings cold, nutrient rich thermocline waters very near the surface (a few tens of meters), most prominently in the feature known as the Costa Rica Dome centered near 90°W, 9°N [5]. The Intertropical Convergence Zone directly overlies the region, resulting in strong seasonal cycles of both wind and precipitation [6]. A unique feature of the wind forcing of the region is the presence of three intense low-level atmospheric jets that are associated with the topographic gaps in the Central America cordillera [7]. These complexities mark the region as one of high physical and ecological interest; however, the large-scale oceanographic conditions are only moderately well described [8] and the mesoscale and submesoscale dynamics in the region are as yet unexplored. Although not the main focus, we anticipate our proposed research will provide opportunities to explore many of these aspects of the regional oceanography, particularly in partnership with University of Costa Rica (UCR) colleagues.

The crux of this proposal concerns dynamics at small scales – those relevant to coral reefs – which requires high-resolution models on the order of 1 km. Of particular interest in this regard are tidally-generated internal gravity waves (IGWs), which are known to play a key role in modulating the heat budget of the nearshore environment and can significantly affect the ecology of coastal and reef zones. A growing body of observations suggests that the resilience of coral reefs to climate stressors is enhanced by the presence of IGWs, which can induce large fluctuations in temperature, nutrient concentrations, and carbonate chemistry [9-12]. Corals exposed to IGWs have been shown to have better tolerance to heat stress [13], improved nutritional status [14], and higher feeding capacity and photosynthetic efficiency [15].

The ocean IGWs most relevant to reef ecology have length scales ranging from a few meters to a few kilometers [16], and their small size means that numerical studies have generally been limited to the scale of individual reefs, e.g. [17]. In contrast, coral populations occur across a network of patchily distributed reefs that can span domains of hundreds of kilometers. The computational requirements to study coral reef ecology at the scales of physical factors (IGWs) and over biologically-relevant regions (larval dispersal) have thus been out of reach until now.

Recent research by Bachman et al. [18] pioneered a new method to identify regions of strong IGW activity using models with much coarser resolution than was previously possible. This method uses Lagrangian filtering [19] to cleanly separate the wave and non-wave components of the flow, from which the wave kinetic energy can be diagnosed as a proxy for wave-induced upwelling and cooling. This method was previously applied in the western Pacific to assess IGW effects on reefs stretching from Taiwan (23.7°N, 120.9°E) to the Solomon Islands (9.6°S, 160.2°E) *in a single simulation*. The advances made via this method mean that it is now possible to study IGW effects over the same large physical domains as are used for larval dispersal studies, opening up new possibilities for research at the intersection of physics and biology.

The numerical modeling to be performed in this study will represent a technical breakthrough: the first ever implementation of regional CESM-MOM6, and the highest-resolution study ever performed for the ETP. It will also represent several scientific "firsts": the first exploration of very high-resolution (VHR) atmospheric effects (3-km MPAS) on ocean IGW statistics and larval dispersal, the first simultaneous climatology of reef resilience due to IGWs and connectivity, and employment of the first larval dispersal model using VHR-derived particle diffusion and Stokes drift. The results offer a unique opportunity to guide the sample collection strategy for a recently funded project (Kleypas) to conduct in situ coral genetic sampling in the same region. Cutting-edge research will thus be conducted in multiple disciplines, which promises to open up opportunities for future work and funding on several fronts.

Approach

Ocean modeling. This research will utilize high-resolution (uncoupled) regional experiments of the ocean and atmosphere in the ETP (Fig. 1), which will serve multiple uses. The baseline experiment will be a 20-year simulation of the ETP (green box, Fig. 1) using CESM-MOM6, with boundary conditions provided by interpolation of the 1/12° MERCATOR global ocean reanalysis (http://marine.copernicus.eu/, simulation 001_024). Atmospheric forcing will be provided by the JRA-55 reanalysis [20], and tidal forcing by the TPXO8.0 global tidal model [21]. The 20-year span of this simulation will be chosen to cover multiple ENSO cycles, which will enable us to assess differences in larval dispersal on interannual timescales. This experiment will serve to validate the broader modeling study through comparison against observations, including: satellite datasets such as AVISO and OSCAR; a global climatology from ocean drifters [22]; sea surface temperature from the global NOAA Optimally Interpolated SST analysis [23], and subsurface temperature and salinity using the mapped monthly mean Argo product [24]. The presentation of the regional model and validation against observations will comprise Anticipated Outcome #1 (**AO1**).

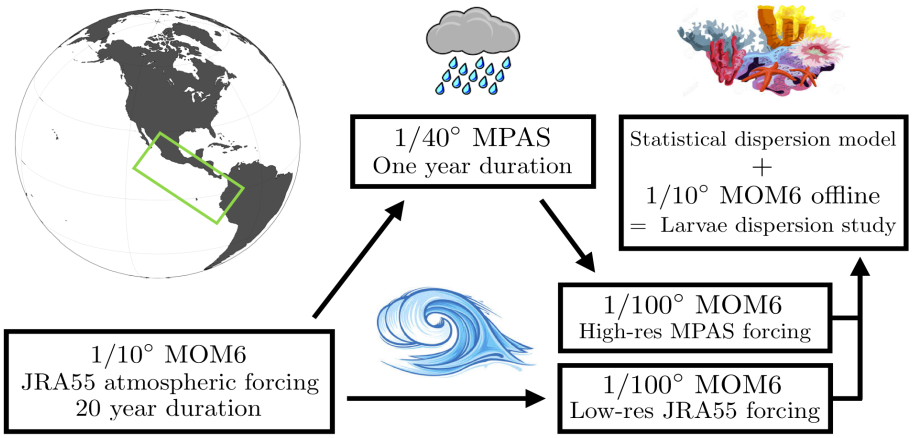

Figure 1: Flow chart of proposed numerical experiments.

A main objective of this proposed research is to assess the effect of VHR atmospheric forcing on the dispersal of coral larvae in a 1/100° ocean simulation, and to use this information to improve the larval dispersal model in the coarser 1/10° simulation. Conventional atmospheric models and reanalyses do not resolve the complex topography of Central America, and thus do not capture the gap wind events that are critical in ocean forcing (Ekman transport, gravity-wave driven mixing and Stokes drift). Beyond producing more realistic flows, high-resolution atmosphere models explicitly simulate convective storms and their effects on the upper ocean, such as gust fronts and freshwater input, and reduced insolation. To this end, the output of the 1/10° CESM-MOM6 simulation will provide the surface boundary conditions for a 1/40°, one-year MPAS [25] simulation, whose output will in turn be used to provide realistic wind forcing for the VHR ocean experiments.

The VHR ocean experiments will consist of two 1/100° CESM-MOM6 simulations run for one year each: one with JRA-55 forcing interpolated to the high-resolution grid, and the other with forcing derived from the MPAS simulation. These experiments will serve multiple uses:

- Run the larval dispersal model (offline, described below) and assess how the dispersal statistics depend on atmospheric forcing (MPAS vs. JRA-55), model resolution (1/10° vs. 1/100°), and proximity to the coastline.
- Assess the sensitivity of larval dispersal to surface-gravity-wave Stokes drift, which contributes a net near-surface mass transport of order centimeters per second and may significantly modify particle trajectories [26, 27]. Wave characteristics will be derived from measurements (wave buoys and remote sensing) and reanalyses (NOAA WAVEWATCH-III), or by applying wind forcing to a wave model (SWAN, [28]).
- Apply a particle-based Lagrangian filtering method [19] to separate wave and non-wave flow based on a rigorous definition of IGWs (the dispersion relation). This has been previously employed by Bachman et al. [18] to identify locations where IGWs induce near-surface heat fluxes and reduce coral heat stress.

The statistics of larval dispersal resulting from the above factors will be assessed and compared as part of **AO2**. These statistics will be used to formulate a diffusion parameterization that will be used with the larval dispersal model in the 1/10° CESM-MOM6 simulation.

Coral environment, larval dispersal & connectivity: The evaluation of reef locations for inclusion in a coral reef restoration network (**AO3**) will be based on both environmental conditions (e.g. location of IGWs), and connectivity of "larvae" will be conducted for the 1/10° CESM-MOM6 simulation and both 1/100° CESM-MOM6 simulations shown in Fig. 1. Most coral larvae rise to the surface after spawning, then behave as neutrally buoyant particles until they encounter a suitable environment for settlement. Lagrangian particle tracking will be performed offline using daily averaged and hourly averaged surface current velocity and direction from the 1/10° and 1/100° simulations, respectively. Most ETP corals spawn monthly, 1-2 days after the full moon, and near sunset, except during particularly cold months (e.g. during upwelling). The offline particle tracking will thus initiate particle releases based on temperature, time of day, and moon phase. Particles will be released from each reef location over a 10-hr period, beginning at sunset the day of spawning. The location of each particle will be tracked for a maximum of 100 days, and potential connectivity (the probability of a particle from a spawning site, R*i* enters the grid cell of another reef site, R*j*) will be calculated for all reef pairs similarly to that described in [29], and considering that most larvae require 3-5 days before they are viable for settlement. Potential connectivity will also be used to delineate the boundaries between coral populations (those reefs that are likely to share genetic information). The population boundaries calculated in both 1/10° and 1/100° runs will be compared to the boundaries based on known distributions of genotypes of commonly studied species (e.g., *Porites* sp. and *Pocillopora* sp.; [3]), as well as locations where high coral recruitment rates have been reported [30].

Anticipated outcomes

AO1: Implementation of a CESM-MOM6 regional model for the ETP, and its validation against observations

AO2: Evaluation of the sensitivity of larval dispersal to low- versus high-resolution atmospheric forcing, model resolution, and to the inclusion of a Stokes drift parameterization

AO3: Design of a coral restoration network for the ETP based on a combination of environmental exposure and larval connectivity. Identify locations where reef conservation and restoration efforts are the most beneficial to coral reef populations along the Marine Conservation Corridor of the ETP.

The regional modeling, data analysis methods, and simulation output developed during this effort will be disseminated to the broader community. Furthermore, this project builds on existing international collaborations with the University of Costa Rica and Australian National University and helps to support and enhance their capabilities directly. All of these benefits support the NCAR mission to build capacity and capability of university partners and the broader community. Finally, this research will open several avenues to future funding and establishes a bridge to a new branch of research at NCAR (coastal oceanography).

Budget Summary (detailed budget is included in Supplementary document)

We seek funding for 0.5 FTE of Project Scientist I (split among the three PSI project members), with a small additional funding request to host and train a UCR graduate student at NCAR for four months. The latter request capitalizes on PI Kleypas' existing collaborations with UCR and her extant funding to conduct a survey of coral genetics in Costa Rica. The training of the graduate student and relevance to Costa Rican fisheries and marine economy satisfy NCAR Imperatives 5 (transfer of science to meet societal needs) and 6 (educate a diverse group of students), in addition to the fundamental research being performed to advance physical and biological oceanography (NCAR Imperative 1).

In total, this proposal requests $128,558. Co-sponsorship will be provided from CGD and MMM in the form of ladder-track scientist time (Bachman: 0.1 FTE, Kleypas: 0.1 FTE, Bryan: 0.05 FTE, Judt: 0.05 FTE).

Narrative response to questions

This proposal promises novel research in several areas that are central to NCAR's scientific mission. The core scientific team possesses expertise in the biology, ecology (Kleypas), and physics (Bachman, Shakespeare, Bryan, Judt) at the heart of this highly interdisciplinary research, making this endeavor especially powerful for the training of early-career scientists and for seeking avenues for future funding. The team includes recent NCAR hires in coastal oceanography and meteorology whose work on this project will pave the way to future opportunities, particularly in the areas of regional/coastal-scale oceanography with a focus on connecting physics to productivity and fisheries. Furthermore, the team comprises a multi-national partnership between NCAR scientists, early-career faculty (ANU), and graduate students (UCR), and will strengthen NCAR's collaborative network abroad and build capacity and capability both internally and for NCAR's university partners.

This research is scientifically and technically ground-breaking, representing the first-ever synthesis of two new NCAR models (CESM-MOM6 and MPAS) with a focus on new scientific frontiers for the Center (VHR air-sea interactions, coastal oceanography, coastal ecology). In addition to expanding NCAR's simulation and scientific capabilities, the interdisciplinary nature of this research offers an entry point into a number of future funding calls from NOAA (e.g., Climate Program Office, Regional Ecosystem Prediction Program), NSF (e.g., Growing Convergence Research, Physical & Biological Oceanography), and nonprofit organizations (e.g., Blue Action Fund, Prince Albert II of Monaco Foundation).

The computing flow chart (Fig. 1) demonstrates a straightforward path to completing the simulations, and each step of the research will leverage the expertise of the appropriate team member(s). AO1 is the logical first step that will establish both the validation of the model and the data needed for the larval dispersal code; we anticipate the coarse simulation will be complete within the first four months. AO2 and AO3 can progress in parallel once the VHR models are in place. We anticipate that the computing will take another four months, and the data analysis will begin immediately once the output is compressed and committed to long-term storage. The particle dispersal parameterization from AO2 is expected to be deployable by the end of Year 1, after which all subsequent work can be performed offline. The remainder of the project is largely expected to occur on co-sponsored time; a no-cost extension may be requested to take each piece to completion.