THE TRANSPORT AND DYNAMICS OF WAVE-DRIVEN REEF JETS UNDER THE INFLUENCE OF ROTATION AND BOTTOM FRICTION

Walter Torres, Duke University
2018–2019 Graduate Fellow

EXECUTIVE SUMMARY

Predicting the fate of pollutants, heat, nutrients, carbon, and larvae in the coastal ocean is of acute ecological, commercial, and social importance—especially so on coral reef islands and atolls. On many reefs, jets arising from the interaction of reef topography and waves are responsible for exchanging water between the nearshore and open ocean, and so their dynamics are of particular interest.

This project involves a computational fluid dynamics study of an idealized coral reef island and demonstrates how the interaction among small-scale physical forcing (friction due to bottom roughness) and large-scale processes (e.g., the Coriolis force) modulates the behavior of wave-driven reef jets. Preliminary results show that lower bottom frictional regimes that are associated with degraded reef conditions increase the offshore export of the jets, simultaneously attenuating the relative importance of the Coriolis force that facilitates alongshore transport.

RESULTS & IMPACT

The results indicate that degraded reefs may be less retentive of larvae than healthy reefs, thereby having lower potential for regeneration. The model results also suggest that the interaction of small-scale frictional processes and large-scale forcing (friction due to bottom roughness and Coriolis force) modulates the behavior of wave-driven reef jets. Preliminary results show that lower bottom frictional regimes that are associated with degraded reef conditions increase the offshore export of the jets, simultaneously attenuating the relative importance of the Coriolis force that facilitates alongshore transport.

RESEARCH CHALLENGE

Coral reefs are hotspots for marine biodiversity. Reefs provide habitat for a panoply of taxa and also culturally significant heritage sites [1,2]. Unfortunately, coral reefs face global-scale threats such as ocean warming and acidification; reefs worldwide have already experienced significant degradation, so it is paramount to understand how environmental processes affect coral health in order to inform ecological management efforts [3].

The resilience of a coral reef ecosystem to stressors is tightly entwined with the circulation field. Waves and currents replenish nutrients, transport coral and fish larvae between populations, moderate temperatures, and modify the coastal geomorphology [4]. Computational fluid dynamics modeling provides a way to investigate fundamental circulation processes on reefs that are otherwise analytically intractable, allowing us a deeper understanding of the physics underlying this complex multiscale system.

This study focuses specifically on the dynamics of wave-driven reef jets, which are common hydrodynamic features on reefs that arise owing to the interaction of reef topography and wave transformation in shallow water [5]. As surface gravity waves shoal and break, there is a vigorous shoreward input of energy, momentum, and mass; this is balanced by the presence of strong oceanward jets that form in the crenellations of the reef topography. These features can remain coherent over several kilometers yet are driven by wave-shoaling processes that happen over short spatial scales (10–100 m) in extremely shallow water (0.1–10 m). And so, this problem is inherently multiscale: a modeling challenge that demands a short timescale and fine spatial resolution for the structure and evolution of kilometer-scale features such as jets and eddies, confining them nearer to shore via the Stokes drift mechanism. It is highly interesting that small-scale frictional processes on the very shallow back reef and reef crest have ramifications for the structure and evolution of kilometer-scale features such as jets and eddies. Future runs carried out over longer integration times in COAWST was critical for simulating wave-driven reef jets.

WHY BLUE WATERS

The Blue Waters supercomputing resource was essential in producing physically realistic results; because we were able to achieve high spatial and temporal resolution for a coupled model over long integration times, the model captures the salient physics and time-evolution of barotropic reef jets. In addition, the Blue Waters support team provided outstanding and expedient technical support with software installation and module use.

METHODS & CODES

We modeled circulation on an idealized grid representing a coral reef island with a reef crest, inner lagoon, and a series of reef passes and reef flats. This annular domain was constructed in polar coordinates using variable grid spacing to conserve computational time. A uniform shoreward wave forcing was applied symmetrically to the domain on the open boundary, with a closed inner boundary and periodic lateral boundary conditions. Results shown here are from a series of pilot numerical experiments that were carried out under permutations of bottom roughness and Coriolis force conditions (healthy rough reef vs. degraded smooth reef [P and SS/flat rate]). Simulations used the Coupled–Ocean–Atmosphere–Wave–Sediment–Transport (COAWST) modeling system [6]. COAWST produces circulation and wave fields by coupling the ocean (Regional Ocean Modeling System) and wave (Simulating Waves in the Nearshore) models, which numerically solve the 3D primitive equations and 2D wave action equation, respectively. The wave-circulation coupling provided in COAWST was critical for simulating wave-driven reef jets.

RESULTS & IMPACT

The results indicate that degraded reefs may be less retentive of larvae than healthy reefs, thereby having lower potential for regeneration. The model results also suggest that the interaction of small-scale frictional processes and large-scale forcing (friction due to bottom roughness and Coriolis force) modulates the behavior of wave-driven reef jets. Preliminary results show that lower bottom frictional regimes that are associated with degraded reef conditions increase the offshore export of the jets, simultaneously attenuating the relative importance of the Coriolis force that facilitates alongshore transport.

Figure 1: A snapshot of relative vorticity (ψ) for the idealized annulus domain showing eddies shed off the wave-driven reef jets that begin to approach nearshore owing to Stokes drift via waves and or reentrainment. This simulation was carried out at 30°C with bottom roughness (ūt = 10 cm).

Figure 2: Particle trajectories illustrate the deflection of wave-driven reef jets in the shallow annular domain owing to the earth’s rotation. This simulation was carried out at 40°C, and the scale is identical to Fig. 1.

This research has made progress in understanding fundamental exchange processes between the open ocean and nearshore reef environment, leveraging the high-resolution model simulations made possible by Blue Waters. The work has generated new hypotheses and predictions that will be evaluated in situ on Mo’orea, a coral reef island in French Polynesia, and will also aid the interpretation of ecological data being collected through the National Science Foundation’s Long Term Ecological Research (LTÉ) initiative, especially on factors affecting coral resilience such as larval recruitment, nutrient loading, and organismal behavior.

Walter Torres is a third-year Ph.D. candidate in marine science and conservation at Duke University, working under the direction of Jim Hench. He expects to graduate in the third quarter of 2021.