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.

RESEARCH CHALLENGE

Coral reefs are hotspots for marine biodiversity. Reefs provide habitat for a panoply of taxa while also providing vital ecosystem services such as food security, economic well-being, coastline protection, and they are 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 timestep and fine spatial resolution in certain parts of the domain. Furthermore, reef jets often occur in proximity to one another, providing the opportunity for recirculation of scalars and particles under the right conditions, making it of interest to study an entire island system comprising an array of reef jets.

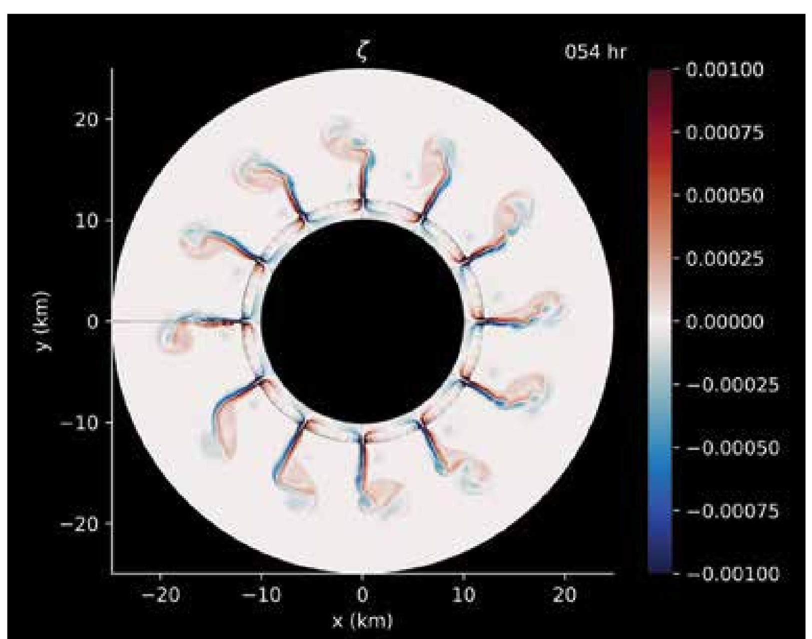

Figure 1: A snapshot of relative vorticity (ζ) for the idealized annulus domain showing eddies shed off the wave-driven reef jets that begin to approach nearshore owing to Stokes drift via waves and/or entrainment. This simulation was carried out at 30°S with bottom roughness (z0 = 10 cm).

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 computation time. A uniform shoreward wave forcing was applied symmetrically to the domain on the outer 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, 0° and 30°S latitude). 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 and experience shorter residence times owing to the decrease in bottom friction associated with the lower structural complexity of unhealthy coral. Preliminary model runs demonstrated that (unsurprisingly) the Coriolis force deflects the trajectory of the reef jets at some distance offshore, while jet centerline velocities' magnitudes are weaker for healthy rough reefs owing to the large bottom friction. Stronger bottom friction also increased the relative importance of the Coriolis force in modifying the structure of the jet, as well as the size, speed, and coherence of the eddies shed from it. Surface waves also may influence the advection of these 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 along with detailed particle tracking studies will more clearly identify jet–jet interactions and recirculation patterns.

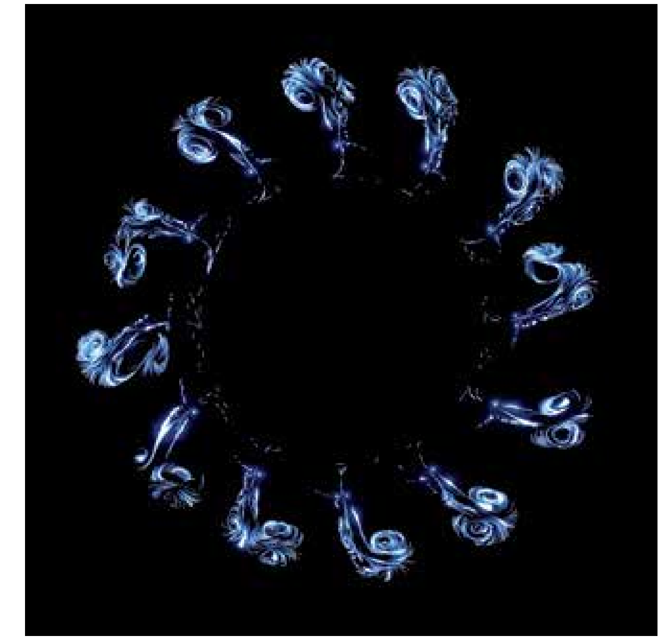

Figure 2: Particle trajectories illustrate the deflection of wave-driven reef jets in the idealized annulus domain owing to the earth's rotation. This simulation was carried out at 45°S, and the scale is identical to Fig. 1.

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 (LTER) initiative, especially on factors affecting coral resilience such as larval recruitment, nutrient loading, and organismal behavior

WHY BLUE WATERS

The Blue Waters supercomputing resource was essential in producing physically representative 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.

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.