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Biophysical model of coral population connectivity in the Arabian/Persian Gulf

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Contents

Abstract

The coral reef ecosystems of the Arabian/Persian Gulf (the Gulf) are facing profound pressure from climate change (extreme temperatures) and anthropogenic (land-use and population-related) stressors. Increasing degradation at local and regional scales has already resulted in widespread coral cover reduction. Connectivity, the transport and exchange of larvae among geographically separated populations, plays an essential role in recovery and maintenance of biodiversity and resilience of coral reef populations.

Here, an oceanographic model in 3-D high-resolution was used to simulate particle dispersion of "virtual larvae." We investigated the potential physical connectivity of coral reefs among different regions in the Gulf. Simulations reveal that basin-scale circulation is responsible for broader spatial dispersion of the larvae in the central region of the Gulf, and tidally-driven currents characterized the more localized connectivity pattern in regions along the shores in the Gulf's southern part. Results suggest predominant self-recruitment of reefs with highest source and sink ratios along the Bahrain and western Qatar coasts, followed by the south eastern Qatar and continental Abu Dhabi coast. The central sector of the Gulf is suggested as recruitment source in a stepping-stone dynamics. Recruitment intensity declined moving away from the Straits of Hormuz. Connectivity varied in models assuming passive versus active mode of larvae movement. This suggests that larval behaviour needs to be taken into consideration when establishing dispersion models, and establishing conservation strategies for these vulnerable ecosystems.

Introduction

Significant fluctuations of population sizes are increasingly common in coral reef organisms. These can be outbreaks of predators, like Crown-of Thorns Starfish (Shafir et al., 2008) or coral-eating snails (De'ath et al., 2012), or competitors such as brown algae (Mumby et al., 2007; Van den Hoek et al., 1995). Population collapses of fishes, corals or other organisms are increasing and frequently demonstrated (McClanahan et al., 2008; Robbins et al., 2006). An ever-growing human footprint leads to more resource-extraction by capture (fisheries, collection of ornamentals, etc.) or resource removal either by mortality events or by destruction of viable habitat (Cinner et al., 2018). Changes in populations of reproducing organisms have obvious repercussions on population dynamics and lead to feedbacks into upward or downward cycles, or in the worst case, one-way trajectories of decline (Case, 2000; Caswell, 2001). Corals and fishes are organisms that show tendencies to get ever rarer on reefs as natural and man-made environmental impacts increase (Kayal et al., 2012).

If organismic populations on coral reefs are to survive in such difficult settings, first principles of population dynamics suggest that replenishment by natural recruitment will be key to survival (Case, 2000; Caswell, 2001; Hutchinson, 1978). Population fecundity, connectivity among populations, and levels of recruitment must, therefore, be known to understand and model the potential survival of coral reef organisms (Paris et al., 2007). This is no trivial task since recruits of virtually all organisms are small and difficult, if not impossible, to track unless sophisticated genetic tools are at hand (Baums et al., 2014; Berumen et al., 2019) to determine the provenance of propagules. While much progress has been made by using traditional field methods (settlement plates, larval capture, etc.; Bauman et al., 2012; Burt and Bauman, 2019), there remains a need to know more details and to better evaluate future scenarios. Also, some predictions regarding the likelihood of population connectivity based on demographic models (Riegl and Purkis, 2015; Riegl et al., 2017) can only be verified by sophisticated analyses of propagule flow among these populations. Biophysical models of larval dispersion that integrate particle transport with physical oceanographic models have been used with much success to explain patterns in biodiversity (Cowen et al., 2000; Paris et al., 2007; Werner et al., 2007), invasion dynamics (Johnston and Akins, 2016; Johnston and Purkis, 2015), and potential pathways of larvae for population recovery (Cavalcante and Burt, 2016; Riegl et al., 2017, 2018). Such approaches bear much promise for understanding and predicting the future of marine resources in increasingly depleted coral reefs. The Arabian/Persian Gulf (hereafter termed “Gulf”) is a peripheral, epicontinental sea connected to the Indian Ocean and was, until relatively recently, home to large reef areas that have since been severely restricted (Riegl et al., 2018; Sale et al., 2011; Sheppard, 2016; Sheppard et al., 2010). A thriving economy and growing human population put massive pressure on the reefs of the region (Riegl and Glynn, 2020), which is home to some of the world’s largest coastal alteration (dredge-and-fill) and desalination projects (Sale et al., 2011; Sheppard et al., 2010; Van Lavieren et al., 2011). With habitat rapidly disappearing and the region being highly sensitive to climate extremes (Bauman et al., 2015; Burt et al., 2014; Riegl and Purkis, 2012), the future of most coral reef taxa and reef areas seems to depend on recruitment to replenish the frequent and severe losses (Pratchett et al., 2017; Riegl et al., 2017). The status, whether extant or soon extinct, of some ecosystem engineering species depends on the availability of upstream populations to seed and allow replenishment of depleted populations (Riegl et al., 2018).

This study uses a three-dimensional oceanographic model at 1 km resolution to model particle transport within the Gulf and to develop predictions of population connectivity. Previous biophysical models of settlement and population replenishment dynamics in this region were two-dimensional and considered only the ocean’s surface layer with low resolution in the coastal areas (Cavalcante and Burt, 2016; Riegl et al., 2017, 2018). However, large areas of the Gulf harbour deeper (to >30m) coral populations and the densest reef assemblages are close to the shoreline. This new model therefore represents an advancement in technical capability to develop much finer-grained scenario-models and predictions. In this paper we use a 3D high-resolution model that reproduces the circulation features of the Gulf, together with an agent-based model that reproduces the transport and biological processes of spawned eggs to first, (i) understand whether the larvae spawned at a certain area can travel to form coral colonies at other areas and, second (ii) to explore how distinct coral populations are connected within the Gulf, which is crucial to coral conservation efforts.

Conclusions

In this study, the developed 3D hydrodynamic model performed as expected for the simulated period. The model was able to simulate the basin-scale circulation and reproduce the observed characteristics of the eddies typical for the period of study, and agreed with in situ observations, the HYCOM database, and other studies on the circulation-driven mechanisms in the Gulf. The 3D model highlighted the importance of atmospheric fields on circulation patterns and the understanding of local circulation characteristics. The hydrodynamic simulations demonstrated the potential for interpreting the key identified physical connectivity pathways of the distinct regions with regards to coral reefs in the Gulf. Coral larvae have the potential to be dispersed long distances under basin-scale currents and eddies, but tend to shorten the travel distance under localized tidal-driven currents.

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