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Ocean circulation drives heterogeneous recruitments and connectivity among coral populations on the North West Shelf of Australia

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ABSTRACT

The North West Shelf (NWS) of Australia features extensive and globally significant fringing coral reef ecosystems with high levels of endemism and consequently has received significant conservation efforts in the form of Marine Parks. The shelf circulation on the NWS is dominated by the southwestward-flowing Holloway Current during austral autumn–winter and by the northeastward monsoonal currents during austral summer. Intraseasonal Oscillation and short-term wind variability also influence advection processes on the NWS. These circulation processes are likely to determine demographic inter-dependencies among reef systems in the region, but the extent and spatial variability of the inter-dependence are not well understood. In this study, we used a 3-dimensional, hydrostatic, primitive equations model, to simulate the shelf circulation on the NWS at 1 km horizontal resolution during 2004–2009. We then used a particle tracking model based on the shelf circulation model to simulate larval dispersal in a representative coral species, *Acropora millepora*, among the 3430 coral reefs on the NWS during its autumn mass spawning. Model results predicted that settling larvae typically reach suitable reef within 10 days of spawning, with a predominantly southwestward tendency of transport. There was significant spatial heterogeneity in larval settlements and the Dampier Archipelago areas seemed to be more isolated from the rest of the NWS. Year-to-year variations of larval dispersals were sensitive to the seasonal and intraseasonal variations of alongshore winds: mass spawning in late March would expose the Dampier Archipelago area to the Holloway Current onset, resulting in it being an occasional source region of larval supply for the rest of the NWS to the southwest; intraseasonal northeastward wind pulses coinciding with the mass larval spawning would bring larvae from coastal regions to the Dampier Archipelago on rare occasions. By aggregating the reefs into 47 subregions, we estimated that the mean rate of self-seeding within the subregions (as a proportion of total supply) was 22% (range from 99% to <1%). Subregions with high retention (as a proportion of total egg production) were not necessarily those with the highest levels of overall larval settlements. Such high "sink" subregions were also some of the most important "source" subregions. Most of the important source and sink subregions were found to be outside existing marine parks, however, existing marine parks did contain subregions with some of the highest levels of self-seeding and larval retention.

1. Introduction

Coral reefs are one of the most highly impacted marine ecosystems on earth by human activities (Halpern et al., 2008), and the threats to reefs under anthropogenic climate change are likely to be extreme (Hoegh-Guldberg et al., 2007; Botsford et al., 2009; Cowen et al., 2007; Munday et al., 2009; Steneck et al., 2009; Gilmour et al., 2013). A significant proportion of the effort devoted to understanding the role of connectivity in the conservation of coral reefs has focused on the role that networks of marine protected areas (MPA) may play in ensuring the resilience of ecosystems and the persistence of populations (Botsford et al., 2009; Bode et al. 2006; Kaplan et al., 2006, 2009; Fernandes et al., 2012; Gaines et al., 2010; Sale et al., 2010). Meta-population models of connectivity suggest that the local retention of larvae is a key factor in population persistence (Kaplan et al., 2006, 2009), although the protection of important larval source (sources of larvae settling on other reefs) and sink (destinations of larvae) areas has also been advocated (Jones et al., 2008; Gaines et al., 2010; Sale et al., 2010). Realistically, understanding the interdependencies of any network of meta-populations, including optimizing any network of protected areas, will rely on a broader understanding of ecological processes, as well as source-sink dynamics and larval retention (Burgess et al., 2014).

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The North West Shelf (NWS) is located in the southeast Indian Ocean between North West Cape and Dampier Archipelago of Australia (Fig. 1). The NWS supports extensive and globally significant fringing coral reef ecosystems with high levels of endemism (Roberts et al., 2002), and these reefs form a complex topography composed of numerous coral shoals and reefs fringing the 2100 rocky islands of sedimentary and igneous origin. These reef ecosystems are located off an arid coast that receives little terrestrial runoff, thereby facilitating exceptionally high levels of coral growth for a continental margin (Veron, 2000). The region features a number of significant marine reserves, including the Montebello/Barrow Island marine protected areas (MBIMPAs) and the Ningaloo Marine Park (Fig. 1), and fisheries resources, closely juxtaposed with an increasing number of oil and gas facilities and growing shipping traffic servicing onshore mining facilities. The region also supports several large port infrastructure developments. Currently planning of a Marine Park in the Dampier Archipelago is well advanced, although reserves are not yet declared, other areas within the region have been suggested as being of potential conservation interest (DPaW, 2013).

The NWS is one of the source regions of the Leeuwin Current, a poleward-flowing eastern boundary current in the southeast Indian Ocean. The shelf circulation on the NWS is dominated by the southwestward-flowing Holloway Current that feeds into the Leeuwin Current during austral autumn and winter (Holloway and Nye, 1985; Holloway, 1995), and by the Australian monsoonal wind-driven northeastward currents over the inner- and mid-shelf during austral summer (Condie and Andrewartha, 2008). Intraseasonal Oscillation (Madden-Julian Oscillation) also drives significant coastal currents on intraseasonal time scales (Marshall and Hendon, 2014). Tidal currents and tropical cyclones are important factors in driving horizontal and vertical mixing processes on the shelf and in the nearshore environment (Condie et al., 2009). The region is susceptible to the influence of Pacific climate variability, transmitted along the coastal waveguide that drives the interannual variability of the Leeuwin Current (Feng et al., 2003; Wijffels and Meyers, 2004). During the consecutive Ningaloo Niño—marine heat wave events in 2011–2013 (Feng et al., 2015), the NWS experienced coral bleaching in various locations (Depczynski et al., 2013; Moore et al., 2012). Thus, the resilience of coral reef ecosystems to disturbance, and consideration of the role of individual reefs as population sources or sinks, influenced by shelf circulation, becomes an increasingly important consideration in ensuring the overall effectiveness of conservation and management efforts on the NWS.

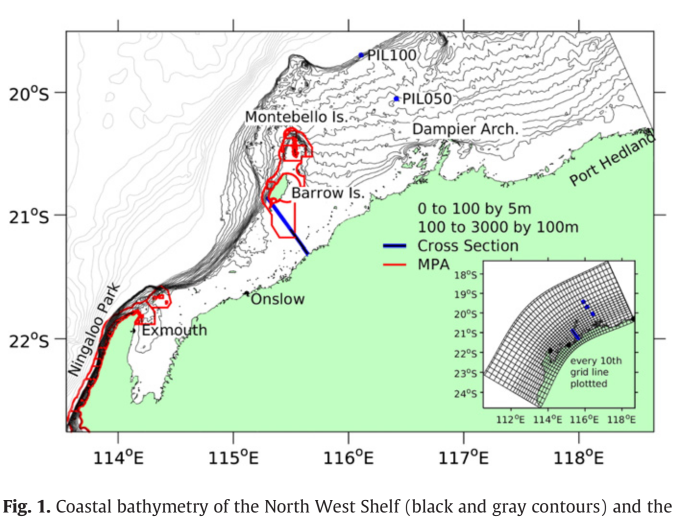

Fig. 1. Coastal bathymetry of the North West Shelf (black and gray contours) and the Marine Protected Areas (red outlines). The inset shows the ROMS model domain and model grid (showing every 10th grid) used in this study. The bottom bathymetry is plotted for every 5 m from 10 to 100 m and every 100 m from 100 to 3000 m.

At present, due to the lack of high-resolution measurements of shelf circulation on the NWS, research into larval retention and connectivity had relied on coarse resolution numerical ocean circulation models, some without considering tidal processes (Radford et al., 2014). Using a 10-km resolution regional model, results averaged across 6 model years (1994–1999) suggested that exchanges from the Barrow and Montebello reefs to Ningaloo Reef may be relatively common over time-scales as short as 1–2 weeks, whereas exchanges from the Dampier Archipelago reefs to Barrow and Montebello might also be significant for larvae that can remain viable for at least 2 weeks (Condie and Andrewartha, 2008). In contrast, based on a 9-km global ocean model, it was predicted that the Commonwealth Marine Reserves containing the Ningaloo–Montebello and Dampier coast regions were likely to have little larval exchange (Kool and Nichol, 2015). These coarse resolution models did not resolve the complex island chain structures and the detailed bottom bathymetry, as well as the mesoscale and sub-mesoscale circulation processes that may be important for particle retentions around reefs. Thus, a high-resolution simulation of the shelf circulation in the region, incorporating tidal currents, is necessary to reassess the degree of larval retention and connectivity among reefs of the NWS.

In this study, we developed a 3-dimensional shelf-scale oceanographic circulation model for the NWS at 1-km resolution. We used this model to deliver a 6-year simulation of the shelf circulation under different climate conditions, capturing the seasonal, interannual, and high-frequency variability of shelf circulation that is modulated by tidal forcing. An individual-based particle tracking model was then used to predict levels of retention and connectivity of a representative coral species among major coral reef habitats in the region. Documented larval life-history (spawning time, survival and competency) was also incorporated into the model to optimize predictions of source-sink dynamics.

2. Models and methods

2.1. Study area

At its southwestern end, the NWS is bounded by Ningaloo Reef, Australia's largest fringing reef system with a narrow continental shelf and an extensive coastal fringing reef ecosystem (Wilson et al., 2010). The shallow shelf areas to the north of Ningaloo are littered with numerous small islands and shoals, most of which support reef-building corals and often considerable coral reef development. Further offshore, Barrow Island and the Montebello Islands are large islands also with considerable levels of coral reef development, whereas at the northern end of the region, the Dampier Archipelago is an area of continental high islands that support substantial fringing reef development. North of Dampier along the west end of the Roebourne Plains East, the coast is more linear and dominated by beaches but does host scattered coastal reefs (Fig. 1).

2.2. Hydrodynamic model

We used the Rutgers version of the Regional Ocean Modelling System (ROMS, e.g., Marchesiello et al., 2003; Shchepetkin and McWilliams, 2005). ROMS is a 3-dimensional (3D), hydrostatic, primitive equations model, featuring a non-linear free-surface in the barotropic mode. It uses terrain following stretched-coordinates (S-coordinates) in the vertical and an orthogonal curvilinear grid transformation in the horizontal. The model domain covered the NWS and Ningaloo Reef region and had a horizontal resolution of ~1 km (Fig. 1). The bottom topography was taken from a collection of sources including GA2009, industry provided LIDAR, and MNF multibeam data. Thirty levels were used in the vertical layers, and we used non-local K-Profile in the vertical mixing parameterisation (Large et al., 1994). The model did not have wetting and drying,