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# The interacting effects of photosynthesis, calcification and water circulation on carbon chemistry variability on a coral reef flat: A modelling study

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ABSTRACT

The diurnal fluctuations in seawater carbon chemistry that occur at sites within a coral reef system are due to water circulation, air-sea heat and gas exchange, and biogeochemical processes. The daily changes in dissolved carbon ion speciation and $pH_T$ on reefs can be larger than the century-scale shifts predicted for open ocean waters under climate change scenarios. We implement a 167 m resolution 3D hydrodynamic model of a coral reef (Heron Island reef, southern Great Barrier Reef, Australia) and couple it to a carbon biogeochemistry model. The model is forced by benthic fluxes calculated using a detailed habitat map and light and habitat-dependent parameterisations of calcification/photosynthesis developed from flume studies on Heron Island. During a two month simulation the model is able to reproduce the observed variability in the water temperature at 8 locations within the reef, demonstrating an ability of the model to capture the circulation. The simulation shows that the dominant processes driving the variability in carbonate chemistry at a location on the reef are the location of the different benthic communities and the path the water has taken to arrive at that location. A spatially-resolved age tracer indicates that the residence time of water over the reef varied between 16 and 60 h, depending on tides, winds and location. The longer transit times over the reef reduced the aragonite saturation state, $\Omega_a$, in the overlying water to as low as 2. In the model simulation, the reef ecosystem reduces $\Omega_a$ at a rate of 0.018 per hour on the reef. A scenario in which we removed the non-calcifying benthic microalgae from the reef showed a reduction in the $\Omega_a$ in some regions from 5 to 2.5, and an average reduction of the coral calcification by 15%. This demonstrates the importance of processes that can alter the photosynthesis/respiration and calcification/dissolution balance when considering climate change impacts due to ocean acidification on corals at the reef scale.

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## 1. Introduction

The Great Barrier Reef (GBR) is the world's largest reef system covering approximately 345,950 km$^2$ with more than 2900 reefs (Woodroffe et al., 2010). Inside and surrounding these reefs, corals communities contain a collection of autotrophic, heterotrophic and calcifying organisms. Over the last decade, coral reef ecosystems have received much attention due to the potentially disastrous impacts of ocean acidification and global warming (Doney et al., 2009).

The interplay of $CO_2$ exchange with the atmosphere and the ocean carbon chemistry determines that an increase of anthropogenic atmospheric $CO_2$ leads directly to ocean acidification (Caldeira and Wickett, 2003). One of the consequences of ocean acidification is a decrease in dissolved carbonate ion concentration, $CO_3^{2-}$, and the aragonite saturation state, $\Omega_a$ (Eq. (1)). Calcifying organisms utilise $CO_3^{2-}$ and dissolved calcium ions $Ca^{2+}$, to produce calcium carbonate ($CaCO_3$) skeletal materials and shells. Aragonite is a metastable form of calcium carbonate that is precipitated biogenically by many reef forming corals and other species. The aragonite saturation state is commonly used to describe the ability of corals to calcify and is given by:

$$\Omega_a = \frac{[CO_3^{2-}][Ca^{2+}]}{K_{sp}} \tag{1}$$

where $K_{sp}$ is the solubility product.

A fall in $CO_3^{2-}$ concentration is expected to cause a decrease in coral accretion (Atkinson and Cuet, 2008). As ocean acidification progresses, changing water chemistry could eventually lead to the dissolution of coral reef systems (Andersson et al., 2009).

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At the current rate of $pCO_2$ increase in the atmosphere, corrosive conditions ($\Omega_a < 1$) in surface waters will only appear in high latitude and some upwelling areas in the middle of the century (Orr et al., 2005). Corals in some shallow reef lagoons are already exposed on short time scales (h) to carbon chemistry conditions like those predicted to occur next century under high $CO_2$ emission climate change scenarios (Shaw et al., 2012).

These extreme $\Omega_a$ values are mostly driven by large benthic fluxes of $CO_2$ due to the diurnal imbalance between: photosynthesis (capture $CO_2$ during the day), calcification (take up $CO_3^{2-}$ during day and night), respiration (release $CO_2$ during day and night), dissolution (release $CO_3^{2-}$ during day and night) water circulation, and temperature-driven shifts in carbon equilibrium states.

Takahashi et al. (2002) highlighted the need to understand regional and local variability to help reduce the uncertainties in assessing the impact of ocean acidification in climate change scenarios. Similarly, Zhang et al. (2012) demonstrated the need to understand the response of mixed communities to an increase of $CO_2$. Understanding the short term variability of carbon chemistry parameters at the scale of coral biogeochemical processes is critical to the design of experiments that assess the impact of global ocean acidification on individual reefs.

A detailed description of the water movement over different regions of the reef is a starting point to understand the complex interplay between biological-driven benthic carbon fluxes and advection of water. Similarly, observing and simulating the physical properties of ocean waters around coral reefs provides important insights for linking ecosystem responses to environmental changes. Thus, it is important to develop a modelling framework that enables us to study the interactions between water movement and metabolic processes.

In this study we describe a high resolution circulation model developed specifically for a shallow water reef system (Heron Island, southern Great Barrier Reef, Australia). Heron Island was chosen due to the extensive research undertaken on its reef flat, and the combination of a large reef and shallow waters which allow for significant changes in carbon chemistry as the water moves over the reef. The hydrodynamic model is first compared against temperature observations on the reef. We then configure this model with maps of benthic communities and force it with light and habitat-dependent calcification and photosynthesis parameterization determined from flume studies at Heron Island (Anthony et al., 2011). Linking circulation with calcification/photosynthesis fluxes for different benthic communities allows us to consider the processes driving the high frequency variability of $\Omega_a$. Finally, we modify those community distributions to investigate ecosystem feedbacks on seawater carbonate chemistry.

## 2. Materials and methods

### 2.1. Study site

Heron Reef covers approximately 27 km$^2$, and is located 80 km off the Australian mainland, northeast of Gladstone (Fig. 1). It is one of the Capricorn Group of islands in the southern Great Barrier Reef. Heron Island is located on the northwest margin of Heron Reef and is 800 m long by 280 m wide. Heron Reef is separated from Wistari Reef by the Wistari Channel (20–30 m deep).

The benthic cover of Heron Reef is characterised by distinct morphological and ecological zones of coral and mixed sediments (Roelfsema et al., 2002; Ahmad and Neil, 1994). The habitat zonation has arisen due to hydrodynamic (waves, tides and currents), geomorphic and ecological processes. The different zones include the outer coral zone, algal rim, and rubble zone on the inside of the reef crest, the coral zone and an inner sandy zone. The hydrodynamic processes of Heron Reef are characterised by semi-diurnal tides with an average spring tidal range of 2.28 m and an average neap tidal range of 1.09 m. At low tide, water depth over much of the reef flat is 0.3–1 m, while in the deeper part of the lagoon it averages 3.5 m (Chen and Krol, 1997). As the tide falls below the reef rim, pooling of water occurs in the lagoon resulting in a higher water level at low tide than the surrounding ocean (Gourlay and Hacker, 1999). Wave heights on the reef are generally less than 0.5 m due to the limited water depth and protection from ocean-generated wave action by the reef rim (Gourlay and Colleter, 2005).

### 2.2. Hydrodynamic model

The Sparse Hydrodynamic Ocean Code (SHOC; Herzfeld, 2006; Herzfeld et al., 2010) is a general purpose hydrodynamic model applicable to scales ranging from estuaries to regional ocean domains. SHOC is a fully three-dimensional finite-difference baroclinic model based on the three dimensional equations of momentum, continuity and conservation of heat and salt, employing the hydrostatic and Boussinesq assumptions. The equations of motion are discretized on a finite difference stencil corresponding to the Arakawa C grid, and can be solved on either a *z*- or sigma vertical coordinate system. The Heron configuration uses a rectangular orthogonal grid in the horizontal and fixed *z* coordinates in the vertical.

In the vertical *z*-coordinate scheme, there are 24 fixed *z*-levels (those above 10 m depth being −10.0 −8.0 −6.5 −5.0 −4.0 −3.0 −2.3 −1.6 −1.0 −0.5 0.0 0.5). The *z*-scheme in SHOC allows partially filled levels at the bottom. Thus, the area-averaged depth for each cell can be specified exactly, avoid volume errors introduced by bathymetric smoothing required by sigma coordinate scheme. The *z*-scheme also avoids instability generated by sudden compression of the vertical layers across step gradient in sigma co-ordinate system. The model uses wetting and drying algorithms to resolve the intertidal processes; wetting and drying capability involves the free surface moving through the constant *z* layers, allowing a given cell to be emptied of water and remain dry for a period of time before it can be submerged again (Fig. 5).

We used a nesting modelling strategy, where a 167 m resolution grid of Heron Reef was nested within a ∼1 km regional grid that covered a larger spatial extent of the Great Barrier Reef. This regional model was in turn nested within a ∼10 km resolution global circulation model. The regional model acts as a nesting vehicle to allow boundary conditions to be downscaled to a resolution appropriate for the Heron Reef grid, and incorporates the influence of tides. The regional grid was forced at the ocean boundaries by outputs from BRAN2.3, a data-assimilating simulation of the Ocean Forecasting Australian Model (OFAM, Oke et al., 2008). The horizontal resolution of the regional grid is 1 km, with a maximum depth in the domain of 275 m. The bottom depth for the 167 m horizontal resolution grid was generated from airborne and sonar bathymetry observations at 2 m horizontal resolution (Hedley et al., 2009). The bathymetry resolves the transition between regions below mean sea level and that at the highest astronomical tide, to allow the model to capture processes in the inter-tidal zone (Fig. 5).

The atmospheric forcing products (wind, pressure, heat fluxes) are supplied by the Bureau of Meteorology (BOM) using the MesoLAPS reanalysis product (http://www.bom.gov.au/nmoc/bulletins/39/opsbul39.shtml). A tidal signal was superimposed on the low frequency sea level oscillation provided by BRAN2.3 on the regional grid open boundary. This tidal signal was introduced via a local flux adjustment.

The OTIS tidal model (http://www.oce.orst.edu/research/po/research/tide/otis.html) was used to generate the tidal signal from amplitude and phase information for 8 constituents. The local grid

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