



## Reduced calcification in Western Australian corals during anomalously high summer water temperatures



T. Foster<sup>\*</sup>, J.A. Short, J.L. Falter, C. Ross, M.T. McCulloch

UWA School of Earth and Environment and Oceans Institute, University of Western Australia, Crawley, Western Australia 6009, Australia  
ARC Centre of Excellence for Coral Reef Studies, University of Western Australia, Crawley, Western Australia 6009, Australia

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### ABSTRACT

Here we report the seasonal response of calcification rates over two years, for three coral species (*Acropora pulchra*, *Pocillopora damicornis* and *Goniastrea aspera*), to anomalously warm summer water temperatures (2012 and 2013), following the most severe marine heat wave on record (2010–2011). The study sites at Coral Bay (Ningaloo Reef), the Houtman Abrolhos Islands and Marmion Reef (Perth) spanned over 10° of latitude and ranged from tropical to temperate habitats. Calcification rates were determined using repeated measurements of buoyant weight normalized to surface area and rates were monitored over two winters and two summers from 2011 to 2013. Average growth rates followed predicted latitudinal trends, with the fastest growth in the tropics (Coral Bay) and slowest growth rates in the temperate zone (Marmion). However, calcification rates did not show the expected seasonality (higher in summer, lower in winter), even at high latitude locations. Instead, there was either little difference between summer and winter growth or growth was slower in the summer (on average, a reduction of ~40% across locations and species). Additionally, differences in species growth rates did not follow expected trends, with usually fast growing branching corals not calcifying much faster than the normally slower growing massive corals (*A. pulchra*, grew ~40% faster than *G. aspera*, which grew ~6% faster than *P. damicornis* across all latitudes and seasons). Survival rates were also reduced in the summer months, while among species, *P. damicornis* had the lowest survival and *G. aspera* the highest. We conclude that high temperature stress through the summers of 2011 to 2013 was the most likely cause for the lack of seasonality in calcification rates, the similarity in calcification rates among species and the increased mortality of susceptible species in the summer months. The effect of prolonged elevated temperature anomalies (1.5 to 3 °C) on the growth and survival of colonies over consecutive years was often greater than the fundamental influences of season and species, highlighting the extent to which climate change could now be re-structuring the life histories of corals on Western Australian reefs.

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### 1. Introduction

Coral growth rates typically vary with season, latitude and taxa (Crossland, 1981; Harriott, 1999; Lough, 2008; Lough and Barnes, 2000; Shinn, 1966). Lough and Barnes (2000) observed that extension and calcification rates decreased with increasing latitude, which was directly related to decreasing water temperature down latitudinal gradients. Similarly, higher growth rates generally occur in summer months, particularly at high latitude locations. For example, Shinn (1966) reported a decrease in linear extension of *Acropora cervicornis* in the winter months in Florida (25°N), while at the Houtman Abrolhos Islands (28°S), growth rates for *Acropora formosa* were 5 times higher in

summer than in winter (Crossland, 1981). A shorter growing season was also reported for corals at high latitude locations on the Great Barrier Reef, with greatly reduced growth in winter (Isern et al., 1996). Similarly, Kinsey (1985) noted that seasonal differences between summer and winter net community calcification rates reported from the northern Hawaiian Islands (French Frigate Shoals, 24°N, Atkinson and Grigg, 1984), the Houtman Abrolhos Islands (Smith, 1981) and across the Great Barrier Reef generally increased with increasing latitude and ranged from a factor of 2 to 4. Even in the tropics, where temperature and daylight hours vary comparatively less throughout the year, community calcification rates were 30 to 40% higher in summer than in winter (Kinsey, 1979). Seasonality appears to be greatest at high latitude reefs, consistent with the presence of more pronounced seasonal changes in both temperature and light (Howe and Marshall, 2002; Isern et al., 1996). Warmer water temperatures increase the metabolism of the zooxanthellae, stimulating calcification (Eckert et al., 1988), while higher light availability enhances calcification by providing photosynthates for energy as well as triggering calcium

<sup>\*</sup> Corresponding author at: UWA School of Earth and Environment and Oceans Institute, University of Western Australia, Crawley, Western Australia 6009, Australia. Tel.: +61 8 6488 3435.

E-mail addresses: [taryn.foster@uwa.edu.au](mailto:taryn.foster@uwa.edu.au) (T. Foster), [shortj02@student.uwa.edu.au](mailto:shortj02@student.uwa.edu.au) (J.A. Short), [jim.falter@uwa.edu.au](mailto:jim.falter@uwa.edu.au) (J.L. Falter), [claire.ross@uwa.edu.au](mailto:claire.ross@uwa.edu.au) (C. Ross), [malcolm.mcculloch@uwa.edu.au](mailto:malcolm.mcculloch@uwa.edu.au) (M.T. McCulloch).

uptake (Al-Horani et al., 2003). Among coral taxa, branching species typically grow much faster than massive species (Harriott, 1999). The fast growing but more fragile branching corals are generally the most dominant in terms of coral cover, but are less able to withstand mechanical damage than the slow growing but more robust morphologies, which dominate high energy areas (Adey, 1978). Branching species such as Acroporids and Pocilloporids grow at rates of approximately 100–150 mm/year and 50 mm/year respectively, while massive morphologies such as *Montastrea* and *Porites* grow around 5–10 mm/year (Dullo, 2005). However, elevated water temperatures in summer months can potentially change the typical pattern of variation in growth between seasons and across coral taxa. Very high temperatures in summer months can stress corals, reducing growth and survival (Shinn, 1966; Yap and Gomez, 1985). Furthermore, it is often the faster growing, branching morphologies, such as the Acroporids and Pocilloporids that are most susceptible to temperature stress, while the massive morphologies such as the Faviids and Poritids appear to be more resilient (Marshall and Baird, 2000).

The optimal temperatures for coral calcification are constrained within their thermal limits, with growth and survival typically reduced when maximum summer temperatures exceed long-term averages (Clausen and Roth, 1975; Jokiel and Coles, 1977; Marshall and Clode, 2004). Growth rates generally increase with temperature only until maximum summer temperatures reach long-term averages, beyond which corals become stressed (Marshall and Clode, 2004). Coral bleaching usually occurs after prolonged exposure to small increases (0.5–1.5 °C), or short exposure to large increases (3–4 °C) in water temperature above the average summer maximum (Glynn and D'croz, 1990; Jokiel and Coles, 1977). Bleaching and the subsequent loss of photosynthetic capacity reduce metabolic energy availability for processes such as calcification (Grottoli et al., 2004), while prolonged temperature stress can result in partial or whole-colony mortality (Baird and Marshall, 2002). Several studies have reported suppressed growth between one and four years following a bleaching event (Cantin and Lough, 2014; Goreau and Macfarlane, 1990; Leder et al., 1991; Omata et al., 2006; Suzuki et al., 2003). On reefs under high local stress, recovery time was shown to take at least eight years based on coral growth banding (Carilli et al., 2009).

Considerably less is known about the impacts of thermal stress on calcification rates before the bleaching threshold has been reached. However, there have been a number of recent studies reporting reduced calcification in situ, in response to increased water temperatures. For example, Cantin et al. (2010) reported a 5% decrease in growth of *Diploastrea heliophora* for every 0.2 °C increase in sea surface temperature (SST) above the summer maximum of 30.5 °C, in the central Red Sea. Overall, a 30% reduction in coral growth was observed after the 1998 mass bleaching event, in corals showing no obvious signs of stress. Additionally, reduced calcification rates in the massive coral *Porites*, which are among the most resistant corals to temperature, were attributed to increasing temperature stress on the GBR in recent years (Cooper et al., 2008; De'ath et al., 2009; D'Olivo et al., 2013). Similarly, around the Thai–Malay Peninsula in Southeast Asia, *Porites* growth rates showed region wide declines, with a significant link to increases in SST, however within region variability suggested that variables aside from temperature were also at play (Tanzil et al., 2013). The in situ studies as well as laboratory temperature studies outlined above indicate that calcification rates are reduced by temperature stress long before the bleaching threshold is reached.

Coral reefs around the world are increasingly impacted by warming oceans, leading to mortality and mass bleaching, as well as reduced growth and reproduction (Baker et al., 2008; Hoegh-Guldberg, 1999; Szmant and Gassman, 1990). There have been comparatively few mass bleaching events reported along the west coast of Australia. For example, most of the coral reefs that occur in the coastal waters of Western Australia (WA) escaped the effects of temperature anomalies that caused mass bleaching on most of the world's coral reefs during

the 1997–1998 El Niño event (Wilkinson, 1998, 2000). However in recent years, there have been apparent increases in the frequency of elevated temperature anomalies on WA reefs. Most notably, in the summer of 2011 a marine heat wave occurred along the coast of Western Australia (Feng et al., 2013; Pearce and Feng, 2013; Pearce et al., 2011). Tropical species were reported far outside of their usual ranges, mass-mortalities of fish, lobster and abalone were observed, there were resulting shifts in benthic community structure and the first widespread coral bleaching event was recorded for locations spanning 1200 km down the WA coastline; from Barrow Island (20°S) to Rottneest Island (32°S) and at most reef systems in between (Depczynski et al., 2013; Moore et al., 2012; Pearce et al., 2011; Wernberg et al., 2013). Decreases in coral cover following the bleaching event ranged from ~20 to 85% (Moore et al., 2012). Corals in these regions were likely still recovering from the heat wave, when in the summer of 2012 water temperatures along WA were again anomalously high and locations in the mid and southwest regions were on bleaching alert level 2 for 3–4 months (NOAA, Coral Reef Watch, 2013). Then in the summer of 2013, the Ningaloo region was again on bleaching alert level 2 from February to April and all other WA bleaching stations were on bleaching warnings or alerts for that period. Patchy bleaching was observed in the northern sections of Ningaloo reef and the Abrolhos Islands in 2013 (Ningaloo, Ningaloo Atlas, 2013; Abrolhos, authors' pers. obs). The initial aims of this study were to examine seasonal survival and calcification rates of three coral species with contrasting life histories and morphologies, from habitats spanning tropical to temperate and to provide baseline coral calcification data for WA corals. However, summer temperatures were anomalously high for the duration of the study from 2011 to 2013. Instead, we investigated the impacts of abnormally high summer seawater temperatures on rates of coral calcification and survival in species with contrasting susceptibilities to temperature stress (Marshall and Baird, 2000), at sites spanning 10° of latitude across WA.

## 2. Methods

### 2.1. Background

Study species included the branching corals *Acropora pulchra* and *Pocillopora damicornis* as well as the massive coral *Goniastrea aspera* (Table 1). Due to cooler winter temperatures, *A. pulchra* is not found at the highest latitude site (Marmion Reef) and could therefore not be included at this location. Study sites were located within three distinct biogeographic regions along 1200 km of the Western Australian coastline, spanning tropical to temperate reefs. Coral Bay (23°09'S) is located within the tropical Ningaloo Reef, the Houtman Abrolhos Islands (28°52'S) exist in a region of biogeographic overlap between tropical and temperate reef environments and Marmion Reef (31°48'S) is in temperate waters (Fig. 1). At all reefs, study sites were located in comparable back-reef habitats, in approximately 4 m water depth. Coral calcification rates were monitored over two years with surveys conducted around months in which water temperatures were warmest (summer) and coolest (winter, Table 2).

**Table 1**  
Species collected from each site.

Location	Species
Coral Bay	<i>Acropora pulchra</i> <i>Pocillopora damicornis</i> <i>Goniastrea aspera</i>
Houtman Abrolhos Islands	<i>Acropora pulchra</i> <i>Pocillopora damicornis</i> <i>Goniastrea aspera</i>
Marmion Reef	<i>Pocillopora damicornis</i> <i>Goniastrea aspera</i>

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