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NOTE

Thermal stress markers in *Colpophyllia natans* provide an archive of site-specific bleaching events

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Abstract Tropical coral reef monitoring relies heavily on in situ diver observations. However, in many reef regions resources are not available to regularly monitor reefs. This lack of historical baseline data makes it difficult to determine how different reefs respond to environmental stressors and what the implications are for management. To test whether coral cores could be used to identify bleaching events retrospectively, three sites in Tobago with pre-existing reef data including water quality and bleaching observations were identified. *Colpophyllia natans* cores were examined for growth anomalies which occurred during periods of thermal stress. If present, anomalies were compared to in situ, real-time bleaching observations and water quality data. Interestingly, sites with better water quality during the 2005 thermal anomaly were less prone to bleaching. We suggest that by reducing terrestrial run-off (e.g., sediment and nutrients), and therefore improving marine water quality, reef managers could enhance near-shore coral reef resilience during high-temperature events.

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Introduction

Globally, climate-induced coral bleaching is one of the most serious threats to coral reefs (Eakin et al. 2010; Graham et al. 2015). However, our knowledge of these events and their implications for future reef development is hampered by a lack of long-term, historical (multi-decadal), continuous data. Coral reef monitoring primarily relies on regular (e.g., annual) in situ observations typically by scientific SCUBA divers (e.g., CARICOMP 1994; English et al. 1997). This is labour intensive and requires adequate resources. However, in many coral reef regions of the world it is logistically impossible to conduct regular reef monitoring programmes across large swathes of reef, primarily due to a lack of manpower and limited funding. As a result, reef monitoring programmes are often highly piecemeal and run for short periods of time (less than a decade). This lack of baseline data makes it difficult to assess how corals have historically responded to climatic stressors. Long-term, continuous bleaching records would enable reef managers to make better-informed decisions. Due to their long lifespan (up to several centuries) and rapid growth (typically >1 cm yr^{-1}), massive-growing tropical corals can provide an ideal archive for reconstruction of seasonal to multi-decadal variability of environmental variables (Hetzinger et al. 2010).

Colonies of the massive brain coral, *Colpophyllia natans*, are ubiquitous on the fore-reef slopes of Tobago. Colonies >1 m in height are common with occasional colonies obtaining >3 m in height. Linear growth rates (skeletal extension) for *C. natans* in Tobago ranged from 12 to 15 mm

yr^{-1} at depths ≤10 m (unpublished data). Colonies of this size, with this growth rate, could therefore contain decadal- and centennial-scale archives. Here we demonstrate that coral cores from this dominant reef-building brain coral can be used to provide continuous, multi-decadal data for retrospectively identifying bleaching events. Furthermore, we show that corals located at sites with better water quality (e.g., reduced coloured dissolved organic matter, CDOM) along Tobago's coastline were less prone to bleaching.

Materials and methods

Three fore-reef sites were selected in Tobago for coring in 2008: Buccoo Reef (eastern outer reef), Speyside and Pirates Bay (Fig. 1). The prerequisites for site selection were (1) a near-shore fringing reef, (2) healthy *C. natans* colonies suitable for coring, (3) prior reef monitoring data, including in situ, site-specific observations during the 2005 bleaching event (O'Farrel and Day 2005; Wilkinson and Souter 2008; Eakin et al. 2010), and (4) site-specific water quality data (Mallela and Harrod 2008; Wilkinson and Souter 2008; Mallela et al. 2010; Mallela 2013). Oceanic remote sensing data for Tobago were used to verify sea surface temperatures (SSTs) and CDOM, used as an indicator of water quality at the three sites during the peak of the bleaching event in Tobago from September to December 2005 (NASA 2015). Data are summarised in Figs. 1, 2 and 3 and Table 1.

Permission to collect coral cores was obtained from the Tobago House of Assembly. Cores were collected from massive healthy *C. natans* brain corals at water depths ranging from 5 to 10 m using a hand-held pneumatic drill (Fig. 4). In order to minimise the impact, all core holes were filled with cement plugs to prevent recruitment by bioeroding organisms and to enable regrowth by coral tissue. Coral cores were 5 cm in diameter and 30 cm long. In the laboratory, cores were cut lengthwise and sectioned into 7-mm-thick slices. Coral slices were X-rayed for annual density bands (a high-density and low-density band) and chronologies assigned accordingly (Knutson et al. 1972) (Fig. 5). Coral cores and their radiographs were examined for visual skeletal markers that could be used as a bleaching indicator in the archive.

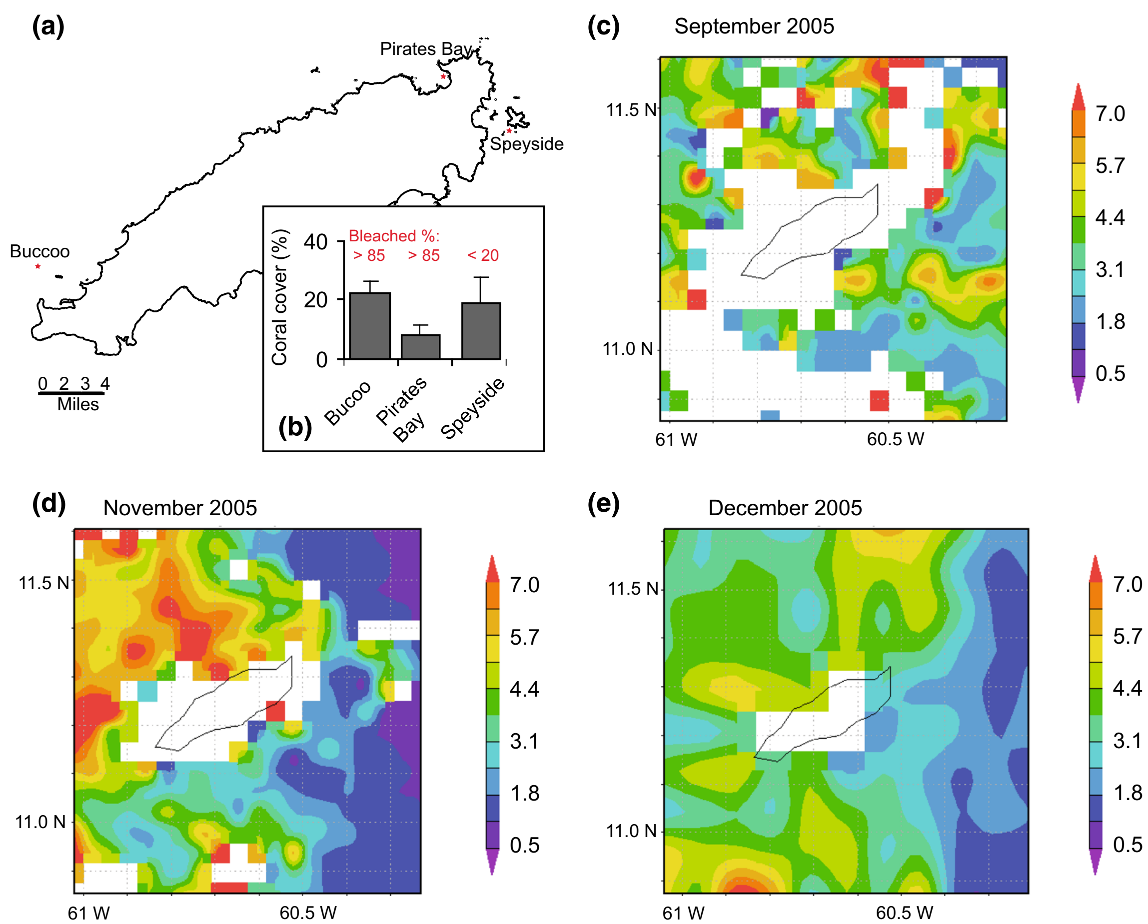

Fig. 1 **a** Map of coral core locations, **b** coral cover and % coral bleached [data sourced from Mallela et al. (2010) and O'Farrel and Day (2005), respectively], **c**–**e** colour dissolved organic matter (CDOM) index, 4 km resolution (unitless), September–December 2005 (data source: NASA 2015)

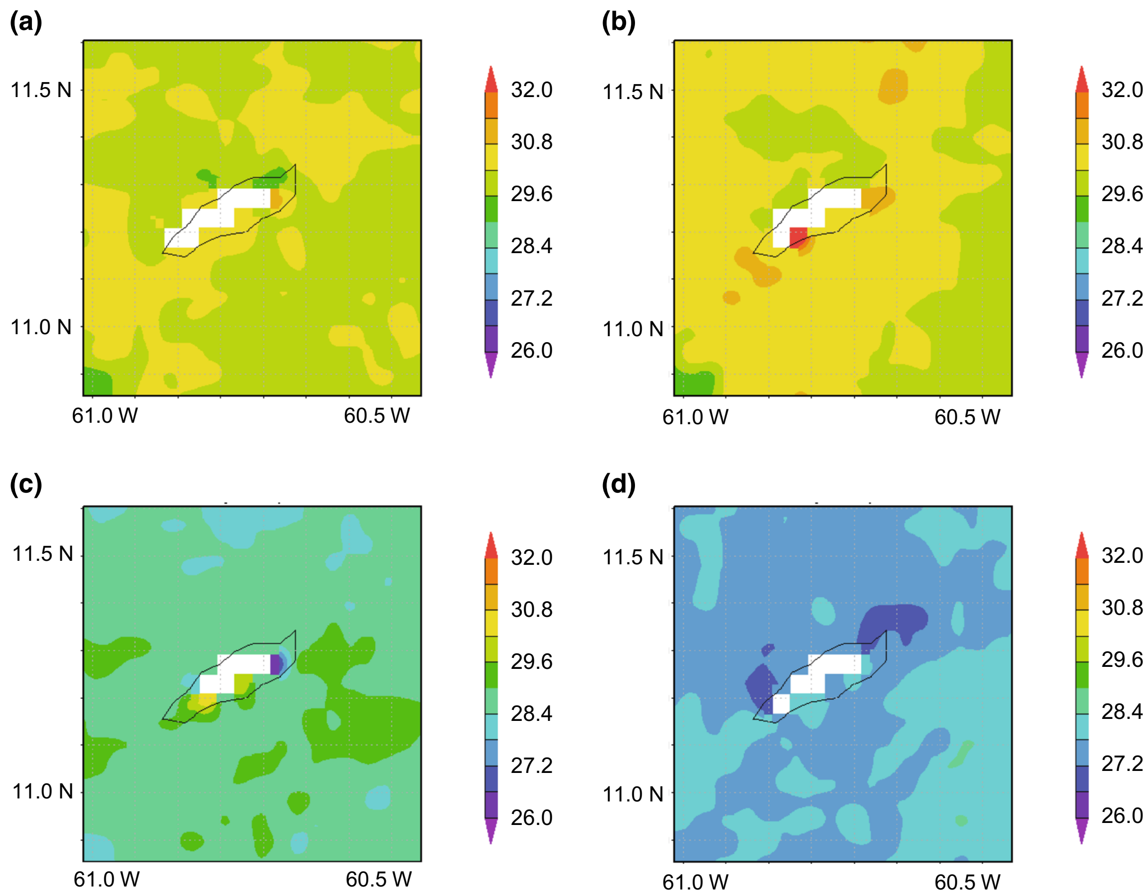

Fig. 2 Sea surface temperature (SST) °C, MODIS Aqua 4 km resolution (11 µm d), **a** September, **b** October, **c** November and **d** December 2005 (data source: NASA 2015)

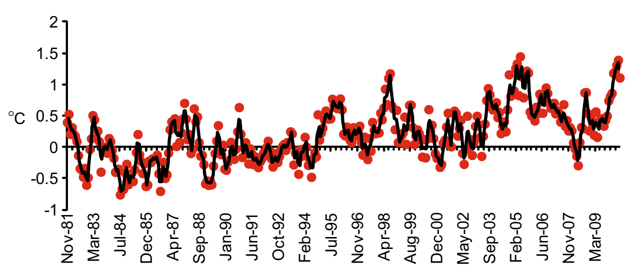

Fig. 3 Sea surface temperature anomalies (°C), *red circles*, in Tobago. Sea surface temperature anomaly is defined here as the difference between measured sea surface temperature at any given time and place and mean (average) sea surface temperature. Sea surface temperature data source: http://iridl.ldeo.columbia.edu/

Results and discussion

Prior to 2005 the brain coral *C. natans* occupied 11 % of the reef substrate in Tobago (Wilkinson and Souter 2008). Following the 2005 bleaching event, mortality was found to be greatest in the brain corals (*C. natans* and *Diploria strigosa* and *D. labyrinthiformis*) with 73 % of these colonies dying (Wilkinson and Souter 2008). Interestingly, a coral recruitment study in Tobago spanning 1980–2006 noted how *C. natans* was one of the four species to recover and successfully recruit following the 2005–2006 bleaching event (Mallela and Crabbe 2009). *Colpophyllia natans* is a large, meandroid faviid with typically long, meandering valleys. In *C. natans*, stress bands appear as unusual sinuous growth anomalies in radiographs and are clearly distinct from horizontal, annual growth bands (Fig. 5). X-ray images from Tobago's surviving *C. natans* revealed different localised bleaching impacts in Tobago during the 1997 and 2005 bleaching events. Stress bands were observed in the cores at two of our three sites: Buccoo (one stress band 2005–2006) and Pirates Bay (two stress bands 1997 and 2005–2006). None were found in the Speyside core. 2005–2006 stress bands coincided with real-time diver observations of bleaching events at each site (Table 1) with a clear gradient of bleaching susceptibility emerging between sites. Diver observations noted similar trends with only 20 % of coral colonies bleaching at Speyside compared to 75–100 % bleaching at Pirates Bay

Table 1 2005 bleaching observations and 2007 sediment trap data

	Colonies bleached 2005 (%)	Water depth (m)	Mean sedimentation rate (mg cm^{-2} d^{-1})
Buccoo	75–100	7	3 ± 1.2 SD
Speyside	20–26	7	Not available
Pirates Bay	94	7	5.2 ± 0.9 SD
Data source	Eakin et al. (2010)	Eakin et al. (2010)	Mallela et al. (2010)

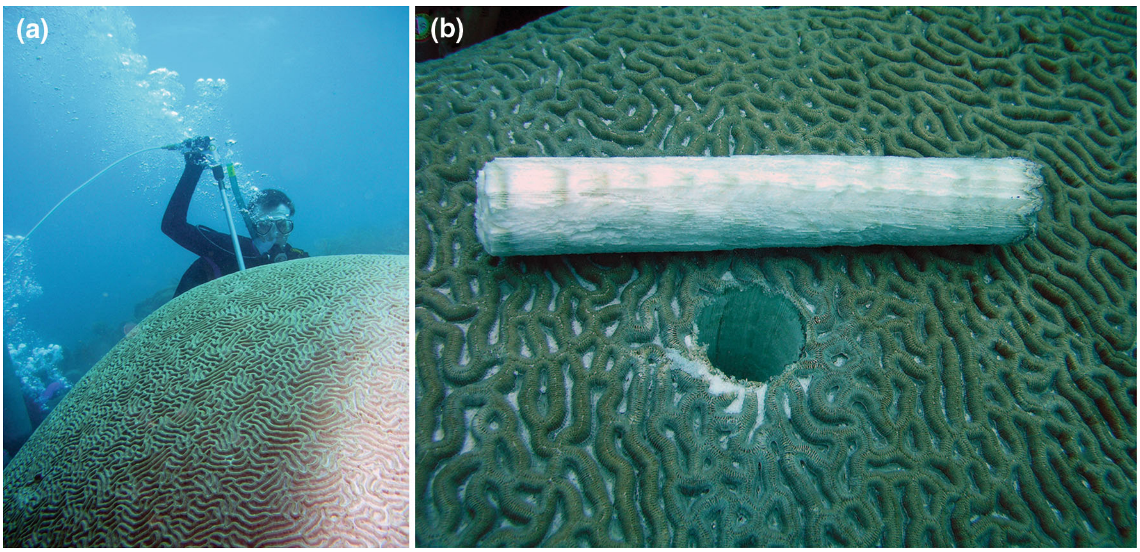

Fig. 4 Coring *Colpophyllia natans*: **a** drilling a colony at Speyside and **b** a close-up of the coral core and core hole

and Buccoo in 2005–2006 (Table 1). At the time scientific divers attributed this to better localised water quality at Speyside and/or localised tolerance during the bleaching event (Wilkinson and Souter 2008). Remote sensing data (Fig. 1c–e) also support this observation by illustrating how the Caribbean side of the island was characterised by elevated levels of CDOM from September to December 2005. Our coral archive confirms these observations with no stress bands apparent in 1994–2008 from the Speyside core, where water quality was highest (Fig. 5; Mallela and Harrod 2008; Mallela et al. 2010). High-resolution satellite data show similarly high SSTs at the two Caribbean sites (Buccoo and Pirates Bay) and slightly elevated temperatures at Speyside (Fig. 2). However, despite higher temperatures at Speyside (Fig. 2) during the 2005 bleaching event, extreme stress bands where coral growth is halted are absent. Instead, the Speyside core displays reductions in growth rates (Fig. 5).

During the 1997–1998 global mass bleaching event Tobago's coral archives only display stress bands at Pirates Bay in 1997, while other sites display slower growth rates during the same time period. Unfortunately, we were unable to obtain any site-specific coral reef monitoring data from 1997 to 1998 to validate this section of our cores. Prior to 1997 stress bands are absent from all three archives despite high-temperature thermal anomalies (Figs. 3, 5). However, recent thermal anomaly data display more frequent, extreme and protracted events from 2002 onwards. The most extreme event occurred during 2005 which most likely explains the increased prevalence of thermal stress markers in our cores.

The data presented here have led us to conclude that (1) more extreme temperature anomalies are resulting in increasingly severe bleaching events where coral growth is halted, and (2) better water quality buffers the effects of thermal stress, promoting coral resilience. There are several management implications of this research. In data-depauperate reef locations, historical (multi-decadal) information could be gleaned from the coral archive. This would enable managers to target key reef areas retrospectively to understand how they are responding to temperature stress.

This research adds to the growing body of the literature which focuses on stress bands in corals and documents how changing environmental conditions impact reef-building colonies (e.g., Hudson et al. 1976; Hudson 1981; Wórum

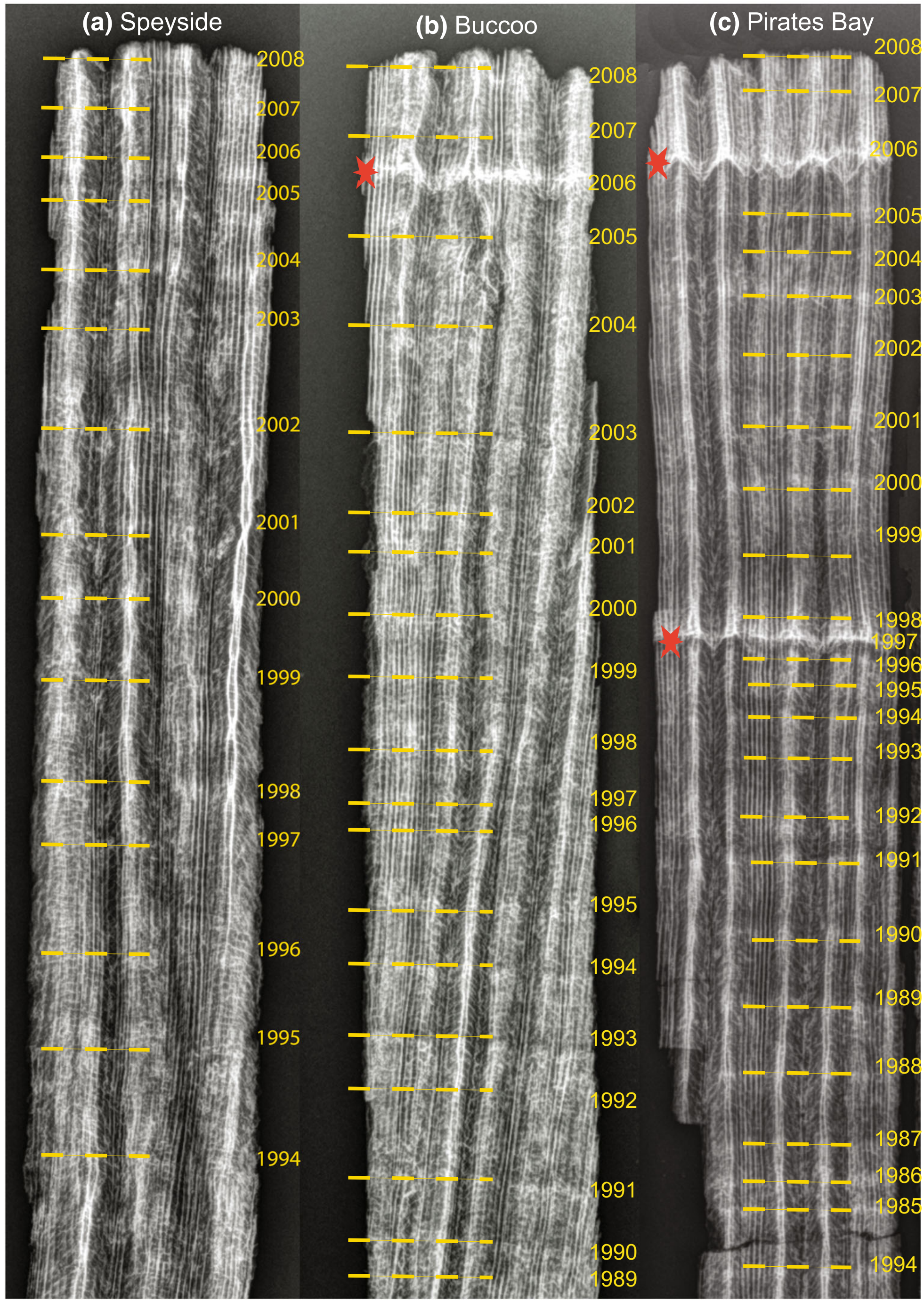

Fig. 5 Radiographs of coral cores from the three studied sites. *Red stars* highlight thermal stress markers in coral skeletons during elevated temperature anomalies, and *dashed yellow lines* indicate annual markers

et al. 2007). Results also confirm findings from other studies linking declining water quality, often resulting from human activities, with reduced coral resilience, increased prevalence of bleaching and subsequent hiatus in skeletal growth (e.g., Carilli et al. 2010; Graham et al. 2015). Interestingly, as satellite-based SST tools now provide early warning bleaching alerts for reef managers and scientists, it may be possible to anticipate and remediate catchment activities impacting coral reefs to minimise and control the impacts of extreme climatic events. With regard to sediment and nutrient impacts on reefs the timing of the event, and whether or not it occurs in conjunction and/or synergistically with other stressors, can be critical for colony growth, survival, recovery and successful reproduction (Risk 2014; Graham et al. 2015). While in many reef locations it has proven difficult to permanently halt land-based run-off (i.e., sediment and nutrient run-off) and improve water quality on reefs in close proximity to human development, we suggest that resource managers may be able to limit or temporarily stop land-based run-off onto reefs (e.g., sewage, fertiliser run-off, sediment from land clearance) during sensitive periods of anomalously high temperature. Improved water quality during these short-term, thermal stress events could alleviate stress and improve coral resilience to elevated temperature anomalies.

In conclusion, we show that one of the key reef framework-builders in the Caribbean, *C. natans*, can be used as an archive of historical bleaching events. The skeletons display distinct thermal stress markers which could be used to identify vulnerable sites and better manage the impacts of future temperature anomalies. We also show that despite similar thermal anomalies and temperature variability not all sites show signs of coral bleaching. In Tobago, this variability in bleaching susceptibility appears to be linked to water quality, whereby a combination of both temperature stress and poor water quality is most likely to result in coral bleaching.

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