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Have coral calcification rates slowed in the last twenty years?

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ABSTRACT

This paper reports a reanalysis of calcification rates of 328 *Porites* cores from the Great Barrier Reef from which previous workers have concluded that a 14% reduction in calcification rates has occurred between 1990 and 2005. In this reanalysis it is shown that the apparent reduction in the *Porites* spp. calcification rate in the last two decades is at least partly due to a combination of (a) ontogenetic effects (disregarded in the previous analysis), combined with a highly variable age distribution of the coral growth bands with time, and (b) a systematic data bias clearly evident in the last growth band of each core. When the outermost growth band in addition to bands which have record age less than 20 years was excluded from the analysis, the dramatic fall in calcification after 1990 was no longer evident.

1. Introduction

There is widespread concern that a hitherto unperceived consequence of global carbon dioxide emissions is a decrease in ocean pH which will have dire consequences for the calcification of calcareous marine organisms such as corals. A recent analysis (De'ath et al., 2009) of coral calcification data extracted from 328 *Porites* corals collected from 69 reefs over the Great Barrier Reef (GBR) that span the last 400 years has indicated that there has been a dramatic decline in coral calcification by as much as 14% between 1990 and 2005. It was suggested that a tipping point was reached in 1990 when declining ocean pH due to increased atmospheric CO_2 combined with increasing temperature stress caused rapid reductions in calcification.

The 14% decline in calcification rate between 1990 and 2005 (De'ath et al., 2009) is *prima facie* a surprising result because a previous comprehensive study (Lough and Barnes, 2000), using a subset of the data used in De'ath et al. (2009), demonstrated a statistically significant 4% increase in GBR coral growth over the 20th century. In addition, it is notable that a more recent paper on calcification rates on Australia's north western coastline does not indicate any significant decline in calcification rates after 1990 (Cooper et al., 2012). However, laboratory experiments show that calcification decreases under increasing pH for a variety of reef organisms (Hoegh-Guldberg et al., 2007), suggesting that modern coral reefs may be facing major challenges due to environmental change (Carpenter et al., 2008). Clearly the precise nature of the trend in coral calcification is of considerable importance for scientists, managers and policy makers alike.

The study of De'ath et al. (2009) used a linear mixed effect (LME) model, an analysis technique that aims to compensate for the many challenges involved with analysing complex data such as coral growth time series. The different number of corals from each location and a large latitudinal sampling range, which implies varying environmental factors leading to variable calcification rates, are examples of confounding variables that can be accounted for by LME. However there are additional important aspects of the data set that were not taken into account in the analysis of De'ath et al. (2009). These include (a) the use of three different types of coral samples (long cores, short cores and colonies) which produce samples of different lengths and therefore record ages (record age is defined as the time between a particular yearly calcification record and the first data record in the series), (b) a strong temporal variation in the average age of the corals over the sampling period, and (c) the likelihood of systematic sampling problems. These three confounding variables intrinsic to the data set are discussed in this paper.

At the centre of the analysis by De'ath et al. (2009) is the assumption that calcification rates for a particular coral do not change with the age of the coral (if environmental conditions remain constant), *i.e.*, there are no ontogenetic effects. Here we reanalyse the coral calcification data from the Great Barrier Reef and show that the apparent decline over the last two decades may be the result of a combination of ontogenetic effects and measurement artefacts

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rather than an abrupt calcification reduction caused by environmental conditions.

2. Material & methods

2.1. Data

The coral calcification data of 328 *Porites* spp. from the Great Barrier Reef (GBR) presented in De'ath et al. (2009) can be subdivided into 3 broad corals categories: 61 long cores, 135 short cores and 132 colonies. Long cores were collected using a large drill rig coring device, from a wide range of locations, and their time span is on average 155 years. Short cores were collected using a small drill, mostly from 5 reefs in the central section of the GBR between 18° and 20°S, and their time span is on average 28 years. Colonies were sampled by taking a saw slice through the coral, and they have on average a time span of 23 years (Fig. 1).

Before 1940, only long core data contributes to the overall calcification rate and most of the long core data ends by 1990. Short core data starts around 1940 and mostly ends around 2005. Colonies also start to contribute data around 1940 and roughly 2/3rds of the colony records terminate around 1990. The other third are generally very short records which end around 2005 (Fig. 1).

Also evident at ca. 1990 is the discontinuity of records especially in the colony data (Fig. 1b). The discontinuity of records at 1990 occurs because the field work when the coral cores were recovered cover two distinct periods: (a) the late 1980's and early 1990's, and (b) the early part of the 2000's, especially in 2003, 2004 and 2005. The short core data (Fig. 1c) does not show a discontinuity at around 1990 as this sampling technique was only used in the later sampling period. For this reason, all the short core data ends on or after 2003.

The number of contributing corals changes dramatically with time (Fig. 2). Before 1940 the total number of corals was around 50 and rose to 269 in the early 1980's before declining to 189 in 1999, and then sharply reducing to only 21 in 2005.

2.2. Data analysis methods

LME analysis for the calcification data was performed in R scripting language (Team, R.D.C., 2009), with the package *mgcv*, using exactly the same R code as provided to us by G. De'ath (*pers. comm.*). When running this code it was necessary to select the *k* value of the *gamm* function, which gives the dimension of the basis used to represent the smooth term in the spline model (Team, R.D.C., 2009). The smaller value of *k* (fewer degrees of freedom) causes some of the detailed temporal changes in the calcification curve to be masked. In short, a

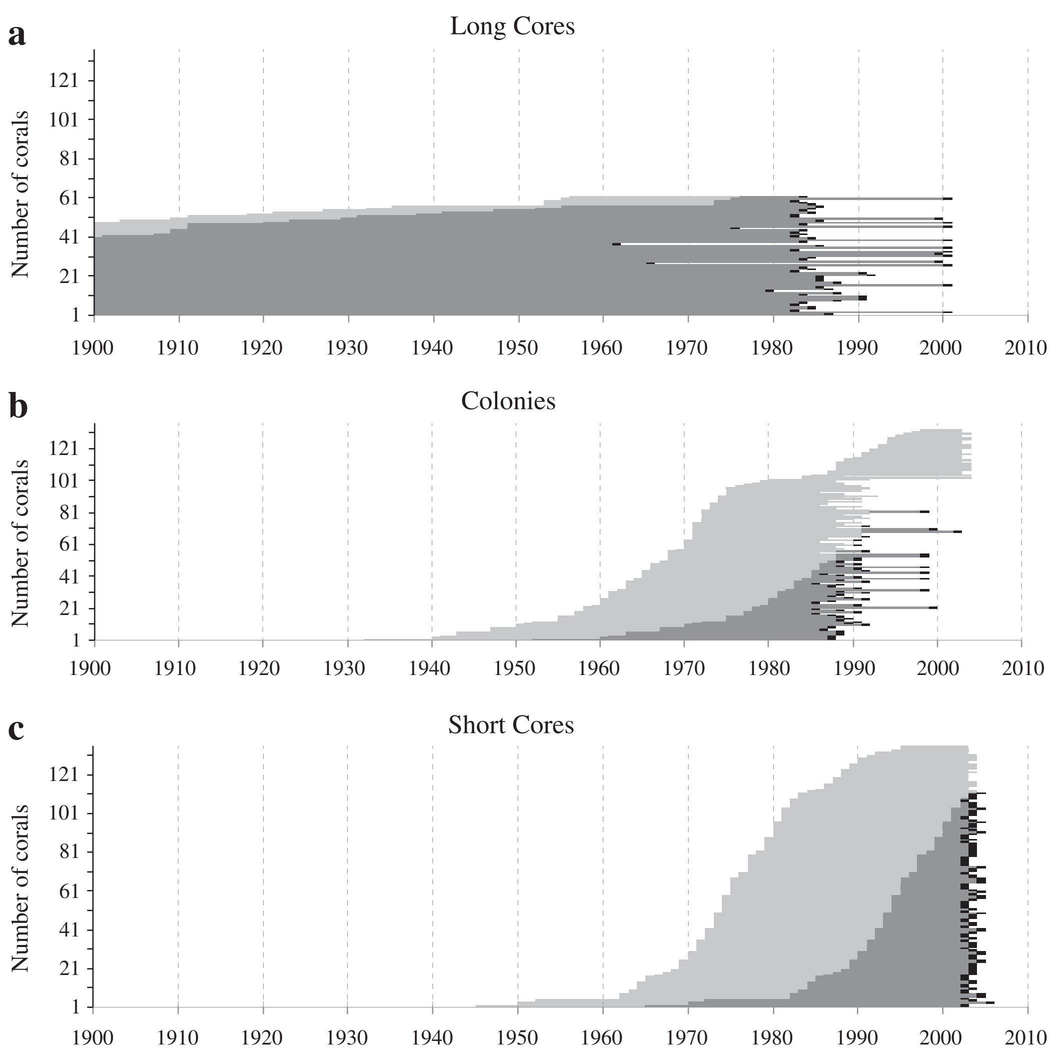

Fig. 1. Time span of each coral record included in the reanalysis. Each horizontal bar represents the time period over which a particular coral contributed to the data set for (a) long cores, (b) colonies, and (c) short cores. Dark Grey represents coral growth bands with record age >20 years. Light grey represents the growth band of corals with record age ≤20 years. Black represents the last growth bands which have record age >20 years.