Coral reef calcification and climate change: The effect of ocean warming

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[1] Coral reefs are constructed of calcium carbonate ($CaCO_3$). Deposition of $CaCO_3$ (calcification) by corals and other reef organisms is controlled by the saturation state of $CaCO_3$ in seawater (Ω) and sea surface temperature (SST). Previous studies have neglected the effects of ocean warming in predicting future coral reef calcification rates. In this study we take into account both these effects by combining empirical relationships between coral calcification rate and Ω and SST with output from a climate model to predict changes in coral reef calcification rates. Our analysis suggests that annual average coral reef calcification rate will increase with future ocean warming and eventually exceed pre-industrial rates by about 35% by 2100. Our results suggest that present coral reef calcification rates are equivalent to levels in the late 19th century and does not support previous suggestions of large and potentially catastrophic decreases in the future.   INDEX TERMS: 1615 Global Change: Biogeochemical processes (4805); 1635 Global Change: Oceans (4203); 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615); 4806 Oceanography: Biological and Chemical: Carbon cycling; 4263 Oceanography: General: Ocean prediction. **Citation:** McNeil, B. I., R. J. Matear, and D. J. Barnes (2004), Coral reef calcification and climate change: The effect of ocean warming, *Geophys. Res. Lett.*, *31*, L22309, doi:10.1029/2004GL021541.

1. Introduction

[2] Calcification is the process by which corals produce calcium carbonate ($CaCO_3$). Coral reef calcification is predicted to decrease 20–60% by 2100, relative to pre-industrial levels [*Kleypas et al.*, 1999; *Müller et al.*, 2004], due to increases in CO_2 levels in the surface ocean as atmospheric CO_2 rises. Such decreases in calcification would cause loss of reefs because construction rates would fall below natural destruction rates. The $CaCO_3$ saturation state of seawater (Ω) is defined by: $\Omega = \frac{[Ca^{2+}][CO_3^{2-}]}{\lambda}$, where λ is the solubility coefficient of different forms of $CaCO_3$. Most authors have used Ω values for aragonite (Ω_{arag}) as it is the form of $CaCO_3$ deposited by corals and green algae. $[Ca^{2+}]$ is quasi-conservative in the ocean, therefore Ω_{arag} is controlled by variations in the carbonate ion (CO_3^{2-}). As CO_2 levels rise in seawater via anthropogenic CO_2 uptake,

pH decreases and the seawater carbonate equilibrium is shifted, reducing dissolved CO_3^{2-} and Ω_{arag} [*Kleypas et al.*, 1999]. Although Ω_{arag} remains super-saturated in tropical surface oceans (>1), reduction of Ω_{arag} has been found to reduce calcification by reef organisms [*Gattuso et al.*, 1999; *Langdon et al.*, 2000; *Leclercq et al.*, 2000, 2002; *Marubini et al.*, 2001, 2003]. On the other hand, coral calcification rates have been found to increase with increasing sea surface temperature (SST) [*Bessat and Buigues*, 2001; *Clausen and Roth*, 1975; *Coles and Coles*, 1977; *Kajiwara et al.*, 1995; *Lough and Barnes*, 2000; *Reynaud-Vaganay et al.*, 1999]. *Lough and Barnes* [2000] showed a significant positive correlation between annual average SST and calcification ($R^2 \sim 0.8$) amongst 554 massive *Porites* colonies from 44 reefs in Australia, Hawaii and Thailand through a temperature range of 23°C to 29°C. Extension increased 3.1 mm.yr^{-1} and annual calcification increased 33% for each 1 °C increase in annual SST (Figure 1). A similar relationship between SST and extension rate in massive *Porites* was found in the South China Sea [*Nie et al.*, 1997]. Additional measurements from 27 massive *Porites* from 5 sites in the Persian Gulf and New Ireland (Papua New Guinea) were also found to follow this calcification-temperature relationship (J. Lough, unpublished data, 2004). Furthermore, recent work has shown that calcification in *Montastrea*, the chief reef-building coral in the Atlantic, is nearly twice as sensitive to temperature as massive *Porites* [*Carricart-Ganivet*, 2004]. These observed increases in coral reef calcification with ocean warming are most likely due to an enhancement in coral metabolism and/or increases in photosynthetic rates of their symbiotic algae [*Buddemeier et al.*, 2004] and highlight the need to include SST as well as Ω_{arag} in predicting future changes in coral reef calcification due to the enhanced greenhouse effect.

2. Methodology

[3] To quantify future changes in coral reef calcification, we used projections of ocean warming and Ω_{arag} from a coupled atmosphere-ice-ocean carbon cycle model developed by the Commonwealth Scientific Industrial Research Organisation (CSIRO) [*Hirst et al.*, 1996]. This climate model includes oceanic, sea-ice and biospheric sub-models with oceanic eddy parameterization. The oceanic sub-model included a prognostic ocean carbon cycle model that simulated phosphate, Dissolved Inorganic Carbon (DIC) and alkalinity in the ocean and allowed us to determine future CO_2 uptake by the ocean. Climate change feedbacks on Ω_{arag} were determined from two climate model experiments. The 'control' experiment did not include atmospheric warming effects of elevated greenhouse gases in the atmosphere while the 'climate change' experiment explicitly included these effects [*Matear and Hirst*, 1999]. For the

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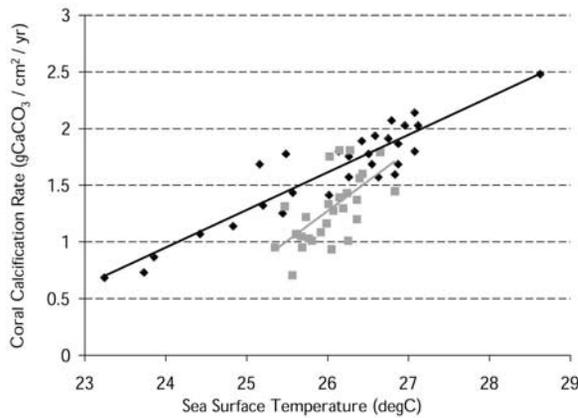[3]Australian Institute of Marine Science, Townsville, Queensland, Australia.

Figure 1. Relationship between annual average SST (°C) and coral calcification shown in two separate studies of *Porite* coral colonies where diamonds show the results from *Lough and Barnes* [2000] and squares from *Bessat and Buigues* [2001].

climate change experiment, CO_2 levels increased according to atmospheric observations between 1880 to 1995 and followed IS92a projections [*Houghton et al.*, 2001] until the year 2100. The 'climate change' experiment included the effects upon Ω_{arag} due to increases in SST and changes in ocean circulation. The climate change feedback on Ω_{arag} was taken as the difference between the 'climate change' and 'control' experiments.

[4] Changes in coral reef calcification were estimated by combining the output of the climate model with empirical relationships between coral calcification rate and Ω_{arag} and annual SST. The coral reef habitat was defined to be the oceanic area where annual average SST > 18°C [*Vaughan*, 1919]. Calcification changes in the coral reef habitat due to Ω_{arag} were projected using the observational results of Langdon et al. [*Langdon et al.*, 2000], obtained in a coral reef microcosm, where calcification (mmol $CaCO_3/m^2/d$) = $41.56 \times \Omega_{arag} - 81.9$. Calcification changes due to SST were projected using the results of Lough and Barnes [*Lough and Barnes*, 2000] where calcification ($gCaCO_3/cm^2/yr$) = $0.33 \times SST - 7.07$.

3. Results and Discussion

[5] Our model predicts annual mean SST within the coral reef habitat to increase from ~25°C during the 1950s to about 28.2°C in 2100 (Figure 2a). The area of the coral reef habitat expands in association with this ocean warming. In estimating changes in Ω_{arag} and, hence, coral reef calcification since 1880, data for the expanded area of coral reef habitat was not included. The level of warming over the last 50 years from our climate change experiment (~0.4–0.5°C) is comparable to the observed warming within the upper 300 m of the ocean of ~0.3 ± 0.2°C [*Levitus et al.*, 2000] and gives us confidence to exploit the model projections. Furthermore, the current aragonite saturation state within the coral reef habitat was calculated from the global carbon dataset ($\Omega_{arag} \sim 3.8$) and compares reasonably well with the model result for the same period (Figure 2b). A technique based upon chlorofluorocarbons [*McNeil et al.*, 2003] was used to normalise the carbon observations to 1995, while

standard carbonate dissociation constants [*Dickson and Millero*, 1987] were used to calculate Ω_{arag} from the in-situ oceanic carbon measurements via the Global Ocean Data Analysis Project [*Key et al.*, 2004].

[6] Previous estimates of future changes to Ω_{arag} have assumed the oceanic CO_2 system to be in steady-state with rising atmospheric CO_2 [*Kleypas et al.*, 1999]. In reality, factors other than the atmospheric concentration of CO_2 influence uptake of atmospheric CO_2 by the oceans. For example, simulations [*Matear and Hirst*, 1999; *Sarmiento et al.*, 1998] show that sea surface warming and a slowdown in the thermohaline circulation will reduce oceanic storage of anthropogenic CO_2 by as much as 20% by 2100, with warming having the greatest effect. Our simulations suggest these climate change feedbacks cause Ω_{arag} in the coral reef habitat to be ~25% higher in 2100 than estimates based upon steady state models (Figure 2b).

[7] Our results show that changes in coral reef calcification associated with ocean warming outweigh those associated with decreases in Ω_{arag} (Figure 3). In our model, coral reef calcification decreases by up to 7% from pre-industrial levels up until 1964 as the CO_2 effects outweighs the temperature effect. After 1964 however, ocean warming far outweighs the CO_2 effect and stimulates recovery of coral reef calcification. Rates recover to their pre-industrial values by about 1995 and are 35% higher than pre-industrial levels by 2100.

[8] *Lough and Barnes* [2000] show an increase in coral reef calcification on the Great Barrier Reef of about 4%
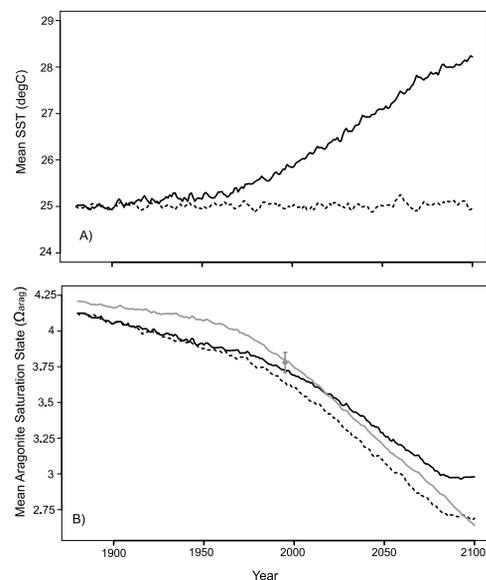

Figure 2. Simulated changes within the coral reef habitat (see methods for description). a) Mean sea surface temperature and b) Mean aragonite saturation state (Ω_{arag}). Dotted line denotes the control experiment while the solid black line denotes the climate change experiment. The observed mean aragonite saturation state for the year 1995 (~3.8 ± 0.15) is also shown. The solid grey line is the aragonite saturate state assuming thermodynamic equilibration with atmospheric CO_2 concentrations (IS92a) with constant alkalinity (2270 μmol/kg) and is used to show the potential bias making such an assumption without considering climate change impacts.
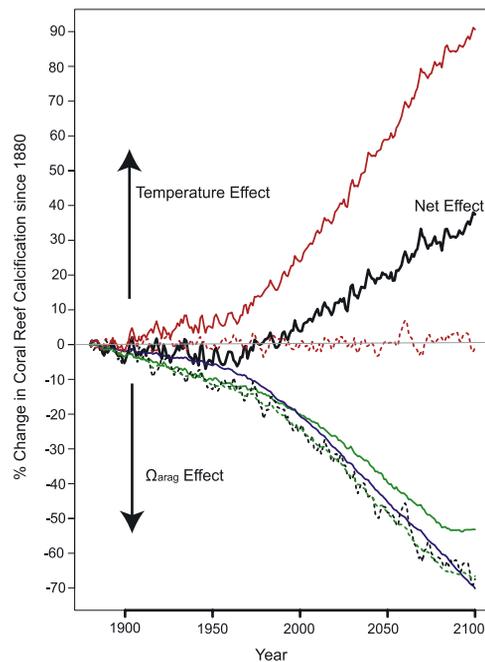
Figure 3. Annual mean percentage change in coral reef calcification relative to pre-industrial levels (1880) for control experiment (dashed lines) and climate change experiment (solid lines). The green lines show the projected changes from variations in aragonite saturation state while the red lines show the projected changes associated with ocean warming. The combined climate change response is shown by the solid black line. For comparison, the solid blue line is equivalent to previous projections [*Kleypas et al.*, 1999; *Müller et al.*, 2004] that calculate Ω_{arag} from thermodynamic equilibration of atmospheric CO_2.

between 1900 and 1979 which is slightly different to our model results that suggest only minor changes ($\sim 0-1\%$) for that period. It is important to emphasise however that our results represent an average over the entire coral reef community and therefore cannot be solely compared with results from the Great Barrier Reef. Regional changes to coral reef calcification will vary considerably depending on local CO_2 conditions and ocean warming. It will be important to undertake more specific regional analysis of models so as to better understand future changes to regions such as the Great Barrier Reef. It is also important to recognize that coral reef calcification and the changes suggested here are separate to the adverse future effects of coral bleaching which is associated with the corals symbiotic micro-algae (zooanthallae) [*Hoegh-Guldberg*, 1999].

[9] Reefs form because red algae cement together a framework built of coral skeletons and then sediments, mostly created by erosion, green algae and foraminifera, become cemented into cavities in this structure. Here, we use in-situ data for the temperature sensitivity of calcification in massive *Porites*, the most significant reef-building coral in the Indo-Pacific. Although calcification in *Montastrea*, the most significant reef-builder on Atlantic reefs, is much more sensitive to temperature, it seemed appropriate to base our estimates upon *Porites*, the more conservative and most thoroughly documented genus. We used *Porites* temperature sensitivity to estimate changes in rates of coral reef commu-

nity calcification with temperature. There are other data for the temperature sensitivity of calcification in corals and other reef organisms [*Clausen and Roth*, 1975; *Coles and Coles*, 1977; *Kajiwara et al.*, 1995; *Reynaud et al.*, 2003] which may suggest the existence of an upper temperature limit for coral reef calcification [*Buddemeier et al.*, 2004]. However, these data were obtained by subjecting organisms collected from one location to a range of temperatures, the extremes of which the organisms never experience. It is then not surprising that such experiments indicate declines in calcification towards the extremes. Data for *Porites* and *Montastrea* quoted here were obtained from measurements on coral colonies that grew at locations representing a range of temperatures (23°C to 29°C) and showed no declines at high and low temperatures. Despite this observation, the potential existence of a thermal upper limit for other coral species is important in the context of climate change and should be further explored.

4. Conclusion

[10] Observational studies show clearly that increasing SST and decreasing Ω_{arag} have opposing effects for coral reef calcification. We combine output from a climate model with empirical measurements of coral reef calcification with respect to both Ω_{arag} and sea surface temperature (SST) to project coral reel calcification rates under climate change. Our results suggest that climate change will increase the net rate of coral reef calcification significantly by the year 2100 as the effect of ocean warming far outweighs those due to decreases in Ω_{arag}. Our projections may be deemed more realistic than previous projections because they incorporate additional environmental parameters that will change in the future (SST and Ω_{arag}). There is evidence however to suggest that different corals display different sensitivities to changes in Ω_{arag} and SST [*Reynaud et al.*, 2003]. Considering that both these environmental parameters are likely to change considerably in the future, additional experiments on a variety of differing coral species will be crucial to obtain a better understanding of future coral reef stability.

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