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

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1. Introduction

[1] *McNeil et al.* [2004] present an analysis indicating that rising sea surface temperature will have a uniformly positive effect on coral calcification over the coming century. The authors claim that this will outweigh the negative effects of declining carbonate ion concentration and result in a substantial increase in net coral reef calcification by the year 2100. We agree that temperature will play an important role in future coral reef calcification; this point is not new, and we find the authors' statement that "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" to be seriously flawed. Many of their critical assumptions are not supported by existing information on the limits of coral growth and calcification, present day coral reef distributions, and temperature responses. We review their assumptions in the context of this existing knowledge.

2. Combining the Calcification: Temperature and Calcification: Ω_{arag} Relationships

[2] The authors assume that calcification in corals and other reef-building organisms is the sum of two linear responses to temperature and aragonite saturation state (Ω_{arag}). While the response of calcification to Ω_{arag} does appear to be generally linear with increasing CO_2 [e.g., *Langdon et al.*, 2000; *Leclercq et al.*, 2000], coral response to increasing temperature is not linear. Calcification rates typically increase with temperature, eventually reaching a plateau at or below the normal peak summer temperature, and then decline rapidly beyond that [*Jokiel and Coles*, 1977; *Marshall and Clode*, 2004]. This optimum temperature varies according the ambient temperature of the coral's environment (summarized by *Marshall and Clode* [2004]). That is, while coral calcification may initially increase with rising temperature, that increase is unlikely to continue throughout a 2–3°C rise.

[3] Many investigators recognize that temperature and CO_2 may interactively affect calcification. However, only one experimental study has been published on the combined effects of temperature and Ω_{arag} on calcification, and the results [*Reynaud et al.*, 2003] do not support the assumption that the calcification responses to temperature and Ω_{arag} are additive. Also, the authors' assumption that Porites calcification is the same as net coral reef calcification is not supported by previous work.

3. The *Porites* Calcification: Temperature Relationship

[4] *McNeil et al.* [2004] largely base their predictions on an excellent dataset of painstakingly measured calcification rates from massive *Porites* cores [*Lough and Barnes*, 2000]. However, this is a calcification:temperature correlation and not a true calcification:temperature curve, as it was derived from corals spanning a range of latitudes with gradients not only in temperature, but also in light and Ω_{arag}, both of which co-vary with temperature [*Kleypas et al.*, 1999a, 1999b; *Gattuso and Buddemeier*, 2000]. For example, carbonate chemistry measurements from their locations are essentially lacking, but a quick estimate of Ω_{arag} across the temperature range they used (23–29°C) is about 3.9–4.7.

[5] In addition, this dataset covers the area where mean annual SST < ~27°C, with one point between 28–29°C that was obtained from a very different environment. Most of the world's reefs occur in waters with present-day mean annual SSTs > 27°C [*Kleypas et al.*, 1999b]. Linear extrapolation of this relationship to higher temperatures is thus not appropriate.

[6] Finally, this spatially derived relationship should not be applied to temporal predictions. Changes from one latitude to another likely involve genetic differences between locally adapted (over thousands of years) corals and

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are thus unrelated to the phenotypic changes that would occur within a single individual.

4. Other Temperature Affects

[7] The authors admit that their analysis ignores the likelihood of coral bleaching. This omission is unrealistic given the history of mass bleaching over the last few decades. Their model produces an average 3°C warming within their defined coral reef habitat, which based on current observations, would likely cause significant coral bleaching [*Hoegh-Guldberg*, 1999] that, even in corals that survive, causes calcification to slow down or stop. They also fail to consider a body of literature on the negative effects of elevated temperatures (regardless of bleaching) on coral metabolism [*Coles and Jokiel*, 1977, 1978; *Leder et al.*, 1991; *Fitt et al.*, 2001], reproduction [*Szmant and Gassman*, 1990], resistance to disease [*Harvell et al.*, 2002], and larval settlement [*Jokiel and Guinther*, 1978]. All of these factors affect calcification, and including them would overturn the central thesis of *McNeil et al.* [2004] that ocean warming will lead to increased coral reef calcification by the end of this century.

[8] Also implicit in their analysis is that corals and coral reef communities will adapt/acclimatize to rising temperature. This assumption is overstated, as the mechanisms involved [*Rowan*, 2004] are likely to apply to a few survivors rather than whole intact communities. Further, it appears likely that the price of high-temperature survival will be a symbiotic coral/algal partnership that is less productive than those adapted to more optimal conditions [*Ware et al.*, 1996; *Baker et al.*, 2004]. Adaptation of coral communities has been documented only on the century-to-millennium time scales of natural climate change [*Veron*, 1995].

[9] Finally, the authors do not consider that temperature change is unlikely to be smooth and gradual. The IPCC projects that increases in temperature variability will be at least as important as increases in the mean, which for corals could mean more frequent exposure to bleaching-level thermal stress.

5. Definition of Coral Reef Habitat and Comparison With Previous Results

[10] *McNeil et al.* [2004] define coral reef habitat as the region where SST > 18°C. In reality, reef habitat is confined to a much smaller region (mainly, the additional constraint of water depth < 30 m). Their definition of habitat produces an average baseline temperature of 26°C, which is cooler than the present-day average temperature of reefs (average 27.6°C) [*Kleypas et al.*, 1999b], and likely skews their results, particularly if their model predicts greater warming in the open ocean than in reef areas. Also, their definition of habitat does not take into account that poleward expansion of reef distribution due to warming is limited by other variables [*Guinotte et al.*, 2003].

[11] *McNeil et al.* [2004] imply that the *Kleypas et al.* [1999a] estimate of future Ω_{arag} did not take into account temperature and alkalinity feedbacks on the carbonate system. In fact, the *Kleypas et al.* study included a comparable temperature rise to that used by *McNeil et al.*, as well as modeled feedbacks on alkalinity.

6. Summary

[12] *McNeil et al.* [2004] attempt to address an important question about the interactions of temperature and carbonate chemistry on calcification, but their projected values of reef calcification are based on assumptions that ignore critical observational and experimental literature. Certainly, more research is needed to better understand how changing temperatures and carbonate chemistry will affect not only coral reef calcification, but coral survival. As discussed above, the *McNeil et al.* [2004] analysis is based on assumptions that exclude potentially important factors and therefore needs to be viewed with caution.

[13] **Acknowledgment.** The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official National Oceanic and Atmospheric Administration or U.S. Government position, policy, or decision.

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