



Coral reefs may start dissolving when atmospheric CO₂ doubles

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[1] Calcification rates in stony corals are expected to decline significantly in the near future due to ocean acidification. In this study we provide a global estimate of the decline in calcification of coral reefs as a result of increase in sea surface temperature and partial pressure of CO₂. This estimate, unlike previously reported estimates, is based on an empirical rate law developed from field observations for gross community calcification as a function of aragonite degree of saturation (Ω_{arag}), sea surface temperature and live coral cover. Calcification rates were calculated for more than 9,000 reef locations using model values of Ω_{arag} and sea surface temperature at different levels of atmospheric CO₂. The maps we produced show that by the time atmospheric partial pressure of CO₂ will reach 560 ppm all coral reefs will cease to grow and start to dissolve. **Citation:** Silverman, J., B. Lazar, L. Cao, K. Caldeira, and J. Erez (2009), Coral reefs may start dissolving when atmospheric CO₂ doubles, *Geophys. Res. Lett.*, 36, L05606, doi:10.1029/2008GL036282.

[2] The sharp anthropogenic increase in atmospheric CO₂ has changed the carbonate chemistry of the surface oceans [Sabine *et al.*, 2004]. Model estimates suggest that the average surface ocean pH has decreased by 0.1 units relative to its pre-industrial revolution (PIR) value and it is expected to decrease by an additional 0.4 units by the close of the 21st century [Caldeira and Wickett, 2003]. Such a drop in pH at constant total alkalinity will decrease the aragonite degree of saturation (Ω_{arag}), which may lower the biogenic precipitation rate of aragonite (the carbonate mineral deposited by reef building corals) in the ocean [Kleyvas *et al.*, 1999; Orr *et al.*, 2005]. Indeed, laboratory studies on individual stony corals and coral communities in mesocosms showed a linear decrease in calcification with decreasing Ω_{arag} [e.g., Langdon and Atkinson, 2005; Schneider and Erez, 2006]. Similarly, whole ecosystem studies on coral reefs in the northern Gulf of Aqaba (Eilat, Israel) and W. Pacific, showed a decrease in net community calcification (G_{net}) with decreasing Ω_{arag} and temperature [Ohde and van Woesik, 1999; Silverman *et al.*, 2007]. Silverman *et al.* [2007] have shown recently that G_{net} values measured on these reefs were remarkably well correlated with rates of inorganic aragonite precipitation (G_i) calculated with the equation,

$$G_i = k_T \cdot (\Omega_{\text{arag}} - 1)^{n_T}$$

$$= \frac{24}{1000} \cdot (-0.0177 \cdot T^2 + 1.4697 \cdot T + 14.893) \cdot (\Omega_{\text{arag}} - 1)^{(0.0628 \cdot T + 0.0985)} \quad (1)$$

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Where, the rate constant (k_T) and the order of the reaction (n_T) change as a function of temperature according to the empirical relations reported by Burton and Walter [1987]. The rate constant (k_T) has units of $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{hr}^{-1}$, which are converted to units of $\text{mmol} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ by multiplying the value of k_T by 24 (hours per day) and dividing by 1000 (μmol per mmol). Application of this rate law for coral reefs includes the horizontal area fraction of the reef actively depositing CaCO₃, i.e., percentage of live coral cover in decimal fraction equivalent ($A_c = 0 - 1$) multiplied by a specific area constant (k'_r). This constant (k'_r) is the ratio between the total area of the reef actively precipitating CaCO₃ and its planar area (i.e., m^2/m^2) for a reef with 100% live coral cover ($A_c = 1$). An additional term in the modified equation for coral reefs is the rate of community CaCO₃ dissolution (D). The modified rate law is therefore:

$$G_{\text{net}} = A_c \cdot k'_r \cdot G_i - D \quad (2)$$

Where the gross calcification is defined as:

$$G_{\text{gross}} = G_{\text{net}} + D = A_c \cdot k'_r \cdot G_i \quad (3)$$

The linear fit between the measured and calculated net calcification for the Eilat reef yielded a slope of $A_c \cdot k'_r = 11.8 \text{ m}^2 \cdot \text{m}^{-2}$ and an intercept $D = 9 \text{ mmol} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ ($n = 17$, $R^2 = 0.89$, Figure 1). The A_c of the Eilat reef is ca. 0.3 yielding a value for k'_r of $39.4 \text{ m}^2 \cdot \text{m}^{-2}$. The D estimated from the correlation value is similar to the average dissolution rate measured *in situ* on the Eilat reef ($13 \pm 7 \text{ mmol} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$) [Silverman *et al.*, 2007]. Comparison of the measured net calcification on other reefs in the tropical and sub-tropical Pacific ocean to their calculated rates included in Figure 1 agrees well with the general trend ($n = 25$, $R^2 = 0.92$). While, this comparison is very encouraging we chose to consider only the Eilat data in calculating the fit parameters for the following reasons: 1) The Eilat reef study is very well documented especially with respect to rates of dissolution and live coral cover; 2) The general trend is strongly biased by the Rokan-Sho Atoll data, which causes the intercept to be > 0 , counter to our understanding of this parameter (dissolution). Thus, the explicit form of G_{net} is:

$$G_{\text{net}} = (G_{\text{gross}} - D) = A_c \cdot 39.4 \cdot G_i - 9 \quad (4)$$

A similar relation between calcification and Ω_{arag} was obtained by Langdon and Atkinson for many of the coral laboratory and mesocosm experiments [Langdon and Atkinson, 2005] (see S2). However, both equation (4) and their empirical equation are unable to account for the well documented optimum behavior of coral calcification with respect to temperature [e.g., Clausen and Roth, 1975;

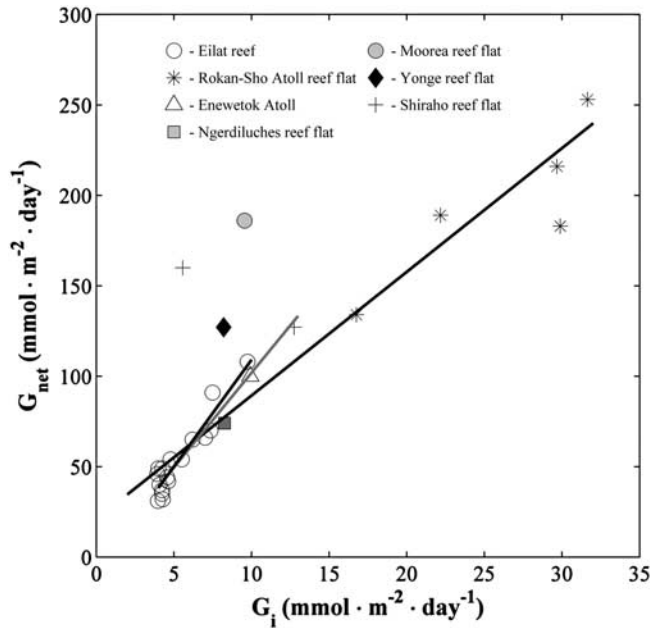


Figure 1. Measured net rate of calcification (G_{net}) vs. inorganic deposition rate of CaCO_3 (G_i) calculated with equation 1 for: 1) Nature reserve reef in Eilat, Gulf of Aqaba, northern Red Sea, Israel (29.5°N); 2) Rokan-Sho Atoll, Okinawa, Japan (26°N) - adopted from *Ohde and van Woosik* [1999]; 3) Enewetok Atoll, western Pacific (11.5°N) - adopted from *Smith* [1973]; 4) Ngerdiluches reef flat in Palau, western Pacific (7.5°N) adopted from *Watanabe et al.* [2006]; 5) Fringing reef flat with 10% live coral cover in Moorea, French Polynesia, central Pacific (17.5°N) - adopted from *Gattuso et al.* [1996]; 6) Yonge reef flat in the northern Great Barrier Reef Australia with 60% live coral cover (14.5°S) - adopted from *Gattuso et al.* [1996] after normalizing calcification rate to 30% live coral cover; 7) Shiraho reef flat at Ishigaki Island south west Japan (24.5°N) - adopted from *Suzuki et al.* [1995] and *Hata et al.* [2002], respectively. The black trend line is computed for the Eilat data only and the grey trend line is calculated for all the data besides Shiraho reef from *Suzuki et al.* [1995] and the Moorea reef from *Gattuso et al.* [1996], which were considered outliers.

Marshall and Clode, 2004]. In order to account for this physiological temperature optimum, we described the coral calcification as a bell-shape function for ${}^T G_{gross}$, of the form:

$${}^T G_{gross} = a \cdot \exp\left(-\left(\frac{k'_p \cdot (T - T_{opt.})}{b}\right)^2\right) \quad (5)$$

Where, a is the amplitude scale of the curve; k'_p is a coefficient expressing the sensitivity of coral calcification to temperature with units of ${}^\circ\text{C}^{-1}$; b is the width scale of the curve around the optimal temperature ($T_{opt.}$) and T is the ambient water temperature. In the studies, which described optimum behavior, $T_{opt.}$ was lower than the maximum summer temperature in the reef by ca. 2° C and appeared to coincide with the measured water temperature during the period of extended daylight, i.e. during summer solstice in

the northern and southern hemispheres, June and December respectively. This may be related to the phenomenon of light enhanced calcification [*Barnes and Chalker*, 1990].

[3] The combined effect of temperature and Ω_{arag} on calcification in the coral *Stylophora pistillata* showed that for a pCO_2 increase from $\sim 460 \mu\text{atm}$ to $\sim 770 \mu\text{atm}$ calcification did not change at $\sim 25^\circ\text{C}$ but at $\sim 28^\circ\text{C}$ was reduced by almost 50% [*Reynaud et al.*, 2003]. It is worth noting that the optimal temperature for calcification of this species in that study was 27–28° C (Op. Cit.). Accordingly, we used $G_{gross} = A_c \cdot k'_r \cdot G_i$ (see above) as the amplitude, a , of the ${}^T G_{gross}$ equation (equation (5)) and Ω_{arag}^2 as its width, b , yielding:

$${}^T G_{gross} = A_c \cdot k'_r \cdot G_i \cdot \exp\left(-\left(\frac{k'_p \cdot (T - T_{opt.})}{\Omega_{arag}^2}\right)^2\right) \quad (6)$$

Where,

$${}^T G_{net} = {}^T G_{gross} - D \quad (7)$$

According to equation (6), ${}^T G_{gross}$ increases with Ω_{arag} and becomes less sensitive to temperature and visa versa as Ω_{arag} decreases. Fitting the Eilat reef data to equation (6) assuming $T_{opt} = 25^\circ\text{C}$ (summer solstice water temperature in the Eilat reef) and $k'_p = 1^\circ\text{C}^{-1}$, yields $k'_r = 38 \text{ m}^2 \cdot \text{m}^{-2}$, $D = 5 \text{ mmol} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ and $R^2 = 0.9$ (See S3), very similar to the values obtained from the monotonic behavior of calcification (equation (4)). According to equation (6), while at high Ω_{arag} values ${}^T G_{gross}$ increases with temperature and Ω_{arag} , at low Ω_{arag} (<3.5) it will start to decrease with increasing temperature above the optimal temperature as seen in Figure S4 of the auxiliary material.¹ The Eilat data points agree generally well with the calculated temperature contours considering the uncertainty in the measurements as indicated by the error bars. The monotonic increase in calcification with temperature according to equation (6) can be misleading considering that above a certain temperature threshold corals will bleach and will cease to calcify entirely. At the community scale this effect could be expressed by a reduction in the live coral coverage parameter (A_c) dependent on the proportion of susceptible species in the community.

[4] Following the method of *Cao and Caldeira* [2008], we use a coupled climate/carbon-cycle model, together with the chemistry routine from the OCMIP-3 project <http://www.ipsl.jussieu.fr/OCMIP/phase3> to obtain monthly average values of Ω_{arag} and sea surface temperature over an annual cycle for stabilized pCO_2 levels of 280 ppm (PIR, or Inter Glacial maximum value), 330 ppm (1970's value), 380 ppm (present day), 450 ppm, 560 ppm (doubling relative to PIR) and 750 ppm. These values were employed in equation (8) for coral reef locations obtained from the Reef Base web site (M. Tupper et al., ReefBase: A Global Information System on Coral Reefs, <http://www.reefbase.org>). The model did not resolve for the marginal seas of the Middle East, including the Red Sea, Persian Gulf and the Gulfs of Aqaba and Suez. We therefore excluded 283 coral reef locations from the original data set, leaving 9733

¹Auxiliary materials are available in the HTML. doi:10.1029/2008GL036282.

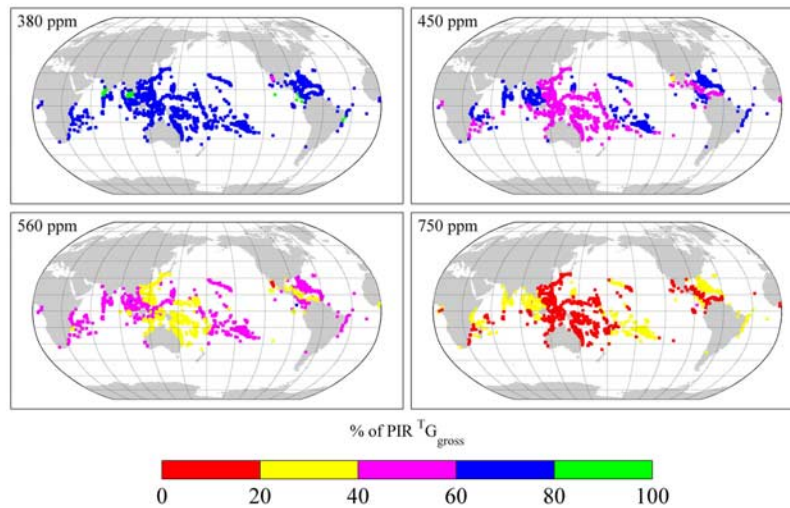


Figure 2. Global coral reef distribution and their $T_{G_{gross}}$ relative to their pre-industrial rate (280 ppm) in percent calculated with equation (6) employing modeled sea surface Ω_{arag} and temperature values from *Cao and Caldeira* [2008], and assuming no change in live coral cover ($A_c = 0.5$) for each reef location at pCO₂ stabilization levels of 380, 450, 560 and 750 ppm.

locations to be included in the analysis. The optimal temperatures for coral calcification at each reef location were assigned according to their 280 ppm scenario SSTs for the months of June or December (for northern and southern hemisphere reef locations, respectively) as discussed above. Application of the current (pCO₂ = 380 ppm) Ω_{arag} and SSTs to equation (6) indicates that most coral reefs are already calcifying 20% to 40% less than their PIR rates (Figure 2). Reefs that are located in the warm water pool of the Western Pacific and along the North Eastern coast of Australia show the strongest response to changes in water chemistry and temperature. At a pCO₂ level of 750 ppm ca. 75% of coral reefs will calcify at a rate between 0 and 20% of their PIR rate (Figure 2). It should be noted that the terminal seas of the Middle East may act as reef sanctuaries even at higher CO₂ levels due to their high total alkalinity (and hence Ω_{arag}). However, due to model restrictions, we cannot make a calculated prediction for these seas (see above).

[5] According to *Silverman et al.* [2007] the community rate of CaCO₃ dissolution in a coral reef may offset as much as ca. 20% of the gross rate, similar to the offset of ca. 30% observed by *Barnes* [1988] on Davies Reef Flat in the Great Barrier Reef, Australia (~19°S). Hence, at CO₂ partial pressure of 750 ppm most reefs may start to be net dissolvers of CaCO₃ assuming that dissolution rates within the reef framework are not sensitive to acidification. Obviously, the inability of coral reefs to maintain their framework will significantly reduce the habitat they provide for a wide diversity of organisms as well as their vital role in shore protection.

[6] The recent increase in bleaching event frequency and resulting coral mortality on a massive scale during the last two decades suggests that this process may cause coral reef degradation and ultimate demise within the 21st century [*Goreau and Hayes*, 2005; *Hoegh-Guldberg*, 2005]. This issue however is still a matter of debate amongst coral reef scientists considering the tolerance of certain coral species to increased temperatures and the recurrence of coral reefs after an almost complete disappearance from the geological

record [*Coles and Brown*, 2003]. The calculations in this study are based on the assumption that an increase of 1°C in the maximum summer monthly average SST (relative to PIR) will result in bleaching (Op. Cit.) that will reduce the live coral cover by 50%. This was calculated for each CO₂ stabilization level at each reef location. For example, the A_c of a reef will decrease from 0.5 to 0.25 when monthly average model SST increases by $\geq 1^\circ\text{C}$ above the temperature of the warmest month during PIR. A further decrease of A_c to 0.125 is invoked by the model on the next encounter with $\geq 1^\circ\text{C}$ SST increase. Including bleaching events in the calcification model, results in reduced gross calcification (Figure 3). The calculations show that ca. 30% of coral reefs have experienced bleaching already at 380 ppm and decreased their gross calcification by 60% to 80% relative to their PIR rate. This value is significantly lower than the observed spatial distribution of bleaching events based on visual reports and satellite observations [*Goreau and Hayes*, 2005], and is likely the result of the coarse resolution of the model used to simulate SST and Ω_{arag} [*Cao and Caldeira*, 2008]. Regardless, according to our model results, all coral reefs are expected to reduce their calcification by >80% relative to their PIR rate by pCO₂ doubling (560 ppm). It should be noted that our calculations include estimates for the decrease in live coral cover due to bleaching alone. This is a rather conservative estimate considering that pollution and crown-of-thorns starfish outbreaks at many reef locations will most probably result in an additional reduction in live coral cover [*Bellwood et al.*, 2004].

[7] Unlike previous reports, this study bases its predictions on relations between calcification, temperature and Ω_{arag} from field observations rather than lab or mesocosm studies [*Kleypas et al.*, 1999; *Langdon and Atkinson*, 2005]. While, this is not the first study, which tries to predict the combined affect of future changes in temperature and Ω_{arag} on coral reef calcification globally [*McNeil et al.*, 2004], it addresses this issue with a more realistic treatment of their combined influence as well as considering the effect of CaCO₃ dissolution [*Kleypas et al.*, 2005]. Increasing ocean

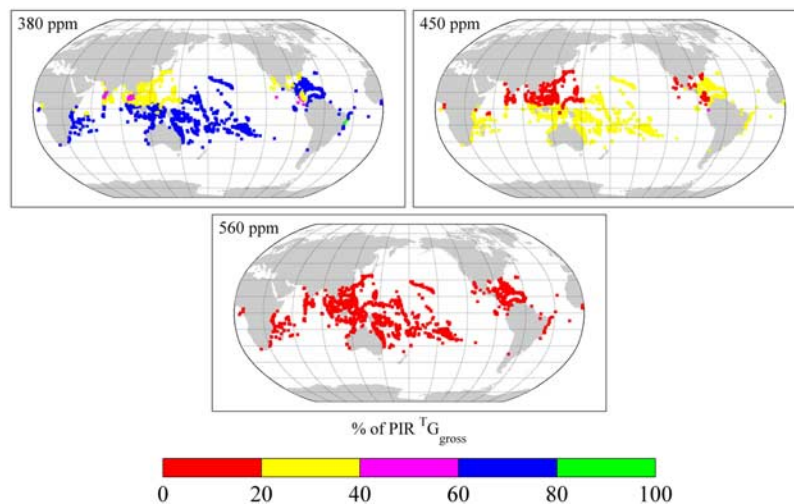


Figure 3. Global coral reef distribution and their $T_{G_{gross}}$ relative to their pre-industrial rate (280 ppm) in percent calculated with equation (6) employing modeled sea surface Ω_{arag} and temperature values from *Cao and Caldeira* [2008], taking into account the change in live coral cover due to bleaching for each reef location at pCO_2 stabilization levels of 380, 450 and 560 ppm. Live coral cover in all reefs was reduced by 50% cumulatively from an initial value of 50% when the SST at the reef location exceeded $1^\circ C$ over its maximum monthly average summer SST at the 280 ppm stabilization level.

acidification has been shown to cause greater rates of $CaCO_3$ dissolution within the carbonate framework of coral reefs [Yates and Halley, 2006; Manzello et al., 2008]. However, a functional relation between dissolution and Ω_{arag} has yet to be established. Finally, while equation (6) captures what is currently known about coral growth as a function of Ω_{arag} and temperature in essence, and its results correlate satisfactorily with observations, it doubtless requires further testing and verification in both future experimental and observational studies.

[8] Despite the potentially marked effect of ocean acidification and warming on the growth of coral reefs around the globe it has practically no effect on the global carbon budget. Converting all of the coral reefs around the world from net precipitation (source of atmospheric CO_2) to net dissolution of $CaCO_3$ will result in a CO_2 sink of $0.017 \cdot 10^9$ ton $C \cdot yr^{-1}$ [Vecsei and Berger, 2004; Gattuso et al., 1999]. This is a negligible sink compared to the $8.4 \cdot 10^9$ ton $C \cdot yr^{-1}$ emitted annually to the atmosphere from fossil fuel burning and cement production [Canadell et al., 2007]. Finally, we are aware that coral reefs were exposed throughout their geological history to higher temperatures and CO_2 levels than at present and yet have persisted. The geological record however reveals that coral reefs have undergone many cycles of expansion and decline that lasted several millions of years [Kiessling, 2001]. Similarly, the current and predicted changes may represent a severe global decline of coral reef abundance but not a complete extinction. However, from the perspective of human experience, one of the most beautiful, diverse and economically important marine ecosystems may considerably decline for generations to come.

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