Low coral cover in a high CO$_2$ world

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• 284,300 square kilometers
• Less than 0.2% of the ocean, yet,
  – 100,000 species, possibly 1-9 million total
  – High productivity in a nutrient desert
• 100 million people directly dependent on healthy coral reefs
• Billion dollar tourism and fisheries
Outline

• Coral reefs: temperature, light and alkalinity
• Climate change and coral reefs
  – Sea temperature
  – Aragonite saturation
• Acclimation, adaptation and range migration
• Concluding remarks
Warmest, most sunlit, highest alkalinity
Environmental limits to coral reefs development

**TEMPERATURE**
Average min/max: 24.8 – 27.6°C
Min: 16°C

**SALINITY**
Average min/max: 34.3 – 35.3 ppt

**MIN LIGHT PENETRATION**
Range: -7 to -72

**ARAGONITE SATURATION**
Average min/max: 3.28 – 4.06

**NITRATE**
Average: 0.25 μM

**PHOSPHATE**
Average: 0.13 μM

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Kleypas et al. (1999) Am Zool 39: 146-159

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**Table 3. Statistically derived environmental averages and extremes among reef sites (does not include non-reef coral communities).**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Min</th>
<th>Max</th>
<th>Avg</th>
<th>SD</th>
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<td>Temperature (°C)</td>
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<td>34.4</td>
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<td>Salinity (PSU)</td>
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<td>23.3</td>
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<td>41.8</td>
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<td>Nutrients (μmol L⁻¹)</td>
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<td>NO₃</td>
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<tr>
<td>PO₄</td>
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<td>Aragonite saturation (Ω-arag)</td>
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<td>average</td>
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<tr>
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<td>−10</td>
<td>−91</td>
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Environmental limits to coral reefs development

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  – Sea temperature
  – Aragonite saturation
• Acclimation, adaptation and range migration
• Concluding remarks
Coral bleaching and mortality

- Six major events since 1979
- None reported formally before 1979
- Thousands of square miles affected
- May be followed by huge mortalities
- Increasing frequency and severity

1998 & 2002 & 2004
Estimated loss of living coral colonies from reefs in 1997-98: 16% world wide.

Fig. 4. Dates and locations of when severe bleaching began in 1998. Data obtained from Coral Health and Monitoring Network e-mail list (http://coral.aoml.noaa.gov).
Mass coral bleaching caused by thermal stress

- 95% correlation with increases in sea temperature (1-2°C above long-term summer sea temperature maxima) and bleaching.
- Backed up experimentally
- Basis for a highly predictive SST program at NOAA (HotSpots):
Threshold temperature – above which bleaching manifests itself (1-2°C above the long-term summer maximum temperatures)

WHAT DOES THE FUTURE HOLD?

Hoegh-Guldberg (1999)
Table 6. Comparison of recent Degree Heating Months and mass bleaching mortality estimates from incidents of bleaching within the 1998 mass bleaching event (adapted from Hoegh-Guldberg 2002).

<table>
<thead>
<tr>
<th>Severe events (mortality &gt; 80%)</th>
<th>Location</th>
<th>Degree heating months</th>
<th>Mortality</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palau</td>
<td>3.9</td>
<td>70-90%</td>
<td>J. Bruno, unpublished data</td>
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<tr>
<td>Seychelles</td>
<td>3.1</td>
<td>Up to 75%</td>
<td>Spencer et al. (2000)</td>
<td></td>
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<tr>
<td>Okinawa</td>
<td>3</td>
<td>90-95%</td>
<td>Loya et al. (2001)</td>
<td></td>
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<tr>
<td>Scott Reef</td>
<td>2.6</td>
<td>75-90%</td>
<td>L. Smith and A. Heyward, unpublished data</td>
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<tr>
<td>Mean ± 95% CI</td>
<td>3.2 ± 0.47</td>
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</table>

<table>
<thead>
<tr>
<th>Mild events (mortality &lt; 10%)</th>
<th>Location</th>
<th>Degree heating months</th>
<th>Mortality</th>
<th>Source</th>
</tr>
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<tbody>
<tr>
<td>Southern GBR (reef crest)</td>
<td>1.7</td>
<td>10-30%</td>
<td>Jones et al. (2000)</td>
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<tr>
<td>Central GBR (inner reefs)</td>
<td>1.4</td>
<td>1-16%</td>
<td>Marshall and Baird (2000)</td>
<td></td>
</tr>
<tr>
<td>Moorea (outer reef crest)</td>
<td>0.9</td>
<td>0% mortality</td>
<td>Personal observation (10% bleached)</td>
<td></td>
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<tr>
<td>Cook Is (Southern; reef crest)</td>
<td>0.4</td>
<td>0% mortality</td>
<td>Personal observation (5% bleached)</td>
<td></td>
</tr>
<tr>
<td>Mean ± 95% CI</td>
<td>1.1 ± 0.49</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Degree Heating Months (°C mth^-1)

A. Southern GBR

Not yet experienced
Mass death
Bleaching
A. Southern GBR

Logic:

Reefs that receive a bleaching event (DHMs > 0.5) every two years will start to look degraded.

Reefs that experience Mass mortality events (DHMs > 3.2) will only have remnant corals.
A. Southern GBR

B. Central GBR

C. Northern GBR

Degree Heating Months (°C mth⁻¹)  Events per Decade (mth⁻¹)

Remnant corals

Degraded reefs
What about decreasing pH and the concentration of carbonate ions?
R E P O R T S

Geochemical Consequences of Increased Atmospheric Carbon Dioxide on Coral Reefs

Joan A. Kleypas, Robert W. Buddemeier, David Archer, Jean-Pierre Gattuso, Chris Langdon, Bradley N. Opdyke

A coral reef represents the net accumulation of calcium carbonate (CaCO₃) produced by corals and other calcifying organisms. If calcification declines, then reef-building capacity also declines. Coral reef calcification depends on the saturation state of the carbonate mineral aragonite of surface waters. By the middle of the next century, an increased concentration of carbon dioxide will decrease the aragonite saturation state in the tropics by 30 percent and biogenic aragonite precipitation by 14 to 30 percent. Coral reefs are particularly threatened, because reef-building organisms secrete metastable forms of CaCO₃, but the biogeochemical consequences on other calcifying marine ecosystems may be equally severe.

Atmospheric CO₂ is expected to reach double preindustrial levels by the year 2065 (1). CO₂ research in the marine environment has focused on the ocean’s role in sequestering atmospheric CO₂ (2, 3), but the potential effects of the resulting ocean chemistry changes on marine biota are poorly known.

Dissolved inorganic carbon occurs in three basic forms: CO₂⁻ (CO₂(aq) + H₂CO₃), HCO₃⁻, and CO₃²⁻. Under normal seawater conditions (pH 8.0 to 8.2), [HCO₃⁻] is roughly and calcium carbonate (CO₂ + H₂O + CaCO₃ ⇌ 2HCO₃⁻ + Ca²⁺) illustrates how addition of CO₂ enhances CaCO₃ dissolution and removal of CO₂ enhances its precipitation. Calcium carbonate saturation state (Ω) is

Ω = $\frac{[\text{Ca}^{2+}][\text{CO}_3^{2-}]}{K_{sp}}$

where $K_{sp}$ is the stoichiometric solubility product for a particular mineral phase of CaCO₃ [calcite (calc), aragonite (arag), or

rates correlate well with saturation state (6). Current reef distribution also correlates with saturation state (7), and large-scale biogeochemical studies have found a positive relationship between saturation state and calcification (8). Fragile coral skeletons have been reported from high-latitude, low Ω-arag reefs and coral communities (9), and reefs in well-mixed, highly supersaturated waters such as the Red Sea tend to have abundant internal carbonate cements (10), whereas those in low saturation waters such as the eastern Pacific have none (11). Modern aragonitic ooids and “whittings” also form only where Ω-arag is high (for example, Bahama Banks, Persian Gulf).

Experimental studies of calcification versus saturation state in marine organisms or communities are rare. In a recent review (12), six such studies on corals and marine algae (the major reef-building taxa) were identified, and, despite methodological differences, all showed a significant positive correlation between saturation state and calcification. Recent experiments in the Biosphere 2 coral reef mesocosm show a strong dependence of community calcification on saturation state (13).

We used two methods to predict changes in surface saturation state. The first assumed constant alkalinity through the middle of the next century and that ocean surface response to increased $P$CO₂ atm is strictly thermodynamic ($P$CO₂ surf is near equilibrium with $P$CO₂ atm)
Effect of Temperature on $[\text{CO}_3^{2-}]$

- 1x$\text{CO}_2$
- 2x$\text{CO}_2 + 2^\circ\text{C}$

Warming lessens effect by $\sim10%$
$[CO_3^{2-}]$ at 280 ppmv and 560 ppmv
Is it changing?

- Hawaii Ocean Time Series

- Slope in $\Omega$-arag = $-0.022 \pm 0.08$ y$^{-1}$, 95% CI
  - C. Langdon, pers. comm.

- Calculate decrease over next 80 years
  - Decrease of -1.76
  - Takes average $\Omega$-arag to 2.07
Figure 5. Relationship between net community calcification rate ($G$) and $\text{CO}_3^{2-}$ concentration for the period of time covered by Figure 4. The data are segregated into three periods of time corresponding to different concentrations of $\text{Ca}^{2+}$. The solid squares correspond to the period between April 2 and June 25 when $[\text{Ca}^{2+}]$ was 7.0-6.9 mmol kg$^{-1}$, the solid circles correspond to the period between July 10 and September 3 when $[\text{Ca}^{2+}]$ was 9.4-8.7, and the solid triangles correspond to the period September 10 to October 22 when the $[\text{Ca}^{2+}]$ had declined to 8.7-8.4. The three lines show the expected $G$-$\text{CO}_3^{2-}$ relationship as a function of $[\text{Ca}^{2+}]$ based on the rate expression obtained in Figure 6.
Pre-industrial pCO₂ – 280 ppm

2060-69; pCO₂ – 517 ppm

Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin

J. M. Guinotte · R. W. Buddemeier · J. A. Kleypas

DOI 10.1007/s00338-003-0331-4
Calcification decreases with decrease in carbonate ion concentrations

<table>
<thead>
<tr>
<th>Conclusion</th>
<th>Lab/field</th>
<th>Literature</th>
<th>Outcome predicted for 2100 (doubling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support</td>
<td>Lab and mesocosm</td>
<td>Gattuso et al. (1998); Marubini and Atkinson (1999); Langdon, et al. (2000); Leclercq et al. (2000); Marubini et al. (2001, 2002); Leclercq et al. (2002); Langdon et al. (2003)</td>
<td>20-54% decrease in calcification</td>
</tr>
<tr>
<td>Against</td>
<td>Coring study</td>
<td>Lough and Barnes (2000)</td>
<td>Increase</td>
</tr>
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</table>
Fig. 8. Percentage increase in calcification of massive *Porites* along the GBR estimated from observed SST differences between 1903–22 and 1979–98. Estimates based upon the relationship shown in Fig. 5c. Triangles and solid line represent regions within the GBR; squares and dashed line represent regions to the south of the GBR. Brisbane is at latitude 27.5°S. The Solitary Islands, which have extensive coral communities but no reefs, are around 30.0°S.
Implication: Increase in calcification (due to temperature increase on calcification) counters the effect of decreasing W-arag (carbonate ion concentration) on calcification.
Assumption: Photosynthesis (the power house of calcification) increases linearly with temperature up to 2.7°C above today’s temperatures.

Is this so?
Figure 7. $F_v/F_m$ of zooxanthellae in *Stylophora pistillata* exposed to water temperatures of 28, 30, 32, 33 or 34 °C for 1 or 4 h (experiment 1), or 4 h (experiment 2, inset), under artificial 1°C warming. Jones et al. (1998)

Temperature

0 5 10 15 20 25 30 35 40

Change (fraction)

1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3

Temperature

25 27 29 31 33 35

Ω-arag

Metabolic

Sum
Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin
Consequences?

- Increasing thermal stress
- Loss of reef function and services
- Reduced support to subsistence usage
- Reduced tourist value
- Reduced fish populations
- Increased symbiotic dysfunction & mortality
- Reduced tourist value
- Other?
- Coastal protection

Confidence levels:
- High confidence
- Medium confidence
- Low confidence
Summary

• Increasing sea surface temperatures and decreasing carbonate alkalinites are a severe threat to coral reefs. Any more than +2oC has huge implications for coral reefs.

• Under a doubling of CO$_2$, projections suggest a change over from coral dominated coral reefs to those that are mostly not dominated by coral.

• This has critical implications for people and livelihoods in tropical coastal areas. These flow on effects are ill-defined at this point.
The ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC) is "to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."
Fig. 5  Comparison of areal changes in the $18^\circ$C isotherm vs the 4.0 “iso-saturation” between the preindustrial conditions and those predicted for the middle of next century (doubled CO$_2$ and 2°C increase in SST)

Joan A. Kleypas · Robert W. Buddemeier  
Jean-Pierre Gattuso

The future of coral reefs in an age of global change

DOI 10.1007/s005310000125