LETTERS

edited by Jennifer Sills

Coral Adaptation in the Face of Climate Change

IN THEIR REVIEW, "CORAL REEFS UNDER RAPID CLIMATE CHANGE and ocean acidification" (14 December 2007, p. 1737), O. Hoegh-Guldberg *et al*. present future reef scenarios that range from coral-dominated communities to rapidly eroding rubble banks. Notably, none of their scenarios considers the capacity for corals to adapt. The authors dismiss adaptation because "[r]eef-building corals have relatively long generation times and low genetic diversity, making for slow rates of adaptation [relative to rates of change]." We think the possibility of adaptation deserves a second look.

Many features of coral life histories, such as extended life spans, delayed maturation, and colony fission, do result in long generation times (*1*) [some between 33 and 37 years (*2*)]. However, other corals, such as many species of *Acropora* and *Pocillopora*, mature early, grow rapidly, and suffer whole-colony mortality, as opposed to colony fission, after mechanical disturbances (*3*) and thermal stress (*4*). The life histories of these ecologically important and abundant species suggest an underappreciated capacity to adapt rapidly to changing environments.

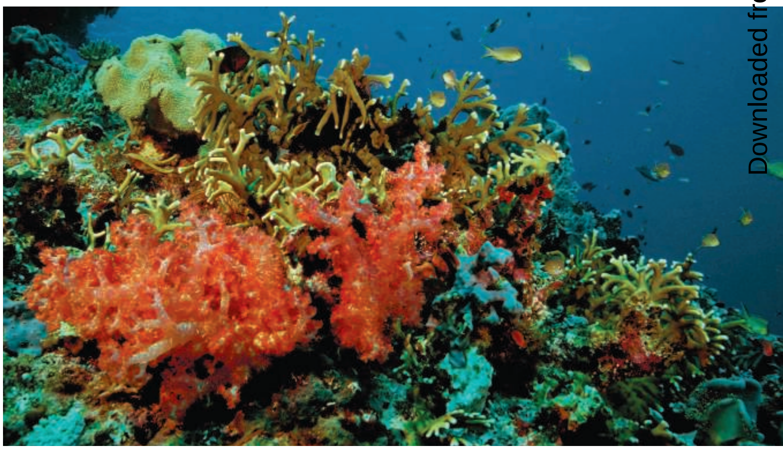
Repeated bleaching episodes in the same coral assemblages and the increasing scale and frequency of coral bleaching have been cited as evidence that corals have exhausted their genetic capacity to adapt to rising sea surface temperatures (*5*). However, comparisons of the rates of mortality within populations among bleaching events are not available. Without these data, it is not possible to assess whether the adaptive response has been exhausted. Indeed, the effects of temperature and acidification on even the most basic vital rates in corals, such as growth, mortality, and fecundity, are largely unknown, as are the physiological trade-offs among these traits. Consequently, the sensitivity of population growth to climate-induced changes in vital rates remains almost completely unexplored [but see (*6*)]. In the absence of long-term demographic studies to detect temporal trends in life history traits, predicting rates of adaptation, and whether they will be exceeded by rates of environmental change, is pure speculation. Indeed, where such data are available for terrestrial organisms they demonstrate that contemporary evolution in response to climate change is possible (*7*).

ANDREW BAIRD[1] AND JEFFREY A. MAYNARD[2]

[1]ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811, Australia. [2]Centre of Excellence for Environmental Risk Analysis, University of Melbourne, Parkville, VIC 3010, Australia.

References

1. T. P. Hughes, D. Ayre, J. H. Connell, *Trends Ecol. Evol*. **7**, 292 (1992).
2. R. C. Babcock, *Ecol. Monogr*. **61**, 225 (1991).
3. J. S. Madin, S. R. Connolly, *Nature* **444**, 477 (2006).
4. A. H. Baird, P. A. Marshall, *Mar. Ecol. Prog. Ser.* **237**, 133 (2002).
5. O. Hoegh-Guldberg, *Mar. Freshwater Res*. **50**, 839 (1999).
6. M. Wakeford, T. J. Done, C. R. Johnson, *Coral Reefs* **27**, 1 (2008).
7. D. K. Skelly *et al*., *Conserv. Biol*. **21**, 1353 (2007).



CREDIT: SIMON FOALE/ARC COE

Response

WE CERTAINLY HOPE THAT BAIRD AND MAYNARD are right and that in the coming years corals will exhibit an adaptive capability that they have not yet exhibited in situ or in the laboratory. At this point, however, it appears unlikely.

As Baird and Maynard point out, the coral genera *Acropora* and *Pocillopora* have generation times that are short (several years) relative to the generation times of other corals. The majority of coral generation times, however, are still long (decades) relative to the accelerating pace of climate change, throwing doubt on the scope of most coral species for rapid adaptation (*1*).

Corals, like other organisms, can also modify the risk of coral bleaching over the short term through physiological acclimation (*2*). Acclimation, however, as with any phenotypic change, is limited. In the same vein, corals that form symbioses with more than one variety of dinoflagellate can shift their populations so that they are dominated by their more thermally tolerant dinoflagellate genotypes during thermal stress. Unfortunately, these short-lived changes have not yet resulted in the novel host-symbiont combinations that will be required for survival in the challenging temperatures and acidities of future oceans under rising atmospheric carbon dioxide.

It is important not to confuse genetic adaptation with the increased average thermal tolerance observed for some coral communities over the past 25 years, which has occurred largely because thermally sensitive species have died out, leaving robust species behind

(*3*). Equally important is the lack of evidence that corals have the capacity to either acclimate or adapt to falling aragonite saturation states. It seems unlikely that genetic adaptation will solve the problems of global change facing corals. Indeed, paleontological evidence indicates that calcifying marine organisms including corals suffered a protracted period of absence after large and rapid changes in atmospheric carbon dioxide associated with the Permian–Triassic extinction event (*4*, *5*). It took millions of years for these organisms and ecosystems to recover.

O. HOEGH-GULDBERG,[1]* P. J. MUMBY,[2] A. J. HOOTEN,[3] R. S. STENECK,[4] P. GREENFIELD,[5] E. GOMEZ,[6] D. R. HARVELL,[7] P. F. SALE,[8] A. J. EDWARDS,[9] K. CALDEIRA,[10] N. KNOWLTON,[11] C. M. EAKIN,[12] R. IGLESIAS-PRIETO,[13] N. MUTHIGA,[14] R. H. BRADBURY,[15] A. DUBI,[16] M. E. HATZIOLOS[17]

[1]Centre for Marine Studies, The University of Queensland, St Lucia, QLD 4072, Australia. [2]Marine Spatial Ecology Laboratory, School of Biological and Chemical Sciences, University of Exeter, Exeter EX4 4PS, UK. [3]AJH Environmental Services, 4900 Auburn Avenue, Suite 201, Bethesda, MD 20814, USA. [4]School of Marine Sciences, Darling Marine Center, University of Maine, Walpole, ME 04573, USA. [5]The Chancellery, University of Queensland, St Lucia, QLD 4072, Australia. [6]Marine Science Institute, University of the Philippines, Diliman, Quezon City, Philippines. [7]Department of Ecology and Evolutionary Biology, E321 Corson Hall, Cornell University, Ithaca, NY 14853, USA. [8]International Network on Water, Environment and Health, United Nations University, Hamilton, ON L8N 1E9, Canada. [9]School of Biology, Ridley Building, University of Newcastle, Newcastle upon Tyne NE1 7RU, UK. [10]Department of Global Ecology, Carnegie Institution of Washington, Stanford, CA 94305, USA. [11]National Museum of Natural History, Smithsonian Institution, Washington, DC 20013, USA. [12]NOAA Coral Reef Watch, NOAA E/RA31, Silver Spring, MD 20910–3226, USA. [13]Unidad Académica Puerto Morelos, Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, Cancún, 77500 QR, México. [14]Wildlife Conservation Society, Bronx, NY 10460, USA. [15]Resource Management in Asia-Pacific Program, Australian National University, Canberra ACT 0200, Australia. [16]Institute of Marine Sciences, University of Dar es Salaam, Tanzania. [17]Environment Department, MC5-512, The World Bank, Washington, DC 20433, USA.

*To whom correspondence should be addressed. E-mail: oveh@uq.edu.au

References

1. D. K. Skelly *et al.*, *Conserv. Biol.* **21**, 1353 (2006).
2. S. L. Coles, B. E. Brown, *Mar. Biol.* **46**, 183 (2003).
3. P. W. Glynn, J. L. Maté, A. C. Baker, M. O. Calderón, *Bull. Mar. Sci.* **69**, 79 (2001).
4. G. D. Stanley Jr., *Earth-Sci. Rev.* **60**, 195 (2003).
5. R. S. Steneck, *Paleobiology* **9**, 44 (1983).

Freshwater Forcing: Will History Repeat Itself?

IN THEIR RESEARCH ARTICLE "REDUCED North Atlantic deep water coeval with the glacial Lake Agassiz freshwater outburst" (4 January, p. 60), H. F. Kleiven *et al.* present compelling evidence for an abrupt deep-ocean response to the release of freshwater from glacial Lake Agassiz into the northwest Atlantic about 8400 years ago. Such data are particularly important in evaluating the response in ocean models of the Atlantic Meridional Overturning Circulation (MOC) to freshwater forcing. For this event, the freshwater forcing was likely large but short; Clarke *et al.* (*1*) estimate that the flood had a freshwater flux of 4 to 9 Sv released in 0.5 years.

In this context, we are aware of no possible mechanism that might reproduce such a forcing in response to global warming, and all available model simulations, including those with estimates of maximum Greenland Ice Sheet (GIS) melting rates, indicate that it is very unlikely that the MOC will undergo an abrupt transition during the course of the 21st century (*2*). Multimodel ensemble averages under Special Report on Emissions Scenario (SRES) A1B suggest a best estimate of 25 to 30% reduction in the overall MOC strength (*2*). In one example, 14 coupled models simulated a 100-year 0.1-Sv freshwater perturbation to the northern North Atlantic Ocean—17 times the recently estimated melt rates from the GIS—and the MOC weakened by a multimodel mean of 30% after 100 years; none of the models simulated a shutdown (*3*). Another model simulated greenhouse gas levels that increased to four times preindustrial values and then remained fixed; the resulting GIS displayed a peak melting rate of about 0.1 Sv, with little effect on the MOC (*4*). One model simulation uses the SRES A1B scenario but adds an additional 0.09-Sv freshwater forcing as an upper-bound estimate of potential GIS melting. In this case, the MOC weakened but subsequently recovered its strength, indicating that GIS melting would not cause abrupt climate change in the 21st century (*5*). Accordingly, we urge caution in drawing comparisons of the abrupt change 8400 years ago to future scenarios involving, for example, the melting of the GIS and its relevance to human societies.

PETER U. CLARK,[1] THOMAS L. DELWORTH,[2] ANDREW J. WEAVER[3]

[1]Department of Geosciences, Oregon State University, Corvallis, OR 97331, USA. [2]Geophysical Fluid Dynamics Laboratory/NOAA, Princeton, NJ 08542, USA. [3]School of Earth and Ocean Sciences, University of Victoria, Victoria, BC V8W 3P6, Canada.

References

1. G. K. C. Clarke, D. W. Leverington, J. T. Teller, A. S. Dyke, *Quat. Sci. Rev*. **23**, 389 (2004).
2. G. A Meehl *et al.*, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon *et al.*, Eds. (Cambridge Univ. Press, New York, 2007), pp. 747–845.
3. R. J. Stouffer *et al.*, *J. Clim*. **19**, 1365 (2006).
4. J. K. Ridley, P. Huybrechts, J. M. Gregory, J. A. Lowe, *J. Clim*. **17**, 3409 (2005).
5. J. H. Jungclaus, H. Haak, M. Esch, E. Roeckner, J. Marotzke, *Geophys. Res. Lett*. **33**, 10.1029/2006GL026815 (2006).

Response

WE THANK CLARK *ET AL*. FOR REITERATING AN important point regarding the relevance of our study (4 January, p. 60) for future global warming scenarios. We agree with Clark and colleagues that the 8400-year deep circulation anomaly we reported, although useful for evaluating the response of ocean models

CORRECTIONS AND CLARIFICATIONS

News Focus: "Puzzling over a Steller whodunit" by V. Morell (4 April, p. 44). On the map on page 45, Steller sea lion stocks were mislabeled. The eastern stock is in the eastern Gulf of Alaska, whereas the western stock extends westward into the Bering Sea.

Policy Forum: "A case study of personalized medicine" by S. H. Katsanis *et al*. (4 April, p. 53). Owing to editorial error, some corrections sent by the author were not made for publication. The author's affiliation omitted the name of the institute and should read as follows: Genetics and Public Policy Center, Berman Institute of Bioethics, The Johns Hopkins University, Washington, DC 20036, USA. In the first paragraph, the reference to "biomarkers" should read "tests" as follows: "To date, there have been only a few genetic tests whose clinical validity in predicting drug response has been clearly established…." In refs. 10 to 13, the date of access to material published online should have been updated to show that, as of 12 March 2008, these companies had not reflected the recommendations of a December report from the expert panel for Evaluation of Genomic Applications in Practice and Prevention.

News Focus: "Dueling visions for a hungry world" by E. Stokstad (14 March, p. 1474). The story indicates that the International Food Policy Research Institute had raised money for a modeling exercise on policy options for the future of agriculture but did not carry out the study. In fact, modeling was completed—-albeit scaled back—-and is presented in Chapter 5 of the International Assessment of Agricultural Science and Technology for Development report.

Reports: "Cancer proliferation gene discovery through functional genomics" by M. R. Schlabach *et al*. (1 February, p. 620). On page 624, the contents of the Supporting Online Material inadvertently included "Data Sets S1 to S9."

Reports: "Solid-state thermal rectifier" by C. W. Chang *et al*. (17 November 2006, p. 1121). The material deposited onto the nanotube was Trimethyl [(1,2,3,4,5-η)-1-Methyl-2, 4-Cyclopentadien-1-yl] Platinum, also known as (trimethyl) methylcyclopentadienyl platinum, with chemical formula $(CH_3)_3(CH_3C_5H_4)Pt$. The empirical formula ($C_9H_{16}Pt$) and molecular weight (~319 g/mol) of this material were stated correctly in the paper. However, the name of the material that appeared on page 1122—trimethyl-cyclopentadienyl platinum—was incorrect. This correction does not change any results of the paper.

to sudden fluxes of freshwater, does not represent the most realistic (one-to-one) analog for possible future changes. Indeed, we found that only one such extreme deep circulation anomaly occurred in the Holocene and that it followed the rapid drainage of an enormous proglacial lake, for which we also know of no foreseeable equivalent in our future. In addition, we pointed out that the ocean circulation prior to the outburst flood was most likely different than it is today—Labrador sea convection and Danish Straight Overflow Water were both thought to be weaker than today (*1*, *2*). Finally, our records demonstrate just how complex the relationship between climate and ocean circulation was during the rest of the Holocene.

We demonstrated that the ocean sensitively responded to the extreme freshwater forcing event ~8400 years ago. Our results agree with modeling studies applying similarly large freshwater fluxes, confirming that the deep ocean can change just as quickly as models predict (*3*). In the most general sense, this supports the idea that the estimated 25 to 30% reduction (*4*) in Meridional Overturning Circulation (MOC) referred to by Clark *et al.* is plausible on century time scales.

Our approach for understanding the extreme and distinctly different scenario ~8400 years ago may also be useful in determining the sensitivity and thresholds of ocean circulation for the more modest but sustained freshwater forcing expected in our future. Further work will be necessary to validate the scale and rate of MOC changes estimated by models in these intermediary states. A natural next step would be to provide a detailed characterization of deep-water properties and circulation at times in our past that contain elements more in common with our future. One obvious candidate is the previous interglacial period (Marine Isotope Stage 5e), which was warmer than the present (*5*), had a smaller Greenland Ice Sheet, and may have experienced a sea-level rise at a similar rate to that projected (*6*).

H. F. KLEIVEN,[1] CATHERINE KISSELL,[2] CARLO LAJ,[2] ULYSSES S. NINNEMANN,[3] THOMAS O. RICHTER,[4] ELSA CORTIJO[2]

[1]Bjerknes Centre for Climate Research and Department of Earth Science, University of Bergen, Allegaten 41, 5007 Bergen, Norway. [2]Laboratoire des Sciences du Climat et de l'Environnement, Avenue de la Terrasse, Domaine du CNRS, Gif-sur-Yvette cedex, 91198, France. [3]Department of Earth Science and Bjerknes Centre for Climate Research, Allegaten 41, 5007 Bergen, Norway. [4]Royal Netherlands Institute for Sea Research, 1790 AB Den Burg, Netherlands.

References

1. C. Hillaire-Marcel, A. de Vernal, D. J. W. Piper, *Geophys. Res. Lett*. **34**, L15601 (2007).
2. C. Hillaire-Marcel, A. de Vernal, G. Bilodeau, A. J. Weaver, *Nature* **410**, 1073 (2001).
3. A. P. Wiersma, H. Renssen, H. Gosse, T. Fichefet, *Clim. Dyn*. **27**, 831 (2006).
4. G. A. Meehl *et al*., in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon *et al*., Eds. (Cambridge Univ. Press, New York, 2007), pp. 747–845.
5. B. L. Otto-Bliesner *et al*., *Science* **311**, 1751 (2006).
6. E. J. Rohling *et al*., *Nat. Geosci.* **1**, 38 (2008).

Letters to the Editor

Letters (~300 words) discuss material published in *Science* in the previous 3 months or issues of general interest. They can be submitted through the Web (www.submit2science.org) or by regular mail (1200 New York Ave., NW, Washington, DC 20005, USA). Letters are not acknowledged upon receipt, nor are authors generally consulted before publication. Whether published in full or in part, letters are subject to editing for clarity and space.