latch to fire. The tongue-retractor complex (see the figure) prevents the elongating accelerator muscle from sliding backward while the front end of the muscle moves closer and closer to the tip of the tongue bone. The catapult is released at the moment when the muscle's most distal end slips off the tongue skeleton. This built-in trigger adds no extra moving parts or controls to the catapult. All it requires is a tongue skeleton that tapers off only at the very tip, so that the muscle can build up enough elastic energy before it begins sliding off.

The chameleon's "sliding spring" is remarkably compact, efficient, and easy to control. Conventional catapults store tensile energy in a rope or tendon that is loaded and unloaded along the same path. By using a collagen tube rather than a tendon, the chameleon can load the spring by global longitudinal tension but release its energy by local radial contraction. This asymmetric loading-and-unloading pattern has two advantages. First, the loading structure (the accelerator muscle) and the energy-storage structure (the collagen tube) can be arranged concentrically. The tongue projector is thus compact, with admirably few moving parts or force transducers that would increase wear and reduce efficiency. Second, the sliding spring releases its elastic energy gradually as consecutive portions of the collagen tube slide off the tongue tip. Sudden acceleration is particularly unfavorable when shooting soft projectiles such as a tongue: Much energy can be lost in internal deformations and vibrations. Salamanders of the genus *Hydromantes*, which also project their tongue ballistically (*5*), avoid this problem by shooting out the stiff tongue skeleton together with the tongue itself.

In a primitive catapult, the force and acceleration are directly proportional to the extension of the spring (Hooke's law) and, therefore, are greatest at the moment of release. Conventional engineering designs, such as the compound bow, modify these characteristics by means of non-Hookean springs and dynamic levers. In a sliding-spring catapult (*1*), the course of energy release is determined in a radically different way. Its components are arranged in parallel along an axis that corresponds to the time course of the driving force. Thus, spatial modulation of elastic loading along this axis programs the time course of the launching force. The chameleon can presumably "tune" the launch of its tongue by changing muscle recruitment (on the animal's time scale), or the muscle's shape and size (on an evolutionary time scale), without having to "invent" new lever elements or change the mechanical properties of existing elements. The extraordinary degree of functional integration in the chameleon's tongue, so unlike the modular designs of mechanical engineers, might explain how the chameleon has hidden its secret catapult from biologists for so long.

References

1. J. H. de Groot, J. L. van Leeuwen, *Proc. R. Soc. London Ser. B* **271**, 761 (2004).
2. A. A. Biewener, R. Blickhan, *J. Exp. Biol.* **140**, 243 (1988).
3. M. Burrows, *Nature* **424**, 509 (2003).
4. G. N. Askew, R. L. Marsh, *J. Exp. Biol.* **204**, 3587 (2001).
5. S. M. Deban *et al.*, *Nature* **389**, 27 (1997).

ATMOSPHERIC SCIENCE

In Search of Paleo-ENSO

Yair Rosenthal and Anthony J. Broccoli

In the past several years there has been a shift in the perceived importance of the tropical Pacific Ocean to global climate on glacial-interglacial and millennial time scales. Modeling studies have indicated that the El Niño–Southern Oscillation phenomenon (ENSO), which is the primary source of year-to-year variations in tropical sea surface temperature (SST) in the modern world, may be highly sensitive to orbital influences (*1*, *2*). In these studies, the dynamical interaction between the atmosphere and ocean in the tropics is influenced by the modulation of the seasonal cycle of solar radiation by the precession of Earth; simulated tropical Pacific SST anomalies, akin either to warm El Niño or cold La Niña events, can be sustained for several hundreds to thousands of years and generate a globally synchronous climate response. Just as ENSO-related SST variations exert a major effect on modern atmospheric circulation and climate, models suggest that changes in tropical Pacific SST patterns might also have had large consequences for global climate during the last glacial maximum (LGM) about 20,000 years ago (*3*). There is, however, still a large uncertainty as to the relationships between ENSO characteristics and the background mean climate state. Given that instrumental data are limited to the past century, paleoceanographic records can provide better constraints for assessing future effects of global warming on ENSO and their ramifications for Earth's climate (*4*).

Because ENSO is an interannual phenomenon with a strong seasonal signal, its long-term history is best reconstructed from annually banded corals (*5*). However, their reliability as recorders of long-term climate change is still debatable (*6*). Similarly, lake sediments with annually resolved varves provide valuable insights into variations in ENSO throughout the Holocene, but as yet we have no record that spans the LGM (*7*, *8*). More recently, however, lower resolution sediment records from key locations in the tropical Pacific have also been used to infer long-term variability in ENSO and its possible role on both orbital and millennial time scales. In particular, two lines of evidence, both based on reconstructions of SST and salinity from measurements of Mg/Ca and $\delta^{18}O$ in foraminifera shells, have been proposed in support of long-term ENSO variability.

The first of these suggests that LGM relaxation of SST gradients within the cold tongue of the eastern equatorial Pacific was likely a result of reduced upwelling caused by weakening of the trade winds in an "El Niño–like" fashion (*9*). The second, which argues for "super ENSO" conditions during the cold Northern Hemisphere stadial intervals, is based on changes in the distribution of surface salinity and, by inference, precipitation in the western equatorial Pacific (*10*). These observations are very intriguing, yet they raise questions as to whether they are representative of the entire tropical oceans or only reflect local conditions (*11*). For example, the western Pacific salinity record is in a site that is currently strongly influenced by the east Asian monsoon system, which is tightly linked to Northern Hemisphere climate (*12*). There are also questions as to the fidelity of, and compatibility among, different paleo-proxies. For instance, faunal-based studies argue for intensification of the eastern equatorial Pacific cold tongue with the corollary of prevailing La Niña–like conditions during the LGM, in contrast with Mg/Ca-based SST reconstructions (*13*, *14*). These concerns about the reliability of paleo-proxies in capturing the full scope of climate variability clearly need to be addressed (*15*).

Even in the absence of important uncertainties in paleoceanographic records, interpreting proxy evidence for changes in

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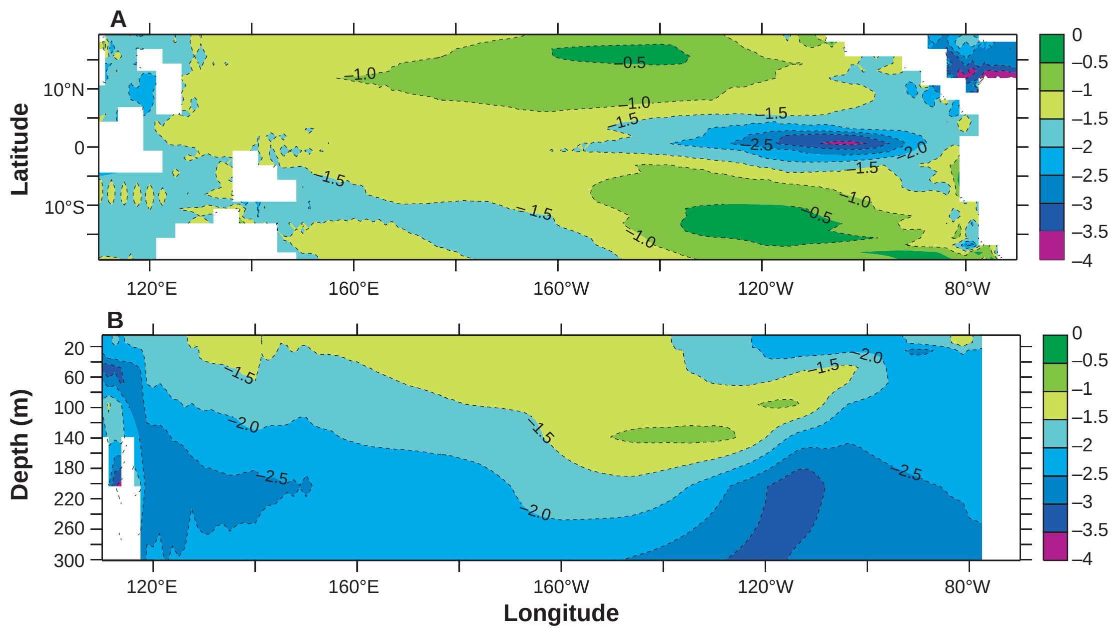
mean tropical climate can be difficult because there is insufficient knowledge to assume that climate variations on longer time scales exhibit the same patterns that are expressed in interannual variability. Such an assumption implicitly underlies descriptions of "super ENSO" or "El Niño–like" changes in climate deduced from paleodata, especially when the proxy evidence is sampled at only one or two sites. Thus, there is some risk in extrapolating from local reconstructions of SST or surface salinity to the entire tropical Pacific basin on the basis of patterns derived from interannual climate variability. To be sure, the same underlying physical and dynamical mechanisms may be involved across all of the time scales captured in the climate record, but this does not necessarily imply that patterns of millennial or orbital climate variability will be identical with those that have been identified on the basis of intensive observations of the tropical Pacific in the last two decades.

Coupled atmosphere-ocean models are used to develop physically based estimates of climate response to forcing on paleoclimatic time scales. Several coupled model simulations of LGM climate have been made during the past few years (*16*–*19*). An enhanced cooling of the eastern equatorial Pacific relative to the western warm pool (that is, an increase in the zonal SST gradient relative to the present) is simulated in two of these studies (*16*, *17*), whereas the opposite response is simulated in the other (*18*, *19*). Air-sea interactions play a critical role in these responses. In the simulations with enhanced zonal SST gradients, the trade winds strengthen in association with an intensification of the pole-to-equator temperature gradient, a response that is evident even in simpler models in which an atmospheric circulation model is coupled to a simple slab ocean (*20*). A weakening of the equatorial easterlies occurs in the simulation with reduced zonal SST gradient, consistent with the "ocean dynamical thermostat" hypothesis (*21*).

The inconsistency among the coupled simulations suggests an incomplete understanding of LGM climate. Most coupled models have significant biases in simulating ENSO variability, and these biases have been associated with deficiencies in the simulation of the mean state of the tropical Pacific. Thus, one cannot dismiss the possibility that none of the current models are responding correctly to LGM forcing. Indeed, the apparent discrepancy between some model results and a paleoceanographic reconstruction of tropical Pacific climate (*9*) suggests that substantial uncertainties remain.

Coupled models also provide explicit simulations, albeit imperfect, of interannual climate variability and changes therein. In a recent study using the National Center for Atmospheric Research (NCAR) Climate System Model, interannual SST variability associated with ENSO was found to decrease during the mid-Holocene and to increase during the LGM (*19*). At first glance, the enhanced glacial ENSO variability in this model appeared inconsistent with coral records of decreased isotopic variability in the western Pacific during the same period (*5*). A closer look at the model results revealed, however, that the increase in LGM ENSO variability was accompanied by a substantially smaller precipitation signal in the western Pacific, brought on by subtle changes in Walker circulation and an overall reduction in precipitation (*19*). Such results illustrate the need for careful interpretation of paleodata, particularly when large-scale patterns are being inferred from local conditions. The potentially complex relationship between changes in interannual variability and changes in mean climate state warrants caution when interpreting proxy records.

In building a more comprehensive picture of tropical climate variability, progress can come from a number of avenues. When gathering data, greater coordination among paleoclimate experts is necessary to better constrain large-scale patterns of climate variability. Particular attention should be given to data quality as well as spatial coverage. In addition, we need to develop new proxies to accurately reconstruct subsurface properties, because the relationships among variations in thermocline depth/temperature, SST, and wind stress might have been different in the past than expected on the basis of present interannual variability (see the figure). Paleoclimate experts should use simulations by climate system models to guide their data-gathering efforts. Likewise, experts in climate dynamics, including modelers, can sharpen the questions they investigate through a better awareness of the paleoclimate record. Perhaps most important, an interdisciplinary community with an interest in tropical climate variations could better address the salient questions about changes in ENSO variability and mean climate state (*15*). The emergence of such a community could go a long way toward reducing uncertainties regarding past variations in tropical climate and their larger impact.



Looking below the surface. Temperature differences between glacial and modern simulations with the Hadley Centre coupled atmosphere-ocean model HadCM3 (*16*). (**A**) At the surface, the simulated cooling in the eastern equatorial Pacific is enhanced relative to the rest of the tropical Pacific. (**B**) A more complex pattern of temperature change along the equator (5°S to 5°N) is simulated at depth, illustrating the importance of reconstructing subsurface as well as surface conditions.

References

1. A. C. Clement, M. Cane, R. Seager, *Paleoceanography* **14**, 441 (1999).
2. A. C. Clement *et al.*, *J. Clim.* **14**, 2369 (2001).
3. J. H. Yin, D. S. Battisti, *J. Clim.* **14**, 565 (2001).
4. A. V. Fedorov *et al.*, *Science* **288**, 1997 (2000).
5. A. W. Tudhope *et al.*, *Science* **291**, 1511 (2001).
6. T. J. Crowley, T. M. Quinn, W. T. Hyde, *Paleoceanography* **14**, 605 (1999).
7. C. M. Moy, G. O. Seltzer, D. T. Rodbell, D. M. Anderson, *Nature* **420**, 162 (2002).
8. D. T. Rodbell *et al.*, *Science* **283**, 516 (1999).
9. A. Koutavas *et al.*, *Science* **297**, 226 (2002).
10. L. Stott *et al.*, *Science* **297**, 222 (2002).
11. Y. Rosenthal, D. W. Oppo, B. K. Linsley, *Geophys. Res. Lett.* **30**, 1428 (2003).
12. S. Dannenmann, B. K. Linsley, D. W. Oppo, Y. Rosenthal, *Geochem. Geophys. Geosyst.* **4**, (1). 10.1029/2002GC000390 (2003).
13. I. Martinez *et al.*, *Paleoceanography* **18**, 1033 (2003).
14. A. C. Mix *et al.*, *Paleoceanography* **14**, 350 (1999).
15. K. E. Trenberth *et al.*, *Science* **300**, 589 (2003).
16. C. D. Hewitt *et al.*, *Clim. Dyn.* **20**, 203 (2003).
17. S.-J. Kim *et al.*, *Clim. Dyn.* **20**, 635 (2003).
18. S.-I. Shin *et al.*, *Clim. Dyn.* **20**, 127 (2003).
19. B. L. Otto-Bliesner *et al.*, *Geophys. Res. Lett.* **30** (23), 10.1029/2003GL018553 (2003).
20. A. J. Broccoli, *J. Clim.* **13**, 951 (2000).
21. A. C. Clement *et al.*, *J. Clim.* **9**, 2190 (1996).

MATERIALS SCIENCE

Understanding How Nanocrystalline Metals Deform

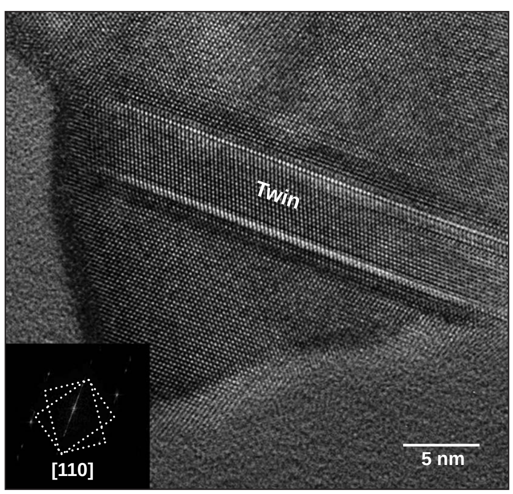
Kevin J. Hemker

The functionality and overall reliability of emerging micro- and nanoscale devices are closely tied to the mechanical properties of the nanocrystalline materials from which they are constructed. Most engineering materials are composed of thousands if not millions of tiny crystallites (called grains), and it is now widely recognized that reducing the grain size of a material will result in greatly increased strength and hardness. What is not currently understood is how these nanocrystalline materials accommodate plastic deformation—the phenomenon in which materials permanently change shape. The experiments described by Budrovic *et al.* (*1*) on page 273 of this issue are exciting because they provide a new avenue for characterizing the deformation behavior of nanocrystalline metals.

Ensuring the reliability of next-generation microelectromechanical systems (MEMS), nanoelectromechanical systems (NEMS), integrated circuits, and micro- and nanoscale devices in general will require a fundamental description of their mechanical behavior. To be truly predictive, this description must be based on a solid understanding of operative deformation mechanisms. The fact that these mechanisms have not been clearly identified for nanocrystalline materials, however, is currently exacerbated by the limitation that many of the plasticity models that were developed to describe conventional coarse-grained materials are known to break down at these reduced length scales.

The importance of dislocation activity, grain boundary sliding, diffusive processes, fatigue, and fast fracture have been addressed in microcrystalline metals and alloys, but the relative importance of these processes has yet to be established in their nanocrystalline counterparts. Methodologies used to characterize deformation behavior in microcrystalline metals have also been used to study nanocrystalline metals, but difficulties associated with the proliferation of intergranular regions and the inherent characteristics of the deformation processes have seriously hindered these efforts. The results obtained by Budrovic *et al.* (*1*) using in situ peak profile analysis of samples being deformed in the Swiss synchrotron Light Source provide a unique thumbprint of plastic deformation in nanocrystalline nickel. As such, these experiments provide a valuable complement to ongoing theoretical and experimental studies of deformation mechanisms in nanocrystalline materials.

X-ray diffraction profile analysis is a well-established technique for indirect characterization of dislocation substructures. Peak broadening occurs as a result of both limited scattering volume and the presence of inhomogeneous lattice strains. In microcrystalline metals the latter is often related to dislocation storage, and the shapes of x-ray peaks have been used to deduce indirect measures of dislocation densities, arrangement parameters, dipole polarization, and dislocation character (*2*). The results for coarse-grained copper reported by Budrovic *et al.* (*1*) are in agreement with previous studies, but their discovery that peak broadening in nanocrystalline nickel is fully recovered upon unloading was not expected, and this surprising experimental result has two important implications. First, it implies that dislocation activity is fundamentally different in nanocrystalline nickel. Second, the peak broadening that occurs when the sample is loaded provides an indirect measure of the as-yet undiscovered process, or processes, that lead to plastic deformation in nanocrystalline nickel.



Nanoscale deformation. High-resolution transmission electron micrograph of a twin in deformed nanocrystalline aluminum (*10*). This atomic resolution image illustrates the mirror symmetry between the twin and the matrix. The presence of the twin and the fact that it extends from one side of the grain to the other are unique to nanocrystalline aluminum.

In metals with grain sizes of greater than 100 nm, strengthening at reduced grain sizes is attributed to the pile-up of dislocations at grain boundaries and is modeled by the semi-empirical Hall-Petch relation. The physical basis for this model breaks down as grain size is reduced to several tens of nanometers, and measured values of the flow strength have confirmed that this relation cannot be extrapolated to nanocrystalline grain sizes (*3*, *4*). Grain boundaries are highly effective dislocation sinks and sources, and it is generally acknowledged that traditional dislocation sources cease to operate when the metals become nanocrystalline. Postmortem transmission electron microscope (TEM) observations of deformed nanocrystalline metals have failed to uncover any evidence of dislocation activity or debris characteristically observed in microcrystalline metals (*5*, *6*). The building consensus that deformation processes are different in nanocrystalline metals is further supported by Budrovic's measurements (*1*), because observation of fully reversible peak broadening would not be compatible with dislocation plasticity involving dislocation tangling and storage.

Molecular dynamics (MD) simulations have been used to study the atomic-scale processes that occur during the plastic deformation of polycrystalline

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