Nonglacial rapid climate events: Past and future

Jonathan Overpeck* and Robert Webb

National Oceanic and Atmospheric Administration Paleoclimatology Program, National Geophysical Data Center, Boulder, CO 80303

The paleoclimate record makes it clear that rapid climate shifts of the 20th century are only a subset of possible climate system behavior that might occur in the absence of glacial conditions, and that climatic surprises could be a challenge for society even in the absence of significant greenhouse warming.

Paleoclimatologists have been aware for decades that the climate system is capable of behavior quite unlike that of the present day. At the same time, however, paleoclimatology has tended to follow the lead of the climate dynamics community, and to pursue research primarily under the paradigm that the Earth's climate tends to change gradually in response to slowly changing climate forcing. For example, the first major revolution of modern paleoclimatology was the identification of a slowly oscillating Earth–Sun relationship as the pacemaker of the Ice Ages (i.e., "Milankovitch Theory"). On the other end of the climate variance spectrum, early successes with seasonal to interannual climate prediction benefited from a well described stable mode of the El Niño/Southern Oscillation (ENSO) variability in the late 1980s.

However, a new paradigm of climate variability is emerging. Rapid step-like shifts in climate variability that occur over decades or less, as well as climatic extremes (e.g., drought) that persist for decades, occurred repeatedly in recent earth history. For example, a substantial amount of work now focuses on abrupt ice-age climate shifts (e.g., other papers in the Rapid Climate Change special feature of this issue of PNAS), and significant research has also focused on the abrupt climate shift that took place over the Pacific basin in the mid-1970s (1). This mid-1970s shift represents a transition into a mode of variability characterized by frequent and strong El Niño conditions relative to earlier decades.

Here we review a representative subset of the growing body of paleoclimatic evidence regarding rapid climatic change since the last deglaciation and highlight the conclusion that climate variability in the past has changed substantially in response to altered climate forcing. Building on a recent review (2), we focus on rapid climate change of "warm climates" like those of today and the future, rather than on the well described rapid changes of glacial or deglacial climates—periods of time when the Earth's climate system may have been heavily influenced by large Northern Hemisphere ice sheets. Equally important, we focus on climate phenomena (e.g., El Niño, monsoons, and drought) of primary interest to society. The growing body of paleoclimatic evidence indicates that the climate system may have many potential surprises in store for scientists and society alike.

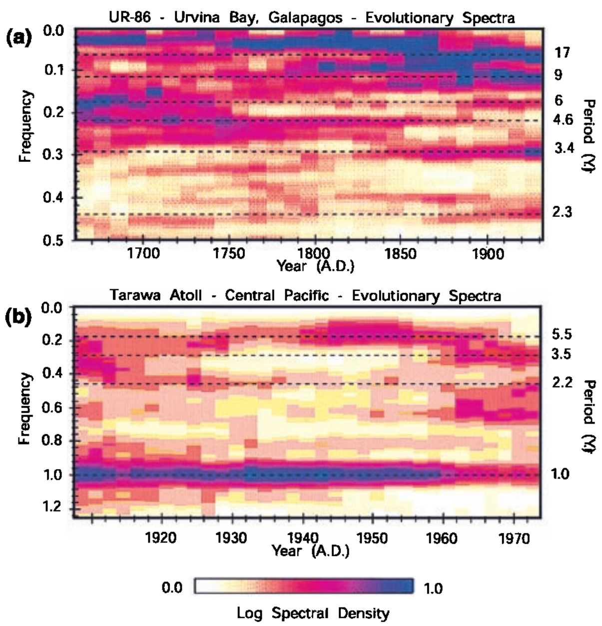

Fig. 1. Evolutionary variance spectra from a 375-year coral-based SST record from the Galapagos (eastern Pacific) (*a*) and a 97-year coral-based precipitation record from the Tarawa Atoll (central Pacific) (*b*), illustrating how the variance of tropical Pacific climate may have changed over the past four centuries. Note how the variance of the last few decades appears unique with respect to the longer record, and how multiple different variance states are visible over the last five centuries. A major objective is to produce centuries-long, coral-based records at many sites and thus eliminate any potentially spurious variability in the proxy records that is related to biological or other nonclimatic processes (from ref. 3, after refs. 4 and 5).

Case Study 1: ENSO/Pacific Variability. Recent well known shifts in Pacific climate variability have heightened awareness that seasonal to interannual variability is modulated by longer-period modes of climate variation. Moreover, shifts between different "modes," or "states," of variability have taken place without warning and within a few years (e.g., mid-1970s). Major questions remain to be answered. What other modes or states of Pacific variability are possible? What drives the climate system to change from one mode to another? Are the abrupt changes between modes predictable? Was the 1976 ENSO shift truly unprecedented? Paleoclimatic stud-

Abbreviations: ENSO, El Niño/Southern Oscillation; SST, sea-surface temperatures.

*To whom reprint requests should be addressed at present address: Institute for the Study of Planet Earth and Department of Geosciences, University of Arizona, Tucson, AZ 85721. E-mail: jto@u.arizona.edu.

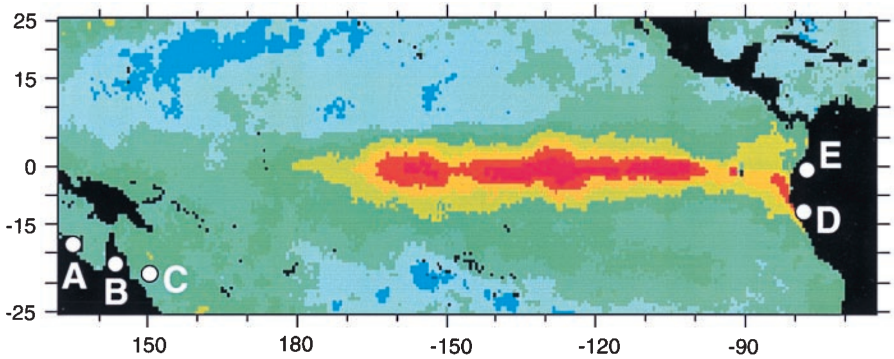

Fig. 2. Map showing sites with paleoclimatic data relevant to the mid-Holocene tropical Pacific climate (i.e., 7,000 to 5,000 years before present; see Table 1 for key and descriptions of data). Although available data indicate that climate variability at this time was distinctly different from today, the data are still too sparse to define the exact nature of the differences or the reasons for them. Paleoclimatic records mapped here suggest that interannual ENSO variability was substantially reduced, or even absent, during parts of the mid-Holocene. Locations of mid-Holocene sites shown on map of SST anomalies are associated with the 1982–1983 ENSO (red, warm; blue, cold).

ies are revealing that the 20th century modes of variability and associated abrupt changes are but a subset of the full range of possible variability.

The chemistry and isotopic composition of annual growth bands of corals provide records that closely match instrumental record of ENSO variability. Pacific coral records spanning the last several centuries indicate that synchronous shifts in frequency domain variance take place at annual, interannual, and multidecadal periods (Fig. 1). Coral records of the past several centuries are revealing new modes of Pacific variability, providing more evidence that ENSO may change in ways that we do not yet understand. Hints are also emerging from coral, and other climate proxy data, that still other modes of variability typified periods before the past several centuries. An update (Fig. 2; Table 1) to a previous review of published data (9) for the mid-Holocene ($\approx$7,000 to 5,000 years before present), a period known to have been characterized by seasonal insolation external forcing that was distinct from today (13), confirms that mid-Holocene Pacific climate was also quite distinct from the present day. Data from mid-Holocene corals reveal that western Pacific surface waters were substantially warmer and saltier than present (Fig. 3). When compared with a variety of paleoclimatic data from around the tropical Pacific basin (Fig. 2; Table 1), it becomes even more apparent that the climate of the mid-Holocene tropical Pacific was distinct from that of the last several centuries. Data from both the western and eastern Pacific suggest that interannual ENSO variability, as we now know it, was substantially reduced, or perhaps even absent (Fig. 2; Table 1). The exact significance of this possibly unprecedented mode of tropical climate variability is difficult to assess because the spatial and temporal availability of paleoclimatic data for this time period remains relatively sparse. However, climate forcing of the mid-Holocene was more similar to today than are many of the projected forcing scenarios for the 21st century. This suggests that significant shifts in variability could take place in the future, even given modest greenhouse warming.

Case Study 2: African-Asian Monsoon Variability. Just as ENSO and Pacific variability seems to be susceptible to abrupt shifts, variability of the Earth's principal monsoon systems appears to be characterized by substantial interdecadal, and often abrupt, change. The sparse long records of Sahel rainfall suggests that conditions of the last couple decades may be unprecedented in the context of the last several centuries (ref. 14; Fig. 4) and also that shifts from one variability state (e.g., "wet") may shift to another (e.g., "dry") in the matter of a couple years. Over longer time scales, a similar picture emerges (Fig. 5). Moisture balance records spanning the last 10,000 years from both East and West Africa indicate that large abrupt changes in monsoon moisture availability have occurred multiple times in the past (15). This evidence for unprecedented abrupt change is clear; however, a lack of research prevents precise reconstruction, explanation, or modeling of the these changes. Although abrupt reductions in monsoon intensity during the last 6,000 year may have contributed to the demise of an entire civilization [i.e., the Indus Valley Civilization (17, 18)], an understanding of major abrupt change associated with the Asian monsoon systems is even more elusive because of the current lack of research attention. The fact that more than one quarter of the Earth's population depends on monsoon rainfall for food and livelihood suggests that it is imperative that we learn more about the potential for future abrupt changes in monsoon variability.

Case Study 3: North American Drought Variability. Droughts are one of the most devastating natural hazards faced by the United States today [e.g., the brief 2-year drought ending in 1989 cost society more than an estimated 7 billion dollars (19)]. The paleoclimatic record indicates the droughts of the 20th century were relatively minor compared with those in the past, and opens up the possibility that future droughts may be much greater as well (20). The severe "Dust Bowl" drought of the 1930s only involved limited activation of eolian sand dunes and sand sheets; however, paleoclimate evidence indicates that much more severe and per-

Table 1. Summary of evidence for altered tropical Pacific climate in the mid-Holocene

Map letter*	Source of data	Type of mid-Holocene anomaly	Reference(s)
A	Lake sediment and fossil pollen	Stable, wet conditions; little or no interannual ENSO variability	6
B	Lake sediment and fossil pollen	Stable, wet conditions; little or no interannual ENSO variability	7
C	Coral geochemistry	Stable, warmer (1.5°C) SSTs; significantly reduced hydrologic (runoff) variability	8
D	Fossil marine fauna and terrestrial sediment data	Consistently warm SSTs; reduced ENSO variability	9–11
E	Lake sediment	Reduced hydrologic variability in modern interannual ENSO frequency band	12

*See Fig. 2.

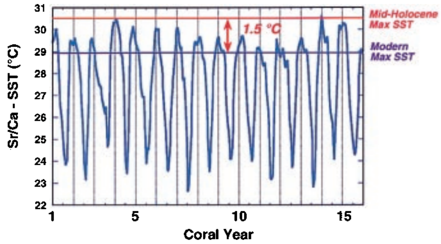

Fig. 3. Geochemically based SST data from a 5,800-year-old coral head from the Great Barrier Reef (see Fig. 2 and Table 1, site C), indicating that maximum SSTs were 1.5°C warmer than those of today. Other data from the same coral head (not shown) indicate the region was subject to much higher evaporation at that time, as well as less interannual variability (after ref. 8).

sistent droughts over the last two millennia resulted in active sand movement across significant portions of the agriculturally important U.S. High Plains (e.g., refs. 2 and 21–23). Given a wider North American regional perspective, it is becoming clear that multidecadal drought has also occurred in other water-sensitive regions such as California, the U.S. Southwest and Central America (e.g., refs. 20, 24, and 25). Society would be impacted substantially should a decade-or-longer drought occur in the future in any of these regions.

A recently produced paleodrought record raises the possibility that a sequence of different relatively stable states (or modes) of drought variability has characterized the U.S. High Plains over the last 2,000 years [Fig. 6 (26)]. This record suggests that the current mode of drought variability in the High Plains [and farther west (see ref. 20)] is relatively wet and free of truly severe drought. The current mode of drought appears in sharp contrast with the period before approximately A.D. 1200–1300 that was characterized by much longer and more severe droughts. These results indicate that the current mode of High Plains drought variability encompassing the modern instrumental record is not representative of the full range of drought variability. To understand the

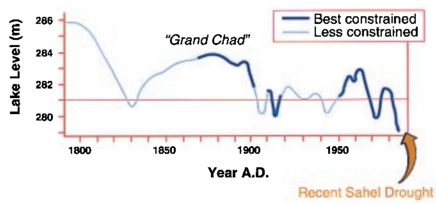

Fig. 4. Recent 20th century decadal Sahel drought variability from the perspective of 200 years of Lake Chad level fluctuations (dark lines). Lake levels inferred from less constrained data are shown in lighter lines (adapted from ref. 14).

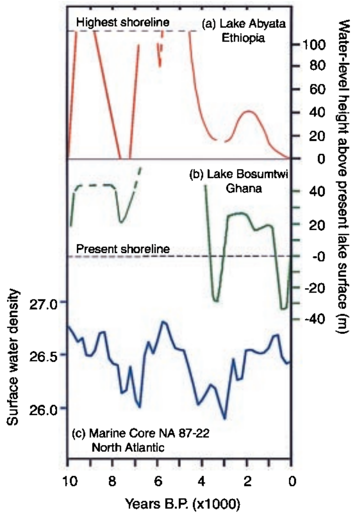

Fig. 5. (*a* and *b*) Century-scale hydrologic balance reconstructed from two widely separated sites in subtropical North Africa by using lake sediments illustrates that monsoon variability changes substantially over the last 10,000 (adapted from ref. 15). In response to insolation forcing, the monsoon was much stronger than present between 10,000 and 4,000 years ago, but it was also subject to dramatic century-scale abrupt changes for poorly known reasons, just as Sahel precipitation has changed dramatically on interdecadal time scales in the late Holocene (Fig. 4). Abrupt change in the North African monsoon may have been in response to abrupt changes in the North Atlantic, here represented (*c*) by sea-surface density changes reconstructed from marine faunal and isotopic changes in sediment cores (data from ref. 16). Although the deglacial (i.e., 13,000 to 7,000 years ago) shifts have been linked with meltwater discharge events into the North Atlantic, the cause(s) of the later Holocene aridity and sea surface density events remain poorly understood.

full range of drought variability in the High Plains, it is therefore imperative that we develop the paleoclimate observations, explanations, and process modeling that is needed to anticipate any future possible "surprise" shifts in the duration and severity of drought. For example, a recent paleoclimatic investigation (27) of the North Atlantic suggests that a shift in Atlantic variability may be linked to the rapid shift in drought variability by some poorly understood mechanism of ocean–atmosphere interaction.

A new paleoclimatic study of the relationship between ENSO/Pacific variability and conterminous U.S. drought based on tree-ring reconstructions (28) confirms the instrumental-based relationship between Pacific sea-surface temperatures (SSTs) and U.S. drought (29, 30). In addition, the paleoenvironmental proxy data suggest that modes of Pacific variability-drought relationship have changed significantly through time. The ENSO/tree ring (28) analysis suggests that La Niña-related droughts extended throughout most of the conterminous U.S. in the late 19th century while being restricted to the southwestern U.S. for the last century. Their results also suggest that the modern relationship between El Niño and droughts in the southeastern U.S. was absent before the 1920s. Given the potential of drought to cause extreme economic and other hardship on U.S. society, there is an urgent need to expand current efforts to examine the paleoclimate record of the U.S. and adjacent oceans much more carefully to ensure that we are not surprised by a mode of climatic extremes [e.g., one of frequent decadal droughts (Fig. 6)] that overwhelms the economic and emergency management mechanisms society has in place to deal with such natural disasters.

Conclusions. Research focused on defining and understanding seasonal to interdecadal climate variability of the last several centuries by using seasonally to annually resolved paleoclimatic proxies is generating much needed insight, as well as the time series of past forcings and variability, needed for climate change detection and attribution. Nevertheless, our understanding of past abrupt climate change under warm climate conditions remains limited. Substantial progress in terms of understanding the large abrupt "cold climate" shifts of the last glacial and deglacial periods has contributed to the consensus that an abrupt shift in North Atlantic circulation is possible in the

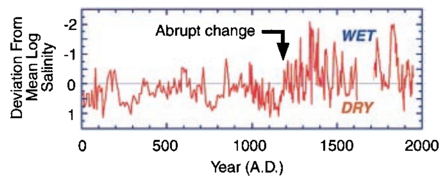

Fig. 6. Lake salinity record reconstructed for Moon Lake, ND, illustrating drought variability over the last 2,000 years for an important agricultural region of the U.S. The severe droughts of the 1930s and 1890s (positive inferred salinity) are well reconstructed but were eclipsed by more extensive droughts before the beginning of the instrumental period. There is a large abrupt change in drought variability at approximately A.D. 1200. Before A.D. 1200, the High Plains were characterized by much more regular and persistent (e.g., interdecadal) droughts; the current wet climate mode did not always exist and could thus also change or end abruptly in the future. The mechanisms for major shifts in drought variability of the past are not well understood, and no processes model has successfully simulated these types of changes. Note that the gap in 17th century data coverage represents absence of data (data from ref. 26).

future (31, 32). However, we still lack even a basic understanding of the many rapid climate shifts and events that have taken place outside the North Atlantic region during the Holocene. Investigation of warm climate rapid change and associated forcings (i.e., that of the present "Holocene" interglacial or in the future) lags the study of cold climate abrupt change, increasing the risk that future warm climate abrupt shifts in variability will not be anticipated. With the possibility that abrupt climate change becomes more frequent during periods of accelerated low-frequency climate change (e.g., related to greenhouse warming) comes the likelihood that climate predictions of the next decades will be plagued by unanticipated (and unwanted) climate surprises.

We thank J. Michael Hall for suggesting we write this document. We also would like to thank Richard Alley, David Anderson, Heather Benway, Chris Charles, Peter Clark, Julia Cole, Jean-Claude Duplessy, C. Mark Eakin, J. Michael Hall, Lloyd Keigwin, and Kevin Trenberth for helpful discussions and comments on the manuscript.

1. Trenberth, K. E. (1990) *Bull. Am. Meterol. Soc.* **71,** 988–993.
2. Overpeck, J. T. (1996) *Science* **271,** 1820–1821.
3. Duplessy, J.-C. & Overpeck, J. T. (1994) *The PAGES/CLIVAR Intersection: Providing Thepaleoclimatic Perspective Needed To Understand Climate Variability and Predictability* (IGBP PAGES Core Project Office, Bern, Switzerland).
4. Cole, J. E, Fairbanks, R. G. & Shen, G. T. (1993) *Science* **262,** 1790–1793.
5. Dunbar, R. B., Wellington, G. M., Colgan, M. W. & Glynn, P. W. (1994) *Paleoceanography* **9,** 291–316.
6. Shulmeister, J. & Lees, B. G. (1995) *The Holocene* **5,** 10–18.
7. McGlone, M. S., Kershaw, A. P. & Markgraf, V. (1992) in *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*, eds. Diaz, H. F. & Markgraf, V. (Cambridge Univ. Press, Cambridge, U.K.), pp. 435–462.
8. Gagan, M. K., Ayliffe, L. K., Hopley, D. Cali, J. A., Mortimer, G. E., Chappell, J., McCulloch, M. T. & Head, M. J. (1998) *Science* **279,** 1014–1018.
9. DeVries, T. J. (1987) *J. Geophys. Res.* **92,** 14471–14479.
10. Sandweiss, D. H., Richardson, J. B., Reitz, E. J., Rollins, H. B. & Maasch, K. A. (1996) *Science* **273,** 1531–1533.
11. Fontugne, M., Usselmann, P., Lavallée, D., Julien, M. & Hatté, C. (1999) *Quat. Res.* **52,** 171–179.
12. Rodbell, D. T., Seltzer, G. O., Anderson, D. M., Abbott, M. B., Enfield, D. B. & Newman, J. H. (1999) *Science* **283,** 516–520.
13. COHMAP Members (1988) *Science* **241,** 1043–1052.
14. Kadomura, H. (1992) in *Proceedings of the International Symposium on the Little Ice Age Climate*, ed. Mikami, T. (Tokyo Metropolitan Univ. Press, Tokyo), pp. 40–45.
15. Gasse, F. & van Campo, E. (1994) *Earth Planet. Sci. Lett.* **126,** 435–456.
16. Duplessy., J. C., Labeyrie, L. D., Arnold, M., Paterne, M., Duprat, J. & van Weering, T. C. E. (1992) *Nature (London)* **358,** 485–488.
17. Singh, G., Wasson, R. J. & Agrawal, D. P. (1990) *Rev. Palaeobot. Palynol.* **64,** 351–358.
18. Enzel, Y., Ely, L. L., Mishra, S., Ramesh, R., Amit, R., Lazar, B., Rajaguru, S. N., Baker, V. R. & Sandler, A. (1999) *Science* **284,** 125–128.
19. Riebsame, W. E., Changnon, S. A. & Karl, T. R. (1991) *Drought and Natural Resources Management in the United States: Impacts and Implications of the 1987–89 Drought* (Westview, Boulder, CO).
20. Woodhouse, C. A. & Overpeck, J. T. (1998) *Bull. Am. Meteorol. Soc*. **79,** 2693–2714.
21. Forman, S. L., Oglesby, R., Markgraf, V. & Stafford, T. (1995) *Global Planet. Change* **11,** 35–55.
22. Madole, R. (1994) *Geology* **22,** 483–486.
23. Muhs, D. R., Stafford, T. W., Jr., Swinehart, J. B., Cowheard, S. D., Mahan, S. A., Bush, C. A., Madole, R. F. & Matt, P. B. (1997) *Quat. Res.* **48,** 162–176.
23. Hodell, D. A., Curtis, J. H. & Brenner, M. (1995) *Nature (London)* **375,** 391–394.
24. Hughes, M. K. & Graumlich, L. J. (1996) in *Climate Variations and Forcing Mechanisms of the Last 2000 Years*, eds. Jones, P. D., Bradley, R. S. & Jouzel, J. (Springer, Berlin), pp. 109–124.
25. Grissino-Mayer, H. D. (1996) in *Tree Rings, Environment and Climate*, eds. Dean, J. S., Meko, D. M. & Swetnam, T. W. (Radiocarbon, Tucson), 191–204.
26. Laird, K. R., Fritz, S. C., Maasch, K. A. & Cumming, B. F. (1996) *Nature (London)* **384,** 552–554.
27. Black, D. E., Peterson, L. C., Overpeck, J. T., Kaplan, A., Evans, M. & Kashgarian, M. (2000) *Science*, **286,** 1709–1713.
28. Cole, J. E. & Cook, E. R. (1998) *Geophys. Res. Lett.*, **25,** 4529–4532.
29. Trenberth, K. E. & Guillemot, C. J. (1996) *J. Climate* **9,** 1288–1298.
30. Ting, M.-F. & Wang, H. (1997) *J. Climate* **10,** 1853–1873.
31. Manabe, S. & Stouffer, R. J. (1993) *Nature (London)* **364,** 215–218.
32. Wood, R. A., Keen, A. B., Mitchell, J. F. B. & Gregory, J. M. (1999) *Nature (London)* **399,** 572–575.