The earliest evidence of fire in these forests is considerably older than the earliest evidence of human presence. Recent palynological findings indicate that climatological changes in the Amazon Basin may have been relatively frequent during the late Holocene. Dry phases are recorded from the Amazon Basin between 6000 and 4000 years B.P., 2700 and 2100 years B.P., and at about 1500, 1200, 700, and 400 years B.P. (*15*). Under drier climatic regimes, wildfires may have destroyed large areas of forest, resulting in a large-scale mosaic of successional forests. This pattern would account for the amounts and extent of charcoal that we have found in tierra firme forests as well as the presence of charcoal in nonagricultural (caatinga and igapo) forest soils.

It can no longer be assumed that lowland tropical rain forests have been free of fire disturbance. The abundance of charcoal of mid- to late-Holocene origin commonly found in rain-forest soils of the upper Rio Negro suggests that fire has for a long time been a disturbance factor in these tropical forests. Episodes of fire disturbance have modified the forests during the mid- to late Holocene, perhaps as a result of different climatic circumstances, perhaps as a result of human intervention alone, or possibly as a result of the interaction of human disturbance and climate. The fire ecology of tropical rain forests should now be considered in both an ancient and a present-day context.

ROBERT L. SANFORD, JR.
Department of Forestry and Resource Management, University of California, Berkeley 94720

JUAN SALDARRIAGA
Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

KATHLEEN E. CLARK
Institute of Ecology, University of Georgia, Athens 30602

CHRISTOPHER UHL
Biology Department, Pennsylvania State University, University Park 16802

RAFAEL HERRERA
Centro de Ecologia, Instituto Venezolano de Investigaciones Cientificas, Caracas, 1010 Venezuela

References and Notes

1. T. Webb III, *Bull. Ecol. Soc. Am.* **65**, 2 (1984); E. W. B. Russell, *Ecology* **64**, 78 (1983).
2. J. H. Connell, *Science* **199**, 1302 (1978); M. Huston, *Am. Nat.* **113**, 81 (1979).
3. G. Budowski, in *Proceedings of the 5th Annual Tall Timbers Fire Ecology Conference* (Tall Timbers Research Station, Tallahassee, Fla., 1966), pp. 5–22; D. Mueller-Dumbois, in *Fire Regimes and Ecosystem Properties*, H. A. Mooney, T. M. Bonnicksen, N. L. Christensen, J. E. Lotus, W. A. Reiners, Eds. (U.S. Department of Agriculture Forest Service General Technical Report 26, Washington, D.C., 1981), pp. 137–176.
4. P. W. Richards, *Tropical Rain Forest* (Cambridge Univ. Press, Cambridge, Mass., 1952), p. 378.
5. J. P. Schulz, *Ecological Studies on Rainforest in Northern Suriname* (North-Holland, Amsterdam, Netherlands, 1960), pp. 8 and 126–128; H. Klinge and R. Herrera, in *Actas del IV Symposio Internacional de Ecologia Tropical* (Panama, 1979), vol. 1, pp. 393–420; G. T. Prance and H. O. R. Schubart, *Brittonia* **30**, 60 (1978).
6. N. J. H. Smith, *Ann. Assoc. Am. Geogr.* **70**, 553 (1980).
7. H. Klinge, E. Medina, R. Herrera, *Acta Cient. Venez.* **28**, 270 (1977).
8. C. Uhl, thesis, Michigan State University, Lansing (1980).
9. A. de Humboldt and A. Bonpland, *Personal Narrative of Travels to the Equinoctial Regions of the New Continent During the Years 1799–1804* (Longman, Hurst, Rees, Orme, and Brown, London, 1821), vol. 5, pp. 367–368; B. J. Meggers, *World Archaeol.* **8**, 227 (1977).
10. All transects began on riverbanks and were oriented inland perpendicular to the river course. Charcoal carbon was sorted with a 0.5-mm sieve, oven-dried at 80°C, and weighed.
11. Samples were dated by Beta Analytic, Inc., Coral Cables, Fla. Carbonates and humic acids were eliminated from cleaned samples. Benzene synthesis of the cleansed samples proceeded normally.
12. C. Uhl and C. Jordan, *Ecology*, in press.
13. J. Saldarriaga, thesis, University of Tennessee, in preparation.
14. B. J. Meggers, in *Biological Diversification in the Tropics*, G. T. Prance, Ed. (Columbia Univ. Press, New York, 1982), p. 492.
15. T. A. Wijmstra and T. van der Hammen, *Leidse Geol. Meded.* **38**, 88 (1966); M. L. Absy, thesis, University of Amsterdam (1979); V. Markgraf and J. Platt, *Striae* **16**, 41 (1982).
16. We thank P. Maquirine, S. Carianil, C. Damasio, and P. DaSilva for assistance in the field. We thank J. Bartolome, R. Byrne, P. Fiedler, F. Golley, R. Laven, J. McBride, M. McClaran, R. Robichaux, J. Strahan, W. Waters, and P. Zinke for constructive comments on earlier drafts. Research sponsored in part by the National Science Foundation's Ecosystem Studies Program under interagency agreement BSR-8315185 and with the U.S. Department of Energy under contract DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc. Publication No. 2408, Environmental Sciences Division, Oak Ridge National Laboratory.

25 June 1984; accepted 2 October 1984

Climatic Forcing: Effects of El Niño on a Small, Temperate Lake

Abstract. *Temperature profiles measured regularly for 21 years reveal the interannual differences in winter-to-summer heat gain in Castle Lake, California, a small subalpine lake. Year-to-year changes in large-scale climatic surface forcing, especially the amount of snowfall from February through April (which determines the date of thaw) coupled with the early heating and wind mixing after thaw, causes this interannual variation. The seasonal thermal structure for years in which the lake gains significantly more or less heat than normal—all of the El Niño years and several others—shows that the depth of the mixed layer and the mixing of heat into the stratified thermocline region control the storage of heat. The temperature of the mixed layer does not reflect abnormal thermal storage. Variations in mixing during early spring, which controls the heat content at Castle Lake, may also affect the annual average of the primary productivity.*

The magnitude of year-to-year variation in climate has increasingly become a concern of ecologists, oceanographers, hydrologists, agriculturalists, resource planners, and policy analysts (*1*). The El Niño of 1982 to 1983, the eruption of El Chichón, and the possible "greenhouse effect" (*2*), have become of general interest. There are scant data concerning the responses to interannual variability of natural systems that average climatic effects over different periods of time. Such systems include watersheds, active glaciers, ocean sediments, long-lived trees, and lakes. We have analyzed a long-term record of data from a small lake that reacts to variability in climate. We show that some parameters of this data are a function of climatic effects.

Castle Lake in Northern California (*3*) has been intensively studied during the last 25 years (*4*). Researchers have paid particular attention to details of the processes controlling the rate of photosynthesis of the phytoplankton community (that is, primary productivity) (*5*). Care has been taken to ensure consistent data collection, and, during the ice-free months (*6*), many limnological parameters (including physical, biological, and chemical quantities) are measured approximately every 5 days; measurements are taken less frequently during the winter (ice-covered) months.

Once the surface is free of ice, the lake quickly gains heat because of the balance between solar radiation, net infrared exchange, evaporation, and sensible heat transfer at the air-water boundary (*7*). Wind stress at the surface stirs the lake, mixing heat downward (*8*). The lake continues to gain thermal energy so long as the net flux of heat is positive (*9*). The maximum amount of heat stored (*10*) and the time it takes to reach this maximum varies from year to year. The reasons for interannual variation in maximum heat content may involve large-scale (regional or global) climatic effects. For example, a heavy snowfall can move the date of thaw to more than 1 month later in the spring. Local processes may also play a

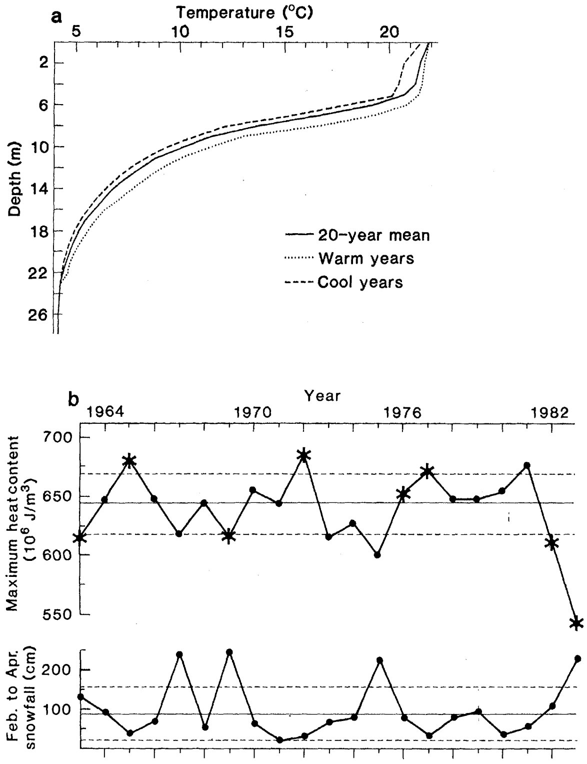

Fig. 1. (a) The profile of the mean August temperature, over 20 years versus depth. August is the time of the lake's maximum heat content. The dashed line and the dotted line show the mean August temperature plotted against the depth for the anomalously cool and warm years, respectively. (b) The maximum heat content of Castle Lake and the February to April snowfall there from 1963 to 1983. The solid horizontal lines indicate 20-year averages (1963 to 1982); the dashed horizontal lines indicate 1 standard deviation interval above and below the 20-year means. Years in which an El Niño and Southern Oscillation occurred (ENSO years), as identified in table 1 of (*14*), are shown by asterisks (*).

crucial role. For example, thermal energy mixed downward and stored at substantial depths may be unaffected for long periods by heat losses at the surface. We now report how large-scale climatic events acting in concert with local mechanisms can account for much of the interannual variability in this small lake.

Thermistor probes measured the temperature of the water at various depths below the surface (*11*). A typical midsummer profile (Fig. 1a) shows an isothermal mixed layer (the epilimnion) overlying a stratified thermocline where the temperature varies with depth. Temperatures were measured at 1/2-m intervals near the surface and in the thermocline and at 1-meter intervals at lower depths.

Figure 1b shows the maximum heat content of Castle Lake and the February to April snowfall there (*12*) for each year from 1963 to 1983. In Fig. 1a, the mean August temperature for 20 years (1963 to 1982) is plotted as a function of depth. August is the time of the lake's maximum heat content. Also depicted are profiles of mean August temperature against depth for the four anomalously warm years and the six anomalously cool years of this period (*13*). El Niño and the Southern Oscillation (*2*) affect the entire Pacific basin and are commonly invoked to account for both anomalous oceanic and continental weather conditions. In each El Niño year from 1963 to 1983 [except 1976 (*14*)] an anomalous maximum heat content was found. In addition, anomalous maximum heat contents occurred in 4 years in which El Niño was not active (*15*). In all years with anomalously large thermal storage (1965, 1972, 1977, and 1981) the snowfall was significantly lower than average. Except for 1973, in all years with anomalously small heat contents (1963, 1967, 1969, 1973, 1975, 1982, and 1983), the snowfall was significantly higher than average (*16*). Heavy snowfall between February and April is commonly associated with later thaws. The thaw dates for the 6 years with anomalously small heat contents and high snowfalls were an average 6 weeks later than those for the 4 years with large heat contents and low snowfalls. The extraordinary values of maximum heat content and precipitation associated with 1982 to 1983 support the belief that the El Niño that year was the most pronounced of the century (*2*). The data show that El Niño conditions produce both anomalously warm and anomalously cool conditions, supporting the cautions of Namias and Cayan (*17*) against simple interpretations of effects from the El Niño–Southern Oscillation phenomenon.

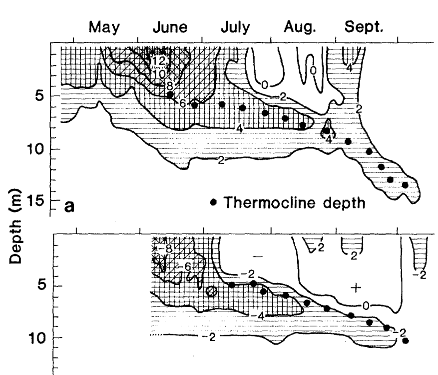

Fig. 2. (a) The average seasonal changes of the positive anomaly in maximum heat content for the four warm years in the period from 1963 to 1983. Contour units are 10^6 J/m^3. The thermocline depth equals the depth of the maximum temperature gradient. See Fig. 1a. (b) The average seasonal changes of the negative anomaly in maximum heat content for the six cool years in the period from 1963 to 1982, as in (a).

The distribution of thermal energy with depth illustrates how the lake stores significantly more heat during years with light snowfall and an early thaw and, conversely, less heat during years with heavy snowfall and a late thaw. In the years of significantly larger heat content (*13*), 83 percent of the additional thermal energy is found below the mixed layer, largely insulated from the effects of short-term surface heating and cooling (*18*). During the years of significantly smaller thermal storage, 55 percent of the cold anomaly is below the mixed layer. Figure 2 shows the seasonal changes and the depth distribution of the heat content for both the "warm" and "cold" years. The early thaw date of the warm years (Fig. 2a) allows more absorption of energy near the surface and subsequent mixing of energy downward during May and June. In cold years (Fig. 2b), the thaw is later; there is less absorption; and less heat is mixed downward, which results in anomalously low heat content below the mixed layer. By August, the time of maximum heat content, warm years differ from cold years largely below the mixed layer; only negligible differences occur near surface (*19*).

This small lake is an excellent indicator of climatic effects. Other small lakes with related vertical heat transfer and storage characteristics may be similar indicators. Weather variations on a day-to-day basis, or the effects of storms that last for days, are integrated by the lake into a longer term seasonal response. The year-to-year variation is evident in the maximum heat content, which is readily obtained from the available data. The lake's coupling to large-scale variations, such as the El Niño and the Southern Oscillation, is particularly apparent.

A number of questions remain to be answered, however. Why, for example, can El Niño conditions trigger both heavy and light snowfall, and thus small and large thermal storage, respectively?

What local and large-scale mechanisms, if any, account for the anomalous heat content during those years in which El Niño conditions do not occur?

Local mechanisms, especially the stratification and the vertical mixing of heat downward, below the mixed layer, play a crucial role in coupling Castle Lake to long-term interannual variation. For a small lake, local meteorological and topographic conditions might be expected to predominate; however, these local effects are most strong in surface waters, not below the mixed layer where the effects we report are observed (*19*). Our study also suggests that there are significant effects from El Niño and the Southern Oscillation in temperate latitudes away from oceanic and coastal areas where it has been best studied (*2*, *20*).

Important ecological processes in Castle Lake may also be controlled by the interaction of surface meteorological forcing and vertical mixing. Goldman and de Amezaga (*4*) suggest that annual primary productivity is a function of the amount of precipitation because nutrients and algae are washed out of the lake during years with high runoff. Moreover, in 1975, a year with a late thaw and low productivity, the lake did not mix completely (overturn) in spring (*4*) and thus did not fully renew the upper euphotic zone with nutrients. In contrast, Castle Lake mixed completely to the bottom in 1976, a year with an early thaw and high productivity. Finally, during 1983, when the lake stayed frozen until 6 July and the maximum heat content was 4 standard deviations below normal, the primary productivity during the summer was only 25 percent of normal. Other quantities that can be measured in terrestrial systems, some ecological in nature and thus related to precipitation or other meteorological parameters, show significant year-to-year variations. These may also have a strong link to large-scale phenomena, just as interannual variations in Castle Lake are linked to El Niño and the Southern Oscillation.

P. TED STRUB*
THOMAS POWELL†
CHARLES R. GOLDMAN
Division of Environmental Studies, University of California, Davis 95616

References and Notes

1. G. E. Hutchinson, *Bull. Amer. Mus. of Nat. Hist.* **96**, 65 (1950); R. A. Warrick, *Clim. Change* **6**, 5 (1984); J. S. Boyer, *Science* **218**, 443 (1982); M. H. Glantz and J. D. Thompson, Eds., *Resource Management and Environmental Uncertainty* (Wiley, New York, 1981).
2. S. G. H. Philander, *Nature (London)* **302**, 295 (1983); M. A. Cane, *Science* **222**, 1189 (1983); E. M. Rasmusson and J. M. Wallace, *ibid.*, p. 1195; R. T. Barber and F. P. Chavez, *ibid.*, p. 1203; J. M. Mitchell, Jr., *Weatherwise* **35**, 252 (1982); National Research Council, *Changing Climate* (National Academy of Sciences, Washington, D.C., 1983).
3. Castle Lake (41°N, 121°W), in the Klamath Mountains near Mount Shasta, is a small (area = 0.2 km^2, average width = 450 m), subalpine lake located in a regularly shaped, granite, cirque basin at an elevation of 1706 m. The average depth is 12 m (maximum depth = 35 m).
4. C. R. Goldman, *Science* **132**, 1016 (1960); in *Nutrients and Eutrophication*, G. E. Likens, Ed. (Special Symposium No. 1, American Society of Limnology and Oceanography, 1972), pp. 21–38; ______, E. A. Stull, E. de Amezaga, *Verh.-Int. Ver. Theor. Angew. Limnol.* **18**, 1760 (1973); ______ and E. de Amezaga, *ibid.*, in press; R. W. Bachmann and C. R. Goldman, *Limnol. Oceanogr.* **10**, 233 (1965); J. C. Priscu and C. R. Goldman, *Can. J. Fish. Aquat. Sci.* **40**, 208 (1983).
5. C. R. Goldman, in *Proceedings of the Conference on Primary Productivity Measurements, Marine and Freshwater*, M. S. Doty, Ed. (Division of Technology Information Report TID-7633, Atomic Energy Commission, Washington, D.C., 1963), pp. 103–113; *Amer. Zool.* **8**, 31 (1968); B. J. Peterson, *Ann. Rev. Ecol. Syst.* **11**, 359 (1980).
6. The lake is ice-covered in winter and spring and usually thaws in May.
7. G. E. Hutchinson, *A Treatise on Limnology* (Wiley, New York, 1957), vol. 1; A. A. Pivovarov, *Thermal Conditions in Freezing Lakes and Rivers* (Wiley, New York, 1973); R. A. Ragotzkie, in *Lakes—Chemistry, Geology, Physics*, A. Lerman, Ed. (Springer Verlag, New York, 1978), pp. 1–19.
8. J. Imberger and J. C. Patterson, in *Transport Models for Inland and Coastal Waters*, H. B. Fischer, Ed. (Academic, New York, 1983), p. 310; J. Imberger and P. Hamblin, *Ann. Rev. Fluid Mech.* **14**, 153 (1982).
9. The dominant causes of a net heat flux can vary over short periods of time; for example, one cause could be turbulence. We average these contributions. Commonly, a lake gains heat during the day and loses it at night; but a net gain or loss may be seen over several diurnal cycles, the time scale on which we focus.
10. The amount of thermal energy stored in the lake during the period from the date of minimum heat content (that is, the date of minimum average temperature, taken to be 4°C) to the date of maximum average temperature, usually in August. This is commonly called the Birgean heat budget. G. E. Hutchinson, *A Treatise on Limnology* (Wiley, New York, 1957), vol. 1, p. 492.
11. The probes are kept in calibration to ±0.1°C.
12. Snowfall data for Mount Shasta City, approximately 10 km from Castle Lake, were obtained from the National Climatic Data Center, Asheville, N.C. 28801.
13. Anomalous is defined as greater than 1 standard deviation above or below the 20-year mean. The year 1982 to 1983 is excluded because of its extreme values of snowfall and heat content (*2*). Experimental errors associated with the measurement of temperature lead to an error in estimation of the maximum heat content that is at most 10 percent of the year-to-year variation and thus negligible.
14. W. H. Quinn, D. O. Zopf, K. S. Short, R. T. W. K. Yang, *Fish. Bull.* **76**, 663 (1978).
15. The Siegel-Tukey test was applied to the data of Fig. 1b. The spread (or scale) of the distribution of the maximum heat contents for ENSO years is significantly greater ($P \approx 0.99$) than the spread of the distribution of maximum heat contents for non-ENSO years. Statistically, El Niño years are very likely to have anomalous maximum heat contents. See J. D. Gibbons, *Nonparametric Methods for Quantitative Analysis* (Holt, Rinehart & Winston, New York, 1976).
16. In 1973, an average snowfall year, winds in the late spring and early summer months were anomalously low and did not mix downward heat that had been absorbed in the mixed layer at the surface.
17. J. Namias and D. R. Cayan, *Oceanus (Woods Hole)* **27**, 41 (1984).
18. In the stratified thermocline, buoyancy forces attenuate the effects of vertical shearing motions by restoring fluid parcels to their initial positions in the water column, insulating the stratified depth interval and depths below from surface effects (*7*, *8*).
19. Remote sensing by satellite of year-to-year variations in surface temperature alone would have been insensitive to this effect. Figure 1a shows the difference in surface temperature between the warm years and the cool years to be less than 0.5°C—the present limit of resolution of the best satellite temperature sensors. R. L. Bernstein, *J. Geophys. Res.* **87**, 9455 (1982).
20. P. K. Dayton and M. Tegner, *Science* **224**, 283 (1984).
21. We thank C. N. K. Mooers and D. Peterson for the invitation to discuss this work at a joint National Oceanic and Atmospheric Administration and U.S. Geological Service Workshop on Climate Variability of the Eastern North Pacific and Western North America; R. Axler, L. Botsford, T. Dillon, J. Reuter, P. Richerson, and J. Zehr for their critical comments on the manuscript; and the National Science Foundation (grant NSF-BSR 84-09448) and the National Aeronautics and Space Administration (grant NAG5-217) for their support.
* Present address: College of Oceanography, Oregon State University, Corvallis 97331.
† To whom requests for reprints should be sent.

10 September 1984; accepted 25 October 1984

Deepest Known Plant Life Discovered on an Uncharted Seamount

Abstract. *The discovery of abundant autotrophic macrophytes living below 200 meters indicates their importance to primary productivity, food webs, sedimentary processes, and as reef builders in clear oceanic waters. Estimates concerning minimum light levels for macroalgal photosynthesis and macrophytic contributions to the biology and geology of tropical insular and continental borderlands must now be revised.*

A record depth (268 m) for living marine macrophytes was directly determined during a survey of the flora of San Salvadore Island, Bahamas, with the use of the Harbor Branch Foundation's submersible Johnson-Sea-Link I (JSLI). It had been thought (*1*) that plant life could not develop below about 200 m because of low light intensity.

Until recently, scientists had available for study only fragmentary samples of deep-sea plant life collected by dredgings taken with hooks, nets, buckets, chains, chisels with hemp tangles, or trawls. Because of problems in accurately determining the sampling site and whether specimens were attached or broken free and carried to depth secondarily, results obtained from these remote methods are inherently imprecise.

The deepest recorded frondose seaweeds were dredged below 100 m off Florida (*2*) and 200 m near Hawaii (*3*). A chisel-edged drill containing hemp tan-