through a gas-to-particle conversion of sulfur dioxide to form nonabsorbing sulfate particles (*13*).

For this study, data from four days (9 July and 19 November 1981, 3 April 1985, and 13 February 1986) were found to have ship tracks. Of the tracks found on these days, 15 independent tracks were found in which the ship contamination was contained wholly within a large-scale stratiform cloud layer and the population of cloud properties for contaminated and noncontaminated fields of view were nearly identical, as indicated by their distributions of 11-μm radiances. For this sample of tracks the increase in percent reflectivity at 3.7 μm was 3.9 ± 0.4 (SEM) and at 0.63 μm was 1.6 ± 0.7; the change in 11-μm radiance was 0.0 ± 0.05 mW m^{-2} sr^{-1} cm. The reflectivities were calculated as though the clouds were isotropic reflectors and the change in emission at 3.7 μm, which is expected to accompany the change in reflectivity, was ignored. The change in 3.7-μm reflectivity was underestimated by at most 10% by neglecting the accompanying change in emission.

The above changes are influenced by the fractional cloud cover found in the observations. To a first approximation, taking the ratio of the changes in reflectivity removes the effect of fractional coverage. The ratio of the change in 0.63-μm reflectivity to that at 3.7 μm for the 15 cases is 0.4 ± 0.8 (SD). Radiative-transfer calculations performed for several cloud models, in which the shift in droplet size compensates for a shift in droplet number so that the liquid water content is constant and no absorption is added, yielded ratios that ranged from 0.6 to 2.6 depending on droplet size and liquid water content. The observed changes thus seem to fall below the values expected on the basis of simple theoretical calculations. The shortfall might be due to extra absorption in the contaminated clouds, a decrease in the amount of liquid water for these clouds, or a change in cloud geometry so that the contaminated clouds have more surface texture.

The satellite observations reported here support the thesis that an increase in man-made aerosols will lead to an increase in cloud albedo. This finding differs from that previously reported for clouds over industrial centers of the Soviet Union where the polluted clouds had lower albedos (*14*). The differences may be due to much higher concentrations of absorbing particulates in the Soviet study.

Satellite observations may not elucidate the mechanisms by which aerosols affect droplet size, concentration, and absorptivity; nevertheless, they offer the opportunity for obtaining practical estimates for the net changes in cloud reflectivity. Because the effect of aerosols on cloud reflectivity appears to have a much greater influence on the earth's radiation budget than that due to the direct interaction of aerosols with solar radiation, and since the effect on cloud reflectivity may lead to changes in the earth's radiation budget that are comparable to those caused by the increased concentration of trace gases, the effect should be considered in assessments of potential climate change. This study has focused on changes in the maritime environment. Because continental environments have significantly higher concentrations of cloud-condensation nuclei and lower relative humidities, a similar study should be undertaken to determine the effects of stack effluents from industrial centers on continental stratiform clouds.

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Seasonal Mixing and Catastrophic Degassing in Tropical Lakes, Cameroon, West Africa

GEORGE W. KLING

Lethal gas releases from Lakes Nyos and Monoun in Cameroon seem to be more lacustrine than volcanic in origin. Both of these events occurred in August and were only 2 years apart. Data show that the period of deepest mixing and lake turnover also occurs during late summer in this region of tropical Africa. In addition, recent trends of decreases in both air temperatures and effective insolation relative to long-term means suggest that weakening of stratification, coupled with a predictable seasonal interval of reduced stability in August, may be responsible for the timing of these events.

ON 21 AUGUST 1986 A MASSIVE release of CO$_2$ from Lake Nyos claimed 1700 lives in northwest Cameroon (*1*). According to one theory (*1*), CO$_2$-rich gas of magmatic origin rising through the diatreme beneath the lake contacted local ground water. In turn, this ground water became the vehicle for gas transport into the lake's hypolimnion. Stable stratification prevented mixing of bottom water with surface water and allowed gas accumulation well in excess of atmospheric saturation. Some unknown disturbance of this unstable system culminated in the gas release. A similar model has been put forth to explain the 15 August 1984 gas release at Lake Monoun, 95 km southeast of Lake Nyos (*2*). What is most intriguing about this phenomenon of lethal gas release from lakes is that both events occurred in August, just 2 years apart. The timing and limnologi-

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cal nature of these events suggest that chance alone is not responsible and that predictable seasonal mixing in these lakes may coincide with the release of gas (*3*). Several studies on tropical lakes in East Africa and on isolated lakes in Southeast Asia and South America suggest a consistent pattern of deep mixing during the winter (*4–6*). Forcing this mixing are decreases in air temperatures and solar heat input and often an alteration of wind regime (*4–9*). Little is known, however, about mixing and stratification in West African lakes (*7, 10, 11*). In this report I present data on the thermal regime of Barombi Mbo, the largest crater lake in Cameroon. The relation of stratification, mixing, heat flux, and stability to the annual cycle of regional climate provides an initial, critical test of the idea that reductions in water column stability caused by seasonal mixing were in part responsible for the gas releases at Lakes Nyos and Monoun.

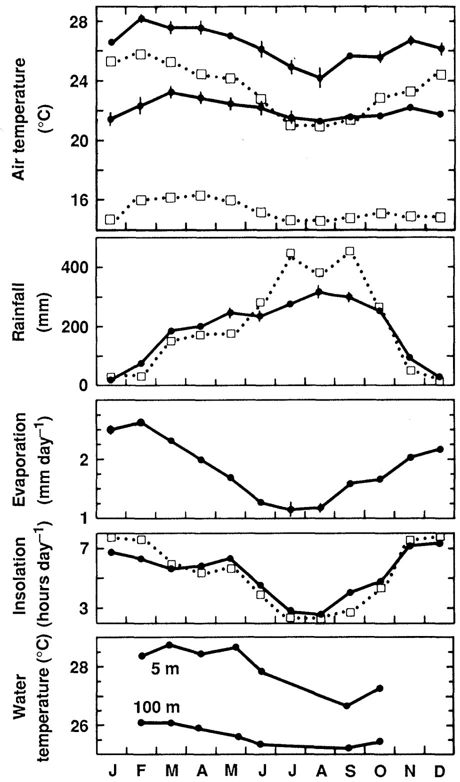

Fig. 1. Weather data from the Barombi-Kang meteorological station 5 km south of Barombi Mbo (solid lines), and from the Bamenda meteorological station ~50 km south of Lake Nyos (dotted lines). For air temperature, the maximum and minimum values are shown by the upper and lower curves, respectively, of the sets of solid and dotted lines. For Barombi-Kang, rainfall is in mean monthly totals from 1968 to 1985 (n = 18); air temperature (n = 4), evaporation (n = 8), and insolation (n = 6) are monthly means of daily values. For Bamenda, rainfall (n = 54), air temperature (n = 24), and insolation (n = 24) are measured similarly. Bars represent standard errors of the mean; n = number of years.

Barombi Mbo lies 200 km south of Lake Nyos at an elevation of 301 m above sea level [4.40°N, 9.24°E; area, 415 ha; maximum depth, 110 m; and mean depth, 68.7 m (*12*)]. Two high-pressure air masses influence the seasonal variation in climate around Barombi Mbo (*13*) (Fig. 1). The first is the unstable and humid monsoon, or southeast trade wind, which moves northward across Cameroon beginning in March or April. During this time, clouds are light and scattered, and precipitation typically occurs for 1- or 2-hour periods. Beginning in June the clouds become thicker and precipitation increases. Low, heavy cloud cover and maximum monthly precipitation occur in August and September. Effective solar heat input is also drastically reduced during this monsoon period. Air temperatures and evaporation decrease steadily after April until annual minimums are reached in August. In October the Intertropical Front is pushed south by the second major air mass, the dry harmattan or northeast trade wind, which flows into Cameroon across the Sahara Desert. The period from November through February is thus the driest time of year.

Lake water temperatures at 5 and 100 m followed the seasonal trend of maximum and minimum air temperatures (Fig. 1). Early morning surface water temperatures reached a maximum of 28.85°C during February. There was a progression from strong stratification in February to a weakened thermal structure and minimal temperatures in September (*14*), followed by a return to higher temperatures in October (Fig. 2). The lake accumulated heat from February to March at the rate of 40 cal cm^{-2} day^{-1} (Fig. 3). Heat loss began in mid-March and continued at a rate of 27 cal cm^{-2} day^{-1} until mid-May. After this point, heat loss rates accelerated until the time of minimal heat content in September. The lake then began to warm rapidly, and the highest rate of heat gain was observed between the September and October samplings [75 cal cm^{-2} day^{-1} (*15*)]. This seasonal pattern of stratification appears to be consistent from year to year (*16*).

Lake stability is controlled by the amount of energy available to overcome buoyancy forces maintaining stratification and to mix the lake to a uniform density (*17*). In many Cameroon crater lakes, shelter from the wind and great depth help create stable stratification (*18*). Total water column stability in Barombi Mbo ranged from 2750 to 5780 J m^{-2} (Fig. 3). Stability values paralleled the seasonal variation in heat content, except for a period in May when stability was greatest even though the lake had been losing heat steadily for 2 months. Few data exist for comparison, but maximum stability usually precedes or is concurrent with maximum heat content in both tropical and temperate lakes (*4, 5, 8*). A decline of hypolimnetic temperature while surface temperature increased slightly was responsible for the maximum stability in Barombi Mbo, although the exact mechanism of heat distribution is unclear. If extensive nocturnal cooling of surface water produced convective currents that penetrated the hypolimnion, one would also expect to find a considerable disruption of metalimnetic structure. Instead the thermocline actually sharpened as the bottom water cooled (*12*). Preservation of thermocline integrity may be possible during nearshore shallow water cooling and subsequent flow of denser water down

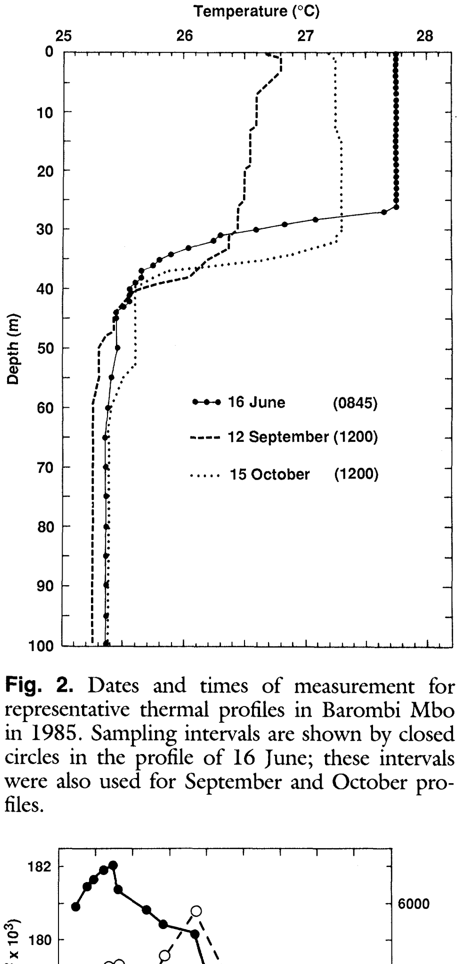

Fig. 2. Dates and times of measurement for representative thermal profiles in Barombi Mbo in 1985. Sampling intervals are shown by closed circles in the profile of 16 June; these intervals were also used for September and October profiles.

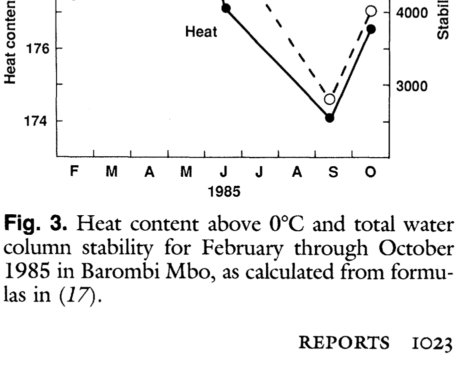

Fig. 3. Heat content above 0°C and total water column stability for February through October 1985 in Barombi Mbo, as calculated from formulas in (*17*).

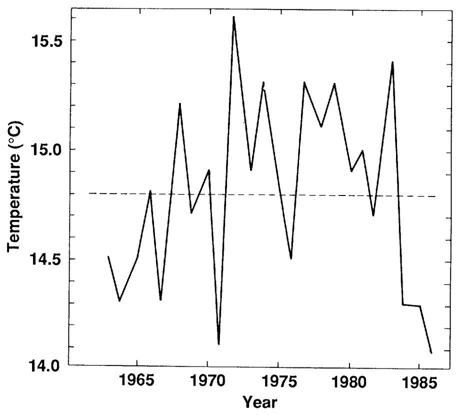

Fig. 4. Mean minimum air temperatures for August from daily values (1963 to 1986); dotted line, overall mean minimum temperature. Data are from the Bamenda station (Fig. 1).

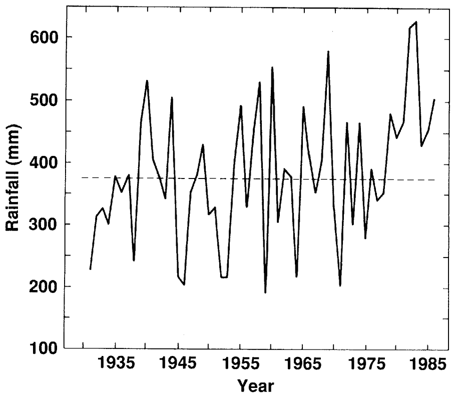

Fig. 5. Total precipitation for August (1931 to 1986); dotted line, mean rainfall. Data are from the Bamenda station (Fig. 1).

the sides of the basin (*19*). However, there is very little shallow water in Barombi Mbo (*20*). Because average air temperatures are 2°C lower than bottom water temperatures during May, input of cooler water from the catchment to the hypolimnion may explain part of the observed stability increase. In the spring of 1985 about one-half the volume of water in Barombi Mbo was below the metalimnion. Given the abnormally high precipitation during May of 1985 (489 mm versus the May average of 250 mm for 18 years) (Fig. 1), the volume of cooler water brought into the lake by inflow streams could account for ~50% of the measured change in hypolimnetic heat content (*21*).

Minimum stability in Barombi Mbo was concurrent with minimum heat content in September (Fig. 3). The seasonal cycle of climate forcing this pattern is consistent over time and appears to extend at least to 7°N, encompassing Lakes Nyos and Monoun (Fig. 1). Data on mixing regimes from other tropical West African lakes are scarce, but the information available confirms deep mixing in late summer and fall (*11*). Further work is needed to determine if turnover in August or September is a widespread phenomenon in tropical lakes north of the equator, and how far north the pattern reaches. North temperate lakes typically mix during fall and spring, and north tropical lakes mix during winter (*4, 5, 8*). Although the seasonal cycles for lakes within a few degrees of the equator may depart from the norm as determined for lakes at higher latitudes, minimum stability during August and September in the Cameroon lakes is contrary to that expected for a Northern Hemisphere lake.

Rapid influx of gas into Lakes Nyos and Monoun may have occurred just before the 1986 and 1984 events. However, it appears that gas concentrations had been slowly building for many years (*1, 2*), and geomorphological evidence suggests that similar events occurred in past millennia (*22*). Perhaps recent, atypical trends in climate led to reduced water column stability and a greater potential for gas release. Decreases in temperatures and solar heat input are necessary but perhaps not sufficient conditions for this proposed model of lake mixing and gas release. During the last several years minimum August air temperatures around Lake Nyos were significantly below the long-term average (Fig. 4). This is consistent with a hypothesis of degassing during short-term climatic cooling; however, a similar interval of low temperatures occurred in the early 1970s without any known gas release. Obviously, air temperature is not a singular predictor of mixing and degassing. Deep seasonal mixing also correlates with reductions in insolation caused by greater precipitation and cloudiness. August rainfall data for northwest Cameroon since 1931 indicate distinctly wetter summers in recent years (Fig. 5) (*23*). Thus the annual cycle of climate as well as the long-term climatic trends are consistent with the hypothesis that normal, seasonal changes in stratification and mixing are significant factors determining the timing and occurrence of catastrophic gas release. In lakes charged with CO_2, measurements of density structure, especially during the late summer mixing period, are necessary to establish the potential of future, similar events.

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14. Even at the time of lowest lake water temperatures in September, the water column showed distinct thermal structure. The thermocline had moved down to 38.5 m from a mean depth of 29 m in February through April (*12*), but the water column was still quite stable. The minimum value of stability in Barombi Mbo was greater than maximum values found in some tropical lakes (*4, 8*). Oxygen and conductivity profiles suggest that the lake did not mix completely during the summer months. Surface water conductivity at 20°C (K_{20}) (45 to 50 µS) and hypolimnetic K_{20} (80 to 100 µS) were maintained during the study period. In addition, the hypolimnion was anoxic below 40 m in September.
15. Short-term heat fluxes were on the order of 250 to 400 cal cm^{-2} day^{-1}. These rates of cooling and heating are typical for tropical lakes, but lower than typical rates for temperate lakes (*4, 8*).
16. For example, on 14 September 1986 a weak thermocline existed at a depth of 48 m, and the lake was oxygenated down to 55 m, whereas on 27 May 1987 the lake had a strong thermocline at 19 m and was anoxic below 26 m.
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18. Fifteen of 17 Cameroon lakes surveyed in 1985 (*12*) showed some degree of stratification, and ten had distinct thermoclines and well-developed hypolimnia. Values of water column stability were similar to or greater than those of other tropical and temperate lakes. A deeper lake requires more energy input for complete mixing because of the increased mass of water below the thermocline (*17*).
19. This phenomenon apparently explains the stratification of Lake Mobutu (Lake Albert) [J. F. Talling, *Limnol. Oceanogr.* **8**, 68 (1963)]. Also, Lewis (*4*) reported cool underflow currents (unspecified origin) in tropical Lake Lanao, in the Philippines.
20. At a distance of 200 m from shore the water is already 50 to 80 m deep.
21. Inlet stream temperature at 0800 on 21 May 1985 was 24°C. Ground-water flow and convective currents might augment cooling.
22. Discontinuous exposure of pyroclastic surge material around Lake Nyos suggests erosion by previous gas releases (*1*), and investigations in Cameroon may reveal past, unrecorded events.
23. Positive sea surface temperature anomalies are strongly related to decreased rainfall in the Sahel since the early 1970s [C. K. Folland, T. N. Palmer, D. E. Parker, *Nature (London)* **320**, 602 (1986)], which may relate to higher rainfall at lower latitudes during the same period (*3*).
24. I thank the Cameroon Ministry of Higher Education and Scientific Research and the French Office of Overseas Scientific and Technical Research (ORSTOM) for their cooperation in this research, especially the Cameroon Ministry of Transport for allowing access to their raw climatic data. Supported by the Office of U.S. Foreign Disaster Assistance of the Agency for International Development, ORSTOM, Centre National de la Recherche Scientifique, and NSF grants 83-04488, 84-005322, and 85-16925. G. Greer, J. C. Stager, and N. Paul provided field assistance, and W. H. Schlesinger provided helpful comments on the manuscript.

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