Reports

Effects of Climatic Warming on Lakes of the Central Boreal Forest

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Twenty years of climatic, hydrologic, and ecological records for the Experimental Lakes Area of northwestern Ontario show that air and lake temperatures have increased by 2°C and the length of the ice-free season has increased by 3 weeks. Higher than normal evaporation and lower than average precipitation have decreased rates of water renewal in lakes. Concentrations of most chemicals have increased in both lakes and streams because of decreased water renewal and forest fires in the catchments. In Lake 239, populations and diversity of phytoplankton also increased, but primary production showed no consistent trend. Increased wind velocities, increased transparency, and increased exposure to wind of lakes in burned catchments caused thermoclines to deepen. As a result, summer habitats for cold stenothermic organisms like lake trout and opposum shrimp decreased. Our observations may provide a preview of the effects of increased greenhouse warming on boreal lakes.

Recent climate models predict increases in air temperatures and decreases in soil moisture throughout much of North America in the next several decades as the result of increased greenhouse warming. In North America, some models predict that greatest effects in summer will occur at about 48° to 52°N and 90° to 100°W, where summer temperature increases of up to 9°C and soil moisture decreases of greater than 50% are predicted (*1*). If these forecasts are correct, the boreal ecosystems of northwestern Ontario should be severely affected, because the area is already quite warm and arid (*2*) and has thin, sandy soils with small water storage capacities. During periods with lower than normal precipitation, forest fires are common, because the small moisture reserves in soils are depleted rapidly when dry periods exceed a few weeks in duration (*3*).

Beginning in 1969 to 1971, we have collected continuous records of weather, hydrology, the chemistry of lakes and their inflow and outflow streams, and biology of lakes at the Experimental Lakes Area (ELA), northwestern Ontario, near the area of predicted maximum summer greenhouse effect (*4*). Consistent sampling and analytical methods were used throughout (*5*). The period of record has been one of almost continuous warming and increasing incidence of intermittent drought. The increases in temperature that we have observed in the past 20 years are comparable to the maximum changes expected due to increased greenhouse warming for many areas. Whether or not the observed warming is due to increasing greenhouse effect, our observations on a variety of ecological processes provide a preview of how climatic change may affect boreal lakes and catchments in the next century. In this report, we present results for Lake 239, which has been used as a reference basin for many of the long-term experiments at ELA. The lake is typical of many small boreal lakes on the Precambrian Shield (*6–8*).

During our period of record, the mean annual air temperature at the ELA site has increased by about 2°C, from 1° to 2°C in the late 1960s and early 1970s to 3° to 5°C by the mid-1980s [(*9*) Fig. 1A]. This warming has caused corresponding increases in the mean and maximum water temperatures of lakes in the area, in the heat content of the lakes during the ice-free season, and in the duration of the period that lakes are ice-free [(*10*) Fig. 1, B and C].

The incidence of years with precipitation below the long-term average has increased since the mid-1970s (Fig. 1D). The higher-than-normal air and water temperatures have also caused evapotranspiration to increase (*9*). As a result, the volume of runoff from terrestrial basins has decreased during the period of record, and the rates of water renewal for lakes in the area decreased dramatically [(*11*) Fig. 1E].

The observed decreases in water renewal would be expected to concentrate chemical solutes in the lakes (*12*). This has happened for both total dissolved N and more conservative ions (Fig. 1, F and G). For P, a gradual increase from 1972 to 1985 was followed by a dramatic decline, with values remaining low from 1986 to 1988. Overall, the trend for P was not statistically significant, but the combined opposite trends in N and P led to a near doubling of the ratio of total N to total P from values of about 25:1 by weight to approximately 50:1. The concentrations of relatively conservative ions exceeded those predicted by models based solely on water renewal, because of increased input of these ions from streams draining burned forested watersheds and wetlands with low water tables (*14*). Thus, a combination of decreased water flows and increased incidence of forest fires should cause increased chemical concentrations and P limitation in lakes and streams of the boreal zone.

The decreased water flows and denudation of large areas by fire have also affected the physical properties of lakes. Lakes have become clearer, because of lower imports of dissolved, colored organic matter and longer residence times (*15, 16*). The resulting increase in penetration of solar energy (Fig. 1H) plus the increased wind velocity (Fig. 1I) resulting from the disappearance of forest cover caused the thermoclines of lakes to deepen [(*17*) Fig. 1J].

The average duration of the ice-free season increased by about 20 days for lakes in the area (Fig. 1C); this trend primarily reflects earlier ice-out dates in the spring. No significant changes were observed in the date of freezeup in the autumn. The strong effect in spring is probably the result of two factors. First, increases in air temperature were most pronounced in the months of April and May (*18*). Second, below-average snow covers and warm temperatures in March caused snow to disappear from lake surfaces earlier in the later years of the record (Fig. 1L); as a result, the amount of solar radiation absorbed by the lake in spring has increased (*19*).

Increases in the standing crop of phytoplankton accompanied increases in temperature and nutrient concentration (*20*) Fig. 1K). The diversity of the phytoplankton community also increased slightly, but there were no major changes in dominant species. Phytoplankton abundance correlated well with average temperature, although abun-

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dance is also likely to have been influenced by increases in nutrients and water clarity (*21*). On the other hand, the lack of a clear effect of the warming on phytoplankton production indicates that the phytoplankton response is complex (*22*). Among the attached algae that occupy the littoral zone of lakes, warmer temperatures appear to have favored filamentous green algae of the order Zygnematales, similar to those observed in the early stages of lake acidification. Maximum rates of photosynthesis in epilithic algae are also increased by higher lake temperature (*23*).

The increased water temperature that we observed would be sufficient to extirpate some temperature-intolerant species from some boreal lakes. A number of cold stenothermic glacial relicts (*24*) are unable to survive in lakes that are too shallow to have cold, well-oxygenated hypolimnions. At present, these limitations confine some species to subarctic locations in unstratified lakes, although they occur much farther south in thermally stratified systems where cold, oxygen-rich hypolimnions offer midsummer refugia (*26*). Climatic warming would certainly shift northward the southern boundary for the occurrence of these species in unstratified lakes. It would also extirpate them from small lakes where deepening of the thermocline would destroy cold, oxygen-rich hypolimnions. Even though the extirpated fauna might be replaced by warm-water assemblages, it is by no means certain that fisheries of comparable value or ecosystems of comparable diversity would be reestablished quickly.

Although the ratios of N to P concentrations both before and after our period of observations were within the range where cyanophytes would not be favored, if similar increases occurred in lakes that had lower N:P ratios, a decreasing relative abundance of cyanophytes might be expected, because they are favored by low N:P ratios (*13*).

The effects of climatic change on freshwaters have been largely disregarded in major global change programs. Obviously, they must be included, because freshwaters are already scarce in many regions of the world, and they are a key element in the maintenance of nonmarine organisms, including man. The disappearance or warming and increased chemical concentrations of boreal freshwaters could cause the extirpation of cold water species assemblages that include

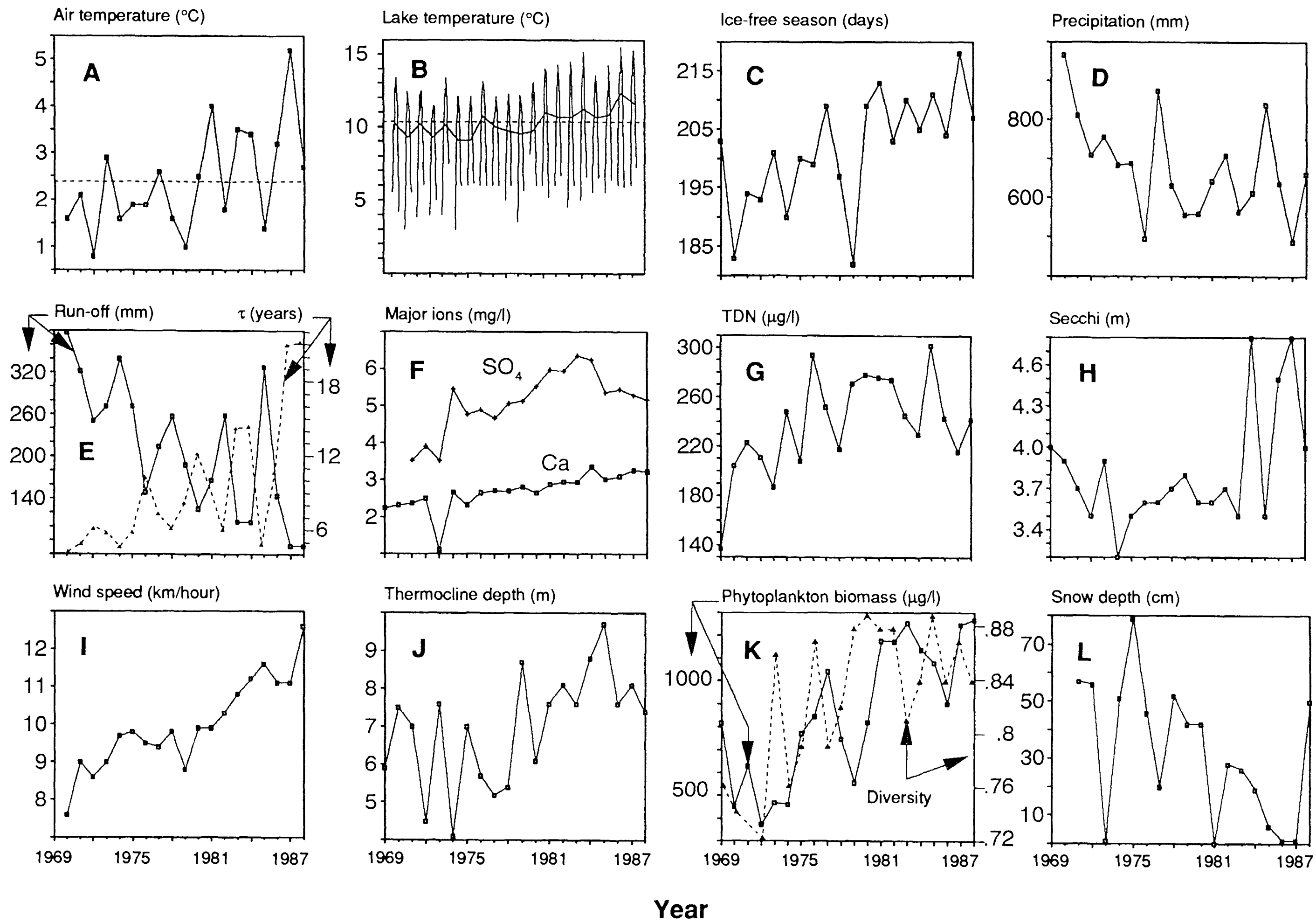

Fig. 1. Records of physical, chemical, and biological variables at the Experimental Lakes Area, northwestern Ontario, from 1969 or 1971 through 1988. (**A**) Mean annual air temperature at Rawson Lake meteorological station in the watershed of Lake 239. (**B**) Volume-corrected average lake temperature of Lake 239 during the ice-free period. Each of the spikes is a plot of monthly water temperatures in the ice-free season for a single year. The jagged line connects means of temperatures from the ice-free season. The horizontal dashed line is the mean temperature for ice-free seasons for the entire period. (**C**) Duration of the ice-free period for Lake 239. (**D**) Annual precipitation at the Rawson Lake station. (**E**) Annual runoff from the Lake 239 watershed (solid line) and water renewal time for the lake (τ, the dashed line). (**F**) Mean annual volume-weighted concentrations of Ca and sulfate in Lake 239. Similar increases were observed in Mg, K, Na, and Cl. (**G**) Mean annual volume-weighted concentration of total dissolved N (TDN) (**H**) Average secci disc readings in the ice-free season. (**I**) Average wind speed in the ice-free season measured 10 m above ground at Rawson Lake meteorological station. (**J**) Average thermocline depth in the ice-free season. (**K**) Average phytoplankton biomass in the epilimnion in the ice-free season (solid line) and Simpson's index of diversity (dashed line). (**L**) Snow depth at the end of March in the Lake 239 watershed.

some of the world's most valuable fisheries (27, 28).

REFERENCES AND NOTES

1. S. Manabe and R. T. Wetherald, *Science* **232**, 626 (1986); Environment Canada, *CO²/Climate Rep. 86-3* (1986).
2. Mean June to August air temperatures averaged 17.8°C between 1969 and 1988. Precipitation during these months averaged 266.1 mm., which is slightly less than the average evaporation of 300 mm.
3. During the dry years of the late 1970s and 1980s, much greater areas of northwestern Ontario and northern Manitoba have burned than at any time since records began. For example, in northern Manitoba, a total of 3.55×10^5 ha burned between 1950 and 1978, whereas over 6.4×10^6 burned in 1989 alone. This is over six times the size of the area burned in the Yellowstone fire of 1988. Large fires in northwestern Ontario caused the area burned from 1970 to 1978 to exceed that for any earlier decade [R. J. Barney and R. J. Stocks, in *The Role of Fire in Northern Circumpolar Ecosystems*, R. W. Wein and D. A. MacLean, Eds. (Wiley, New York, 1983), chap. 8]. Between the 1920s, when fire records began, until the 1950s, the average number of hectares of Canadian forest burned per decade decreased by about one-third, largely because of improved fire suppression methods. However, the average area burned increased continuously from the 1950s through the 1980s. In the 1980s, when the six warmest years on record occurred, about 26 million hectares burned. Even greater fires occurred in the boreal forests of Asia in the 1980s. A general summary is given by J. Schmidt and B. Milne [*Equinox* **8**, no. 6 (1989)]. M. Heinselman [*Quat. Res.* **3**, 329 (1973)] estimated from tree ring analyses that the average frequency of fires in the Boundary Waters, 200 km south of ELA, was 100 years during the past few centuries and that slightly higher frequencies occurred during the settlement period of the late 19th century. Much lower frequencies occurred after the development of modern fire suppression techniques but before the recent periods of drought and heat. At the time, Heinselman and others feared that fire suppression might be so efficient as to extirpate many key boreal species, which depend on fire for reestablishment. This fear appears to be groundless if current climatic trends continue, for even the best fire suppression methods are almost useless against large fires under conditions of high temperature and low humidity. Estimates of average fire frequency during the past few thousand years, as determined by counting layers of charcoal and burned plant fragments in dated lake sediments, are similar to those in the centuries just before settlement. However, in the postglacial sediment record, there is evidence of several periods when fires were much more frequent, perhaps as frequent as at the present [A. M. Swain, *Quat. Res.* **3**, 388 (1973)].
4. A description of the Experimental Lakes Area (ELA) is given by W. E. Johnson and J. R. Vallentyne [*J. Fish. Res. Board Can.* **28**, 123 (1971), and other papers in the same issue]. A review of studies in the area is given by D. W. Schindler [*Verh. Int. Ver. Theor. Agnew Limnol.* **23**, 11 (1988)].
5. Throughout the period, consistent methods were used for measuring air and water temperature, precipitation, hydrology, chemistry, and phytoplankton biomass and diversity. Changes in methods for phytoplankton production were introduced only following extensive periods of intercalibration, and E. J. Fee, J. A. Shearer, and E. DeBruyn performed all measurements and data analyses. Meteorological data for the Rawson Lake Station are part of the official records of the Canadian Atmospheric Environment Service. These and hydrological records have been compiled by K. G. Beaty since the program's inception. Some historical trends are given in K. G. Beaty and M. E. Lyng, *Can. Data Rep. Fish. Aquat. Sci. 759* (1989). M. P. Stainton has supervised analysis of water chemistry throughout the period of records. Changes in methodology have been slight during the period, and intercalibrations have been thorough. See M. P. Stainton, M. J. Capel, F. A. J. Armstrong, "The chemical analysis of fresh water" (*Misc. Spec. Publ. 25*, Fisheries and Marine Service, Canadian Department of the Environment, Ottawa, 1974). Phytoplankton taxonomy and biomass were analyzed by H. Kling until 1971 and D. Findlay after that time. D. W. Schindler supervised and integrated the program throughout the period of record reported here. A complete list of publications and reports from the project can be obtained from the Freshwater Institute.
6. Lake 239 has an area of 54.28 ha, a terrestrial drainage area of 336 ha, a mean depth of 10.9 m, and a maximum depth of 30.4 m. Its chemical and biological characteristics are typical for small lakes of the area [F. A. J. Armstrong and D. W. Schindler, *J. Fish. Res. Board Can.* **28**, 171 (1971); D. W. Schindler, *ibid.*, p. 295 (*7, 8*)]. The forests of the area before burning were pristine mature stands of jackpine (*Pinus banksiana*), black spruce (*Picea mariana*), and a mixture of trembling aspen (*Populus tremuloides*), white birch (*Betula papyrifera*), and other boreal typical species. More detailed information on the watershed is in G. J. Brunskill and D. W. Schindler, *ibid.*, p. 139. The weather station for ELA is also within the Lake 239 watershed. Although the duration of our record is not long enough to provide a basis for development of robust climatic models, it provides some indication of the types of trends that are likely to occur as the result of climatic warming.
7. D. W. Schindler, *ibid.*, p. 157.
8. ______ and S. K. Holmgren, *ibid.*, p. 189.
9. The longer (50-year) weather records (Canadian Atmospheric Environment Service) at Kenora, Ontario, also show the warming trend, which is unequaled during the period of record. Still longer records (120 years) for Winnipeg, Manitoba, 300 km to the west, also show the recent trends, plus a similar rapid warming in the late 19th century. Overall, Winnipeg air temperatures in the 1980s were about 3°C warmer than in the last two decades of the 19th century.
10. Annual average water temperatures in Lake 239 increased by an average of 0.108°C per year from 1969 to 1988. The corresponding increase in air temperature was 0.107°C per year. The number of degree days above 0°C also increased by an average of 18.8 ± 4.9 per year. Similar temperature increases were recorded in Lake 240, which also had its catchment burned. Temperature records for eight or more years in three lakes without burned watersheds, Lakes 223, 224, and 382 also show increases. Temperature profiles in all lakes were measured at weekly to monthly intervals with a portable thermistor calibrated against a standard thermometer. The SD for replicate measurements at one depth is <0.1°C, except in the thermocline, where internal seiches and minor changes in depth may result in an SD of up to 0.5°C. Temperatures were measured over the deepest point in each lake, at intervals of 1 m, except for the region of the thermocline, where 0.25 m depth intervals were used [D. R. Cruikshank, *Can. Data Rep. Fish. Aquat. Sci. 452* (1984); *ibid., 534* (1985); *ibid., 604* (1986); *ibid., 648* (1987); *ibid., 696* (1988)]. Increased duration of the ice-free season has also been recorded for lakes in Finland, where the most pronounced rates of change were observed early in the century [E. Kuusisto, *Aqua Fennica* **17**, 123 (1987)].
11. If chemical inputs are unchanged, a halving of the water renewal rate (doubling the water renewal time) would double concentrations of conservative chemicals in the lakes, once new steady-state conditions are reached. In general, 95% of new steady-state conditions will be reached in about three water renewal times. Water renewal times for the lakes studied ranged from less than 1 to greater than 20 years from 1970 to 1987. For Lake 239, water renewal times averaged 4.6 years for 1970 to 1975, but increased to over 20 years in 1987 and 1988.
12. The known dependence of chemical concentrations on water renewal is reflected in a number of recent chemical management models. For example, models of nutrient concentrations [R. A. Vollenweider, *Mem. Ist. Ital. Idrobiol.* **33**, 53 (1976); P. J. Dillon, *Limnol. Oceanogr.* **20**, 28 (1975)]; base cations [D. W. Schindler, R. H. Hesselein, M. A. Turner, *Can. J. Fish. Aquat. Sci. Suppl.* **44** (suppl. 1), 26 (1987)]; strong acid anions [C. A. Kelly *et al.*, *Biogeochemistry* **3**, 129 (1987)]. An increase in the ratio of total N to total P would be expected to reinforce P limitation that already limits the standing crop of algae in lakes of the area (*13*).
13. D. W. Schindler, *Science* **195**, 260 (1977).
14. Forest fires in the Lake 239 watershed occurred on 24 June 1974 and 20 June 1980. Larger fires that burned several hundred thousand hectares in the adjacent area occurred in the same two summers. Changes in flow volume and chemistry of streams following fires in the three stream watersheds of Lake 239 have been described by D. W. Schindler *et al.* [*Can. J. Fish. Aquat. Sci.* **37**, 328 (1980)] and S. E. Bayley and D. W. Schindler [in *Effects of Atmospheric Pollutants on Forests, Wetlands and Agricultural Ecosystems*, T. C. Hutchinson and K. M. Meema, Eds. (Springer-Verlag, New York, 1987), pp. 531–548]. Chemical concentrations also increased in lakes of the area that did not have their watersheds burned, but to a lesser degree than in Lake 239. Phosphorus inputs to Lake 239 also increased following fire, but only for 2 to 3 years. These increases were too small to cause detectable increases in a lake with such a long water residence time.
15. Colored forms of dissolved organic carbon (DOC) that cause the tea-colored waters of many boreal lakes originate largely in forest soils and wetlands. Upon reaching a lake, DOC is slowly degraded by microbial activity and photooxidation, as well as by flocculation [R. G. Zika and W. J. Cooper, Eds., *Photochemistry of Environmental Aquatic Systems* (*Am. Chem. Soc. Symp. Ser. 327*, American Chemical Society, Washington, DC, 1987); U. Weilenmann, C. R. O'Melia, W. Stumm, *Limnol. Oceanogr.* **34**, 1 (1989); see also (*16*)]. During dry periods, DOC input from streams decreases and its residence times in the lakes increase, rendering lakes clearer. There is also lower export of DOC from watersheds that have been burned severely enough to destroy organic soils [D. W. Schindler, S. E. Bayley, B. Parker, P. J. Curtis, M. P. Stainton, *Hydrobiologia*, in press]. In oligotrophic lakes of the Precambrian Shield, DOC, not phytoplankton, is the major factor attenuating the penetration of light (*7*).
16. S. W. Effler, S. C. Schafran, C. T. Driscoll, *Can. J. Fish. Aquat. Sci.* **42**, 1707 (1985).
17. The thermoclines of lakes with unburned watersheds have also increased slightly in depth, although not significantly, as in Lakes 239 and 240, so that the increased exposure of lakes with burned catchments to wind seemed to be the primary factor causing deeper mixing depth. Effler *et al.* (*16*) and N. D. Yan [*Can. J. Fish. Aquat. Sci.* **40**, 621 (1983)] also noted that thermocline depth increased as water clarity increased. The warming of waters in the region of the thermocline causes a decreased density gradient and thus permits deeper mixing to occur. The dramatically increased wind velocity observed at the ELA meteorological site was not observed in Kenora or Winnipeg. It may be due to extensive denudation of the area between Kenora and ELA by large fires, plus widespread, clear-cut logging.
18. Air temperatures for March, April, and May in the 1980s averaged 3.0° to 3.5°C warmer than in the early 1970s, almost twice the annual average increase. This difference, coupled with low snowfalls in most winters, has meant that lakes are now clear of snow by early April, about three weeks earlier than previously. In a given year, ice-out for all small lakes in the area occurs within a few days. Larger lakes, with mean depths over 50 m, retain their ice for up to 2 weeks longer.
19. A few centimeters of snow effectively block the penetration of light into lakes, whereas ice is nearly perfectly transparent. The disappearance of snow cover in spring therefore allows the solar heating of lakes to increases enormously [R. A. Reid, D. W. Schindler, R. V. Schmidt, *Fish. Mar. Serv. Tech. Rep. 560* (1975)]. On sunny days in spring, water temperatures of 10°C. have been observed just below the ice surface of Lake 239 (D. W. Schindler, unpublished data). As a result, ice usually dissipates within a few weeks after snow cover disappears, unless unusually cold, cloudy weather occurs.
20. In general, there is a strong correlation between phytoplankton standing crop and nutrient concentration in lakes [M. Sakamoto, *Arch. Hydrobiol.* **62**, 1 (1966); D. W. Schindler, E. J. Fee, T. Ruszczynski, *J. Fish. Res. Board Can.* **35**, 190 (1978)].

Phytoplankton were dominated by species of *Chrysosphaerella*, *Dinobryon*, and *Tabellaria* throughout the 20-year period. These genera are typical of natural lakes in the area [(8); H. J. Kling and S. K. Holmgren, *Can. Fish. Mar. Serv. Tech. Rep. 337* (1972)].
21. The effects of nutrients, light, and temperature on phytoplankton are discussed in D. W. Schindler, *Limnol. Oceanogr.* **23**, 478 (1978).
22. Phytoplankton production was measured with ^{14}C [J. A. Shearer, E. R. DeBruyn, D. R. Declercq, D. W. Schindler, E. J. Fee, *Can. Fish. Aquat. Sci. Tech. Rep. 1341* (1985)]. The photosynthesis per unit light at submaximal rates and the rate of maximum photosynthesis varied synchronously in lakes of the area spanning several orders of magnitude in size. The total magnitude of variation was a factor of 2 to 3 in all cases. These results suggest that the responses of phytoplankton production in small lakes like Lake 239 can be extrapolated to lakes of all sizes in the same region (E. J. Fee and R. E. Hecky, unpublished data). However, as in the ELA lakes, the variations in phytoplankton production in larger lakes showed no significant correlation with climatic variables.
23. The distribution of filamentous green algae in the shallows of Lake 239 has been mapped annually during the late summer (M. Jackson, personal communication). During 1982 to 1987, epiphytic coverage by filamentous green algae (chiefly of the genus *Mougeotia*) has been proportional to epilimnetic temperature. The species changes resemble those seen during early acidification of Lake 302S [M. A. Turner *et al.*, *Can. J. Fish. Aquat. Sci.* **44** (suppl. 1), 135 (1987)]. Increasing concentrations of atmospheric CO_2 are also expected to cause a slight increase in the photosynthesis of epiphytic algae in softwater lakes (M. A. Turner, unpublished data). No stimulation of phytoplankton photosynthesis due to increased CO_2 is expected [J. A. Shearer and E. R. DeBruyn, *Water Air Soil Pollut.* **30**, 695 (1986); E. R. DeBruyn, unpublished data]. From 1981 to 1988, maximum annual rates of photosynthesis by epilithiphyton in Lake 239 were also related to maximum epilimnion temperature (M. A. Turner, unpublished data). Contrary to our initial expectations, epilithic respiration was unaffected by epilimnion temperature.
24. Organisms that may be adversely affected by increasing temperature include the lake trout *Salvelinus namaycush* and the opposum shrimp *Mysis relicta*. Both are important in the food chains of boreal lakes with oxygen-rich conditions and temperatures less than 16°C. Both species are also very susceptible to lake acidification, which is also occurring in many boreal lakes (*25*). Prolonged summer stratification also prolongs the period during which oxygen depletion in hypolimnions can occur [P. V. Eloranta, *Water Res.* **17**, 133 (1983)].
25. D. W. Schindler *et al.*, *Science* **228**, 1395 (1985).
26. Geographical distribution maps of fishes in lakes that are suitable are given by W. B. Scott and E. J. Crossman [*Fish. Res. Board. Can. Bull.* **184**, 1 (1973)]; M. J. Dadswell [*Zool. II* (Nat. Mus. Nat. Hist., Ottawa, 1974)] gives similar information for relict glacial crustaceans.
27. An example of how the disappearance of key food organisms can disrupt fish production in boreal lakes is given in (*25*).
28. This work was supported by the Canadian Department of Fisheries and Oceans. P. Campbell, I. J. Davies, R. E. Hecky, G. Koshinsky, and H. E. Welch reviewed the manuscript. B. Parker assisted with data analysis.

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Ridge Spreading, Subduction, and Sea Level Fluctuations

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A numerical model of mantle convection shows that sea level fluctuations are not simply associated with temporal changes in ocean c plate spreading. In the dynamic model, sea level rises rapidly and then falls toward a steady value (but one still higher than the initial) following increased ridge spreading; this time dependence results from profound changes in the deep thermal structure under ocean and continent. The use of past variations in oceanic spreading to infer sea level fluctuations is called into question. With more realistic models and better continental stratigraphy, constraints may be placed on the viscosity structure of the mantle.

WITHIN A FEW YEARS AFTER THE acceptance of plate tectonics, Hays and Pitman (*1*) among others, pointed out that the well-documented Cretaceous transgression occurred at approximately the same time as an increase in the spreading of oceanic plates. Since then, the prevailing view has been that increased rates of plate spreading give rise to an increased volume of oceanic ridges and a decreased volume of ocean basins (*2*). For a constant volume of water, continental platforms have been thought to flood during periods of increased spreading. The determination of past variations in spreading has thus been viewed as an alternative method to estimate global eustatic sea level variations (*3*). This lithospheric model fails to conserve mass, however, because the cold oceanic lithosphere subducting into the mantle is ignored and implicitly assumed to disappear. With a simple model of mantle convection, I show that changes in plate velocity lead to changes in the rate at which cold lithosphere returns to the mantle and that this process leads to sea level fluctuations fundamentally different in both form and magnitude from the lithospheric model. Earlier, Hager (*4*) pointed out some dynamic problems encountered in relating oceanic spreading rates directly to changes in sea level and he suggested that sea level could either rise or fall with increased spreading, depending on whether slabs are returned to the mantle under continents or under oceans, respectively.

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Failure to conserve mass is overcome with the use of a simple thermal-convection calculation in which the oceanic lithosphere acts as an integral part of the overall system of heat and mass transfer. In a two-dimensional rectangular region, the equations of motion, continuity, and energy are solved simultaneously for an infinite Prandtl number and incompressible fluid; a finite-element formulation (*5*) is used to solve these equations. The technique used for simulating oceanic plates is similar to the one presented by Davies (*6*), except that a more stringent set of boundary conditions is used in which the entire oceanic lithosphere moves with horizontally uniform velocity. The use of a kinematically imposed lithosphere provides a framework in which to set up well-posed sea level experiments. Sea level variations caused by variable plate velocity can be directly assessed with this model, and thus the more circuitous method of a fully dynamic model (*7*) can be avoided. In order to control plate velocity with a fully dynamic model, the heat added to the system or a material property must vary; at this exploratory stage, such a complex technique (although a potentially more powerful one) is unwarranted.

The two-dimensional model [(*8*), Fig. 1, A to C] includes both an oceanic region, extending from $x = 0$ to $x = X_c$, and a continental region, extending from $x = X_c$ to $x = X_T$. The shaded areas in Fig. 1B denote zones of uniformly imposed velocity. With a box depth of D, the models had $X_c/D = 3$ and $X_T/D = 5$; these values were chosen so that the ratio of continental area to total surface area is 0.4. At both $x = 0$ and $x = X_T$, the side boundaries are reflecting. Because the oceanic plate has a uniform positive velocity, a symmetrical spreading ridge forms at the origin, and the lithosphere explicitly subducts at $x = X_c$; the continental plate has zero velocity. For this system with a constant viscosity throughout, sea level variations are computed in the following way. On the top surface of the convecting fluid, the topography (called the dynamic topography, w_d) is determined from the vertical deviatoric stress and explicitly includes the contributions from the subsiding oceanic lithosphere. An isostatic component to the topography, w_c, implicitly caused by crustal thickness variations, is added to the area over the continental lithosphere. In other studies involving the interaction of conti-