UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 342

STATUS OF CLIMATE CHANGE EFFECT SIMULATIONS FOR MIRROR LAKE, NEW HAMPSHIRE

by

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Prepared for

ENVIRONMENTAL RESEARCH LABORATORY
U.S. ENVIRONMENTAL PROTECTION AGENCY
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I. OBJECTIVE

To predict the effects of future global warming on water resources, we need to know how climate effects lakes. This knowledge can be gained (1) by comparative studies of similarly–sized lakes located in different climatic regions and (2) by use of simulation models that predict lake characteristics given various climatic conditions. Model results can be validated by comparisons with measurements in different climatic regions or through comparison with the paleorecord from a specific lake. The paleorecord approach can be most powerful because the last 14,000 years encompass a wide range of climate conditions, including much lower and higher temperatures, changes in season, and changes in runoff. Furthermore, it avoids the difference in topography and water chemistry that often characterizes different climatic regions.

We have begun to use the paleorecord approach to investigate the effects of climatic change on a lake whose limnology and history are exceptionally well known, Mirror Lake, NH (Likens, 1985). Six time horizons are considered: 14,000, 11,000, 9,000, 6,000, 3,000, and 0 years before present (B.P.). Climatic characteristics for these time periods are obtained from Kutzbach's (1987) reconstructions of global climate, using the gridpoints in the vicinity of Mirror Lake. Kutzbach used a global circulation model (GCM), inputting ice volume, insolation, CO_2 concentration and sea surface temperatures derived from ocean cores as boundary conditions, to predict global patterns of atmospheric circulation for 300–year time horizons from the present back to the full–glacial period, 18,000 years B.P.

The output from our numerical simulation experiments with the lake water quality and primary biological productivity model MINLAKE (Riley and Stefan, 1988; Stefan, 1989) is validated through comparison with field measurements for present conditions. In the future, we hope to do the same with past conditions, particularly productivity, lake level, depth of thermocline, and redox potential of bottom water reconstructed from paleoecological studies of the sediments (Likens, 1985; Davis *et al.*, 1985a; Davis *et al.*, 1985b). The latter included sediment inorganic chemistry, sedimentary pigments, diatoms, cladocerans, and fossil pollen. Five cores were dated and many additional cores and probes were taken to establish the contours of the basin and the volume of the sediment body. The hydrology of the lake watershed is well known, and detailed weather measurements have been made for the last twenty years (Likens, 1985; Federer *et al.*, 1990).

Our simulation experiments investigate the following questions in sequence:

A. *Effect of lake morphometry*

Mirror Lake, which is 15 ha in size, underwent striking changes in morphometry, from 24m depth 14,000 years ago to 10m at present, due to in-filling by sediment as shown in Fig. 1. Erosion lowered the outlet slightly (probably<1m), and damming in the nineteenth century has raised the lake surface again to its original level. Computer experiments explore the effect of these changes in morphometry on lake water quality, leaving climate constant.

B. *Effect of climate (insolation, wind, air temperature, precipitation).*

In order to avoid the circularity of using climatic reconstructions based on the paleorecord from the lake, we input estimates of past climate derived from GCM's (Kutzbach, 1987) into the simulation model. Circularity cannot be avoided entirely, however, as some information derived from the sediment must also be used as input, e.g. sediment O_2 utilizing capacity and water transparency.

C. *Effect of change in nutrient loading*

A major aim of previous studies (Liken, 1985) of the history of Mirror Lake was to determine past nutrient loading of the lake, in order to estimate nutrient losses from the forest on the lake watershed. Once we have determined the effect of basin morphometry and climate, we experiment with changes in nutrient loading in order to determine the sensitivity of the lake system to this parameter.

D. *Multiple effects*

By combining the effects of climate, morphometry, and nutrient loading, predictions can be made of the changes in the redox potential of bottom water, depth of thermocline, frequency of mixing, stratification and ice cover, as well as primary productivity. Model output can be compared with measurements of the modern lake because the modern lake is so well known. If these comparisons validate the model, further validation of predictions over a wider range of conditions can be made by comparing model output with the paleorecord of the lake. For example, changes in the Mn/Fe ratio of the sediment imply changes in redox potential of bottom waters. Changes in the pattern of sediment accumulation indicate the depth of the thermocline at various times in the past because sediment accumulates only below the level of the thermocline in the lake. Estimates of epilimnetic volume and of the time course of stratification enable coupling of the model with existing complex biological models of Mirror Lake (Lehman, 1975). The biota of the lake can thus be hindcast by the simulations, and those simulation results can then be compared with the fossil record in the sediment.

In summary, aspects of past climate have been reconstructed from paleoecological records in lake sediments, but these reconstructions can be improved. In previous studies, sediments have been related to past climate

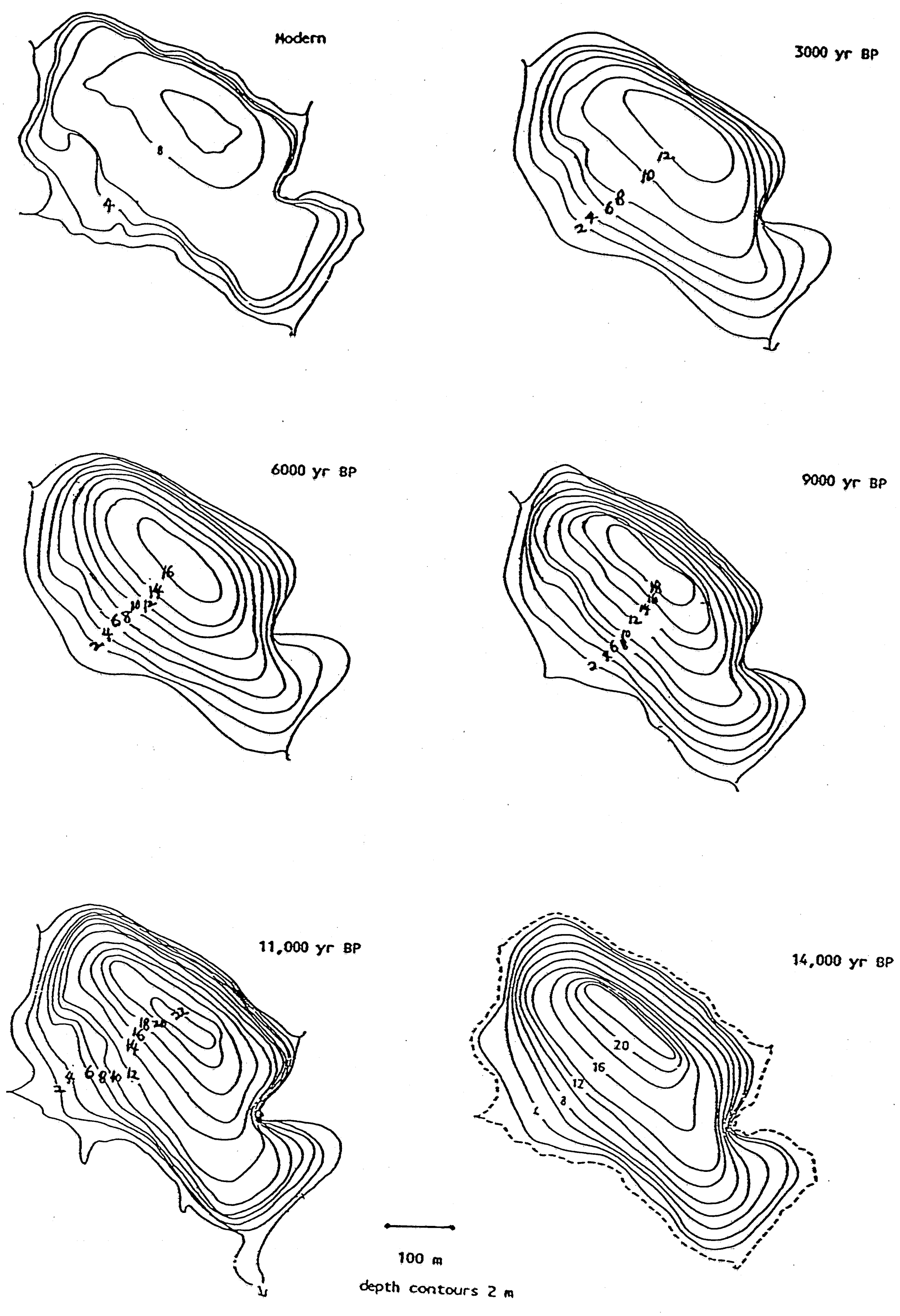


Fig. 1. Mirror Lake morphometry in the past, as reconstructed from sediment cores and probes (from Davis, 1985).

in a variety of ways, including fossil pollen records of regional terrestrial vegetation, and inferred nutrient export from the watershed, runoff, and redox potential. But an additional way in which past climate affects sediments is through the limnological characteristics of the lakes in which sediment is deposited. Direct effects of past climate on lakes, specifically water–quality and the pattern of sediment deposition, and their relationship to the paleoecological record preserved in sediment, are the focus of research for another status report. We expect that additional results can aid significantly in the design of paleolimnological studies and the interpretation of sediment cores, and hence, can improve climate hindcasting. The new information can also be applied to better forecast the effects of projected future climate change on lakes, on sedimentation processes, and on water quality.

II. LIMNOLOGICAL CHARACTERISTICS OF MODERN MIRROR LAKE

1. *Morphometry*

Mirror Lake has a surface area of 15 ha, a maximum depth of 11 m, and a mean depth of 5.75 m. The depth–contour map, the area–depth, and the volume–depth relationships derived from information given by O'Brien (Chapter IV; Likens, 1985) are shown in Fig. 2. The top 4 m contain 58.4% of the total volume. In contrast, the bottom 4m contain only 9.8% of the total volume (Likens, 1985). Mirror Lake is surrounded by northern hardwood vegetation.

2. *Temperature*

Mirror Lake shows many of the thermal characteristics of small lakes in the northern temperate zone (Likens, 1985). It is thermally stratified during the summer, inversely stratified during winter when covered by ice and snow, and usually has an isothermal period in spring and autumn.

The depth–time isotherms (°C) of Mirror Lake from 1968 to 1970 in Fig. 3 (O'Brien, Chapter IV; Likens, 1985) show that Mirror Lake is a dimictic lake. The ice cover started in early December and lasted for more than five months until about the middle of April. Fig. 4 shows average (1967–1980) depth–time isotherms (°C) in Mirror Lake. The vertical temperature differentials in summer were large (on the order of 16°C). Average water temperatures during summer were from 20 to 24°C on the lake surface and from 7 to 10°C at the bottom. The spring overturn was of short duration.

3. *Dissolved Oxygen*

The average (June 1967 to September 1978) distribution of dissolved oxygen in Mirror Lake is given in Fig. 5. Complete vertical mixing during the autumn is obvious from these data. In contrast, the data do not demonstrate spring overturn because dissolved oxygen is replenished near the bottom by advection due to frequent occurrence of meromixis (O'Brien, W. J., Chapter IV, Likens, 1985). A metalimnetic oxygen maximum at depths of 4 to 6 m during summer was obvious from the data, as water at these depths was supersaturated with dissolved oxygen. The dissolved oxygen at 9 to 10 m in later summer was less than 0.5 mg ℓ^{-1}. The metalimnetic oxygen maximum was related to a small attenuation coefficient (oligotrophic lake) and a large algal biomass in the metalimnion.

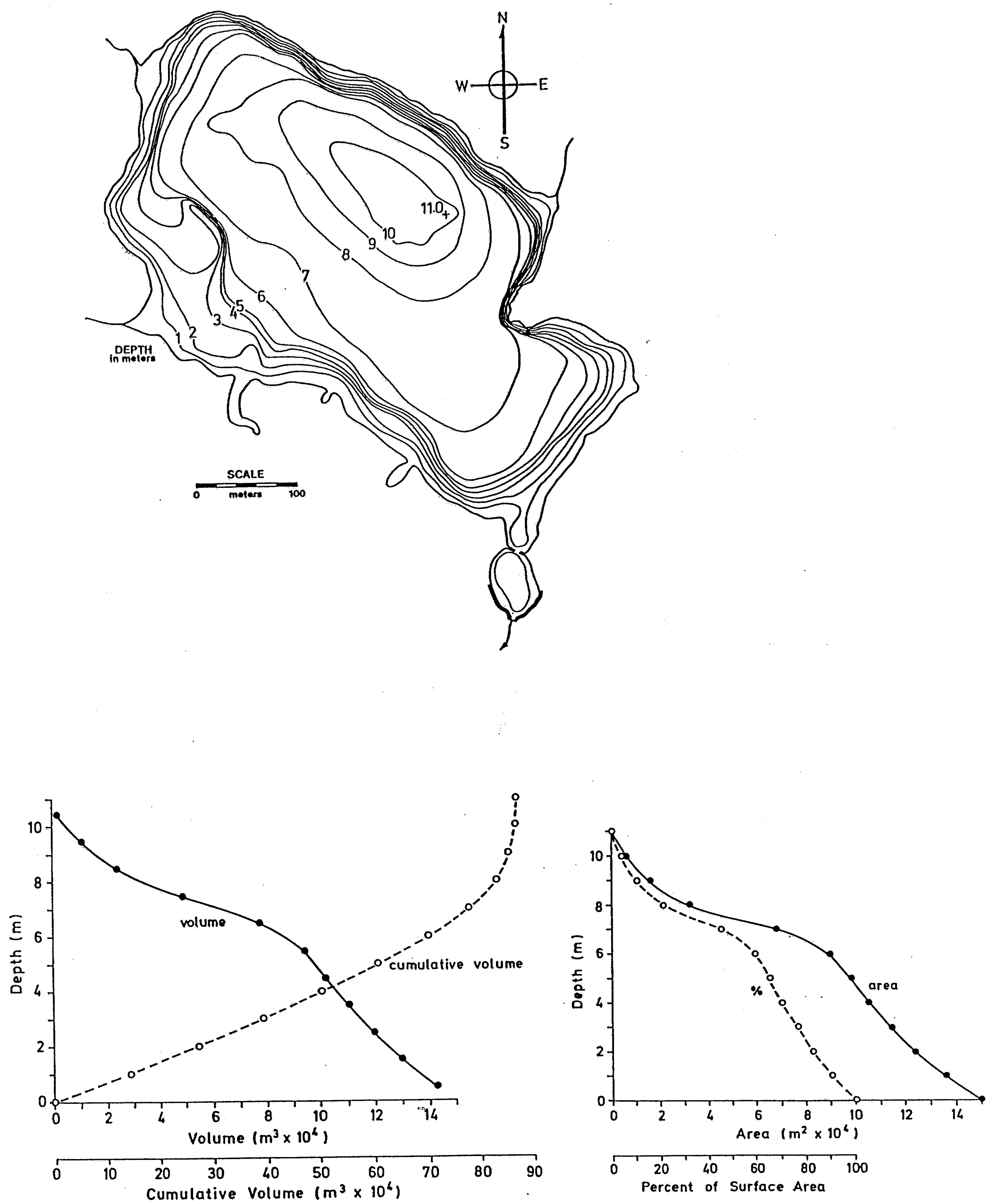


Fig. 2. Depth–contour map, area–depth and volume–depth curves for modern Mirror Lake (from Likens, 1985).

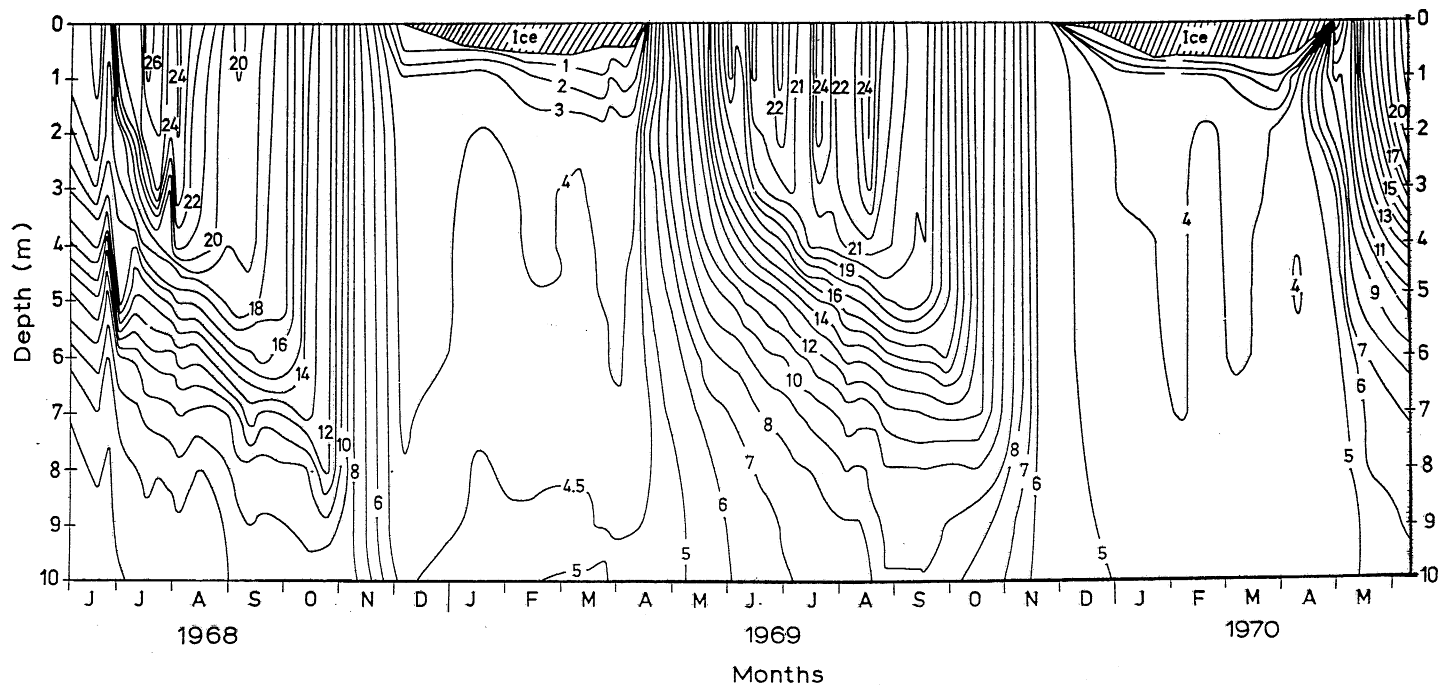


Fig. 3. Water temperatures (°C) observed in modern Mirror Lake (from Makarewicz, 1974).

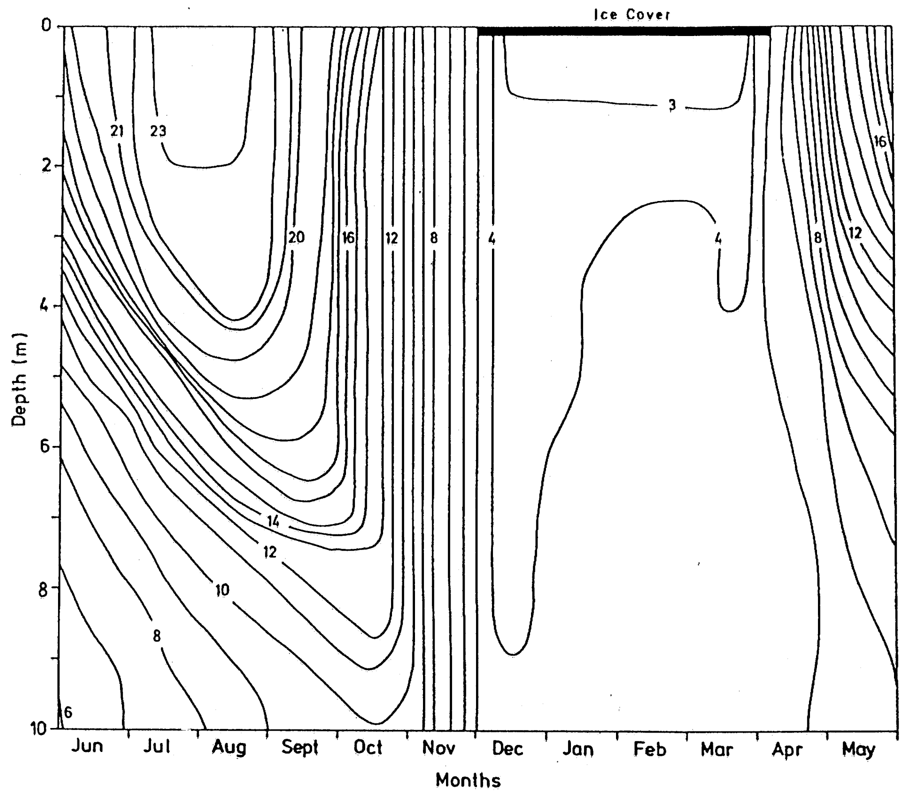


Fig. 4. Average (1967–1980) isotherms (°C) in Mirror Lake. The dark bar at the top represents the ice–cover period (from Likens, 1985).

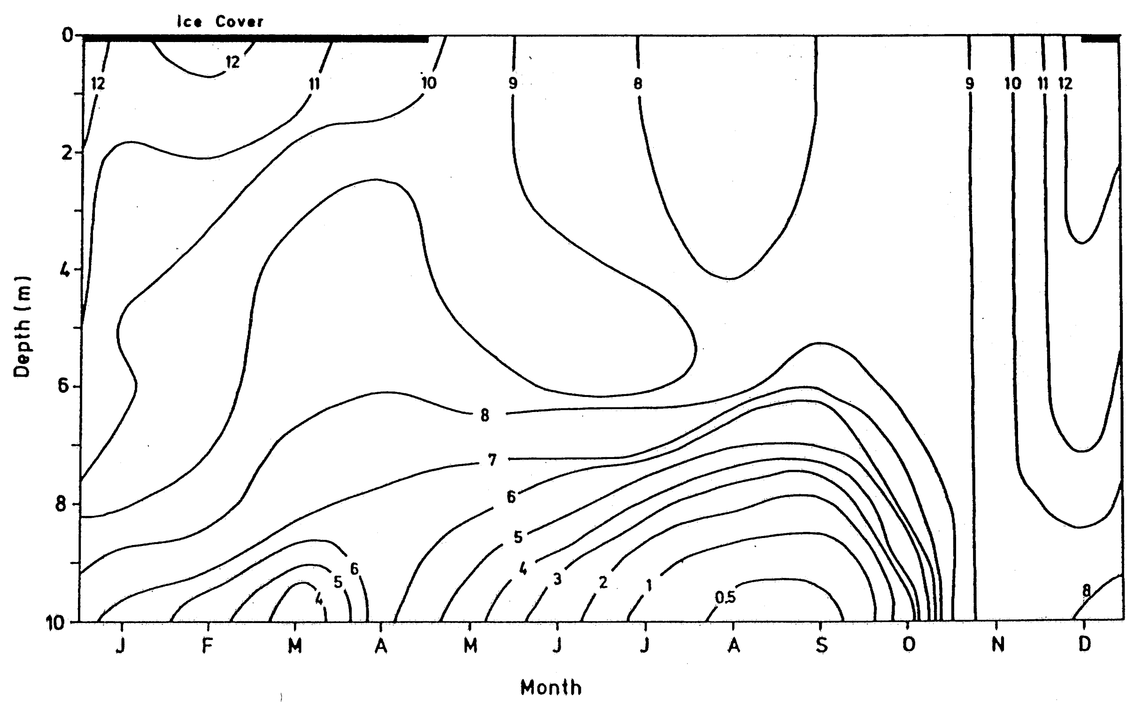


Fig. 5. Average dissolved oxygen isopleths (mg/liter) for the period June 1967 through September 1978 in Mirror Lake (from Likens, 1985).

4. *Water Transparency*

Water transparency can influence penetration of solar energy, which is the major source of energy for physical and metabolic activity in Mirror Lake. Secchi disc values which represent water transparency in Mirror Lake varied appreciably throughout the year (Fig. 6). In summer, Secchi depth ranges from 5 to 7 m and in winter from 2.5 to 3.5 m. The average light attenuation coefficient during the summer is about 0.34 m^{-1} (Kilham and Likens, 1968). Mirror Lake is the eighth clearest lake in Grafton County, New Hampshire.

5. *Phytoplankton*

Fig. 7 (Likens, 1985) gives the depth profiles in Mirror Lake for biomass (mg m^{-3}), as well as dissolved oxygen (mg ℓ^{-1}), water temperature (°C), and depths (m) at which irradiance is 10% and 1% of surface irradiance. The increase in biomass of phytoplankton below the eplimnion corresponding with the metalimnetic oxygen maximum is noteworthy. Samples during the thermal stratification period (June to September) show the greatest biomass occurring from 6 to 9 m depths. The presence of biomass peaks below the epilimnion in Mirror Lake is similar to that in other oligotrophic lakes (Gessner 1948; Findenegg 1964; Baker and Brook 1971; Kiefer *et al.* 1972; Tilzer 1973; Kerekes 1974). The species of phytoplankton recorded in Mirror Lake at all depths are included in the species lists from other oligotrophic lakes (Hutchinson 1957; Schindler and Nighswander, 1970). The composition of the species that dominate the biomass peaks below the epilimnion in Mirror Lake is similar to that of the Experimental Lake Area (ELA), Northwestern Ontario. The dominant species in ELA lakes are chrysophycean flagellates of the genera ***Dinobryon, Synura, Uroglena and Chrysosphaerella*** (Fee, 1976, 1978). In Mirror Lake, ***Chrysosphyaerella longispina and Synura uvella*** are among the dominant species (Likens, 1985).

Vertical chlorophyll–a distributions measured in Mirror Lake were similar in 1972, 1974 and 1979 (Fig. 8). The chlorophyll–a in the epilimnion (<4m) remains relatively constant but begins to increase in the metalimnion. These vertical distributions of chlorophyll–a (phytoplankton) in Mirror Lake are similar to Class–B oligotrophic lakes in ELA (Fee, 1976) as described in Appendix A.

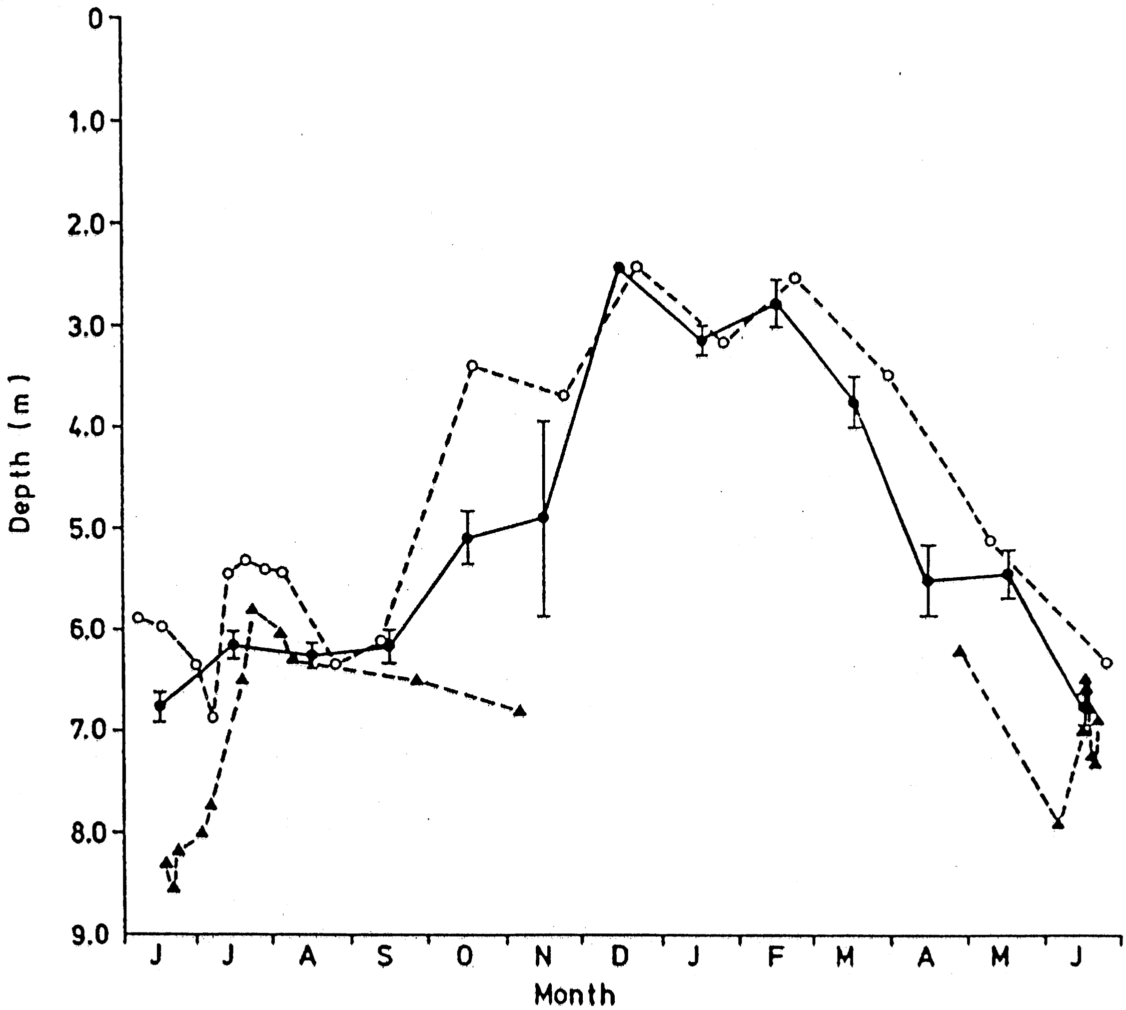


Fig. 6. Secchi disc values in Mirror Lake. Open circles are measurements in 1969–70; solid triangles are measurements in 1979–80; solid circles are monthly averages of all data from 1967 to 1981. Error bars indicate one standard deviation of the mean (from Likens, 1985).

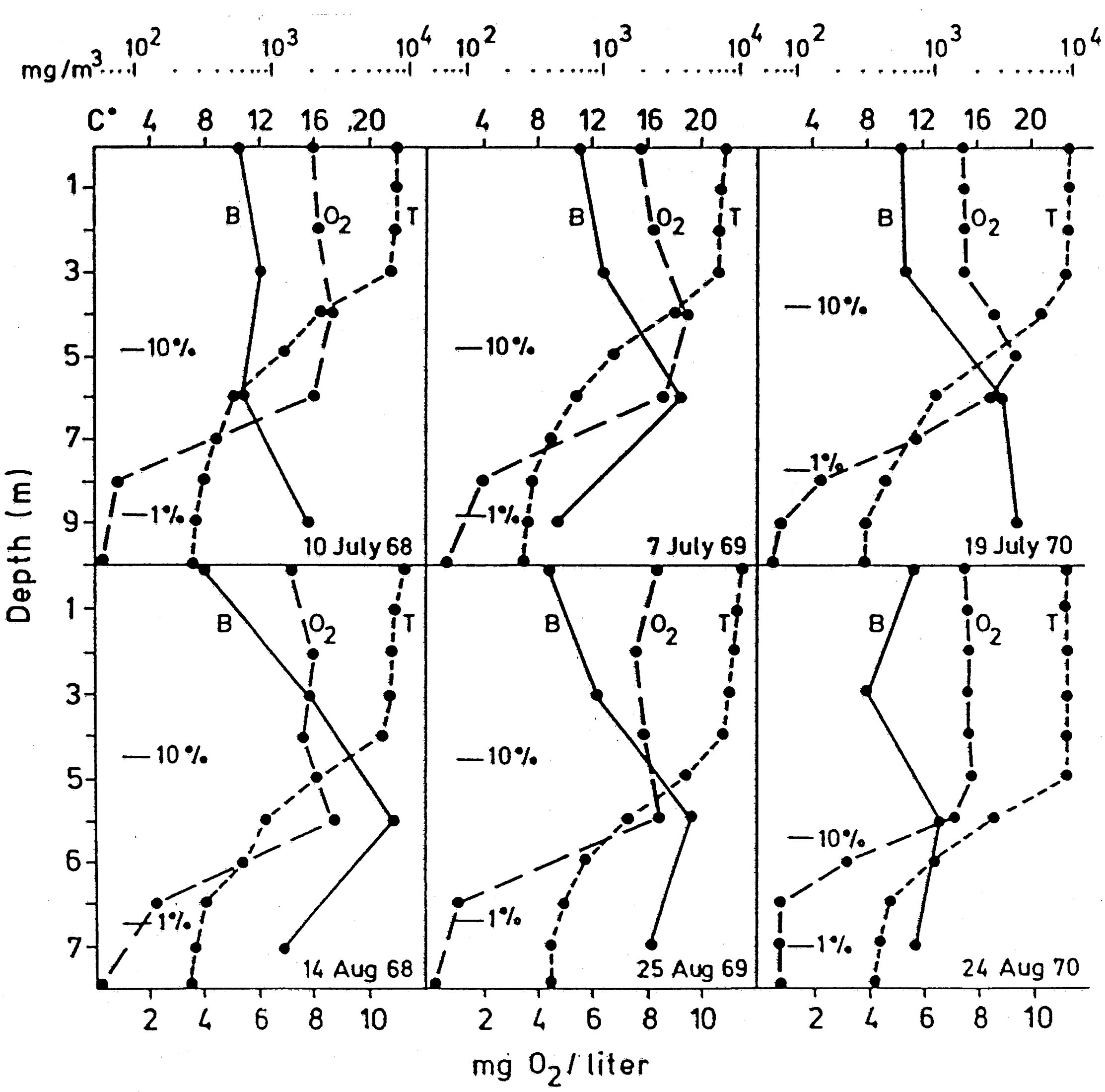


Fig. 7. Profiles for biomass (mg/m³ from volume – converted cell counts), dissolved oxygen (mg/liter), temperature (°C) and irradiance (1% and 10% depths) in Mirror Lake during the summer (from Likens 985).

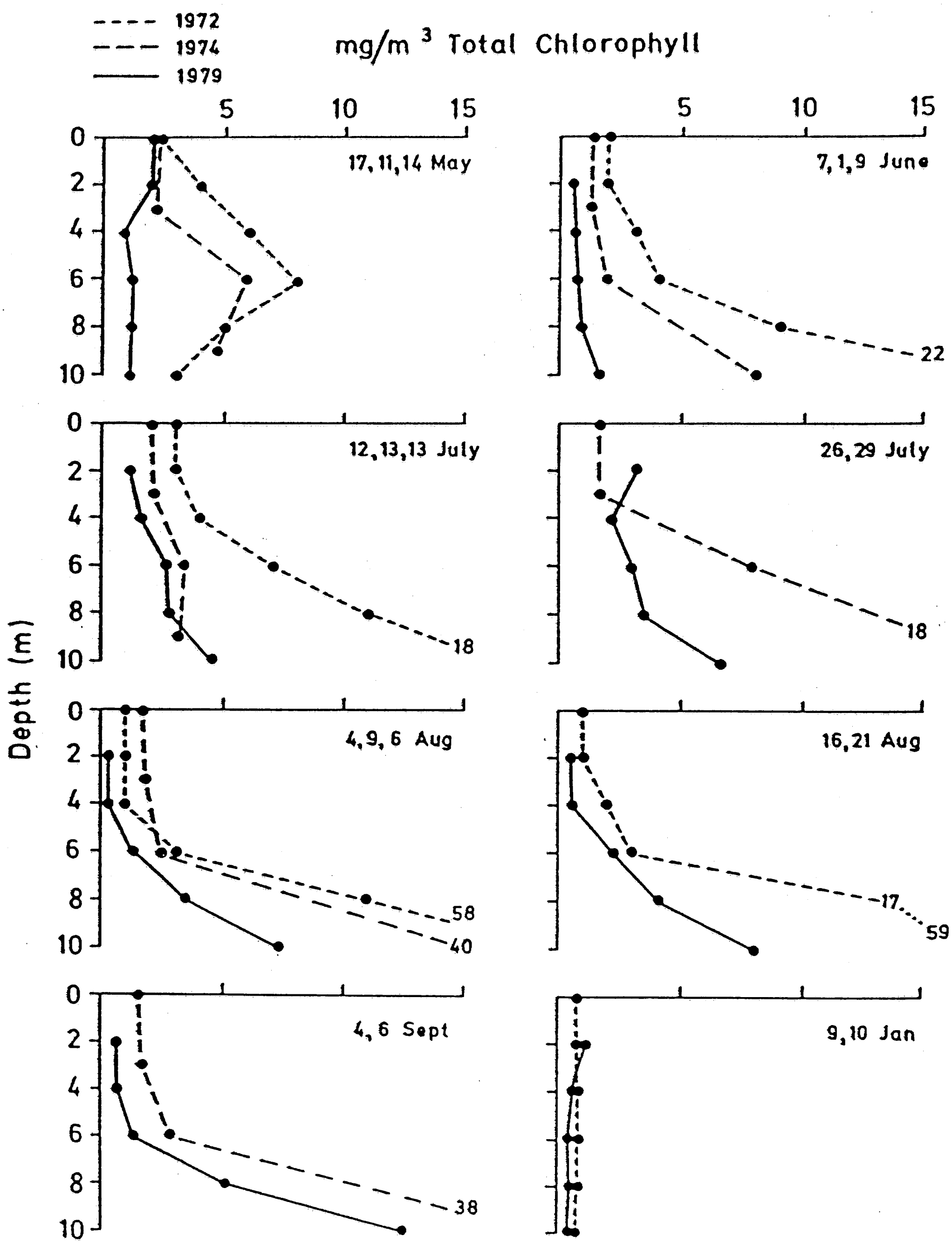


Fig. 8. Chlorophyll profiles from 1972, 1974, and 1979 in Mirror Lake. (from Likens, 1985).

III. DYNAMIC WATER QUALITY MODEL OF MIRROR LAKE

1. *Model Development*

The one-dimensional lake water quality model MINLAKE (Riley and Stefan, 1988), which has been successfully applied to simulate water quality and primary productivity in lakes in Minnesota for a variety of meteorological conditions, was used with some modification. In the model, the lake is divided into well-mixed horizontal layers; parameters vary only in the vertical direction. For water temperature simulation, the model solves a one-dimensional heat diffusion/advection equation with the net heat change rate between water and atmosphere acting as a boundary condition.

$$A \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} (K_z A \frac{\partial T}{\partial z}) + \frac{H}{\rho_w C_p} \qquad [1]$$

Where T(z,t) is water temperature as a function of depth (z) and time (t), A(z) is the horizontal area of the lake as a function of depth, and H is the internal distribution of heat sources due to radiation absorption inside the water column (Hondzo and Stefan, 1992). The model determines the rate of heat exchange by short-wave and long-wave radiation, back radiation, evaporation, and convection/conduction at the water surface. Turbulent mixing and natural convection distribute the total net heat input or loss throughout the water column. The model also has a wind mixing algorithm to determine the depth of the surface mixed layer (Ford and Stefan, 1980). Hypolimnetic mixing is described by a diffusion coefficient, K_z, which is related to lake morphometry and stratification stability (Hondzo and Stefan, 1992). Lake morphometry and daily weather parameters are model inputs.

Heat flux between lake bottom sediments and overlying water can significantly influence water temperature distributions in shallow transparent lakes (Tsay *et al.*, 1992), such as Mirror Lake. The conductive heat flux between the sediment and the lake water is

$$Q_{SW} = - k_S \left(\frac{dT_S}{dz}\right)_{SW} \qquad [2]$$

where T_S is the sediment temperature, k_S is the thermal conductivity of the sediment in w/(m °C), and "sw" denotes the interface of water and sediment (the lake bottom). The temperature distribution in the sediments is determined from the solution of the one-dimensional, unsteady heat conduction equation in a semi-infinite medium (Gu and Stefan, 1990).

$$\frac{\partial T_S}{\partial t} = K_S \frac{\partial^2 T_S}{\partial z^2} \qquad [3]$$

where $K_s = k_s/(\rho_s c_{ps})$ is the thermal diffusivity of the sediment in m^2/day, and $\rho_s c_{ps}$ is the specific heat of the sediment per unit volume. The boundary condition at the lake bottom is $T_s = T_b$, where T_b is water temperature at the lake bottom. A second boundary condition is an assumed adiabatic condition at 6 m below the lake bottom (Gu and Stefan, 1990). Equation [3] can be solved by a fully implicit finite difference method.

For dissolved oxygen simulation, the model solves the one–dimensional unsteady dissolved oxygen transport equation (Stefan and Fang, 1993). Sedimentary oxygen demand (SOD), biochemical oxygen demand in the water column (BOD), and plant respiration are the oxygen sinks in the model. Reaeration at the water surface and photosynthesis are the oxygen sources. Oxygen depletion in the hypolimnion in summer is mainly controlled by SOD rates and vertical mixing. Phytoplankton density is specified as mean chlorophyll–a concentrations, including implicitly nutrient effects such as phosphorus and nitrogen. BOD and SOD are also specified and dependent on lake trophic state. The basic D.O. transport equation used for Mirror Lake is

$$\frac{\partial C}{\partial t} - \frac{1}{A}\frac{\partial}{\partial z}\left(AK_z\frac{\partial C}{\partial z}\right) + \frac{1}{YCHO2}\, k_r \theta_r^{T-20}\, Chla - P_{max}\, Min[L]\, Chla$$

$$+ k_b\, \theta_b^{T-20}\, BOD + \frac{S_{b20}}{A}\, \theta_s^{T-20}\, \frac{\partial A}{\partial z} = 0 \qquad [4]$$

Reaeration is specified as a boundary flux $-\frac{k_e}{\Delta z_s}(C_{sat} - C_s)$ at the water surface. C(z,t) is dissolved oxygen concentration (mg ℓ^{-1}) as function of depth (z) and time (t), C_{sat} is saturated dissolved oxygen concentration (mg ℓ^{-1}) at water surface temperature, C_s is the dissolved oxygen concentration in the surface layer, Chla is chlorophyll–a concentration (mg ℓ^{-1}), BOD is biochemical oxygen demand (mg ℓ^{-1}), P_{max} is the maximum specific oxygen photosynthesis [mg O_2 (mg Chla)$^{-1}$ ℓ], Min[L] is the light limitation for growth, k_e is oxygen transfer velocity in the surface layer (m day^{-1}), Δz_s is thickness of surface layer, k_r is plant respiration rate (day^{-1}), k_b is the organic decomposition rate (day^{-1}), S_{b20} is the sedimentary oxygen demand coefficient (gO_2 m^{-2} day^{-1}) at 20°C, YCHO2 is the ratio of mg chlorophyll–a to mg oxygen utilized, and θ_r, θ_b, θ_s are temperature adjustment coefficients for plant respiration, BOD, SOD, respectively.

Table 1 summarizes parameter and coefficient values for the dissolved oxygen model (Stefan and Fang, 1993). A most important parameter in D.O. modeling is sedimentary oxygen demand coefficient S_{b20}, which is dependent on the trophic state and the maximum depth of a lake. For eutrophic deep lakes $S_{b20} = 1.0 - 1.5$ gO_2 m^{-2} day^{-1} and for eutrophic shallow lakes $S_{b20} =$ 2.0 gO_2 m^{-2} day^{-1}. The range of S_{b20} for a sandy bottom is from 0.2 to 1.0 with an average value of 0.5 (Thomann and Mueller, 1987).

The field data in Fig. 7 (Likens, 1985) show that the metalimnetic oxygen maxima in Mirror Lake start at depths where 20% or 10% of surface light remains. Maximum D.O. occurs between 10% and 1% of surface light,

Table 1 Parameter and coefficient values in the dissolved oxygen model.

Dependent on Trophic Status			
Parameters	Eutrophic	Mesotrophic	Oligotrophic
Secchi Depth (m)	1.2	2.5	4.5
Chlorophyll–a (mg m^{-3})	15	6.0	2.0
BOD (mg ℓ^{-1})	1.0	0.5	0.2
S_{b20} (g m^{-2} day^{-1})			
Deep lake (24 m)	1.0	0.50	0.2
Medium depth lake (13 m)	1.5	0.75	0.4
Shallow lake (4 m)	2.0	1.00	0.5

Independent of Trophic Status		
Coefficients	Range and References	Selected Value
k_b (day^{-1})	0.02–3.4[1], 0.03–0.10[2]	0.10
θ_b	1.047[1], 1.047[2]	1.047 as t≥20°C 1.13 as t<20°C
k_r (day^{-1})	0.05–0.5[1], 0.05–0.15[2]	0.10
θ_r	1.045[3], 1.047[2]	1.047
YCHO2	0.0083[4]	0.0083
θ_p	1.066[5]	1.036
θ_s	1.034 – 1.13[6]	1.065 as t≥10°C 1.130 as t<10°C

1 QUAL2E (Brown and Barnwell, 1987);
2 MINLAKE (Riley, 1988).
3 EUTR04 (Ambrose, Wool, Connolly, and Schanz);
4 *Aquatic Chemistry* (Stumm and Morgan, 1981);
5 Thomann and Mueller, 1987;
6 Zison, Wills, Dimer, and Chen, 1978.

often around the thermocline region. Metalimnetic oxygen maxima occur frequently in transparent mesotrophic/oligotrophic lakes. Typically these lakes have strong stratification and high relative depth in summer (Cole, 1983) and are protected from wind action by surrounding topography and vegetation (Wetzel, 1983). The maxima are nearly always the result of oxygen produced by algal populations that are stenothermal, i.e. adapted to growing well at low temperatures and low light intensities, but that have access to nutrients that are usually more abundant in the lower metalimnion than in the epilimnion (Wetzel, 1983). The bluegreen algae, especially ***Oscillatoria***, thrive in the dim light of the metalimnion. Much of the oxygen produced accumulates in the metalimnion for two reasons: photosynthesis exceeds respiration and turbulence is low at that depth (Cole, 1983).

A small attenuation coefficient allows light to penetrate into the deep water region for photosynthesis. Therefore, the photic zone in oligotrophic lakes is usually deeper than the surface mixed layer depth. For most eutrophic or mesotrophic lakes the Secchi depth is less than 3 or 4 m, and the total attenuation coefficient (k) is larger than 0.5 m^{-1}. For oligotrophic lakes with Secchi depth larger than 6 m, the total attenuation coefficient should remain less than 0.5 m^{-1}. The total attenuation coefficient in the model can be obtained from light or Secchi depth measurements. In the simulations, the attenuation coefficient and the phytoplankton (chlorophyll–a) distribution are the controlling parameters for the metalimnetic oxygen maxima.

Fig. 9 shows parameter profiles derived from the model which are important for photosynthesis, including the chlorophyll–a profile in oligotrophic lakes. No transport equation for phytoplankton is used in D.O. modeling. Instead, phytoplankton biomass is specified as chlorophyll–a concentration over either photic depth or surface mixed layer depth, whichever is larger (Fig. 9). Photic depth is considered the depth at which only 1% of the incoming photosynthetically active radiation remains, and surface mixed layer depth is the depth to which the energy of wind mixes a lake. Both are calculated in the model (Stefan and Fang, 1993). Case I in Fig. 9 is representative for early spring and later fall when the mixed layer depth (Z_m) is still larger than the euphotic zone (Z_p). Case II is for oligotrophic lakes during summer, when $Z_p > Z_m$. The uppermost part of the chlorophyll–a profile in Case II is the surface mixed layer. Below is a second layer which has higher average hypolimnetic chlorophyll–a concentration than the mixed surface layer. The second layer ends with the photic zone. In these two upper layers, photosynthesis contributes significantly to the oxygen profiles. Photosynthetic rate and algal respiration below the euphotic zone are set to zero (Fig. 9). BOD (Fig. 9) and SOD act as oxygen sinks in all layers at all times and include oxygen consumption by the decomposition of detritus in the water column and oxidation of organic matter in the sediment.

The average chlorophyll–a in the hypolimnion is obviously higher than in the epilimnion (Figs. 8 and 9). The two–layer vertical profile of chlorophyll–a in a very transparent lake yields a third type of profile of oxygen production, as described by Findenegg (1964). The third type has

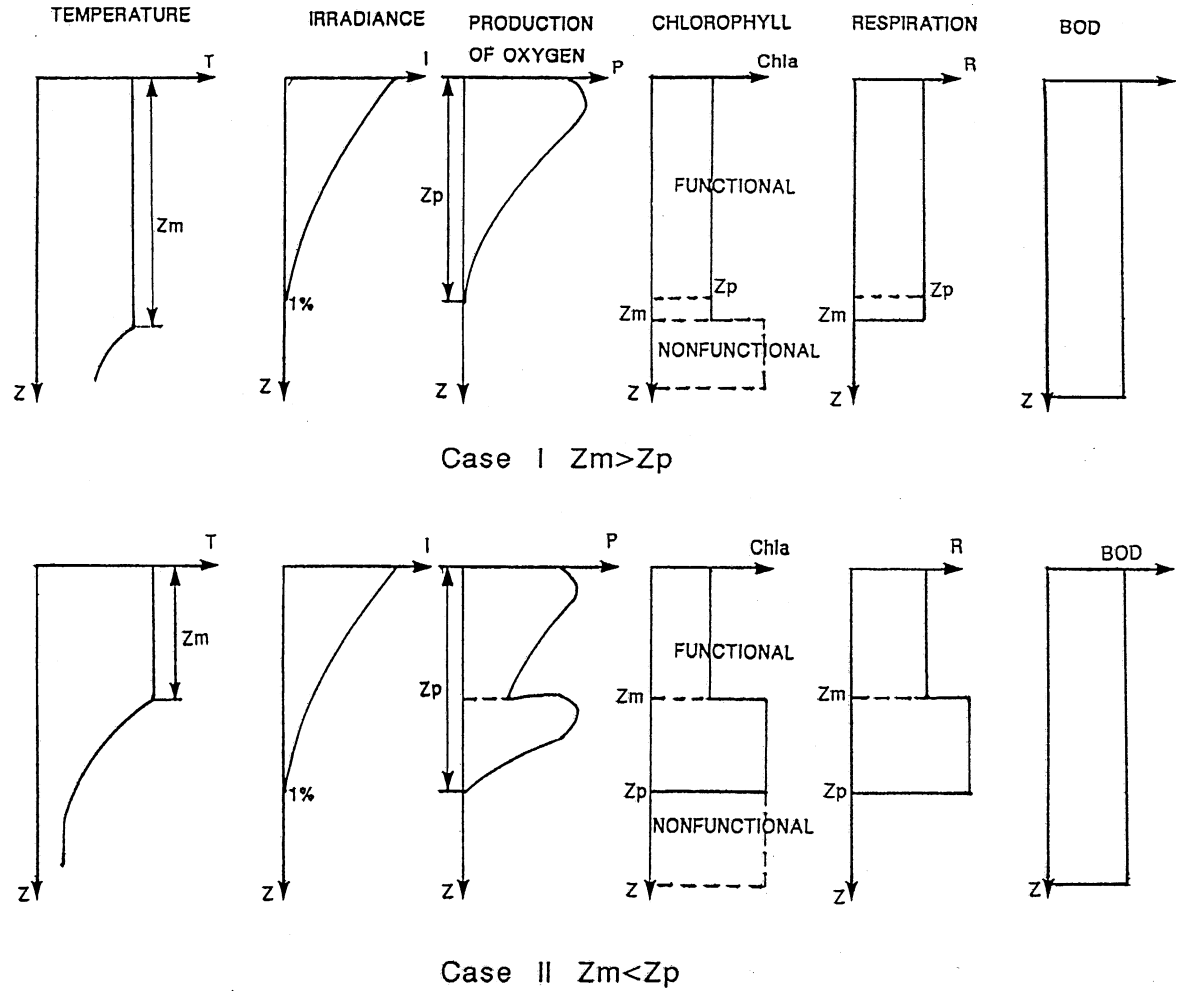


Fig. 9. Schematic vertical distribution of temperature, irradiance, production of oxygen, chlorophyll–a, plant respiration and biochemical oxygen demand (BOD) used in dissolved oxygen model.

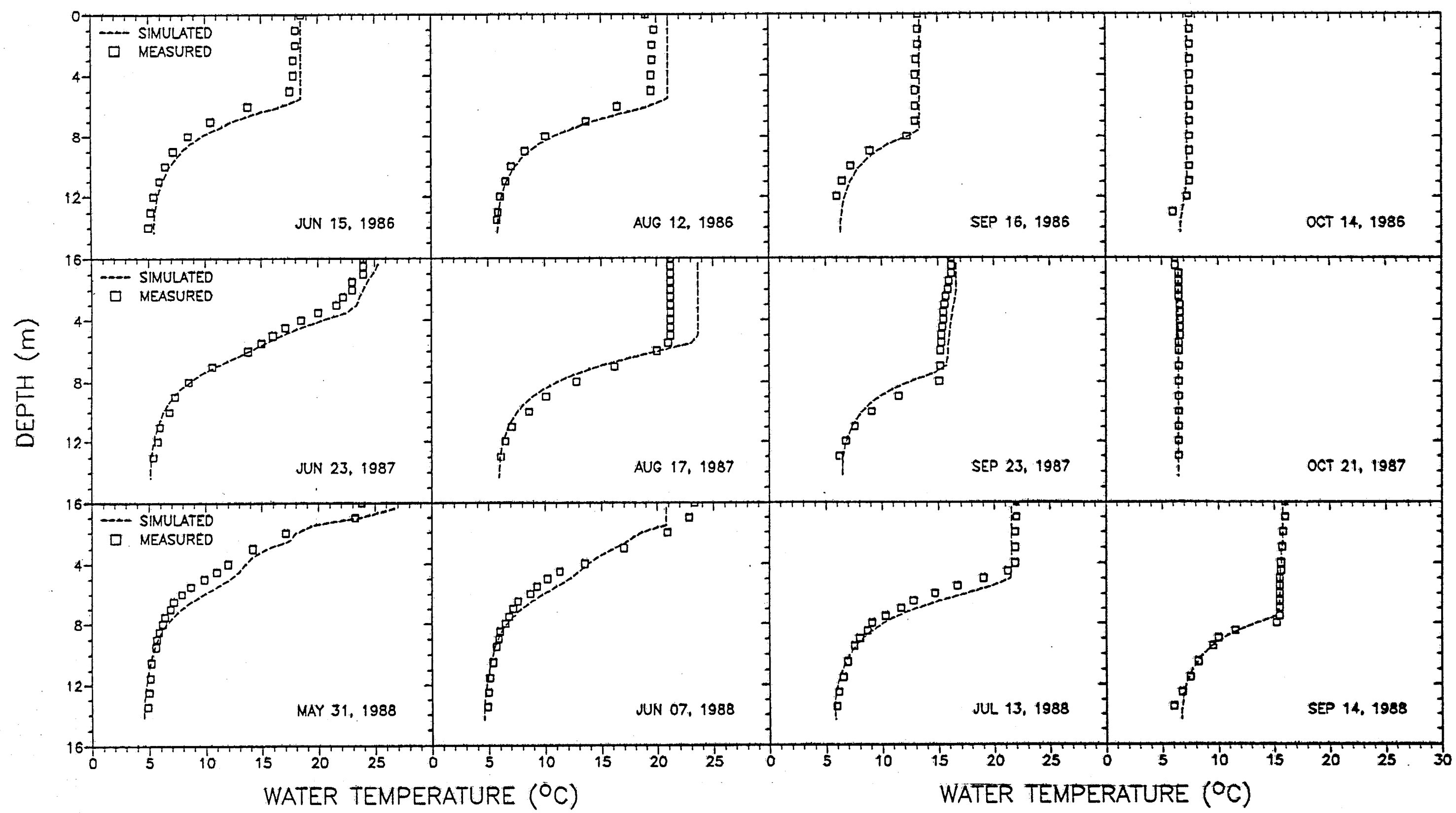


Fig. 10a Measured and simulated vertical profiles of water temperature (°C) in Thrush Lake in 1986, 1987, and 1988.

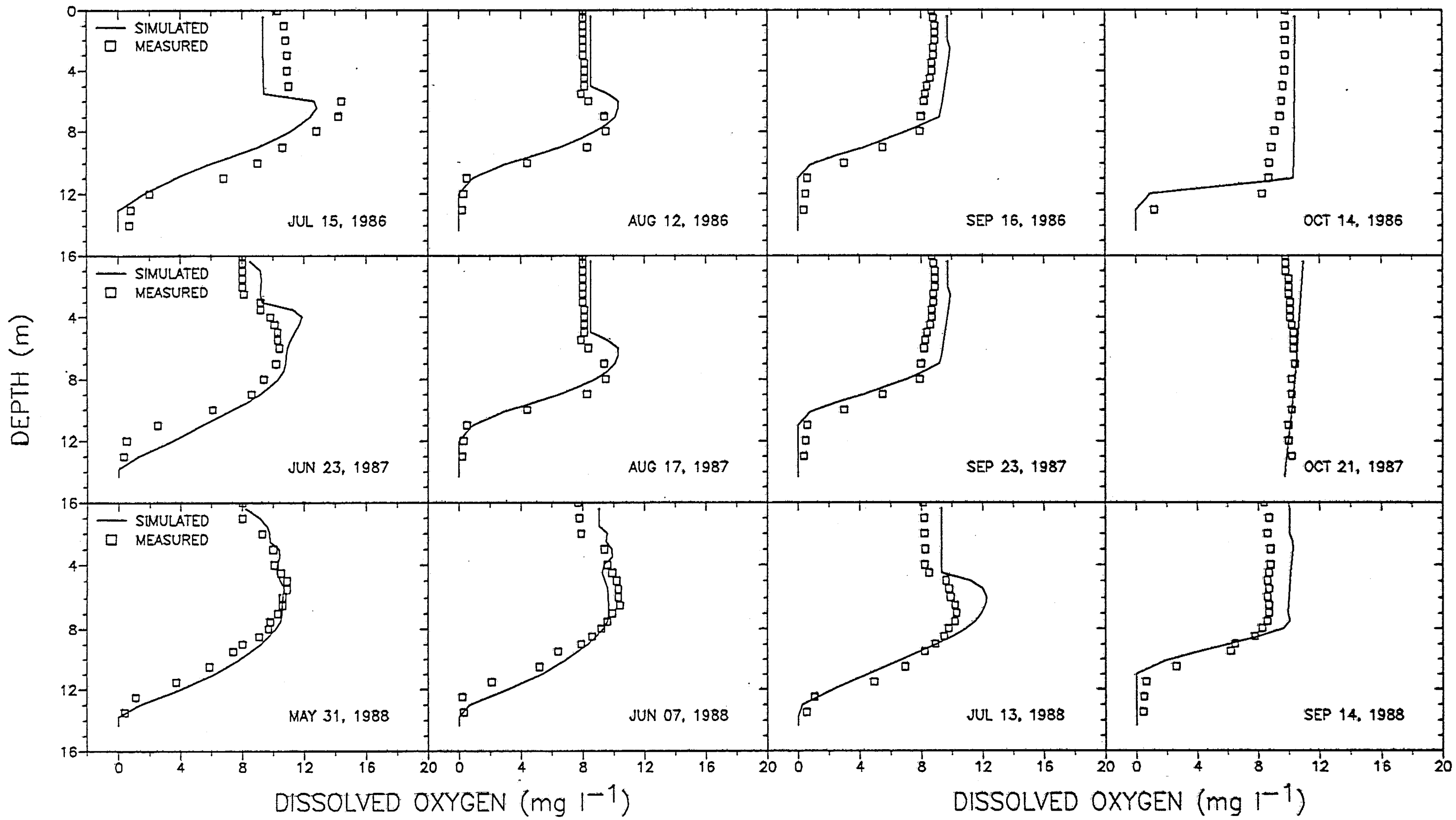


Fig. 10b Measured and simulated vertical profiles of dissolved oxygen (mg/ℓ) in Thrush Lake in 1986, 1987, and 1988.

IV. DATA ASSEMBLAGE FOR MODELING

1. *Data Requirements*

The input data for the one–dimensional lake water quality model (MINLAKE) include daily meteorological data and lake morphometry data. The weather data include daily mean air temperature, dew point temperature, precipitation, wind speed, and solar radiation. Lake morphometry data include surface area, maximum depth and hypsographic curves which are well known (Likens, 1985; Davis, 1985).

2. *Weather Data – Modern Time*

The report, "Thirty Years of Hydrometeorologic Data at the Hubbard Brook Experimental Forest," (Federer *et al.* 1990) gives monthly average weather data from 1956 to 1988. The 33–year averages of these monthly weather data are shown in Fig. 11. Percent sunshine is estimated by solar radiation divided by the maximum solar radiation. Fig. 12 shows the average daily maximum, mean, and minimum temperature (°C) with their standard deviations. These 33–year average weather data can be used for long–term average simulations.

The MINLAKE model requires daily weather data. Since daily weather data were not available, linear interpolation between average monthly values was used to generate synthetic daily values. The 33–year monthly averages were considered to occur on the fifteenth day of each month. Uncertainty of model simulation results by using average weather data and linear interpolation needs further investigation.

The Hubbard Brook Experimental Forest (HBEF) Station Headquarters is located near Mirror Lake. Therefore, the weather data collected at HBEF represent well the weather conditions of Mirror Lake, except for wind speed. Wind speed and direction have been measured at the Headquarters (HQ) of the HBEF since 1956 by an anemometer mounted 3m above the ground. The HQ anemometer is positioned in a somewhat sheltered location, surrounded by trees, a nearby building, and some rolling terrain. Fig. 11 indicates wind speeds of 3.2 mph maximum and 1.5 mph minimum, which appear very low relative to winds generally observed on lakes. Since wind speed is a controlling parameter for lake water temperature dynamics, the low wind speed given by the HQ anemometer, if accepted, would absolutely affect the water temperature simulation results. Therefore, a more representative wind record had to be found.

Daily weather data at Concord, New Hampshire, about 50 miles south of Mirror Lake, were available from the Northeast Regional Climate Center,

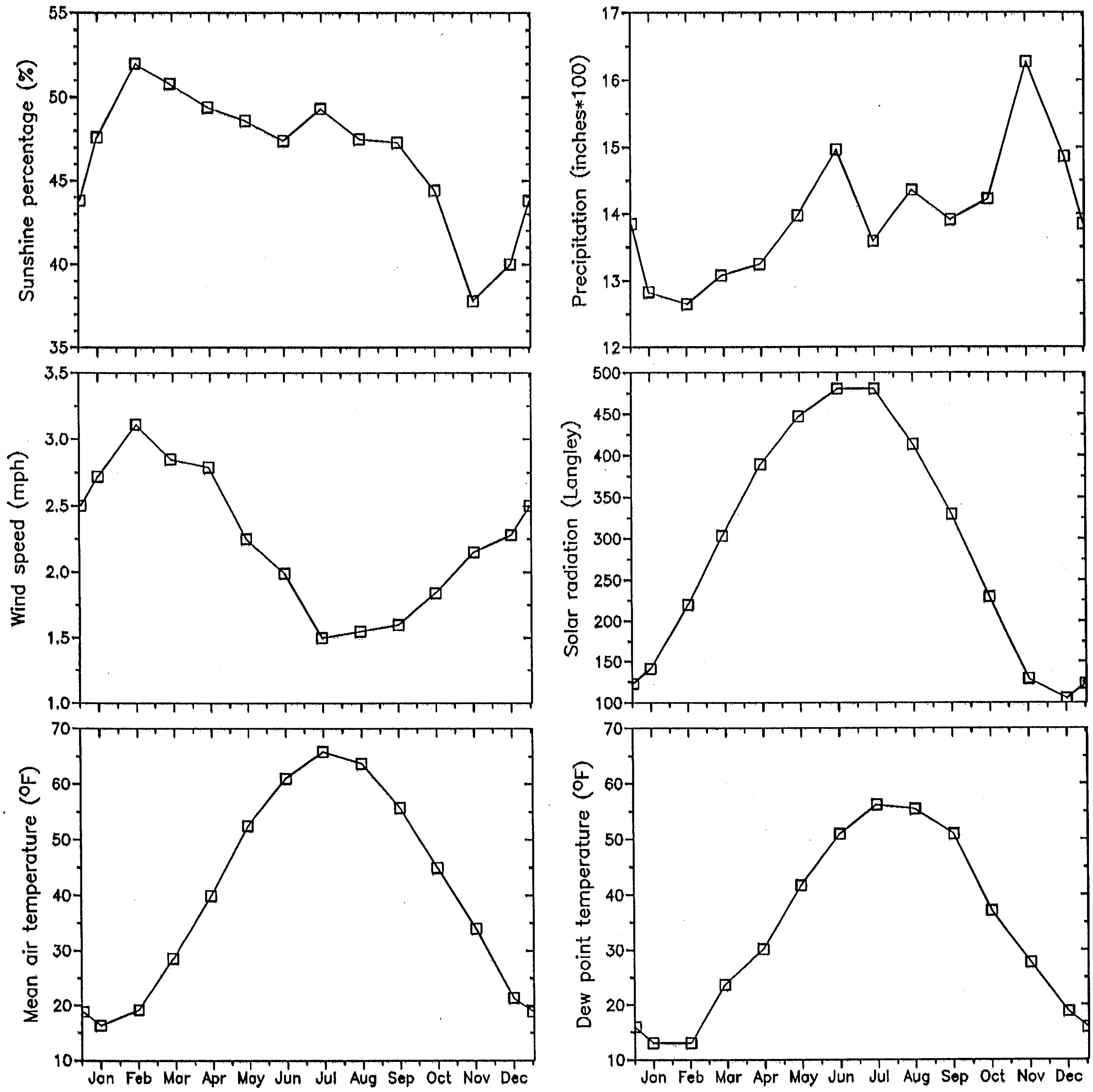


Fig. 11. Monthly averages (1956–1988) of weather conditions at Mirror Lake (from Forest Experiment Service Station) including air temperature, dew point temperature, wind speed, solar radiation, sunshine percentage and precipitation.

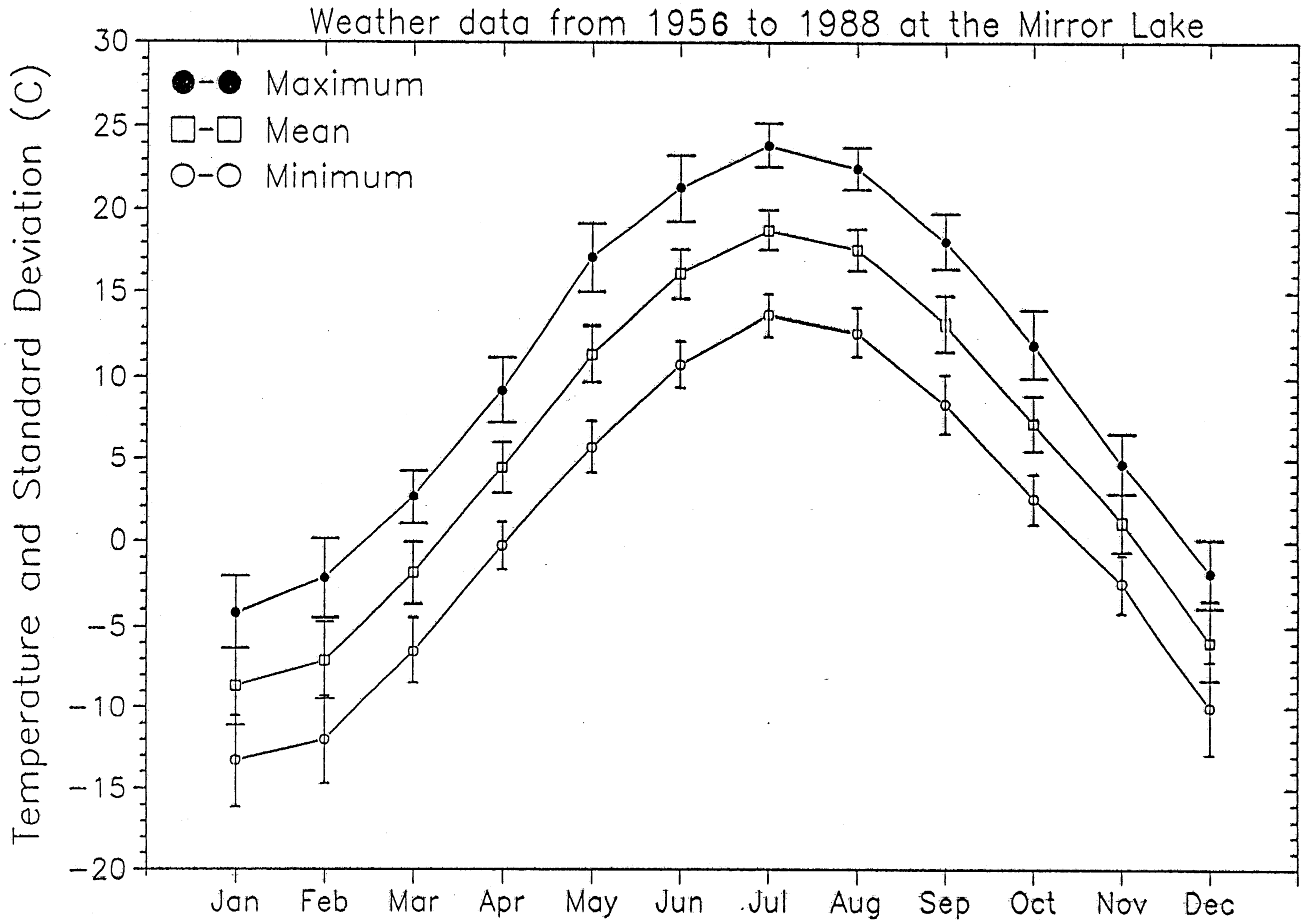


Fig. 12. Maximum, mean, and minimum monthly air temperatures (°C) at Mirror Lake from 1956 to 1988 and their standard deviations.

Ithaca, New York. The data include daily maximum temperature, daily minimum temperature, average dew point temperature, average wind speed, wind direction, precipitation, cloud cover, and sunshine percentage from 1948 to 1990. The Concord data were used because of quality control assurance for that station. The missing meteorological variable is solar radiation. It was estimated using a relationships by Baker and Haines (1969)

$$RAD = RAD_{max} [a + b P_{sun}] \quad [5]$$

where RAD is daily solar radiation in langley, RAD_{max} is clear day solar radiation (possible maximum) as a function of time (Julian day), P_{sun} is percentage of sunshine, and a and b are empirical coefficients which depend on time and geographical location (latitude and longitude). Daily solar radiation estimated from percentage of sunshine at Concord by equation [5] is shown in Fig. 13. Maximum solar radiation RAD_{max} at Mirror Lake (Federer *et al.,* 1990) was used in equation [5]. Coefficient values of a and b for East Lansing, MI, the easternmost station in the Baker and Haines (1969) study, had to be used. This station is about 700 miles from Concord, nevertheless the correlation between mean monthly values of solar radiation calculated from equation [5] and values measured at Mirror Lake in 1986 and 1987 is good; correlation coefficients are 0.996 and 0.998, respectively. Details are given in Appendix B. Unfortunately, the daily data of solar radiation at Mirror Lake could not be obtained.

Fig. 13 shows comparisons of daily weather parameters at Concord and 33–year average weather parameters at the HBEF including air temperature, dew point temperature, solar radiation and wind speed. The correlation coefficients between daily weather data at Concord and the 33–year average weather data at HBEF are 0.90 and 0.85 for air temperature and dew point temperature, respectively. Therefore daily weather parameters at Concord can well represent weather conditions at Mirror Lake. Fig. 13 also clearly shows that wind speeds at the HBEF HQ appear low compared to wind speeds at Concord.

3. *Weather Data – Past*

Weather parameters simulated by global circulation models (GCM) for the past 18,000 years in 3000–year intervals were available from the Center for Climatic Research, University of Wisconsin – Madison, Wisconsin. The available values include ground surface temperature, precipitation, wind speed, wind direction, and sea level pressure (Kutzbach and Guetter, 1986). The weather parameters are available only for January and July. They are the results of numerical simulation experiments with the Community Climate Model (CCM) of the National Center for Atmospheric Research (NCAR) under specific boundary conditions. The simulations were done in a rectangular domain from 180° west to 180° east and from 90° south to 90° north. The mesh system is 48 by 40, therefore the grid points cover 7.5° longitude and 4.5° latitude, respectively.

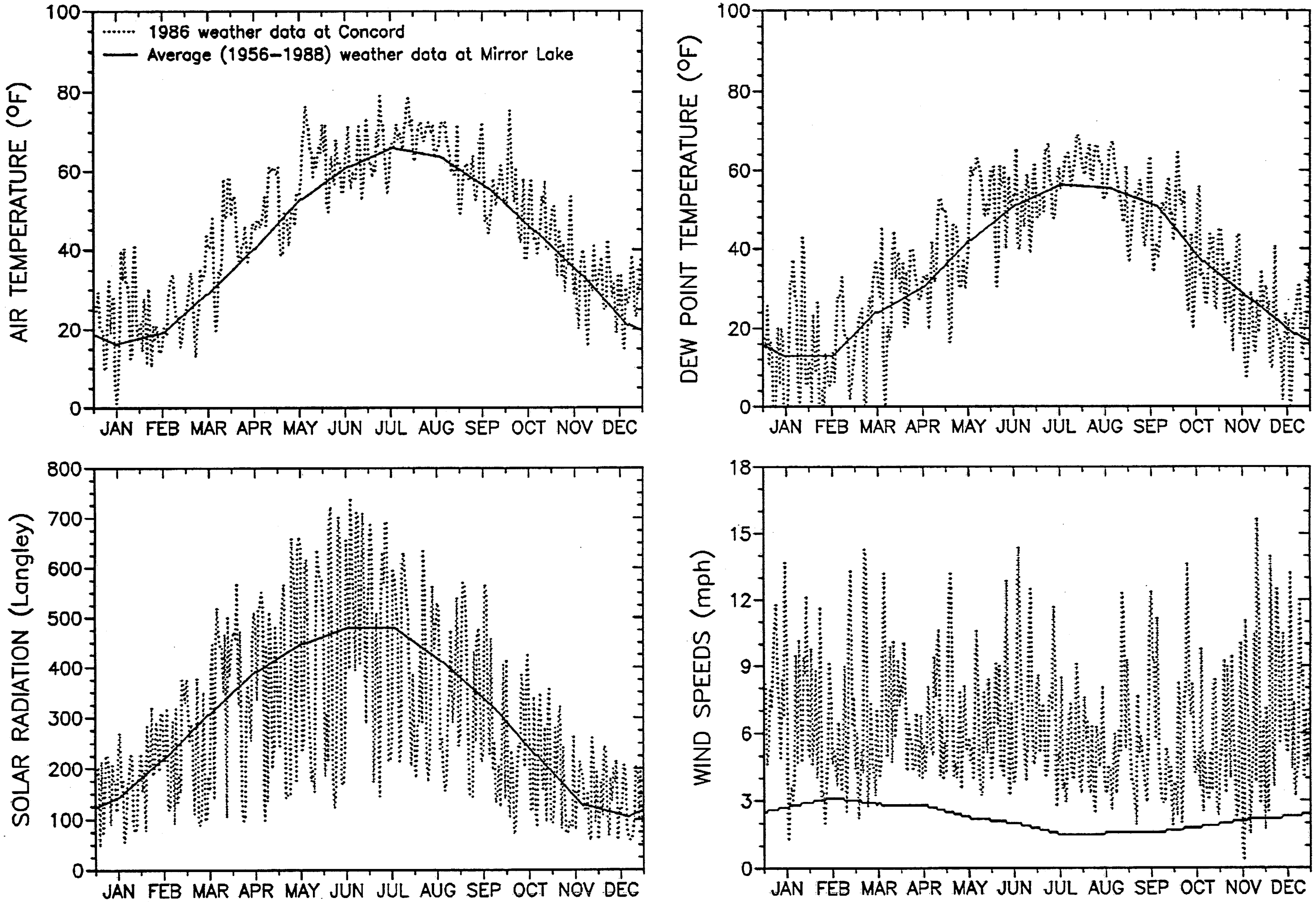


Fig. 13. Comparison of daily weather parameters at Concord and 33–year average weather parameters at Mirror Lake.

Mirror Lake (43°56.5'N, 71°41.5'W) is located in the town of Woodstock. The simulated weather conditions for Mirror Lake in Table 2 are calculated by using linear interpolation between grid points (Kutzbach and Guetter, 1986). The solar radiation data were provided as percent difference from present. To obtain daily weather data for air temperature, dew point temperature, and solar radiation, needed as input to the MINLAKE model, the monthly values available from the CCM model are interpolated by a function, currently specified as a seasonal sine function. The uncertainty of CCM model result interpolation needs further investigation.

4. *Limnological Data*

Limnological data are necessary to validate the model results. Long–term average water temperature and dissolved oxygen data for Mirror Lake were given in Figs. 4 and 5. The vertical water temperature and dissolved oxygen profiles for individual months shown in Fig. 14 were estimated from the contours in Figs. 4 and 5. The positive heterograde profiles of dissolved oxygen for June and August indicate both saturated or supersaturated high D.O. concentrations in the metalimnion.

The D.O. profiles and light measurements in Table 3 in Mirror Lake were provided by the Northeastern Forest Experimental Station. These D.O. profiles were measured by the Winkler method. Light measurements below the water surface on three different days were used to calculate the total attenuation coefficient. The average total attenuation coefficient of the three measurements is 0.39 m^{-1}, which is close to the 0.34 m^{-1} suggested by O'Brien (Chapter IV; Likens, 1985). The light attenuation coefficients in 1986 and 1987 varied from 0.27 m^{-1} to 0.56 m^{-1} with an average of 0.43 m^{-1} (Driscoll *et al.*, 1989).

Table 2 Simulated weather parameters at Mirror Lake back to 14,000 before present in 3,000 yeras interval.

SURFACE TEMPERATURE (C)

	January	July
0KA	-22.1	23.6
3KA	-18.1	24.6
6KA	-21.8	25.7
9KA	-22.5	24.3
12KA	-26.1	10.4
15KA	-32.5	-1.7

PRECIPITATION (inches)

	January	July
0KA	0.087	0.251
3KA	0.111	0.218
6KA	0.096	0.188
9KA	0.095	0.181
12KA	0.091	0.242
15KA	0.053	0.296

SEA LEVEL PRESSURE (mbar)

	January	July
0KA	1021.517	1015.917
3KA	1023.321	1016.459
6KA	1024.491	1016.725
9KA	1023.791	1019.192
12KA	1022.156	1019.562
15KA	1024.212	1019.042

WIND SPEED (miles/hour)

	January	July
0KA	7.32	5.46
3KA	6.58	6.57
6KA	7.28	6.52
9KA	8.12	3.67
12KA	10.54	4.70
15KA	12.42	8.59

WIND DIRECTION

	January	July
0KA	86	178
3KA	68	19
6KA	73	16
9KA	110	161
12KA	106	32
15KA	23	30

Table 3 Dissolved oxygen and light measurements in Mirror Lake in 1986

Dissolved Oxygen (mg/l)

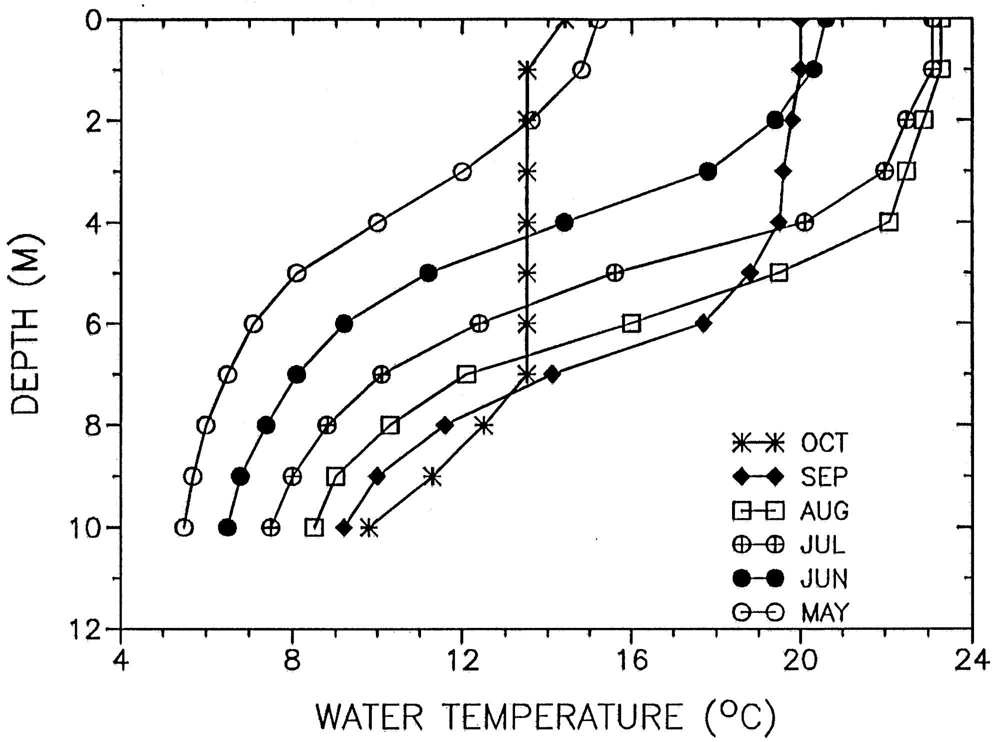
Depth	May 15	Jun 9	Jun 30	Jul 1	Aug 14	Sep 4
0	6.22	8.38	8.37	8.14	7.96	8.02
2	6.50	8.64	8.12	8.22	7.90	8.06
4	6.75	10.33	8.09	8.18	7.90	8.16
6	6.60	9.73	9.27	9.11	9.26	8.06
7	5.63	8.24	7.60	7.84	8.00	7.89
8	4.53	7.35	4.32	3.94	3.95	4.48
9	3.97	2.80	2.08	1.14	0.52	0.22
10	3.74	1.68	1.23	0.30	0.00	0.00

Light Measurements (uE/m**2/sec)

May	15	June	9	June	30
0	1500	0.0	1600	0.0	1475
2	320	0.5	1300	0.5	1150
4	280	1.0	1100	1.0	925
6	140	2.0	650	2.0	750
7	75	3.0	450	3.0	510
8	40	4.0	350	4.0	380
9	30	5.0	250	5.0	290
10	18	6.0	180	6.0	185
		7.0	110	7.0	125
		8.0	70	8.0	73.5
		9.0	40	9.0	34.5

Regression Results:

	May 15	June 9	June 30
Constant	1232	1592	1559
Attenuation k	0.41	0.39	0.38
R**2	0.97	0.99	0.98
Secchi Depth	6.4	5.3	6.5
K*Zs	2.6	2.1	2.5



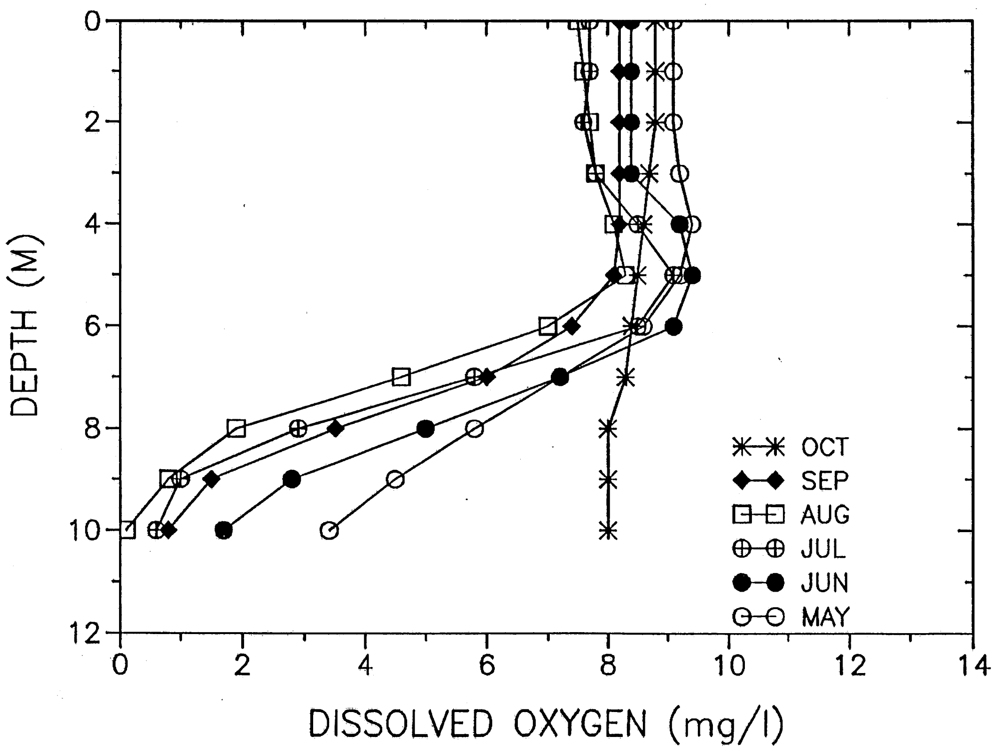


Fig. 14. Temperature (°C) and dissolved oxygen (mg/ℓ) profiles in Mirror Lake interpolated from average isopleths in Figs. 4 and 5.

V. SIMULATION RESULTS

1. *Model Simulations*

Water temperature and dissolved oxygen simulations for modern Mirror Lake were made by using the daily meteorological data from Concord as model input. A total attenuation coefficient k = 0.43 m^{-1} (Driscoll *et al.*, 1989) and wind–sheltering coefficient = 0.1, appropriate for a protected lake with small surface area, were also used. Water temperature simulations include the heat exchange with lake bottom sediments.

Water temperatures measured in 1987 (Driscoll *et al.*, 1989) were compared with the numerical simulation results (Fig. 15). The standard error between measured and simulated values during the open water season (April 1 to November 30) is 0.9°C and the regression slope is 0.96. Results of dissolved oxygen simulations for the year 1986 are shown in Fig. 16 together with measurements tabulated in Table 3. For these simulations, average epilimnetic and hypolimnetic chlorophyll–a concentrations were not available, and had to be estimated from Fig. 8 (2 and 6 $\mu g/\ell$ in the epilimnion and the hypolimnion , respectively). Other parameter and coefficient values are the same as those in the model calibration for Thrush Lake (Table 1). The standard error between measured and simulated values during the open water season is 1.68 mg/ℓ and the regression slope is 0.92. Simulations reproduced the observed metalimnetic oxygen maxima in Mirror Lake, although some were overpredicted.

2. *Sensitivity Analysis*

Fig. 17 shows the effect of wind speed on water temperatures in Mirror Lake. This effect was investigated because the wind speeds reported for Mirror Lake appear unreasonably small and not representative, probably because of the location of the anemometer in a wind–sheltered area surrounded by trees. Water temperature simulations with these low average wind speeds from Mirror Lake as input are compared with those made with three times mean wind speeds in Fig. 17. Simulation results with three times mean wind speeds are similar and close to measured temperature distributions. Wind speed is a controlling parameter for evaporative and convective heat losses, and strongly influences the heat budget of the lake. Therefore the water surface temperature under mean wind speeds is much higher than with three times wind speeds (Fig. 17). The mixed layer depths are also deeper under higher wind speeds. Hypolimnetic water temperatures are only weakly sensitive to wind speeds.

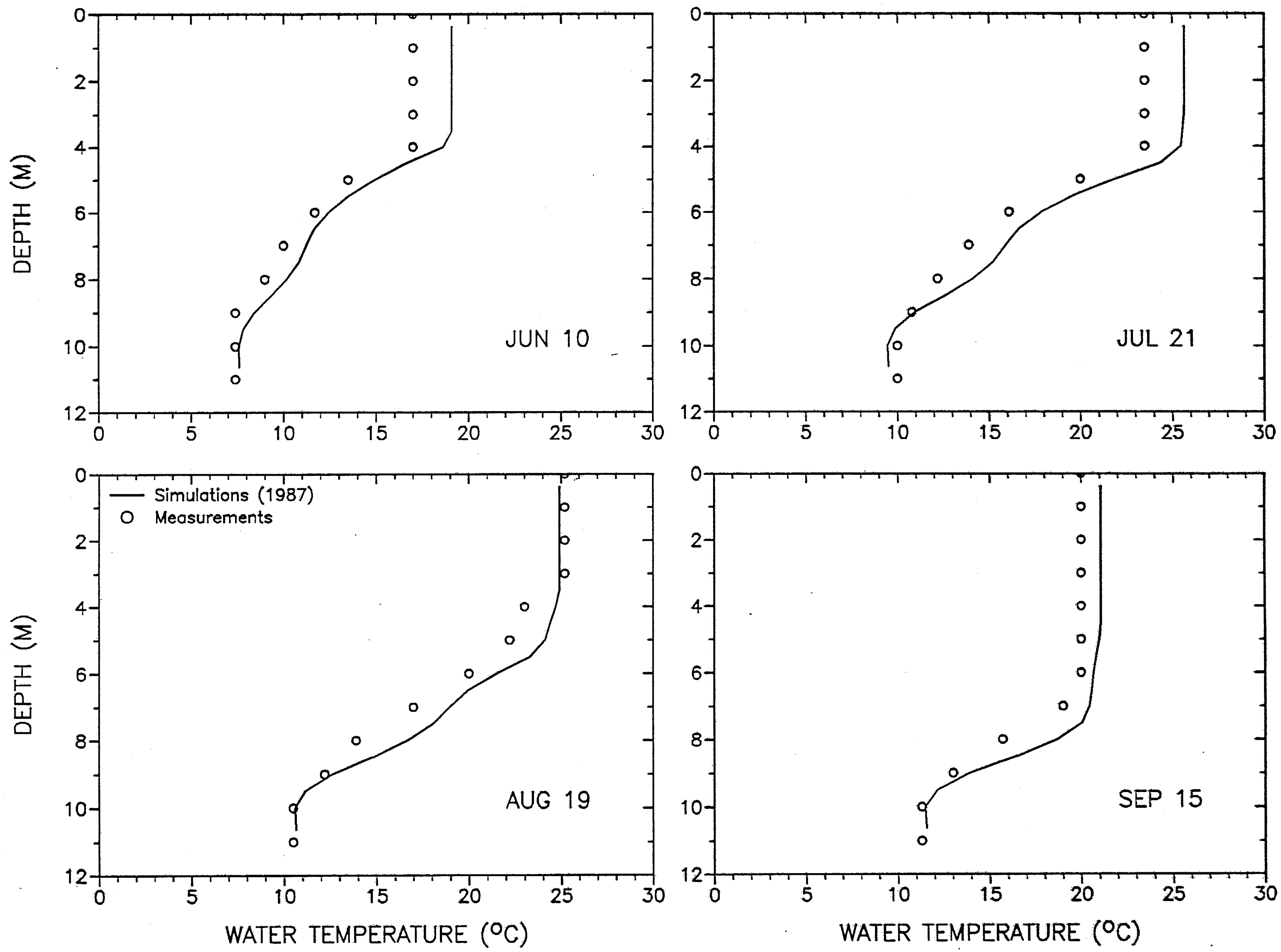


Fig. 15. Measured and simulated water temperature (°C) profiles in 1987, using daily weather conditions at Concord as model input.

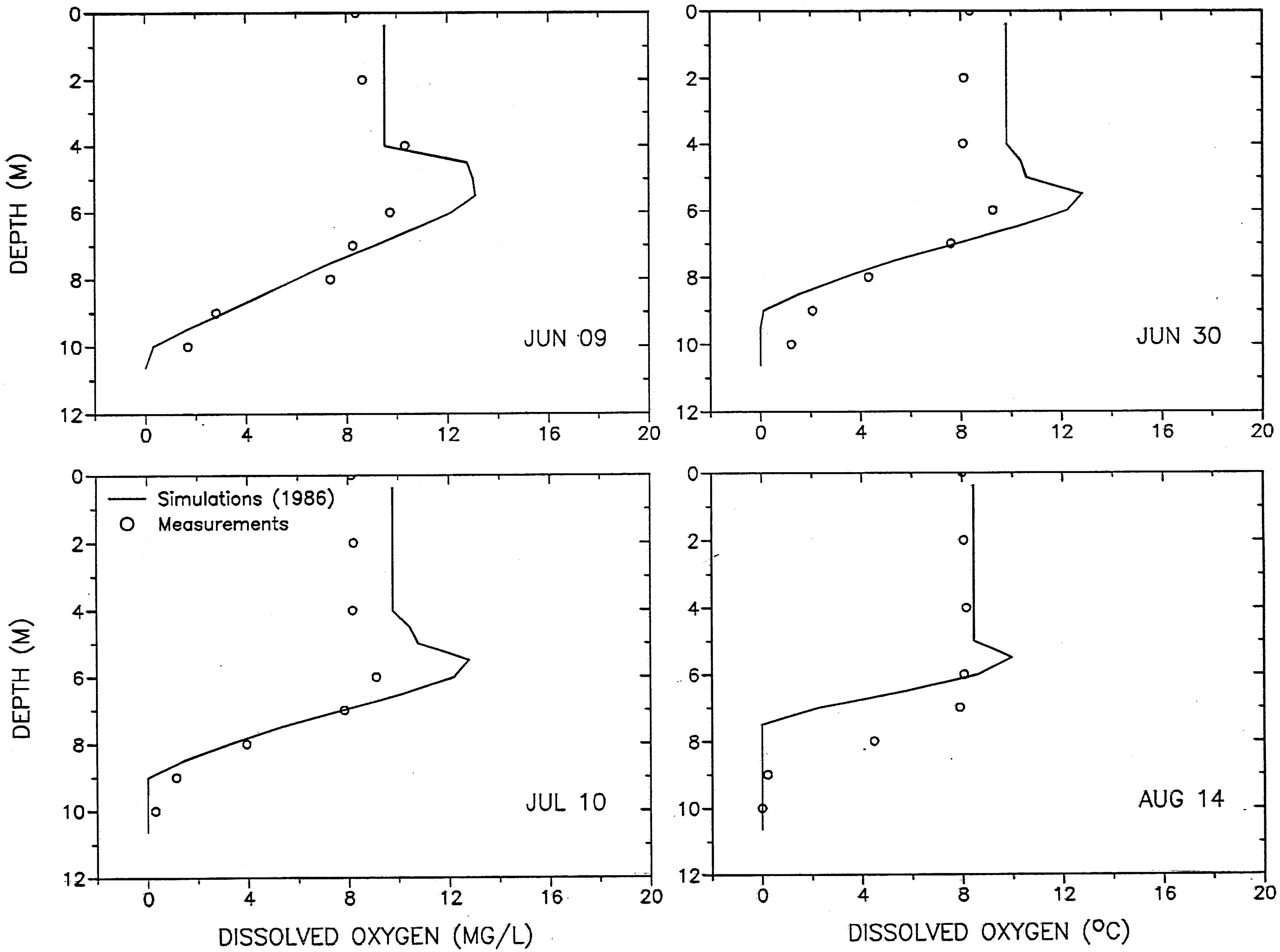


Fig. 16. Measured and simulated dissolved oxygen (mg/ℓ) profiles in 1986, using daily weather conditions at Concord as model input.

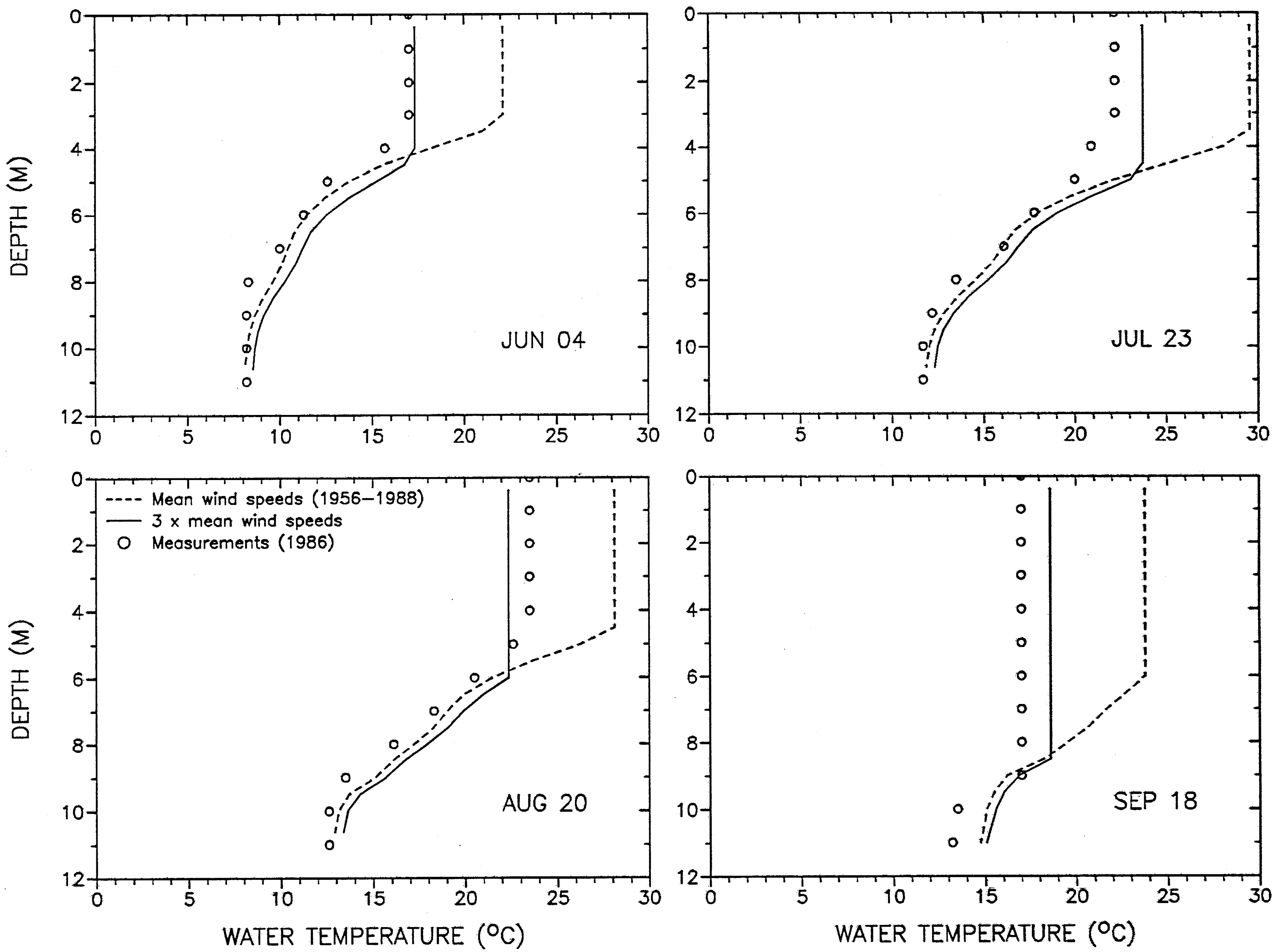


Fig. 17. Water temperature simulations with mean and three times mean wind speeds as model input.

In shallow transparent lakes, the incoming solar radiation can penetrate through the water body and heat the sediments at the lake bottom. Therefore heat exchange between lake sediments and overlying water is important to water temperature distribution in those lakes. Fig. 18 shows the effect of sediment heat flux on water temperature simulations. The sediment heat flux influences water temperatures at the lake bottom greatly, especially in the later summer. In these simulations, thermal conductivity and diffusivity of the sediments are 0.55 w/(m °C) and 0.0225 m^2/day (Gu and Stefan, 1990), respectively. This is representative of organic materials with a high water content. Over the past 14,000 years Mirror Lake has experienced changes in sediments composition (Davis, 1985); therefore, thermal properties of the sediments must have changed correspondingly. Fig. 19 shows the sensitivity of water temperature simulations to thermal properties of the sediments. The dotted lines are simulation results using thermal conductivity and diffusivity representative of sand and equal to 2.5 w/(m °C) and 0.068 m^2/day (Andrews and Rodvey, 1980), respectively. Water temperature differences for different thermal conductivities of the sediments can be 1°C to 3°C at the lake bottom.

Changes in the composition of the sediments also alter the SOD rates S_{b20}. The effect of the SOD rate on D.O. simulations in modern Mirror Lake is shown in Fig. 20. The SOD rates, S_{b20}, vary from 0.5 and 2.0 g m^{-2} day^{-1}. Hypolimnetic dissolved oxygen concentrations under larger S_{b20} are much lower than those under smaller S_{b20}. Differences of hypolimnetic D.O. concentrations can be 5 mg/ℓ when doubling of the SOD coefficient. These changes can significantly affect other water quality parameters.

Over the past 14,000 years Mirror lake has significantly changed its morphometry significantly (see Fig. 1). Surface areas and volumes are different as shown in Fig. 21. The lake 14,000 years B.P. had a surface area of 15 ha, and a maximum depth of 23 m. Water temperature response to these different lake morphometries is shown in Fig. 22. The simulations are made with input of identical modern daily weather conditions observed at Concord. The biggest difference is in the hypolimnetic temperature. The simulated hypolimnetic temperatures of 6°C to 11°C for the shallow, modern lake are considerably higher than those for the lake 14,000 years before present (4°C to 6°C). The simulated mixed layer depths are only 1 m different (in later fall). Epilimnetic temperatures are within 0.3°C for the two cases. The response of dissolved oxygen concentrations to two different lake morphometries is shown in Fig. 23. For the modern lake, the representative SOD rate, $S_{b20} = 0.5$ g m^{-2} day^{-1}, is used. Simulations and measurements for 1986 are shown in Fig. 20. S_{b20} in 14,000 B.P. was unknown. Therefore dissolved oxygen simulations were made at different SOD rates as shown in Fig. 23. Metalimnetic dissolved oxygen concentrations with larger S_{b20} are lower than those with smaller S_{b20}. When hypolimnetic dissolved oxygen concentrations were not zero, they were sensitive to SOD rate. Period of anoxia is longer, and percentage of volume with anoxia is larger as SOD rate is larger. Therefore we can conclude that the composition of the sediments, especially organic materials, greatly affect lake water quality and lake ecosystem.

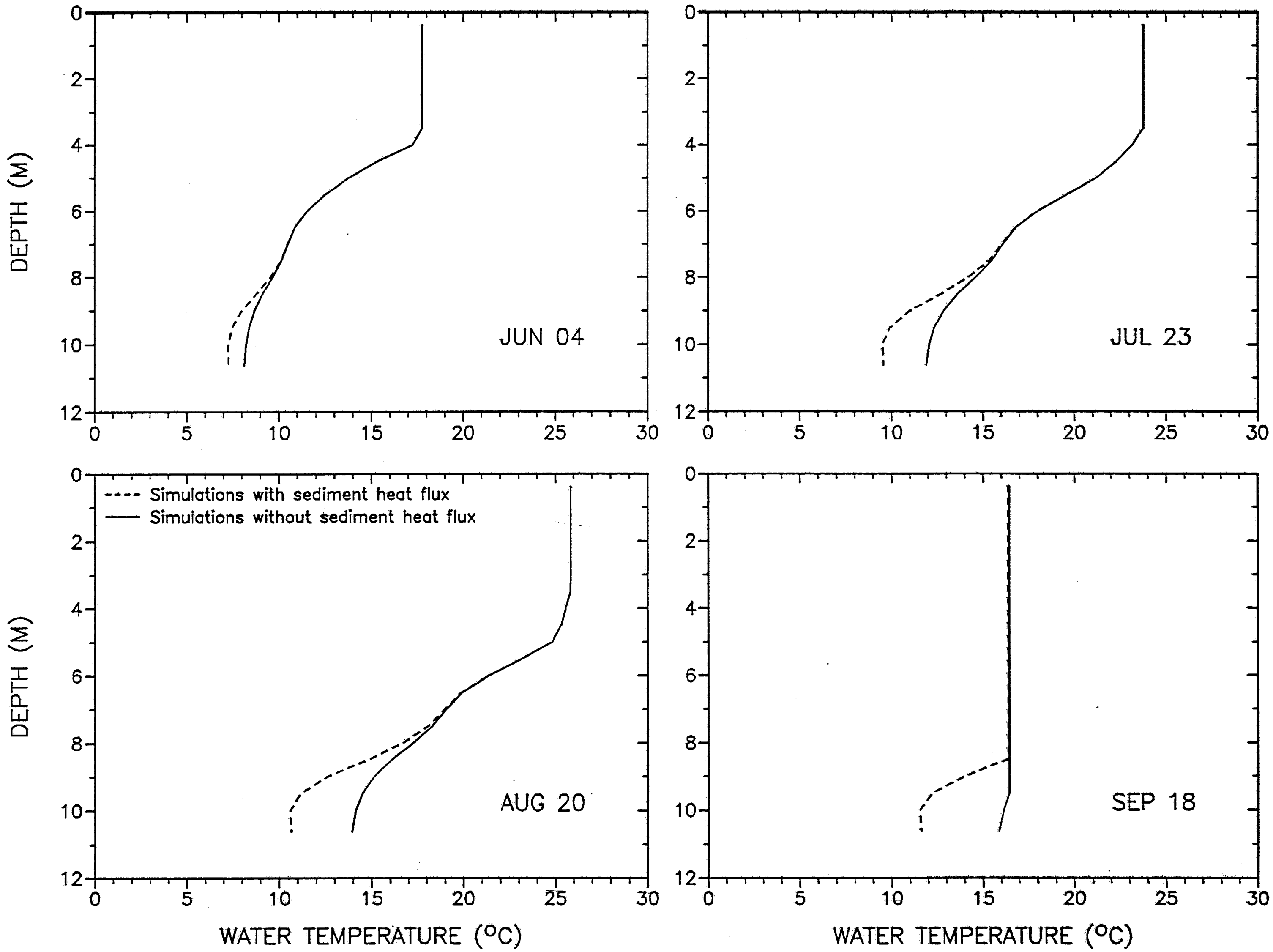


Fig. 18. Water temperature (°C) simulations with and without sediment heat flux at the lake bottom.

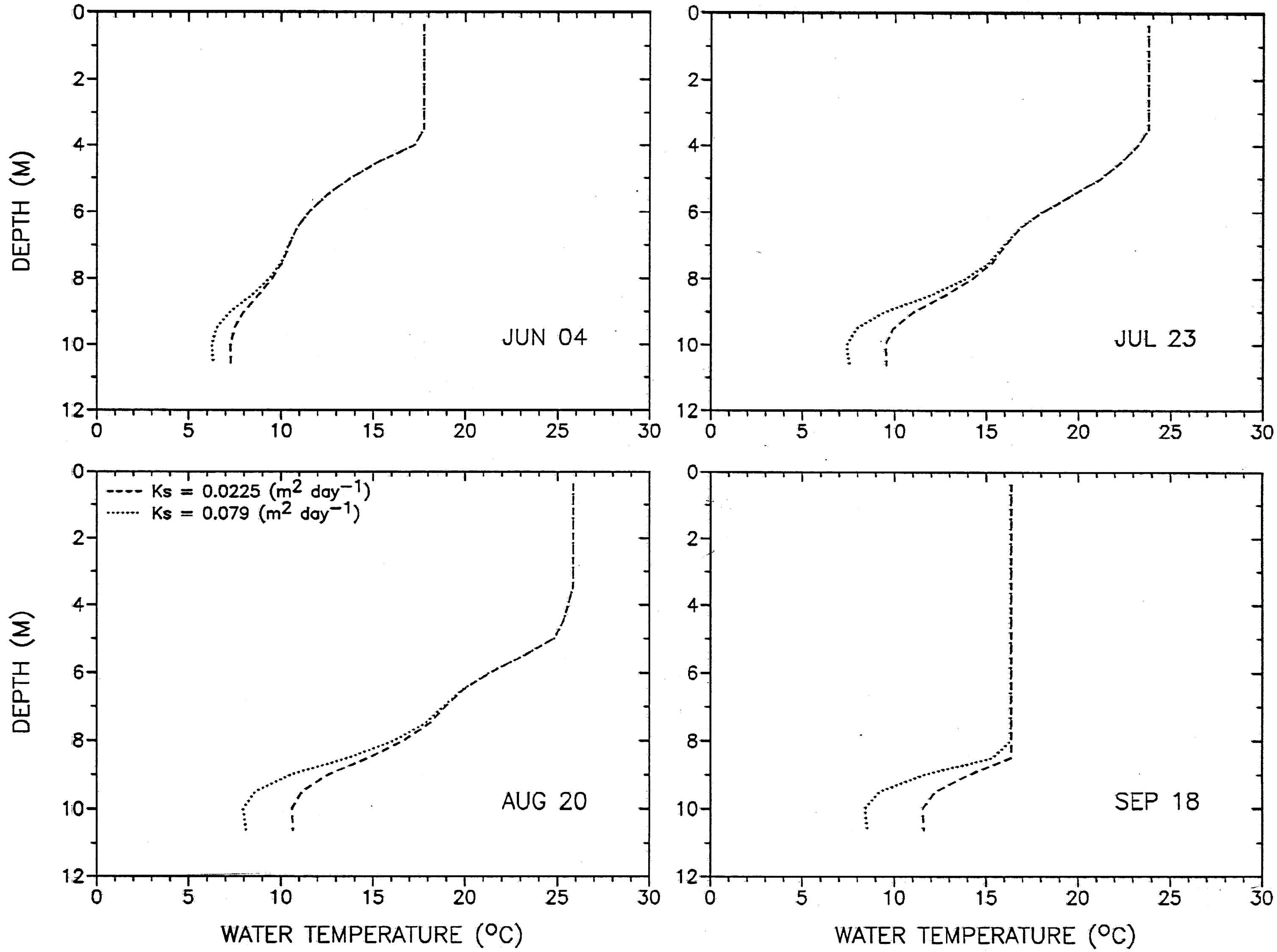


Fig. 19. **Water temperature simulations with different thermal conductivities and diffusivities of the sediments as model input.**

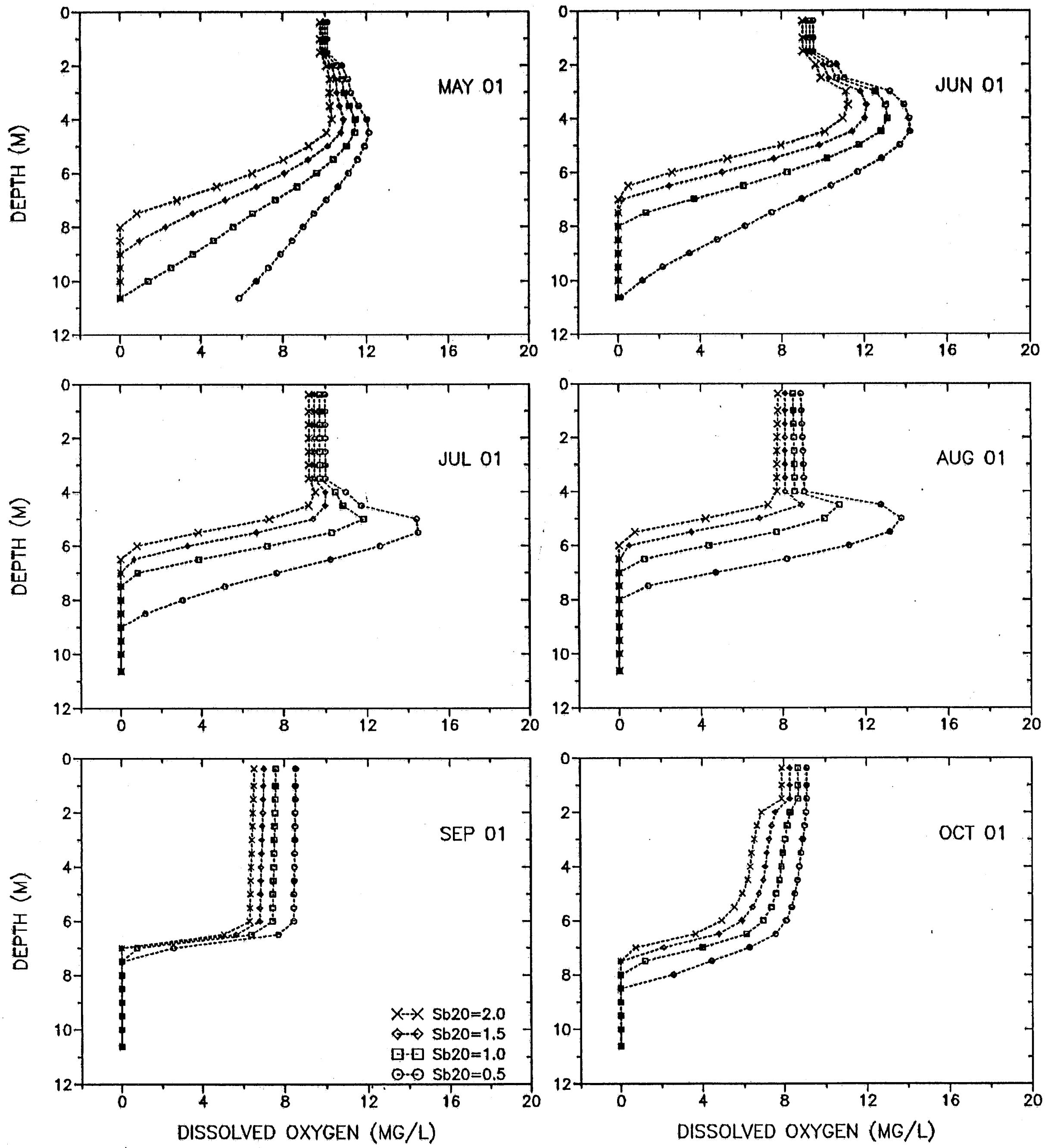


Fig. 20. Dissolved oxygen simulations for modern Mirror Lake with different sedimentary oxygen demand rates as model input.

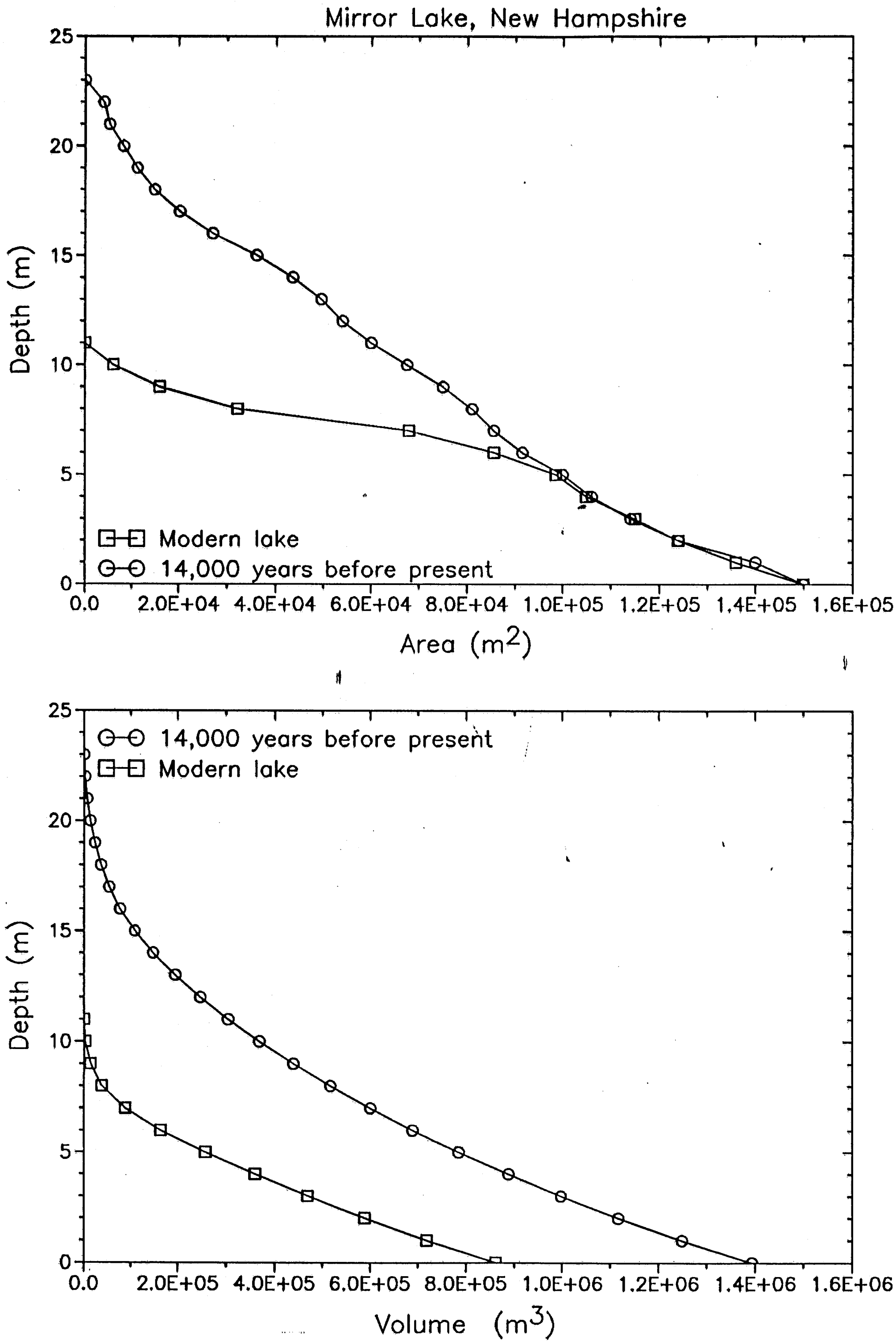


Fig. 21. Area–depth and volume–depth curves of Mirror Lake 14,000 years before present and at present.

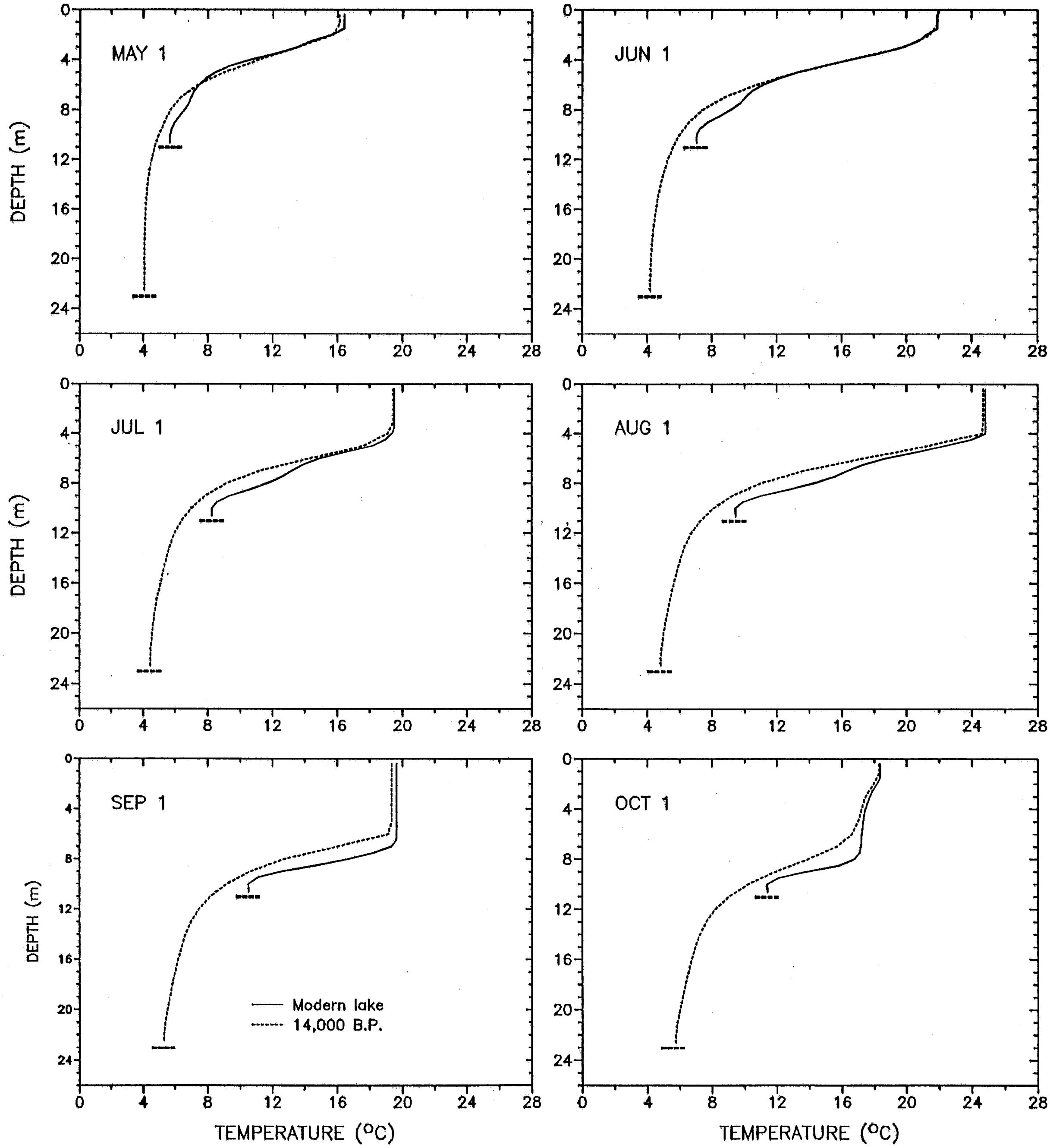


Fig. 22. Water temperature simulations for modern Mirror Lake and 14,000 years before present, using Concord daily weather conditions as model input.

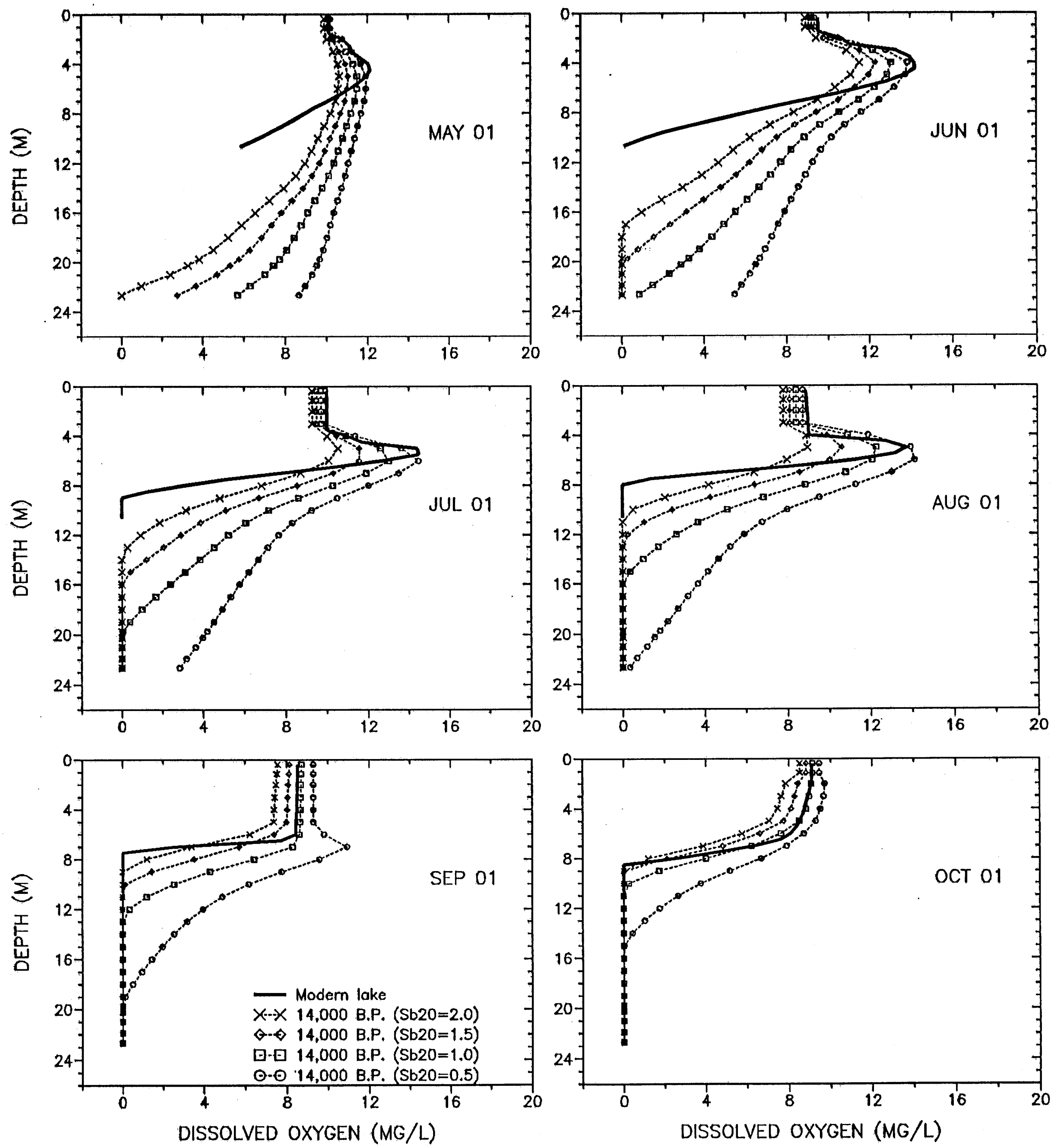


Fig. 23. Dissolved oxygen simulations for modern Mirror Lake and 14,000 years before present, with different sedimentary oxygen demand rates as model input.

VI. PRELIMINARY CONCLUSIONS AND IDEAS FOR FUTURE STUDY

(1) A deterministic, one–dimensional, unsteady numerical simulation model for water temperature and dissolved oxygen was developed. Model input weather parameters are daily mean air temperature, dew point temperature, solar radiation, wind speed, and precipitation. Weather data collected at Mirror Lake (1956–1988) and at Concord, NH, (1948–1990) were assembled. Since wind speeds at the nearest weather station to Mirror Lake appear too small, and solar radiation at Concord is a missing weather parameter, further improvement of the weather database for modern time is necessary.

(2) Wind speed is a key weather parameter to control evaporative and convective heat losses at the lake surface as well as mixing. Sensitivity of water temperature simulations to wind speed (Fig. 17) shows that wind speeds greatly influence epilimnetic temperatures but not hypolimnetic temperatures.

(3) Water temperature and dissolved oxygen simulations of modern Mirror Lake (Figs. 15 and 16) are made with Concord daily weather data as model input. Solar radiation at Concord was estimated from percentage of sunshine. The standard errors between simulations and measurements are 0.9°C and 1.7 mg/ℓ for water temperature and dissolved oxygen, respectively.

(4) Epilimnetic and hypolimnetic water volumes and the time course of stratification throughout a season are the output of the water temperature model. In future study, these results can be coupled with ecological models for Mirror Lake (Lehman *et al.*, 1975). If this is documented for historical weather conditions, the results can possibly be related to sediment core history.

(5) Chlorophyll–a concentrations are model inputs for simulating dissolved oxygen concentrations in modern Mirror Lake. These were obtained from measurements (Fig. 8). In order to investigate multiple effects of climate, morphometry and nutrient loading on lake water quality, a dynamic chlorophyll–a simulation model has to be developed and validated for modern Mirror Lake.

(6) Effect of lake morphometry on water temperature and dissolved oxygen was investigated for two extreme cases (modern lake and 14,000 B.P.) using identical modern daily weather conditions observed at Concord as model input. Figures 22 and 23 show that lake morphometry has an important influence on hypolimnetic water temperatures and dissolved oxygen concentrations. In future studies, epilimnetic/hypolimnetic water temperatures and dissolved oxygen concentrations, mixed layer depths, epilimnetic/ hypolimnetic volumes and areas can be simulated and analyzed for all six morphometries (Fig. 1).

(7) Sediment heat flux is dependent on thermal conductivities and diffusivities of the sediments and has an important influence on hypolimnetic water temperatures (Figs. 18 and 19). Over the past 14,000 years Mirror Lake has experienced changes in sediment composition; consequently, the thermal properties of the sediments have also changed. This historical change of sediment characteristics and its influence on water temperatures needs further exploration in the simulations.

(8) Dissolved oxygen concentrations, especially in the metalimnion and hypolimnion, are sensitive to sedimentary oxygen demand rates as shown in Figs. 20 and 23. More information about sediment composition in the past is necessary as model input to simulate dissolved oxygen concentrations in Mirror Lake more accurately.

(9) Past weather at Mirror Lake was obtained from numerical simulation results with the CCM model (Kutzbach and Guetter, 1987). The database includes ground surface temperature, precipitation, wind speed, wind direction, and sea level pressure in 3000–year intervals. The weather parameters are available only for January and July. In order to simulate past climate conditions, weather data in other months or daily weather parameters are necessary. An uncertainty analysis of the effect of weather parameters on simulated temperature and dissolved oxygen concentrations needs to be performed.

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Appendix A. **Chlorophyll–a Profile in ELA Lakes**

Fee and co–workers (1977, 1978) reported detailed experimental results for 104 ELA lakes by using in vivo fluorometer and transmissometer. The results show that variations of epilimnetic chlorophyll–a concentration are very small. Only the more eutrophic basins have quantitatively important variations of epilimnetic chlorophyll–a. In most cases, chlorophyll–a concentration increases gradually from the surface to the thermocline (Fee, 1978).

A schematic diagram (Fig. A.1, from Fee, 1978) shows the location of the five peaks of chlorophyll–a below the epilimnion with respect to temperature, light, and oxygen. Peak C was first discovered in the 1975 profiles (Fee *et al.*, 1977) and typically occurred at low light levels (about 0.1% of surface light) near the depth where oxygen concentration is close to zero. The peaks of C and D are below the euphotic zone and show no effective contribution to oxygen considering the sedimentary oxygen demand. Peak A was composed predominantly of the colonial flagellated ***chrysophycean*** and occurred at depths of 20% to 10% surface light penetration (Fee, 1978). Peak A was very ephemeral and lasted for a few weeks in late May and early June. Peak A sometimes occurred in both eutrophic lakes (L226NE, L226SW and L302S in ELA) and oligotrophic lakes (L224 in ELA, Fee *et al.*, 1977). Peak B occurred in the most of ELA lakes near the euphotic zone at depths where there was 1% of surface light. Peak S was highly variable in location and persistence and is believed to typically accumulate epilimnion cells from settling (Fee, 1978). Peaks A and S occur less frequently and generally appear less than Peak B. Peaks A, B and S significantly contribute to the metalimnetic oxygen maxima in oligotrophic lakes. There are two points of view in regard to the existence and location of chlorophyll–a peaks (biomass): one is the accumulation of epilimnion cell settlement (Fee *et al.*, 1977) and the other the growth of some particle phytoplankton (*i.e. Oscilatoria*) in the metalimnion (Wetzel 1983; Cole 1983).

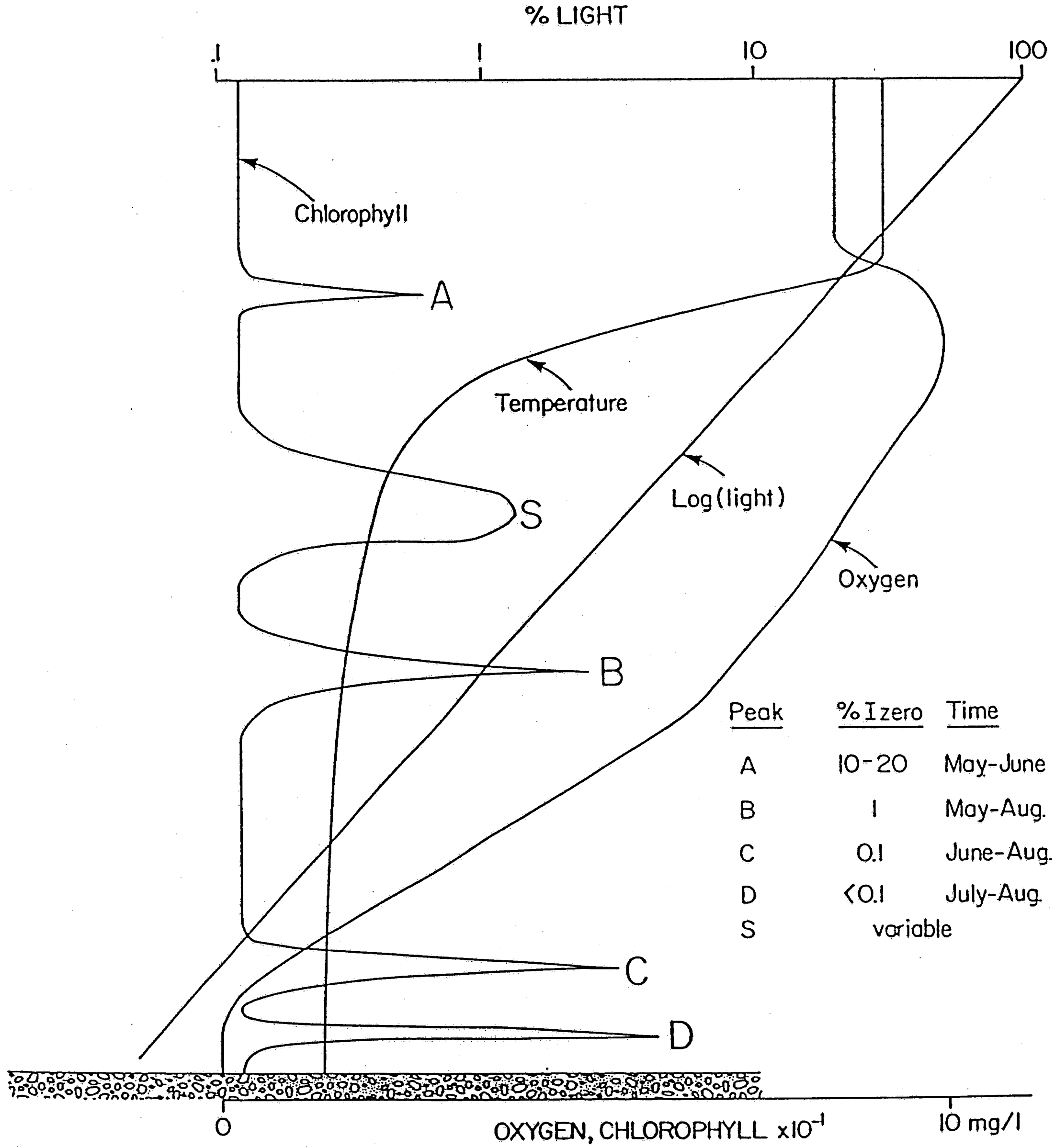


Fig. A.1 Schematic summary of the chlorophyll peaks observed in 1976 together with the relation of these peaks to temperature, light and oxygen. The letters "A", "B", "C", "D" and "S" are used in the text to identify the peaks (from Fee 1976).

Appendix B Estimation of Solar Radiation at Concord

Figure B.1 shows a comparison of mean monthly values (dashed line) of solar radiation calculated from equation [5] (Baker and Haines, 1969) for Concord, NH, 1986 (top) and 1987 (bottom) and values measured at Mirror Lake, NH (Federer *et al.*, 1990) (solid circles). Correlation coefficients between the estimations and the measurements are 0.996 and 0.998 for 1986 and 1987, respectively. Therefore weather data at Concord, NH, which include daily solar radiation estimated by equation [5] were used to simulate water temperatures and dissolved oxygen concentrations in Mirror Lake in 1986 and 1987, even though coefficients a and b had to be taken from East Lansing, MI, which is about 700 miles away from Mirror Lake.

CLIGEN (The WEPP CLImate GENerator Program) (Nicks and Gander, 1989) is another available climate information source which can be used to generate weather data at Concord, NH. CLIGEN uses all available past weather data from class A weather stations in the United States. CLIGEN can generate synthetic single or multiple year weather data, including daily maximum and minimum air temperature, dew point temperature, solar radiation, wind speed, wind direction, and precipitation.

Mean monthly values (solid line) of solar radiation at Concord, NH, in 1986 and 1987 estimated from the CLIGEN model are compared to values measured at Mirror Lake, NH (Federer *et al.*, 1990) (solid circles) in Figure B.1. Monthly averaged solar radiation generated by CLIGEN is lower for the first three months, and higher for the remaining nine months in 1986 than that estimated by Baker and Haines' model. Correlation coefficients between output by the CLIGEN model and measurements at Mirror Lake are 0.989 and 0.992 for 1986 and 1987, respectively.

Weekly and daily average values of solar radiation at Concord, NH, in 1986 (top) and 1987 (bottom) generated by CLIGEN are compared to those estimated by Baker and Haines's model in Figures B.2 and B.3, respectively. Correlation coefficients between output by Nicks and Gander's CLIGEN model and output by Baker and Haines' model are 0.974 and 0.976 for weekly values, and drop to 0.529 and 0.613 for daily values of solar radiation in 1986 and 1987, respectively.

Since solar radiation data estimated by the two models are not significantly different, CLIGEN weather data may not be particularly useful for model simulations at Mirror Lake in the future. CLIGEN generated a synthetic time series from statistical parameter values; therefore, uncertainty of simulation results using weather data generated by CLIGEN needs further investigation. The Baker and Haines' model uses daily measured sunshine values and is, therefore, tied to an actual observation made on each day, although it is not the desired parameter solar radiation. For 1986 and 1987, it does not seem justified to repeat any simulations for Mirror Lake by using weather data generated by CLIGEN at present.

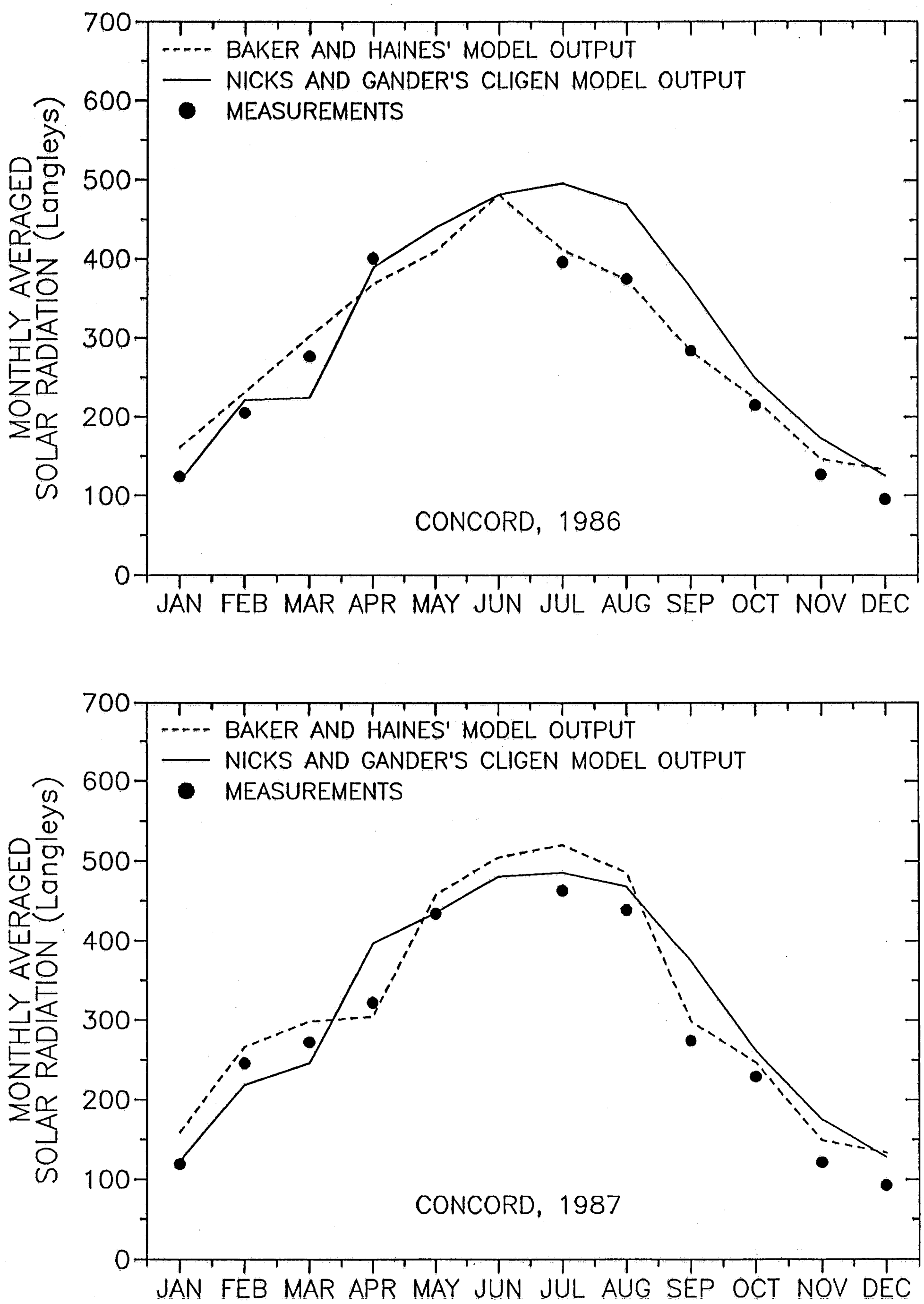
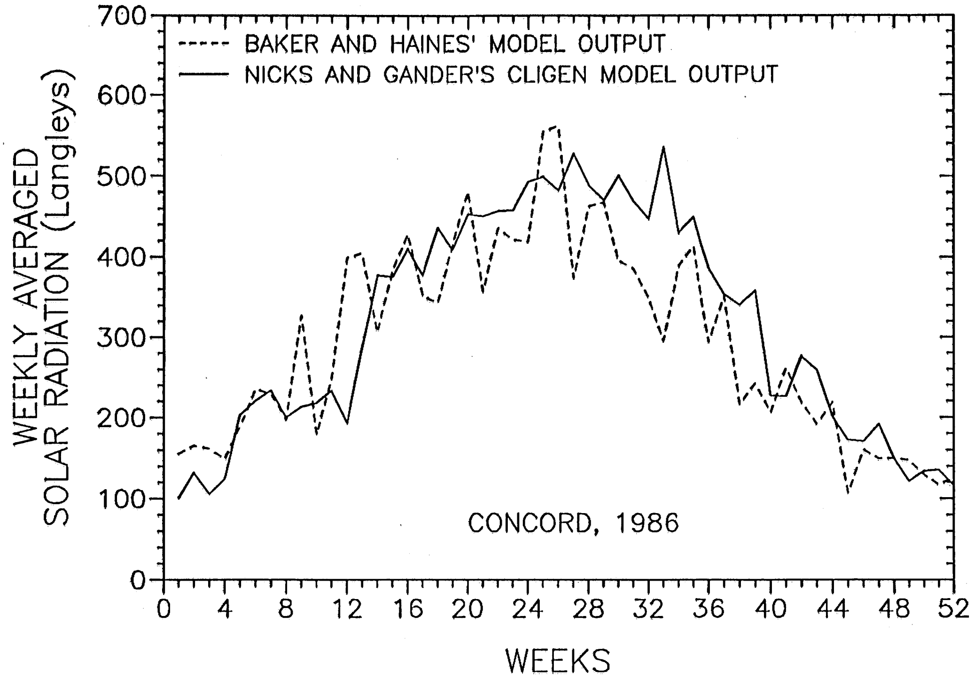


Fig. B.1 Monthly averaged measured solar radiation at Mirror Lake compared to monthly averaged solar radiation at Concord, NH, in 1986 (top), 1987 (bottom) estimated by Baker and Haines' (1969) model and Nicks and Gander's (1989) CLIGEN model, respectively.



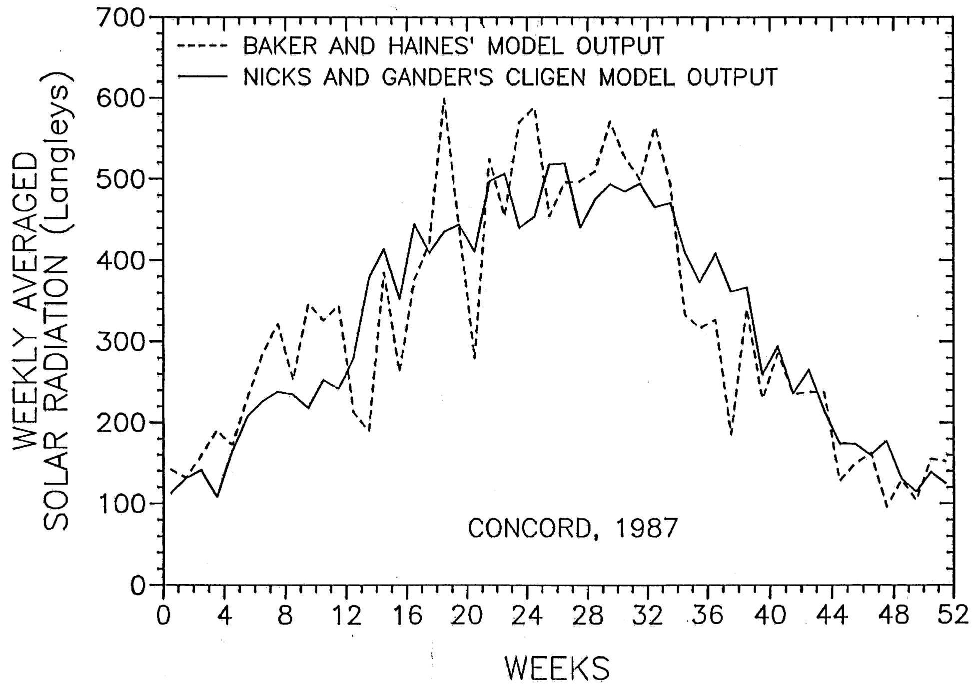


Fig. B.2 A comparison of weekly averaged solar radiation at Concord, NH, in 1986 (top), 1987 (bottom) estimated by Baker and Haines' model (1969) and Nicks and Gander's CLIGEN model (1989), respectively.

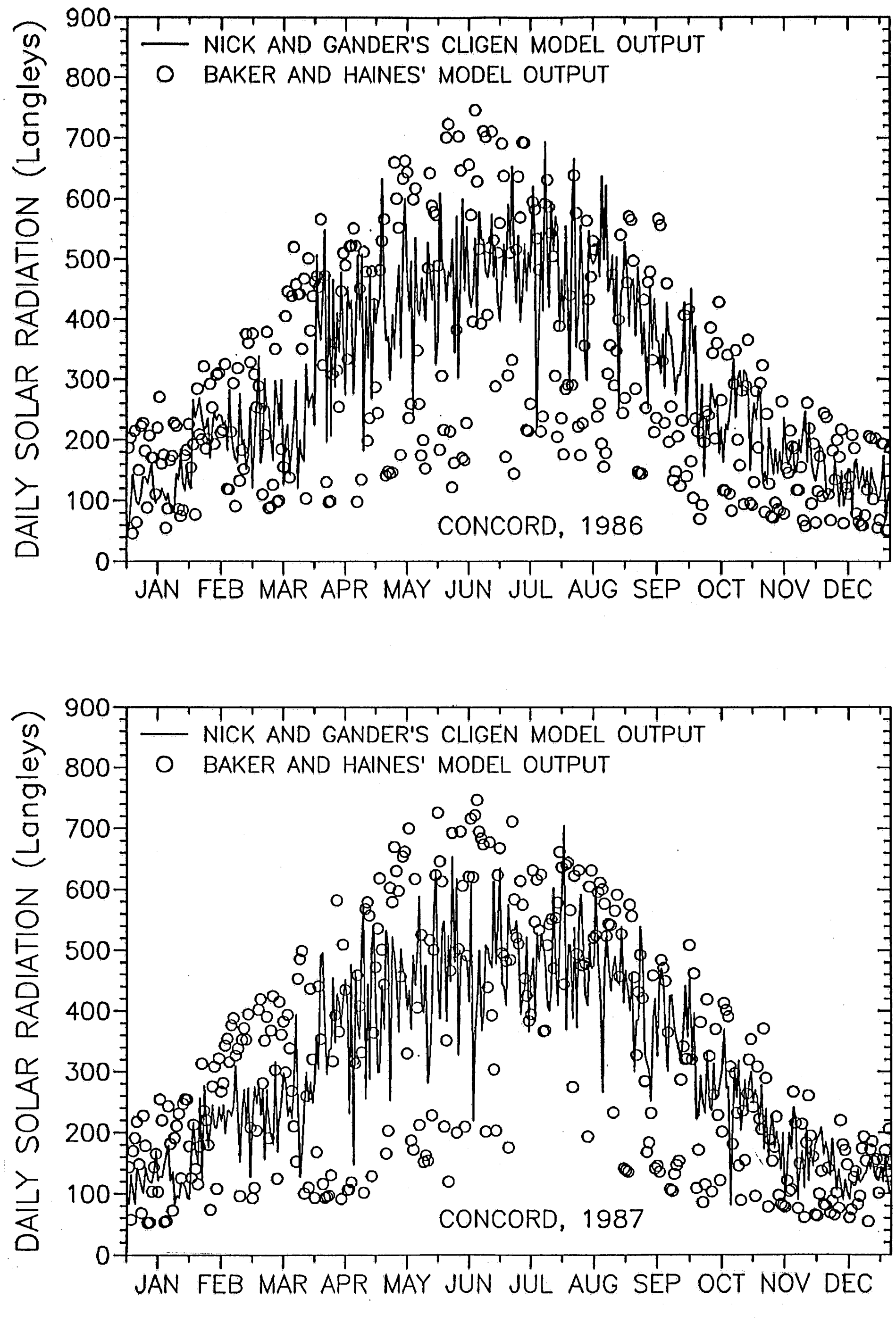


Fig. B.3 A comparison of daily solar radiation at Concord, NH, in 1986 (top), 1987 (bottom) estimated by Baker and Haines' model (1969) and Nicks and Gander's CLIGEN model (1989), respectively.