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Evaporation determined by the energy-budget method for Mirror Lake, New Hampshire

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Abstract

Evaporation was determined by the energy-budget method for Mirror Lake during the open water periods of 1982–1987. For all years, evaporation rates were low in spring and fall and highest during the summer. However, the times of highest evaporation rates varied during the 6 yr. Evaporation reached maximum rates in July for three of the years, in June for two of the years, and in August for one of the years. The highest evaporation rate during the 6-yr study was 0.46 cm d^{-1} during 27 May–4 June 1986 and 15–21 July 1987. Solar radiation and atmospheric radiation input to the lake and long-wave radiation emitted from the lake were by far the largest energy fluxes to and from the lake and had the greatest effect on evaporation rates. Energy advected to and from the lake by precipitation, surface water, and ground water had little effect on evaporation rates. In the energy-budget method, average evaporation rates are determined for energy-budget periods, which are bounded by the dates of thermal surveys of the lake. Our study compared evaporation rates calculated for short periods, usually ~1 week, with evaporation rates calculated for longer periods, usually ~2 weeks. The results indicated that the shorter periods showed more variability in evaporation rates, but seasonal patterns, with few exceptions, were similar.

Determination of evaporation by the energy-budget method requires costly instrumentation and a large commitment of personnel for fieldwork and data processing. For these reasons, energy budgets have been done most commonly for large reservoirs in arid and semiarid regions, where the management of limited water resources has justified the time and expense involved. For smaller lakes, estimates of evaporation generally are made as part of lake-water balances, which are needed for calculation of chemical budgets and management of lake ecosystems. Evaporation usually is determined by less costly empirical methods in such studies because interest and expenditure of funds primarily is on chemical and biological aspects of lakes. A limitation of using empirical methods for estimating evaporation is the lack of knowledge of the uncertainties associated with a given method.

The energy-budget method is considered to be one of the best methods for determining evaporation for extended periods (Harbeck et al. 1958; Gunaji 1968; Brutsaert 1982). The eddy correlation method is more direct, but until recently it could not be used for long-term monitoring because the instruments could not be used in all types of weather. Energy-budget studies of small lakes in various types of landscapes in humid climates are needed to provide a basis for evaluation of the empirical methods that have been used. Energy-budget studies have been done of two small lakes in glacial terrain in the midwestern United States: Pretty Lake in Indiana (Ficke 1972) and Williams Lake in Minnesota (Sturrock et al. 1992) and a lake in mantled karst, Lake Lucerne, in Florida (Lee and Swancar 1997). No study using instrumentation similar to the above studies has been done of a small lake in New England, even though there are >10,000 lakes in that region between 0.5 and 100 ha in size (Charles 1991). With this many lakes, it was felt that an energy-budget study would be useful as a baseline for evaluating empirical methods for determining evaporation and for comparison with the energy-budget studies of small lakes

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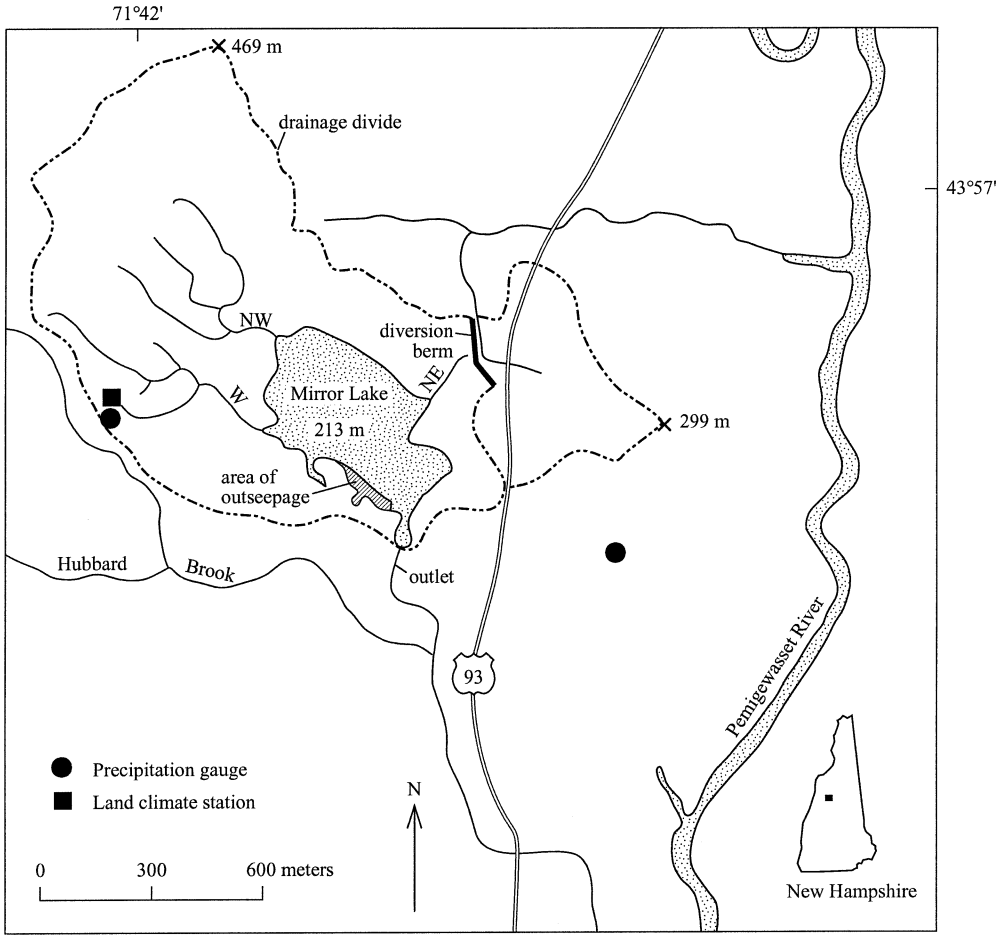


Fig. 1. Mirror Lake, its watershed, and location of land-based climate stations.

conducted in the midwestern United States and Florida mentioned above. Comparisons across different climatic and hydrogeologic settings are needed particularly to evaluate the effects of advected fluxes of energy on evaporation. An energy-budget study of Mirror Lake in New Hampshire had been done previously (Johnson et al. 1985), but that study was done before extensive instrumentation was installed in the late 1970s and early 1980s to measure atmospheric water, ground water, and surface-water fluxes directly at the lake.

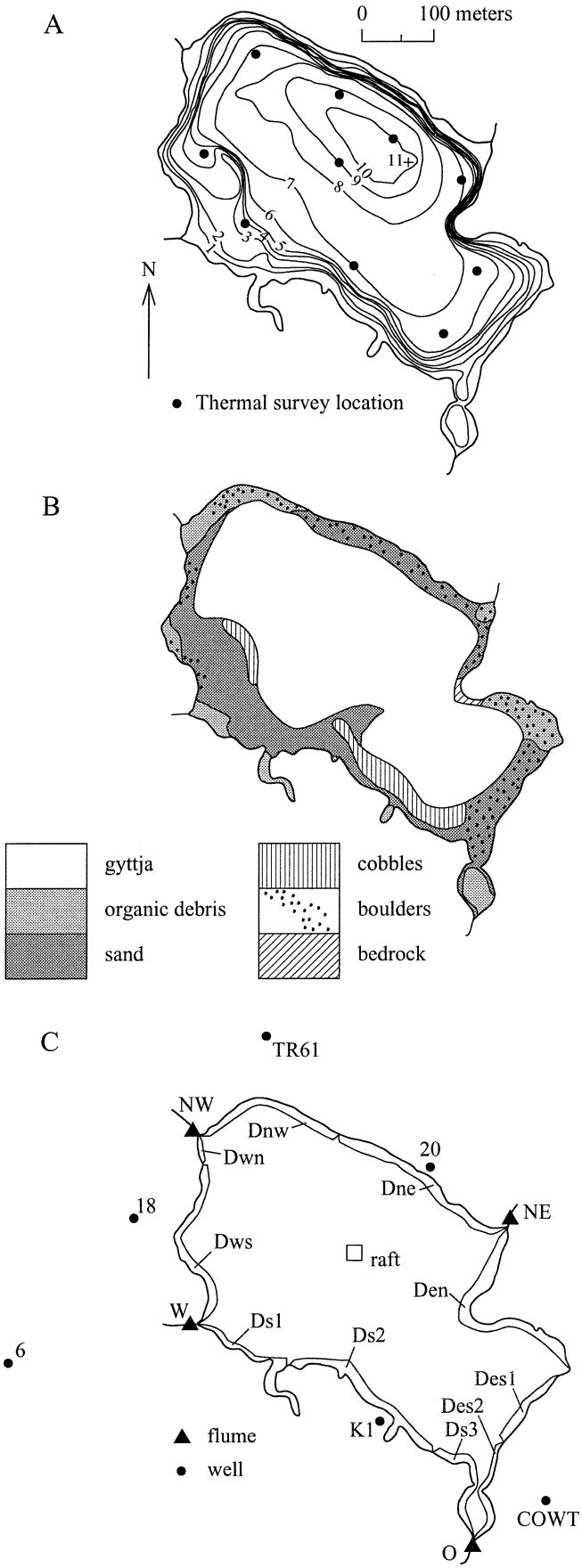
To address the need for energy-budget studies of small lakes in a number of different landscapes and climatic settings, the U.S. Geological Survey's Hydrology of Lakes project, in collaboration with scientists of Cornell University and the Institute of Ecosystem Studies, Millbrook, New York, conducted an energy-budget study of Mirror Lake. The 6-yr study extended from 1982 through 1987. The purpose of the present article is to present the results of this recent evaporation study of Mirror Lake, including an evaluation of some of the terms that make up the energy-budget equation.

Physical and climatic setting and characteristics of Mirror Lake

Mirror Lake is located at the lower end of the Hubbard Brook Valley in the White Mountains of New Hampshire (Fig. 1) (Likens 1985). The drainage basin of the lake is characterized by steep land slopes on the north and west sides and gentle slopes on the east and south sides. The highest point on the watershed is 469 m above sea level. Two streams, northwest and west, that drain ~70% of the lake's drainage basin flow into the west side of Mirror Lake. A third inlet stream, northeast, drains a very small part of the east side of the lake. Most of the water draining the east watershed of the lake is diverted by a berm that was placed upstream of the lake during construction of Interstate Highway 93 (Winter 1985; Rosenberry et al. 1999).

Bedrock underlying the Mirror Lake area consists of fractured crystalline rocks. Glacial deposits overlying the bedrock throughout all of the area except part of the south side of the lake consist largely of silty, sandy till, a heterogeneous mixture of geologic material ranging in size from clay to boulders. Glacial deposits on the south side of the lake consist of sand and gravel that fill a buried bedrock valley. The thickness of the glacial deposits ranges from zero to only a few meters in the higher parts of the drainage basin to as much as 30 m in the lower part. Glacial deposits are as thick as 53 m directly north of the lake.

The climate of the Mirror Lake area is classified as humid continental (Trewartha 1954), which is characterized by short, cool summers and long, cold winters. Mean air tem-



perature in July is 19°C, and in January it is −9°C (Federer 1973). During the evaporation season, continental air masses move into the area, mostly from the southwest. However, at times, cyclonic disturbances move up the east coast, providing an occasional source of maritime air (Likens and Bormann 1995). Average annual precipitation (1963–1993) is ~1,400 mm. In general, the greatest surface water inflows to the lake are in spring as a result of snowmelt and spring rains.

Mirror Lake is a dimictic, oligotrophic lake. The surface area of the lake is ~150,000 m^2, and its volume is ~862,000 m^3 at a surface altitude of 213 m above sea level, which is the approximate altitude of the spillway. Maximum depth of the lake is ~11 m, and the average depth is 5.75 m (Winter 1985). Secchi transparency is ~5.5 m. The lakebed is shaped somewhat like an asymmetric cone, the deepest part being closer to the north shore than to the south shore (Fig. 2A). The central part of the lakebed below a water depth of ~5 m is covered with soft organic deposits. Sediments in the littoral zone on the south side of the lake consist largely of sand and scattered cobbles (Fig. 2B). Sediments in the littoral zone in the remainder of the lake consist of boulders in a silty, sandy matrix.

Methods

Instrumentation and field methods—Instrumentation to measure atmospheric parameters at Mirror Lake consisted of land and raft stations. The raft station (Fig. 2C) consisted of the following primary instruments: (1) anemometers positioned at 1, 2, and 3 m above the water surface to measure wind speed; (2) a thermistor positioned beneath the raft, submerged within 1 cm of the lake surface, to measure water surface temperature; and (3) a thermistor psychrometer positioned at 2 m above the water surface to measure air temperature and vapor pressure. This latter instrument consists of dry-bulb and wet-bulb thermistors. The wet bulb was kept moist by a wick extending into a reservoir of water at the bottom of the unit. Output from these primary sensors was recorded by a digital data logger programmed to scan the sensors every minute and calculate and store hourly and daily averages, as well as the maximum and minimum values and the time they occurred for each day. Secondary analog instruments also were on the raft to provide backup data for wind speed and water temperature.

The land station (Fig. 1) consisted of the following primary instruments: (1) a precision spectral pyranometer to measure incoming short wave solar radiation and (2) a precision infrared radiometer (pyrgeometer) to measure incoming long-wave atmospheric radiation. Data from these instruments also were recorded by a digital data logger

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Fig. 2. Maps of Mirror Lake showing (A) bathymetry and locations of thermal survey stations, (B) geology of the lakebed, and (C) location of raft-based climate station, flumes, wells, and segments of shoreline for determination of groundwater fluxes to and from the lake. Map A is modified from Likens et al. (1985) and map B is modified from Moeller (1978).

programmed like that on the raft. In addition, an analog hygrothermograph was located near the lake shore to provide backup data on air temperature and relative humidity. Precipitation was measured by two pairs of recording and standard volumetric rain gauges (Federer 1990) within half a kilometer of the lake, one each east and west of the lake (Fig. 1).

Continuous records of lake stage were collected using an analog strip chart recorder. Continuous records of discharge of the three inlet streams and the outlet (Fig. 2C) were collected using Parshall flumes equipped with analog strip chart recorders. Discharge from the lake was calculated using a statistical relation of lake stage to discharge measured by a Parshall flume in the stream channel ~10 m downstream of the dam. This method was necessary because the flume was installed after the energy-budget data were collected. Streamwater temperatures were measured continuously using analog disk chart recorders.

Water table wells (Fig. 2C) were drilled using a truck mounted power auger or by a mud rotary drill. The holes were drilled to a depth <1 m below the water table, casing with a well screen attached at its base was lowered into the drilled hole, and sand was packed around the screen if the hole was drilled into till. If the hole was drilled into sand, sand collapsed around the screen below the water table. The annular space between the casing and drill hole wall above the screen was back filled with drill cuttings.

Thermal surveys were done approximately weekly during the open water season. A thermal survey consisted of measuring lake water temperature at the surface, at a depth of 0.5 m, and at 1-m intervals through the water column. Measurements were made at 10 widely spaced locations in the lake where the water was >4 m deep (Fig. 2A).

Energy-budget equation and measurement or calculation of terms—An energy budget for a body of water relates net transfer of energy to and from the water body to the change in energy stored in the water body. The energy budget can be expressed as (Sturrock 1978; Lee and Swancar 1997)

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w - Q_b = Q_x \quad (1)$$

where Q_s is the incoming short-wave solar radiation, Q_r is the reflected short-wave solar radiation, Q_a is the incoming long-wave atmospheric radiation, Q_{ar} is the reflected long-wave atmospheric radiation, Q_{bs} is the long-wave atmospheric radiation emitted from the body of water, Q_v is the net energy advected to the body of water by precipitation, ground water, and surface water, Q_e is the energy used for evaporation, Q_h is the energy conducted from the water as sensible heat, Q_w is the energy advected from the body of water to the atmosphere by the evaporated water, Q_b is the heat transfer from the water to the bottom sediments, and Q_x is the change in energy content of the body of water.

The three terms of Eq. 1 that are not measured directly, Q_e, Q_h, and Q_w, were calculated as functions of the evaporation rate by using the following relationships:

$$Q_e = \rho E_{eb} L \quad (2)$$

$$Q_h = R Q_e \quad (3)$$

$$Q_w = c\rho E_{eb}(T_e - T_b) \quad (4)$$

where ρ is the density of evaporated water (1 g cm^{-3}); E_{eb} is the energy-budget evaporation rate (cm d^{-1}); L is the latent heat of vaporization of water (cal g^{-1}); R is the Bowen ratio (dimensionless); c is the specific heat of water (1 cal g^{-1} °C^{-1}); T_e is the temperature of the evaporated water, presumed to be equal to the water surface temperature T_o (°C); and T_b is an arbitrary base temperature of 0°C. By selecting an arbitrary base temperature of 0°C, $T_e - T_b$ equals water surface temperature T_o.

To calculate the evaporation rate using the energy-budget method for a specific time interval, Eq. 1 has the following form (Ficke 1972; Sturrock 1978):

$$E_{eb} = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_y - Q_x - Q_b}{\rho[L(1 + R) + cT_o]} \quad (5)$$

Values for each term in Eq. 5 were determined as described below. Incoming short-wave solar radiation, Q_s, was measured directly by the precision spectral pyranometer. Reflected short-wave radiation, Q_r, was calculated using the Anderson (1954) method described by Koberg (1964). Incoming long-wave atmospheric radiation, Q_a, was measured directly by the pyrgeometer. When the sensor malfunctioned, which was only for a few weeks during the study, incoming atmospheric radiation was calculated using a modified form of the Brunt (1944) equation:

$$Q_a = (c + d\sqrt{e_a})\sigma T_a^4 \quad (6)$$

where Q_a is the incoming long-wave atmospheric radiation (cal cm^{-2} d^{-1}); σ is the Stefan Boltzman constant (1.171×10^{-7} cal cm^{-2} d^{-1} K^{-4}); T_a is the air temperature (°K); c is a dimensionless constant (not the specific heat of water noted above) selected from a plot in Koberg (1964) using air temperature and the ratio of measured short-wave radiation to calculated clear sky radiation; d is a constant of 0.0263 (mbar$^{-1/2}$) determined in Koberg (1964); and e_a is the vapor pressure of the air (mbar). The Brunt equation was used to fill in values of Q_a for only a few weeks during the study period. A comparison of calculated values and measured values during times when the sensor was functioning well indicated that the calculated values were within 1% of the measured values.

Reflected long-wave atmospheric radiation, Q_{ar}, was calculated as 3% of incoming atmospheric radiation, which was determined by Gier and Dunkle (Anderson 1954). Long-wave radiation emitted from the water surface was calculated from

$$Q_{bs} = \varepsilon\sigma T_o^a \quad (7)$$

where Q_{bs} is the emitted flux (cal cm^{-2} d^{-1}); ε is the emissivity of the water surface, taken as 0.97 (dimensionless); σ is the Stefan Boltzman constant; and T_o is the water surface temperature (°K).

Emitted radiation is controlled primarily by the temperature of the upper few microns of lake water. Surface temperature is difficult to measure at this fine scale. However,

the lake surface is seldom calm enough to result in a sharp temperature gradient in the upper few mm of the water. Therefore, it was assumed that measurement of the water temperature within the top cm of lake water was an adequate estimate for the actual temperature of the water surface.

Net energy advected to the lake, Q_v, was calculated by determining the heat brought into the lake by precipitation, stream flow, and ground water and the heat lost from the lake by surface outflow and seepage to ground water.

$$Q_v = \frac{c\rho qT}{A} \tag{8}$$

where q is water flux ($m^3\ d^{-1}$), T is the temperate of water fluxes to and from the lake (°C), and A is the area of the lake (m^2). Thus, to calculate Q_v, it was necessary to calculate the volume and measure the temperature of water for each of the inflow and outflow components. Precipitation temperature was assumed to be equivalent to the wet bulb temperature at the time of precipitation (Sturrock et al. 1992; Johnson et al. 1985). Streamwater temperatures were measured directly. Groundwater volumes were determined using the Darcy equation (Freeze and Cherry 1979).

$$q_{GW} = KIA \tag{9}$$

where q_{GW} is the groundwater discharge ($m^3\ d^{-1}$); K is the hydraulic conductivity ($m\ d^{-1}$); I is the hydraulic gradient (dimensionless); and A is the cross-sectional area through which the seepage to and from the lake occurs (m^2).

Calculations of groundwater flux were made by dividing the lake perimeter into 10 segments. The segments were determined by the position of the six wells (Fig. 2C) that were used as index wells for calculation of hydraulic gradients. The hydraulic gradient between the water table at that well and the lake surface was assumed to represent the gradient for that segment. For the sandy areas on the south side of Mirror Lake, a hydraulic conductivity of 4.0 $m\ d^{-1}$ was used for segment Ds2, and 5.2 $m\ d^{-1}$ was used for segment Ds3. For all the other segments, which are areas of till, a hydraulic conductivity of 0.1 $m\ d^{-1}$ was used. Hydraulic conductivity was determined by single-well aquifer tests, commonly referred to as slug tests. Area was determined by multiplying the length of shoreline for a given segment by the average thickness of the saturated glacial deposits in that segment. Only a few groundwater levels were continuously recorded—most were measured approximately weekly—therefore, calculations of groundwater flux were made for blocks of time centered on the date of the discrete measurements.

Temperature of groundwater seepage to the lake was estimated to be the same as the average annual air temperature. Temperature of water seeping from the lake was assumed to be equal to the temperature of the lake's water surface. This assumption was confirmed by installing a temperature sensor in a water table well within a meter of the lake shore. The well has a screen length of nearly half a meter; therefore, under the assumption of a largely horizontal flow, the temperature of the water in the well probably is an average of about the top half-meter of lake water. A comparison of daily values of lake water temperatures and groundwater temperatures over a 2-yr period indicated that they differed by an average of 0.15°C. The difference in temperatures was even less during most of the two summers, when evaporation rates are highest.

Heat stored in the lake and the change in heat stored from one thermal survey to the next, Q_x, were calculated from the thermal surveys. A thermal survey consisted of taking a vertical profile of water temperature at 10 locations in the lake (Fig. 2A). At each location, temperature measurements were made at the lake surface, at depths of 0.5 and 1.0 m, at 1-m intervals to near the bottom and at the lake bottom. The time interval between thermal surveys, termed energy-budget periods, are shown in Web Appendix 1 at http://www.aslo.org/lo/toc/vol_48/issue_3/0995a1.pdf. The average quantity of heat stored in the lake was calculated by dividing the lake into horizontal layers. The layers were determined by the number of depths at which temperature readings were taken, and the temperatures were considered to be the midpoint of the layer. The temperatures from all stations at a given layer were averaged to obtain the total heat in the layer, and the total heat in the lake was obtained by totaling the heat in the layers. Areal variability of temperatures within the layers, except for the layer that contained the thermocline, was generally <1°C. Within the thermocline layer, temperatures could range over several degrees Celsius. The volume, V, was calculated by summing a series of truncated irregular cones representing the layers using

$$V = \frac{h}{3}(A_1 + A_2 + \sqrt{A_1A_2}) \tag{10}$$

where h is the vertical thickness of the layer (m), $A1$ is the area of the upper surface of the layer (m^2), and $A2$ is the area of the lower surface of the layer (m^2).

Heat flux through the bottom sediments, Q_b, was computed for the energy-budget periods by using the equation described by Pearce and Gold (1959), which states

$$Q_b = \sin[(2\pi/P) \times t']Q_{max} \tag{11}$$

where P is the length of the year (365 d), t' is the time after start of sine wave which was at ice out each year (d), and Q_{max} is the maximum heat flux (cal $cm^{-2}\ s^{-1}$). Maximum heat flux, Q_{max}, was calculated from

$$Q_{max} = T_s k(2\pi C_v/PK)^{1/2}(8.64 \times 10^4) \tag{12}$$

where T_s is the amplitude of temperature variation at the sediment-water interface (°C), k is the thermal conductivity (estimated as 0.00235 cal $cm^{-1}\ s^{-1}\ °C^{-1}$), C_v is the volumetric heat capacity (estimated as 0.77 cal $cm^{-3}\ °C^{-1}$), and P is the period of temperature variation (1 yr) (s); 8.64×10^4 is the number of seconds in a day.

The method for calculating Q_b presented above was used to be consistent with the methodology that has been used at other lakes studied by the USGS Hydrology of Lakes Project (Sturrock et al. 1992; Parkhurst et al. 1998). Johnson et al. (1985) also calculated energy transfer between the water and sediments of Mirror Lake. Their method also involved use of an annual sine function. Similar to the present study reported herein, Johnson et al. (1985) also indicated that Q_b is only a few W m^{-2}.

The Bowen ratio, R, was calculated from Harbeck et al. (1958),

$$R = \frac{cP(T_o - T_a)}{[(e_o - e_a)]} \tag{13}$$

where c is an empirical constant (°C^{-1}), T_o is the temperature of the water surface (°C), T_a is the temperature of the air (°C), e_o is the vapor pressure of saturated air at the temperature of the water surface (mbar), e_a is the vapor pressure of the air (mbar), and P is the atmospheric pressure (mbar), which was calculated from the altitude of the lake.

The constant c was determined by Bowen (1926) to vary from 0.58°C to 0.66°C. The value of 0.61°C used here was justified by evaluation of this constant in the Lake Hefner studies (Harbeck 1962). The value of 0.61 for the constant c was also found to be appropriate for the energy-budget study of Williams Lake, Minnesota (Sturrock et al. 1992). Atmospheric pressure was estimated as a function of altitude as in Berry et al. (1945).

For each term in the energy-budget equation, daily values were calculated then averaged over the energy-budget period. Using the above equations results in energy flux values in units of cal cm^{-2} d^{-1}. However, throughout our article, all energy fluxes are reported as W m^{-2}.

Direct measurement or calculation of the flux terms in the energy-budget equation have various amounts of uncertainty. Harbeck et al. (1958), for Lake Mead, and Gunaji (1968), for Elephant Butte reservoir, evaluated errors in each term of the equation, and both reported that the largest fluxes Q_s, Q_a, and Q_{bs} have estimated maximum error of 2%. Gunaji indicated that errors in the Bowen ratio could be 10%, and Harbeck et al. indicated it could be as high as 20% when applied to the entirety of Lake Mead. Both studies indicated that errors in advected energy could be ~10%, but neither study considered groundwater fluxes. Both studies reported that the overall effect of the errors in the individual terms resulted in an estimated error in computed evaporation of 10%–15%. Lee and Swancar (1997) did a first-order error analysis in their study of Lake Lucerne in Florida and found results similar to Harbeck et al. and Gunaji for the same estimates of error in the major individual fluxes.

The Lake Lucerne and Mirror Lake studies were designed similarly, including using the same types of instruments and instrument deployment, and they both followed the lead of Harbeck et al. (1958). The difference in the Lake Lucerne and Mirror Lake studies is that ground water was considered. Lee and Swancar (1997) determined that errors in estimates of groundwater fluxes were near 100%. Winter (1981) indicated that errors in estimates of groundwater fluxes to and from lakes commonly is between 50% and 100%. Given an uncertainty of 100% for groundwater, fluxes would not change the overall error in computed evaporation by much because heat energy fluxes to and from groundwater are small, as described later. Indeed, uncertainty in estimates of all of the advected fluxes, including precipitation, stream flow, and ground water, have little effect on estimates of evaporation because they all are small. In a first-order error analysis, large errors in small numbers generally have little effect on the overall uncertainty. As a result, we believe the uncertainty in the values of evaporation reported herein are in the 10%–15% range and are probably closer to 10% because of the high quality of the instruments that were used

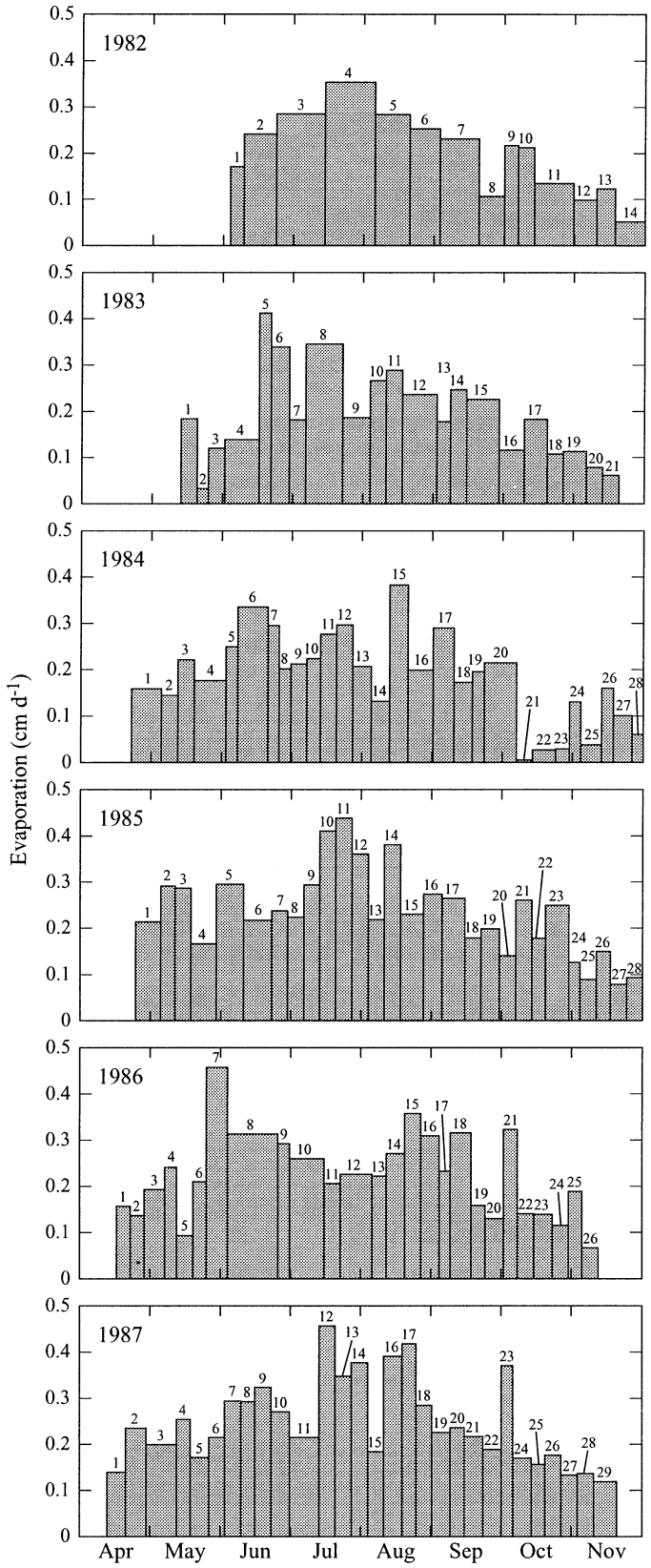

Fig. 3. Evaporation rates for the original energy-budget periods. Numbers above bars are energy-budget period numbers.

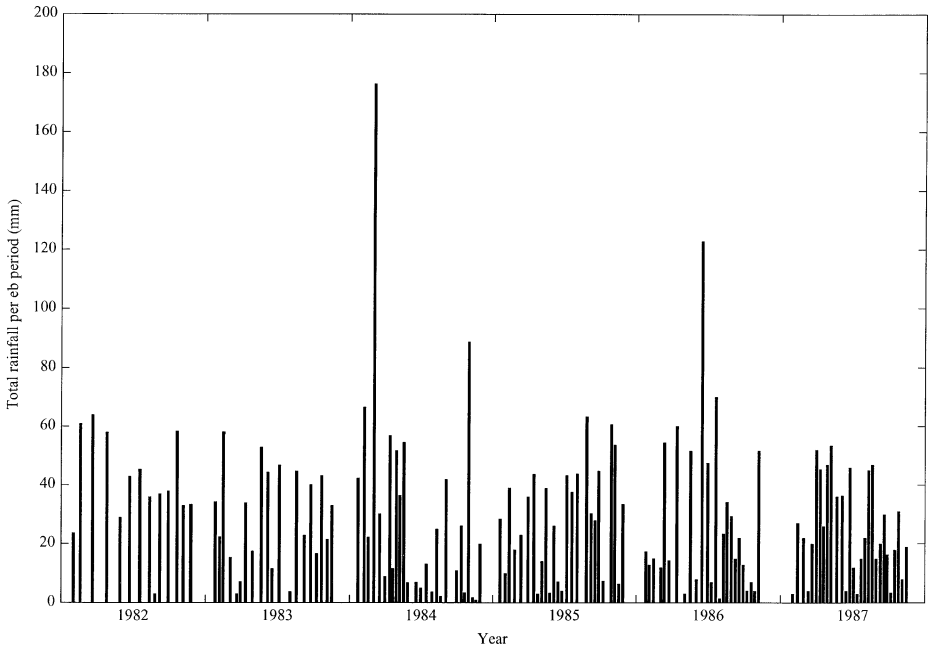

Fig. 4. Total precipitation during energy-budget period.

to measure solar radiation, atmospheric radiation, temperatures, and vapor pressure.

Results and discussion

Evaporation determined by the energy-budget method is calculated on the basis of energy-budget periods, which are bounded by the dates thermal surveys are made. Therefore, the primary calculations of evaporation are the daily average rates during energy-budget periods. During the open water seasons over the 6-yr study, 152 thermal surveys were made, which resulted in 146 individual energy-budget periods. The periods ranged in length from 5 to 22 d (Web Appendix 1). Computed evaporation varied considerably at times when periods of <10 d were used. One of the contentious issues in energy-budget studies is related to the effect of the change in heat stored, the Q_x term, on the calculated evaporation when the energy-budget period is too short. Because many thermal surveys were made at weekly intervals during this study, these data provided an opportunity to evaluate the effect of the length of energy-budget periods on calculated evaporation. Therefore, for the entire 6-yr study, evaporation was calculated two ways: (1) using all of the energy-budget periods, referred to herein as the original periods (OEBP), and (2) using combined periods where original periods <10 d in length were combined into periods of at least 10 d, which are referred to herein as combined energy-budget periods (CEBP).

Calculated evaporation and evaluation of selected terms in the energy-budget equation are most appropriately evaluated on the basis of energy-budget periods. Therefore, the results based on energy-budget periods are presented first. However, thermal surveys were not made on the same dates each year, so it is difficult to compare evaporation rates on the basis of energy-budget periods from season to season or year to year. Therefore, evaporation determined on a monthly basis is presented later in this section, to facilitate multiple-year comparisons and comparisons with studies of other lakes, which most commonly report monthly values.

Evaporation rates based on energy-budget periods—Evaporation rates varied considerably over the open-water season during each year of the study, and the pattern of variation was not consistent from year to year (Fig. 3). On the basis of the OEBPs, evaporation rates were as high as 0.46 cm d^{-1} during OEBP 7 (27 May–4 June) in 1986 and OEBP 12 (15–21 July) in 1987. Evaporation rates were >0.4 cm d^{-1} during only four other OEBPs during the study: 5 (mid-June) in 1983, 10 and 11 (July) in 1985, and 17 (mid-August) in 1987. The lowest evaporation rates calculated were 0.03 cm d^{-1} or less during OEBPs 21, 22, and 23 in 1984, during most of October. An equally low evaporation rate of 0.03 cm d^{-1} was calculated for OEBP 2 (22–26 May) in 1983. The total precipitation that fell during each energy-budget period is shown in Fig. 4.

Evaporation rates during 1982 were the closest to what might be considered an expected seasonal pattern—that is, the rates increased rather uniformly from low values in spring to maximum values in late July and early August and then decreased somewhat uniformly through late fall. Evaporation during the other years was more variable. Maximum evaporation rates occurred during mid- to late July for only two other years, 1985 and 1987. The greatest deviation from the expected seasonal pattern of evaporation was during 1986, when the greatest evaporation rate for the year was during late May and early June. Furthermore, the average rates during mid- to late July were lower than similar periods for the other 5 yr. Evaporation rates also were above average for their respective time periods during the latter part of June in 1983 and during early October in 1986 and in 1987. To

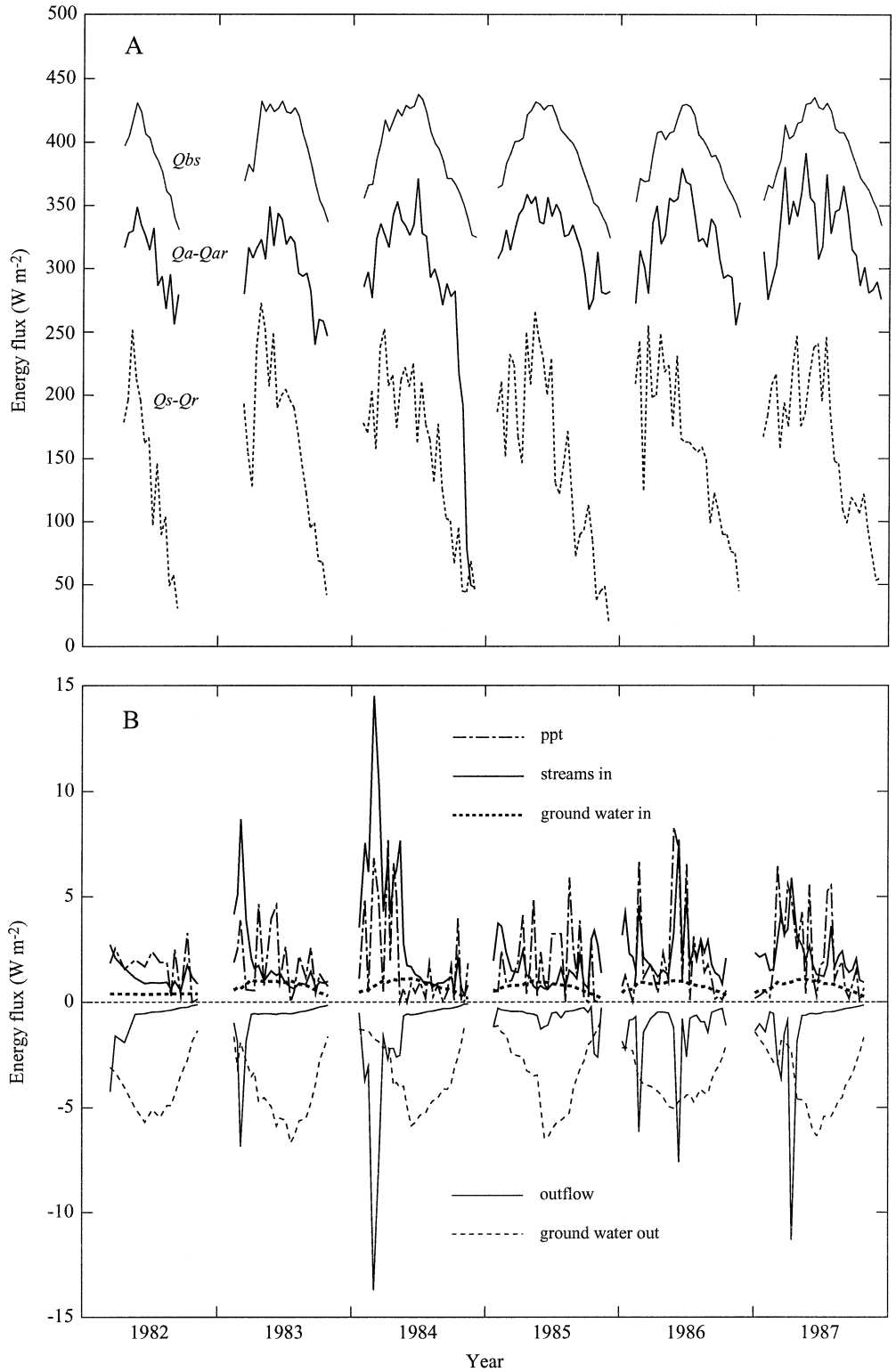

Fig. 5. Energy fluxes to and from Mirror lake. (A) Incoming minus reflected solar radiation ($Q_s - Q_r$), incoming minus reflected atmospheric radiation ($Q_a - Q_{ar}$), and long-wave radiation emitted from the lake (Q_{bs}). (B) Advected energy fluxes related to precipitation, surface water, and ground water.

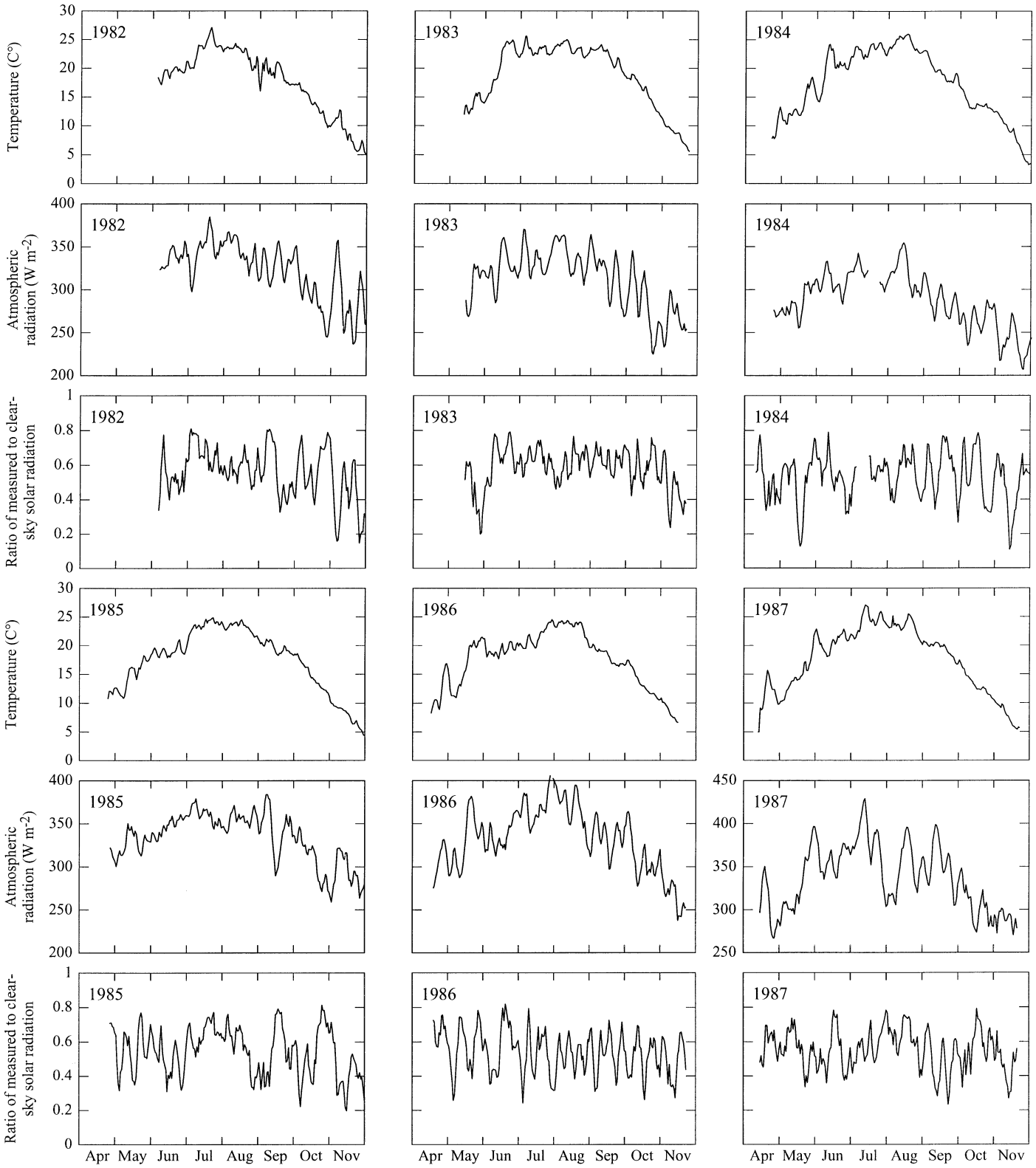

Fig. 6. Daily water surface temperature of Mirror Lake, 5-d moving average of incoming atmospheric (long-wave) radiation, and 5-d moving average of the ratio of incoming measured solar (short-wave) radiation to calculated clear-sky solar radiation for each of the 6 yr of the study.

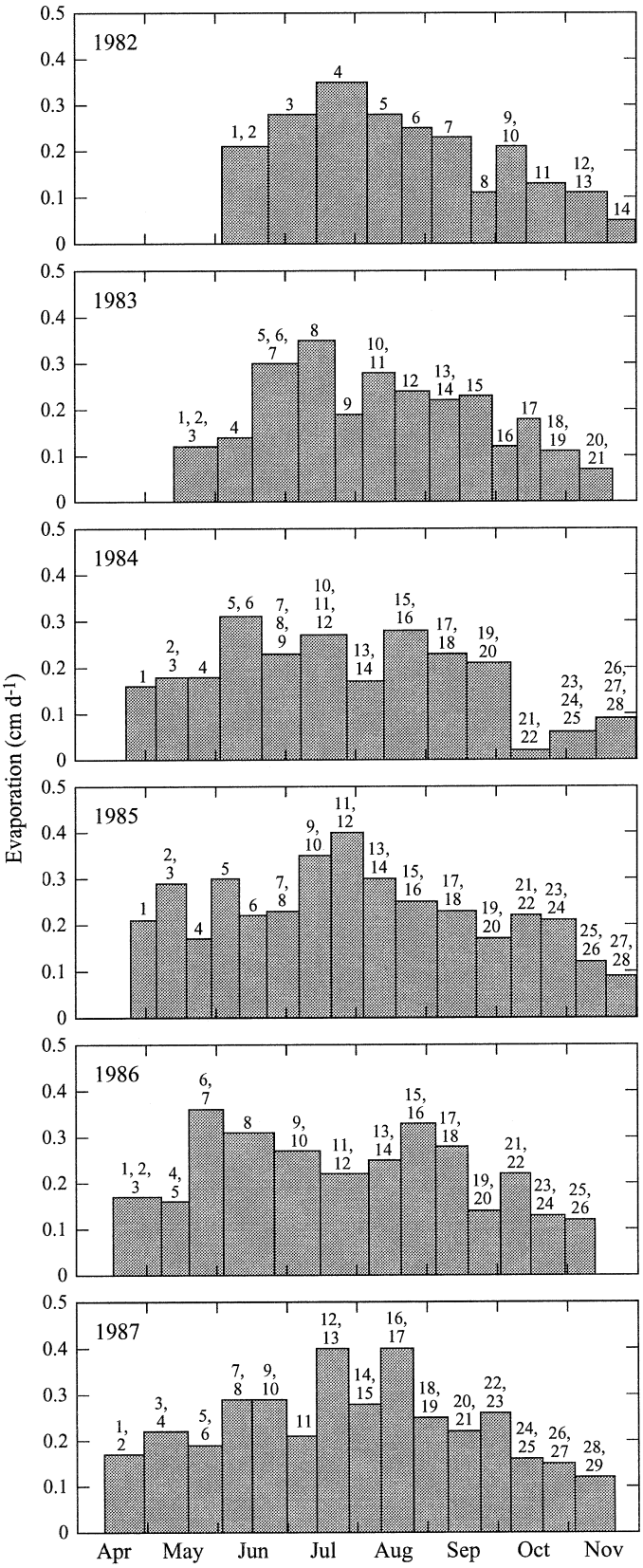

Fig. 7. Evaporation rates for the combined energy-budget periods. Numbers above bars are original energy-budget period numbers.

evaluate the causes for the variability in evaporation rates, it is useful to examine the variability in the energy fluxes that determine evaporation rates.

Effect of solar radiation (Q_s), atmospheric radiation (Q_a), and radiation emitted from the water body (Q_{bs}) on evaporation—Three energy fluxes are much greater than all others (Web Appendix 1); two of the fluxes, Q_s and Q_a, are energy gains to the lake, and the third, Q_{bs}, is a loss of energy from the lake. Plots of these three major energy fluxes for the OEBPs are shown in Fig. 5A. The largest energy flux of all, Q_{bs}, is calculated from the temperature of the water surface (T_o). Plots of T_o are useful because T_o data are used directly or for calculating several other terms in the energy-budget equation; therefore, the patterns of T_o are useful in understanding those terms as well. Daily values of T_o are shown in Fig. 6. Incoming atmospheric radiation, Q_a, is the next largest energy flux for most OEBPs (Web Appendix 1). Incoming solar radiation itself, Q_s, is not plotted, but the ratio of incoming solar radiation measured at Mirror Lake to clear-sky radiation calculated from the solar constant for the latitude of Mirror Lake is shown in Fig. 6. This ratio provides an indication of cloudiness, and it is useful in assessing the affect of cloud cover on solar radiation. Incoming solar and atmospheric radiation are highly variable on a daily basis; therefore, plots of these two fluxes are shown as 5-d moving averages.

Seasonal patterns of water surface temperature and atmospheric radiation (Fig. 6) generally have an expected pattern of increases from spring to midsummer, followed by decreases to late fall. The timing of high and low values of water surface temperature and atmospheric radiation are similar, but the range of variability of water surface temperature is greatly damped compared with atmospheric radiation. The ratio of measured to calculated solar radiation (Fig. 6) generally does not follow similar seasonal patterns: the ratio commonly has an inverse relationship to atmospheric radiation and water surface temperature. For example, using the same period as above for comparison, the ratio decreases to a minimum, whereas atmospheric radiation and water surface temperature increase to maximums, during late October to early November in 1982.

The seasonal pattern of evaporation (Fig. 3) follows the seasonal pattern of water temperature and atmospheric radiation for 1982, 1985, and 1987. The seasonal pattern of evaporation for 1986 was a notable exception. The anomalously high evaporation rates for late May and early June (OEBP7) in 1986 can be explained by the peak in atmospheric radiation during mid May and two periods of relatively clear skies during the month (Fig. 6). The May 1986 values for both types of radiation were higher than all other Mays during the study, resulting in the warmest water surface temperatures compared with all other Mays. Conversely, this period of 1986 was followed by low values of atmospheric radiation during most of June (Fig. 6), which caused the lake to cool and evaporation to decrease (Fig. 3). Furthermore, even though atmospheric radiation increased to values >400 W m^{-2} by late July, much of the summer was characterized by frequent periods of cloudy skies (Fig. 6). As a result, the water surface temperature remained consis-

Table 1. Dates and day of year (DOY) for ice out, maximum heat in storage, fall turnover, ice in, number of days of open water, and number of days between ice out and turnover.

Year	Ice out		Max. heat storage		Fall turnover		Ice in		No. of days of open water	No. of days of ice out to fall turnover
	Date	(DOY)	Date	(DOY)	Date	(DOY)	Date	(DOY)		
1982	29 Apr	(119)	15 Jul	(196)	10 Nov	(315)	10 Dec	(343)	224	196
1983	4 Apr	(94)	11 Aug	(223)	27 Oct	(300)	5 Dec	(339)	245	206
1984	15 Apr	(106)	13 Aug	(226)	14 Nov	(319)	8 Dec	(343)	237	213
1985	12 Apr	(102)	11 Aug	(223)	11 Nov	(315)	6 Dec	(340)	238	213
1986	14 Apr	(104)	12 Aug	(224)	15 Oct	(288)	7 Dec	(341)	237	184
1987	7 Apr	(97)	19 Aug	(231)	3 Nov	(307)	15 Dec	(349)	252	210

tently >20°C only after the middle of July. This example for 1986 is only one of many comparisons that could be made using Figs. 3 and 6, showing the substantial effects of atmospheric radiation and solar radiation on water surface temperature and ultimately on evaporation.

Effect of advected energy (Q_v) on evaporation—The finding of Johnson et al. (1985) that advected heat was a small part of the energy budget of Mirror Lake was confirmed in the present study. Considering the overall energy flux related to all sources and sinks, Q_v is one of the least significant fluxes regardless of season (Web Appendix 1). Nevertheless, because of the large amount of new instrumentation that was installed to measure more accurately the water fluxes to and from Mirror Lake, the individual sources and sinks involved in the calculation of Q_v were reevaluated.

Advected energy related to precipitation was seldom >5 W m^{-2} and never >10 W m^{-2} during the study period (Fig. 5B). Advected energy related to the exchange of surface water with the lake also was minimal because the greatest inflow most years was during spring, when snowmelt and spring runoff brought cold water into the lake. Furthermore, most of the time when inflows were high outflow also was high, resulting in a large water exchange but little net energy input to the lake. The input of energy from ground water was minimal because the volumes of water are small and the water is cold (~10°C) throughout the year. The loss of energy by seepage of lake water to ground water was surprisingly small, always <10 W m^{-2}. It was expected to be much larger because seepage to ground water is one of the largest losses of water from the lake. Because the energy loss to ground water was calculated from the surface temperature of lake water, the pattern of energy loss follows a seasonal pattern of warming and cooling, similar to the water surface temperature.

Evaporation studies of lakes that were designed and carried out similar to the Mirror Lake study; that is, where particularly close attention was paid to advected energy, especially with respect to ground water, also indicated that advected energy had a small effect on evaporation rates. For example, Williams Lake in Minnesota has no streams entering or leaving—its main source of water is ground water and its main loss of water is to ground water—yet advected energy, including from preciptation, generally results in energy fluxes <5 W m^{-2} (Sturrock et al. 1992). Wetland P1 in the Cottonwood Lake area in North Dakota also has no streams entering or leaving and it receives ~90% of its water from precipitation. Advected energy with respect to this small water body generally was <10 W m^{-2} and only several times reached as high as 15 W m^{-2} (Parkhurst et al. 1998). In the study of Lake Lucerne in Florida, a lake also having no interaction with streams, Lee and Swancar (1997) indicated that advected energy fluxes related to precipitation and ground water were minimal.

Evaluation of change in heat stored (Q_x) and thermal characteristics of Mirror Lake—As indicated earlier, one of the contentious issues in energy-budget studies is related to the effect of the change in heat stored from one thermal survey to the next, Q_x, on the calculated evaporation if the energy-budget period is too short. As discussed by Anderson (1954), the problem is related to the uncertainty in calculating the volume of heat stored at any given time. The temperature distribution within a water body is a three-dimensional continuum. The more temperature profiles that can be made at any given time, the more accurate the determination of heat stored will be. Nevertheless, there will always be a certain amount of uncertainty in the determination of heat stored. For a reservoir such as Lake Hefner, Anderson (1954) indicated that intervals of 7–10 d between thermal surveys is probably adequate for determination of evaporation and that determination of evaporation for thermal survey intervals of <1 week should be used with caution. For a small lake like Mirror Lake, where the basin shape is essentially an asymmetric cone, determinations of heat stored are likely to be more accurate than for a large reservoir; therefore, it is likely that adequate determinations of evaporation can be made for intervals <7 d between thermal surveys. During most of the Mirror Lake study, thermal surveys were made at weekly intervals. This frequency of measurements made it possible to evaluate the effect of the length of energy-budget periods on determinations of evaporation.

For Mirror Lake, comparison of evaporation rates for CEBPs (Fig. 7) with evaporation rates for the OEBPs (Fig. 3) indicates that the variability in the OEBPs is reduced by calculating evaporation rates for longer periods. In addition, maximum evaporation rates decreased from 0.46 cm d^{-1} for several of the OEBPs to 0.40 cm d^{-1} for several of the CEBPs. For most years, this ''smoothing'' did not substantially alter the general seasonal patterns of evaporation calculated from the CEBPs compared with those calculated from the OEBPs; moreover, the total evaporation for the

Table 2. Day of year (DOY), date, temperature of lake water at the surface (0), 5 m, 7 m, and bottom (10 m) (°C); difference between top and bottom temperatures ($t - b$) (°C), and heat storage in the lake, U, (cal $\times 10^{12}$).

DOY 1982		175	196	280	314
Date		24 Jun	15 Jul	7 Oct	10 Nov
0		19.8	25.5	16.5	9.0
5		17.4	13.3	16.4	9.0
7		11.0	12.4	16.3	9.0
10		8.3	10.4	12.5	9.0
$t - b$		11.5	15.1	4.0	0.0
U		14.08	17.65	13.57	7.44
DOY 1983		181	251	283	300
Date		30 Jun	8 Sep	10 Oct	27 Oct
0		22.5	23.1	16.9	11.7
5		14.9	22.7	16.5	11.7
7		11.9	10.4	16.4	11.7
10		9.8	12.7	13.3	11.7
$t - b$		12.7	10.4	3.6	0.0
U		15.69	19.12	14.27	10.05
DOY 1984	113	183	226	281	318
Date	22 Apr	1 Jul	13 Aug	7 Oct	13 Nov
0	7.0	22.7	26.3	13.3	8.4
5	6.8	20.4	25.2	12.7	8.4
7	5.8	11.6	15.1	12.5	8.4
10	5.1	9.0	10.9	12.4	8.4
$t - b$	2.0	13.7	15.4	0.9	0.0
U	5.61	15.34	19.17	10.92	7.22
DOY 1985	114	181	223	280	315
Date	24 Apr	30 Jun	11 Aug	7 Oct	11 Nov
0	10.8	20.3	24.5	16.5	8.5
5	6.2	17.3	23.2	16.3	8.5
7	5.8	13.2	19.0	16.3	8.5
10	5.7	10.3	12.1	13.3	8.5
$t - b$	5.1	10.0	12.4	3.2	0.0
U	6.58	14.98	19.34	14.08	7.31
DOY 1986	113	182	224	281	288
Date	23 Apr	1 Jul	12 Aug	8 Oct	15 Oct
0	9.1	19.4	23.6	14.0	12.6
5	5.9	17.7	22.5	13.9	12.6
7	5.4	13.0	18.2	13.8	12.6
10	5.0	10.6	12.5	13.7	12.6
$t - b$	4.1	8.8	11.1	0.3	0.0
U	4.64	15.02	19.00	12.00	10.83
DOY 1987	111	182	231	279	307
Date	21 Apr	1 Jul	19 Aug	6 Oct	3 Nov
0	14.7	21.7	24.5	14.3	9.4
5	8.0	17.6	22.7	14.2	9.4
7	5.2	12.4	17.4	14.2	9.4
10	4.6	9.6	11.6	13.4	9.4
$t - b$	10.1	12.1	12.9	0.9	0.0
U	7.55	16.21	19.25	12.22	8.08

Table 3. Monthly and total evaporation for June through October of 1982–1987, average and standard deviation (SD) of monthly evaporation (cm) for the 6-year period, and deviation of total annual evaporation from 6-year average (cm).

Year	Jun	Jul	Aug	Sep	Oct	Total	Deviation from 6-year average
1982	6.40	9.93	8.91	5.75	5.16	36.05	−0.79
1983	7.10	8.30	7.69	6.54	4.20	33.83	−3.01
1984	8.41	7.65	7.13	6.67	2.10	31.96	−4.88
1985	7.52	10.65	8.77	6.85	6.50	40.29	3.45
1986	9.90	7.45	8.60	6.65	5.30	37.90	1.06
1987	8.61	9.82	10.14	6.36	6.10	41.03	4.19
Average	7.97	8.97	8.54	6.47	4.89	36.84	
SD	1.27	1.34	1.04	0.39	1.58		

open-water period was the same using either approach. However, it is instructive to compare the effects of considering longer versus shorter energy-budget periods for 2 yr, where combining the OEBPs resulted in different seasonal patterns. The two years, 1986 and 1983, both had anomalously high evaporation rates early in the season. The seasonal pattern of evaporation for 1986 is similar whether OEBPs or CEBPs are used; that is, the highest evaporation rate was during late May and early June, decreasing to low values by mid-July, then increasing to higher values by late August. The evaporation rate in late May 1986 remained highest for the season, despite combining the highest rate for the season (OEBP 7) with a low rate for OEBP 6. A converse effect is indicated for 1983, where combining the highest evaporation rate for the season (OEBP 5) with a relatively high rate (OEBP 6) and a low rate (OEBP 7) resulted in the combined period having the second highest evaporation rate for the season.

A different perspective on evaluating the change in heat stored in a lake can be obtained by examining differences in its seasonal thermal characteristics from year to year. The dates and day of year (DOY) for ice out, maximum storage, fall turnover, and ice in for each year of the study are shown in Table 1. Also included in Table 1 are the length of open-water season and the number of days between ice out and the fall turnover for each year. The annual dates of ice out spanned nearly the entire month of April for the 6 yr, whereas annual maximum heat in storage varied over a span of only ~1 week in August for 1983–1987. In 1982, the lake had the latest date of ice out, but it reached the maximum heat in storage about a month earlier than the other years. The maximum heat in storage in 1982 was the lowest for the 6-yr study. Although the turnover dates ranged over ~1 month (from 15 October in 1986 to 14 November in 1984), the rate of cooling from turnover varied for each year because the dates of ice in spanned only 10 d over the 6 yr.

The record of ice in and ice out for the 6 yr discussed herein can be put into a longer term perspective by examining the 30-yr record presented by Likens (2001). That record indicates that, although variable from year to year, the date of ice out between 1968 and 1998 has been occurring earlier during the year. The time of ice out for 5 of the 6 yr

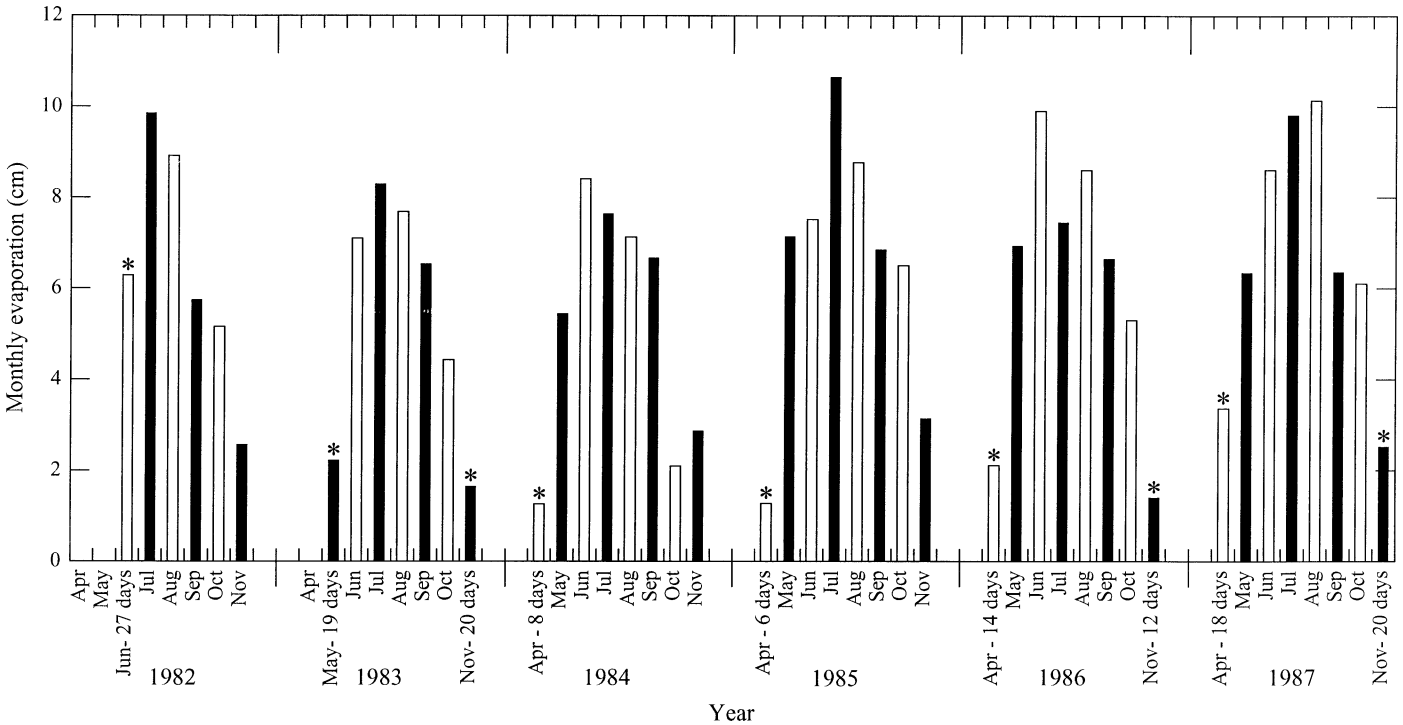

Fig. 8. Total monthly evaporation. Bars with asterisks (*) above them are values for incomplete months; the number of days for which the value applies is shown below the bars.

in the present study was earlier than the 30-yr normal trend line.

Another way to compare changes in heat storage in a lake is to compare the thermal profiles taken as close to the same date as possible for each of the years of study. Selected thermal surveys for 1984–1987 for the first thermal survey after ice out through fall turnover, defined as when the lake was isothermal, are shown in Table 2. Selected thermal surveys for 1982 and 1983 also are shown, but thermal surveys were not made soon after ice out in those years. Data selected from the thermal surveys include water temperatures at the lake surface, 5 and 7 m, and bottom, the difference between the top and bottom water temperatures, and the heat stored. By including temperatures at the intermediate depths of 5 and 7 m, changes in vertical mixing of the lake can be followed as the lake exchanges energy with its environment throughout the open water season. Of the thermal surveys made in early October (DOY 280 in 1982, DOY 283 in 1983, and DOY 280 in 1985), differences between top and bottom water temperatures were $>3°C$. For these years, turnover followed the early October thermal surveys by 35 days in 1982, 17 days in 1983, and 35 days in 1985. For this same early October period in 1984, 1986, and 1987, differences between top and bottom water temperatures were $<1°C$. This difference of $<1°C$ for 1984, 1986, and 1987 would lead to the expectation that the lake would reach turnover much sooner than in 1982, 1983, and 1985; however, turnover followed by 7 days in 1986, 38 days in 1984, and 28 days in 1987. These data indicate that it is difficult to predict the time of turnover from thermal surveys alone. The rate at which the mixing continues depends especially on wind at this time of year, and this is highly variable from year to year. In 1986, the mixing efficiency was very high, but in the other years the turnover was delayed because of variations in the energy inputs to the lake. Johnson et al. (1985) provide additional insights into the thermal stability and hydrodynamics of Mirror Lake.

Monthly evaporation rates—Monthly values of evaporation generally are determined so evaporation rates can be compared for common periods from year to year and for comparison with other lakes. The monthly values were calculated by time-weighting the OEBP values. The monthly values of evaporation for the months that had complete records for all 6 yr (June–October), as well as the average and standard deviation for each month for all 6 yr of the Mirror Lake study, are shown in Table 3. For 3 of the 6 yr (1982, 1983, and 1985), monthly evaporation reached a maximum in July (Table 3, Fig. 8). For 1984 and 1986, the highest evaporation occurred during June. For 1987, the highest evaporation occurred during August, although it was only slightly higher than the July total, and the difference was within the error of measurement. For completeness, months that had only a partial record and the number of days for which evaporation was determined also are included in Fig. 8. The maximum standard deviation of evaporation rates for specific months was 1.58 cm for October, and the minimum was 0.39 cm for September (Table 3).

Interannual variability of evaporation also is shown in Table 3. The average total evaporation from June through October for the 6 yr was 36.84 cm. Evaporation was less than the average for the first 3 yr of the study and greater than

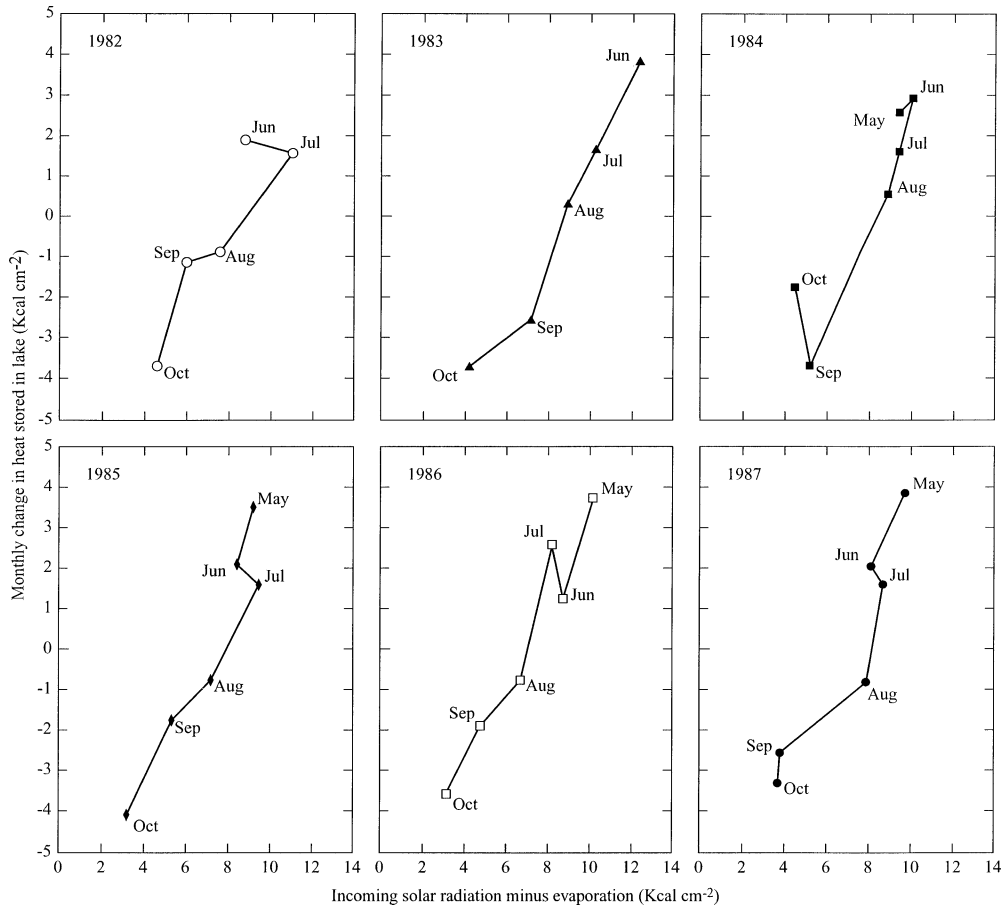

Fig. 9. Relation of change in heat stored in Mirror Lake to the difference between incoming solar radiation and evaporation.

the average for the last 3 yr. Evaporation during 1982 and 1986 were the closest to the average, and the largest difference was for 1984, when evaporation was 4.88 cm less than the average. The evaporation studies of Williams Lake in Minnesota and Wetland P1 in the Cottonwood Lake area in North Dakota showed similar magnitudes of deviation from a long-term average but less variability in interannual evaporation compared with Mirror Lake. For example, both of the studies in the midwest were of 5-yr duration and both showed maximum evaporation occurred during July for 5 of the 5 yr. They both also showed that the highest evaporation rate occurred during June for the other year. In this respect, the three lakes are similar in that, at Mirror Lake, June also had the highest evaporation rates for 2 of the 6 yr. Seasonally highest evaporation rates in June at all three sites generally are related to early-season heating of the lake water by radiation inputs.

To evaluate the relationship of solar energy to the dissipation of heat in Mirror Lake, Johnson et al. (1985) plotted the monthly solar radiation minus evaporation ($Q_s - Q_e$) against the monthly change in heat storage (Q_x). Their study indicated that the largest monthly increase in heat storage was in April, when incoming radiation was high, and that the largest monthly decrease in storage was in November, when radiation was near the minimum. The change in heat storage decreased somewhat proportionately during the intervening months of May–October as the lake gained heat and evaporation increased. A similar plot was made for each of the 6 yr of the present study (Fig. 9). The curves for 1983, 1985, and 1987 generally followed the relationship found by Johnson et al. (1985), but the pattern varied somewhat from year to year. The curve for 1982 diverged somewhat, and the curves for 1984 and 1986 diverged considerably from this expected pattern. For 1984, the June value for Q_x was greater than the May value and the September value was less than the October value. The large loss of heat from the lake during September 1984 was probably caused by the relatively low atmospheric radiation input for the month, the lowest of any September during the study (Fig. 6). The change in heat stored during October was less than September because the lake was already quite cool by early October (Fig. 6). For 1986, the June value for Q_x was less than the May and July values. May 1986 had a large change in heat storage because of unusually high inputs of solar and atmospheric radiation to the lake. In contrast, lower radiation inputs to the lake during June resulted in the lowest change in heat storage for any June of the 6-yr study.

Summary and conclusions

Evaporation was determined by the energy-budget method for Mirror Lake during the open-water periods of 1982–1987. The expected pattern of increasing evaporation from spring to maximum rates in midsummer (July) to decreasing rates into fall occurred for 3 of the 6 yr. For 2 of the yr, maximum evaporation rates occurred during June, and for 1 yr, maximum rates occurred during August. This variability is related to the variability in the three major energy fluxes to and from the lake. Solar (Q_s) and atmospheric (Q_a) radiation are by far the largest energy inputs to the lake, and long-wave radiation emitted from the lake (Q_{bs}) is the greatest energy loss from the lake. Because of the strong relationship of evaporation to these energy fluxes, great care needs to be taken to measure these fluxes as accurately as possible.

Energy advected to and from the lake by precipitation, surface water, and ground water were found to have little effect on evaporation rates. Net energy gain related to surface water was small because water temperatures are low when the largest inflows and outflows occur, during spring and late fall. Net energy gain related to ground water was small because groundwater inflow is a small part of the water budget and the temperature of ground water is relatively low. Even though the loss of lake water to ground water is large, the energy flux is seldom >5 W m^{-2}. This result was of special interest in the present study because the energy flux related to ground water has seldom been determined in energy-budget studies and its importance was unknown. On the basis of our results, it is clear that the large cost and effort of determining energy flux related to ground water may not be needed for lakes in geologic and climatic settings such as Mirror Lake. Furthermore, this result corroborated similar studies in North Dakota, Minnesota, and Florida, which also showed that advected energy from and to ground water was minimal.

The length of energy-budget periods was found to have little effect on overall understanding of evaporation patterns. The shorter periods showed more variability in evaporation rates, but seasonal patterns, with few exceptions, were similar. On the basis of our study, energy-budget periods $\sim$2 weeks in length are sufficient to develop an adequate understanding of evaporation from lakes in climatic settings such as Mirror Lake, thereby reducing the need for making thermal surveys more frequently than every 2 weeks.

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