Energy Budget Processes of a Small Northern Lake

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ABSTRACT

There is a paucity of information on the energy budget of Canada's northern lakes. This research determines processes controlling the magnitude of energy fluxes between a small Canadian Shield lake and the atmosphere. Meteorological instruments were deployed on a floating platform in the middle of a 5-ha lake during the 1999 and 2000 open-water seasons. High attenuation of incoming radiation at shallow depths and the sheltered location of the lake allows a strong thermocline to develop during the summer months, which prevents deeper water from exchanging energy with the atmosphere. Only after the lake becomes isothermal in late August do deeper waters interact with the atmosphere. When the lake is warming, evaporation is controlled by net radiation, but when the lake is cooling, turbulent energy fluxes are mainly influenced by the vapor pressure deficit. An empirically derived logarithmic relationship was identified between the Bowen ratio and the vapor pressure deficit. The Canadian Global Energy and Water Cycle Experiment (GEWEX) Enhanced Study (CAGES) water year was characterized by a cool dry July that prevented the lake from warming to expected normal conditions. With less of the available energy directed to heating the lake, more was available for the turbulent fluxes, but evaporation rates did not increase. Because of the inability of radiation to penetrate to deep water in this lake, it is unlikely that even local extremes in air temperature and incoming solar radiation create the summer isothermal conditions observed in more southern Canadian Shield lakes, which allow more energy to be directed toward evaporation during the summer months.

1. Introduction

Because lakes occupy up to 30% of Canada's northern landscape, an understanding of their energy budgets and evaporation processes is crucial for assessing the impacts of resource development and climate change. Until recently, many resource development proposals in the Northwest Territories and Nunavut used lake evaporation rates from the *Hydrological Atlas of Canada* (den Hartog and Ferguson 1978), which were estimated using a northern network of only five evaporation pans. As suggested by Schindler (2001), this indicates that understanding of the physical characteristics and processes of Canada's northern lakes is poor. It will be necessary to thoroughly understand the energy and water budgets of northern lakes and how they contribute to local and regional climatic and hydrologic regimes as demands for clean freshwater increase in the twenty-first century, and if climate change affects northern Canada as predicted (Maxwell 1997).

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Current knowledge of evaporation from northern Canadian lakes includes work by Reid (1997), who quantified open-water season evaporation rates for small lakes and tailings ponds in the Northwest Territories and Nunavut. Stewart and Rouse (1976) and Rouse et al. (1977) developed and tested an evaporation model for northern lakes, which focused on the Priestley–Taylor (1972) evaporation efficiency (α) term. Testing the same model, Roulet and Woo (1986) found that there was significant variation in α between sites. Recognizing this, Bello and Smith (1990) used α as a means to quantify the impact of advection over a northern lake. Blanken et al. (2000) determined that wind speed and vapor pressure gradients, not net radiation, control evaporation from Great Slave Lake. Many questions remain regarding controls on energy budget processes and evaporation rates from northern lakes in different regions and of different morphology. The purpose of the present research is to determine the processes that control the magnitude of energy exchange during the open-water season in a small northern Canadian Shield lake. How these processes affected the partitioning of the lake's energy budget during the open-water season of the Canadian Global Energy and Water Cycle Experiment

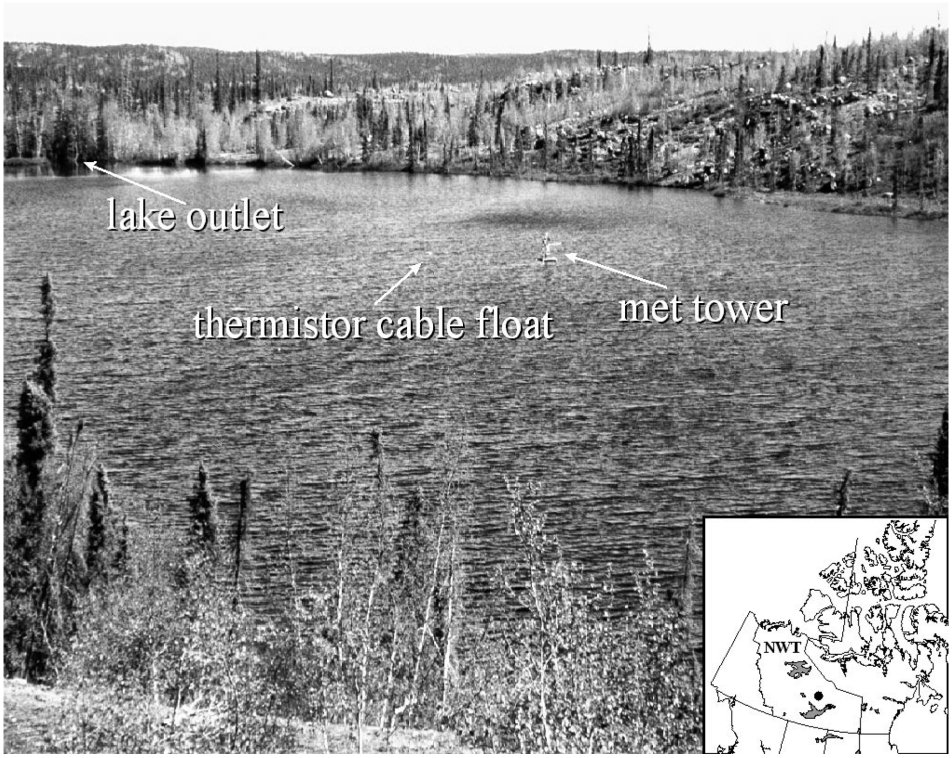

FIG. 1. Photo of Skeeter Lake looking east. The location of the tower, thermistor cable float, and lake outlet are identified. The measurements of surface inflow and rainfall were near the north shore immediately to the left of the photo.

(GEWEX) Enhanced Study (CAGES) water year (from 1 October 1998 to 30 September 1999) will be discussed.

2. Study site

Skeeter Lake, at 63°35.5′N 113°53.5′W, 100-km north of the city of Yellowknife, Northwest Territories, Canada, was selected for the study. It is a headwater lake that drains into the Yellowknife River at Lower Carp Lake (Fig. 1). The lake is ~5 ha in size, and has an average depth of 3.2 m and a maximum depth of 6.6 m. Lake volume varies from 155 000 to 180 000 m^3, depending on water level. The lake is fed by a 57.5-ha peat land and bedrock watershed that contributes to runoff during spring snowmelt, and in wet years during September (Spence and Rouse 2002). During the spring freshet, water levels can exceed the outlet elevation of 1.91 (meters above local datum), but no surface outflow has been observed at any other time of the year because storage availability precludes any autumn surface outflow. The average recession of water levels through three winters indicate that there is a net average groundwater outflow from the lake of 0.5 mm day^{-1}.

3. Methods

The water budget for the period of study is defined as

$$\Delta S = P + R_s \pm G - O - E + \varepsilon, \qquad (1)$$

where ε is an error term. Storage in the lake, S, was estimated using water levels measured with a pressure transducer located at the bottom of the lake at a depth below the maximum winter ice thickness. The pressure transducer can be used to measure water level in the winter because it is vented to the atmosphere, the lake ice is floating, and freezing has no pressure effect on the lake water. Rainfall, P, was measured using a Meteorological Service of Canada Type-B rain gauge. Rainfall intensity was measured using a tipping bucket. Surface inflows, R_s, were measured at a weir at the main inflow channel to the lake, as described in Spence and Rouse (2002). Net groundwater flow rates, G, are assumed to be constant at the same rate as the winter water-level recession rate of 0.5 mm day^{-1} noted above. Surface outflow, O, was measured occasionally just below the outlet using a velocity area method with velocity measured with a pygmy current meter. A stage-discharge curve was calculated so that outflow could be estimated when personnel were not on site. Evaporation, E, was calculated using the following methods.

A meteorological tower on a floating platform was deployed in the center of the lake (Fig. 1) during the 1999 and 2000 open-water seasons. Because of local topography, winds almost always blow from the west or east, which gives open-water fetches to the tower of 160 and 230 m, respectively. A Kipp and Zonen NR Lite net radiometer was placed 1.1 m above the water surface. Vaisala HMP35CF temperature-relative humidity sensors were located at 1.8 and 0.8 m above the water. Met One 013A anemometers were set at 1.7 and 0.8 m above the water surface. These sensor heights result in maximum height:fetch ratios of 1:94 and 1:135 for the predominant wind directions. The water surface temperature was measured continuously with an Onset TidBiT thermistor and integrated every half hour. A Bowen ratio–energy balance approach was used to calculate the latent heat flux (Q_e), where

$$\beta = \frac{Q_h}{Q_e} = \gamma \frac{dT/d\ \ln(z)}{de/d\ \ln(z)}, \tag{2}$$

in which β is the Bowen ratio, γ is the psychrometric constant (kPa °C^{-1}), T is air temperature (°C), and e is vapor pressure (kPa) at height z above the lake surface. Substituting (2) into the basic energy budget equation,

$$Q^* = Q_h + Q_e + J_w, \tag{3}$$

where Q^* is net radiation, Q_h is sensible heat, and J_w is heat storage (all energy terms expressed in W m^{-2}), allows Q_e and Q_h to be solved as

$$Q_e = \frac{Q^* - J_w}{1 + \beta}; \qquad Q_h = \frac{Q^* - J_w}{1 + \beta^{-1}}. \tag{4}$$

The Vaisala sensors have an accuracy of ± 0.2°C (temperature) and ± 2% (relative humidity). This accuracy created potential for significant error in the calculated temperature and vapor pressure gradients obtained from the three measurement levels (0, 0.8, and 1.8 m). The sensors were operated at the same height for a day before deploying and after removing the floating platform each year and no systematic measurement error in either term was detected. In addition, temperature and vapor pressure data were evaluated on a half-hourly basis to ensure proper use of gradient data. Individual half-hourly values were discarded if the regression coefficient of the best-fit line describing $dT/d\ \ln(z)$ or $de/d\ \ln(z)$ was less than an arbitrarily chosen value of 0.6. To avoid errors that occasionally developed in both the magnitude and sign of the calculated fluxes as β approached -1 or de approached zero (Ohmura 1982), the fluxes were removed if $-1.2 \leq \beta \leq -0.8$ (Boudreau 1993). Average daily gradients were calculated from the remaining half-hourly values and used in Eq. (2). Daily values of the turbulent fluxes and their corresponding gradients were evaluated to determine if there was consistent flux direction. If there was disagreement between calculated fluxes and the measured gradient on whether there were lapse or inverse conditions above the lake, that value was discarded.

To determine daily J_w, a thermistor string was attached to a cable anchored to the lake bottom adjacent to the tower; thermistors were located immediately below the surface and every 70 cm to a depth of 6 m. Temperature measurements were continuous and integrated every half hour and were averaged over each day. The mean water temperature $\overline{T_w}(°C)$ is

$$\overline{T_w} = \frac{1}{z} \sum_{i=1}^{n} T_{wi} \cdot \Delta z, \tag{6}$$

which allows the calculation of J_w as

$$J_w = \rho \cdot c_p \frac{\Delta \overline{T_w}}{\Delta t} z, \tag{7}$$

where z is depth (m), T_{wi} is the water temperature (°C) at the individual thermistor, Δz is the depth segment assigned to that thermistor, ρ is the density of water (kg m^{-3}), c_p is the specific heat of water (J °C · kg^{-1}), and t is time (s). Values of J_w were calculated for the entire water column, as well as shallow and deeper portions thereof, separated by the depth of the summer thermocline.

Photosynthetically active radiation (PAR) (400–700 nm) irradiance profiles were measured within 2 h of solar noon on selected days during the summer of 2001 adjacent to the floating tower. A Li-Cor underwater quantum sensor (model LI-192SA), which closely approximates the ideal quantum response for PAR, was used.

Measurements were taken at 25-cm intervals to a depth of 1 m, and every 50 cm thereafter, until the 1% light level was reached. PAR was measured constantly at a given depth, and values were integrated over a period of 1 min, before lowering the sensor and repeating the process. Concurrent measurements of surface and 3.0-m-deep dissolved organic carbon (DOC) were made using high-temperature catalytic oxidation with a Shimadzu 5000 DOC analyzer.

4. Results

a. Site conditions

Continuous measurements were made at Skeeter Lake from 17 June 1999 to 30 September 1999, and 15 June 2000 to 30 September 2000. June and July were the warmest months each summer (Table 1). Temperatures in September were similar in both years, though the temperature dropped below zero for the last week of measurements in 2000. Rainfall for the period of study was 99 and 122 mm in 1999 and 2000, respectively. Strong winds were episodic during both years, but averages were almost identical at 2.8 m s^{-1} in 1999 and 2.6 m s^{-1} in 2000. Relative humidity increased as air temperature decreased over the summer, and mean relative humidity (71%) was identical in both years.

b. Lake temperatures

The high DOC concentration (11.6 mg L^{-1}) in the lake results in very strong attenuation of radiation (Morris et al. 1995; Worth 2002) in the top 2 m of the lake (Fig. 2). In addition, the sheltered location of Skeeter Lake prevents strong winds from thoroughly mixing the lake waters. The result is strong thermal stratification

TABLE 1. Weather conditions at Skeeter Lake during the 1999 and 2000 open-water seasons; T is air temperature, u is horizontal wind speed, RH is relative humidity; and VPD is the vapor pressure deficit.

1999	T_{avg} (°C)	T_{max} (°C)	T_{min} (°C)	u_{avg} (m s^{-1})	u_{max} (m s^{-1})	RH_{avg} (%)	VPD (kPa)
Jun	15.2	23.6	7.8	2.5	4.5	57.8	0.66
Jul	13.0	19.5	7.3	2.9	5.0	64.1	0.41
Aug	13.1	18.1	4.1	2.7	4.7	72.4	0.34
Sep	6.8	12.2	1.3	2.9	4.6	82.0	0.12
2000							
Jun	15.5	19.6	11.4	2.4	4.5	58.1	0.56
Jul	18.0	23.0	11.0	2.4	3.8	62.3	0.60
Aug	11.0	20.7	2.9	2.5	5.0	77.1	0.23
Sep	3.8	11.1	−5.1	3.1	6.0	80.5	0.11

between surface (0–2.3 m) and deeper (2.3–6.0 m) water (Fig. 3). A sharp thermocline beginning near 2.0 m was evident, and this persisted until late August or early September. Lake temperatures were substantially lower than temperatures at similar depths for larger lakes, such as Great Slave Lake (Blanken et al. 2000). This means that during much of the open-water season Skeeter Lake behaved more like a ~2 m deep lake, and the deeper waters exchanged little energy with the atmosphere (Fig. 4, Table 2). However, deeper water provided much of the available energy to the atmosphere in September, when Q^* was small and the lake was cooling and isothermal.

c. Energy and water budget

The lake, on average, stored heat from June to mid-August and released it in late August–September (Fig. 5). Net radiation was highest in late June and early July near the summer solstice, decreasing through August to a minimum for the period of study in September. While Q_e exhibited seasonality with a peak in June or July and then decreased into August and September, Q_h did not vary as much from month to month. Bowen ratios were similar to those from comparable lake surfaces (Roulet and Woo 1986; Blanken et al. 2000; Petrone et al. 2000; Boudreau and Rouse 1995; Stewart and Rouse 1976).

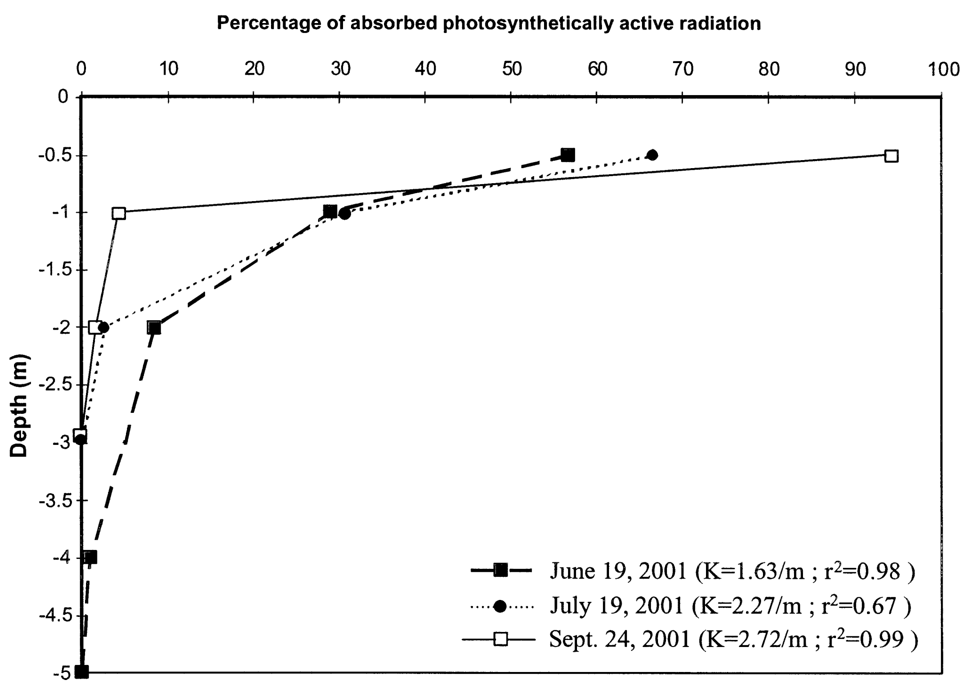

FIG. 2. Attenuation of radiation in Skeeter Lake for three selected days in 2001. The percentages of absorbed radiation are within each layer, bounded by measurements points above the lake surface and at 0.5-, 1-, 2-, 3-, 4-, and 5-m depths, K is the attenuation coefficient. The regression value between in (PAR) and water depth is also shown.

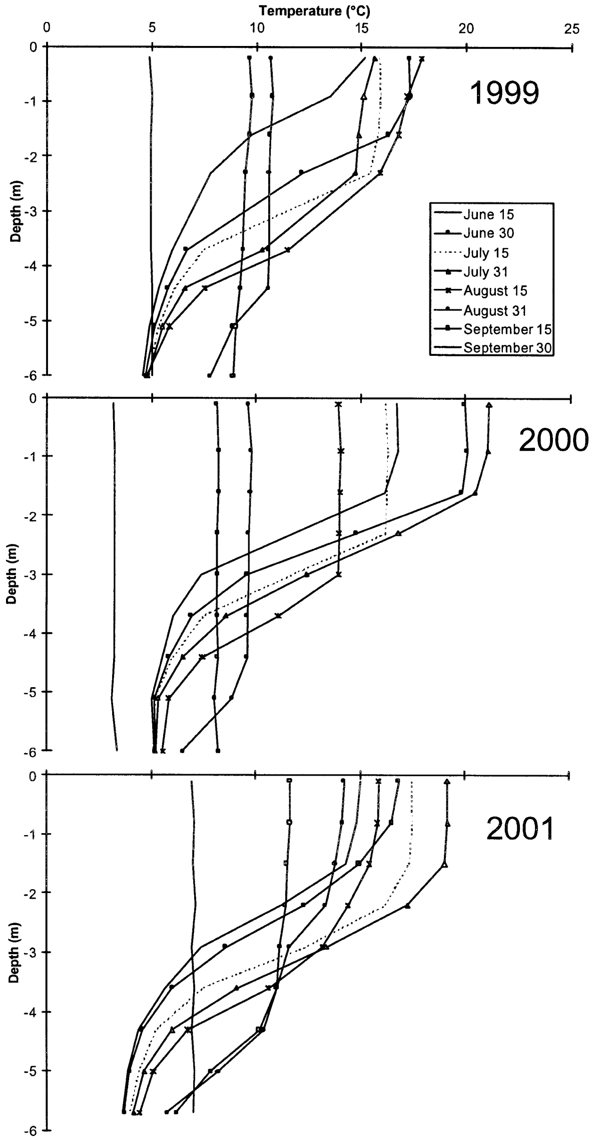

FIG. 3. Water temperature profiles from 1999 and 2000.

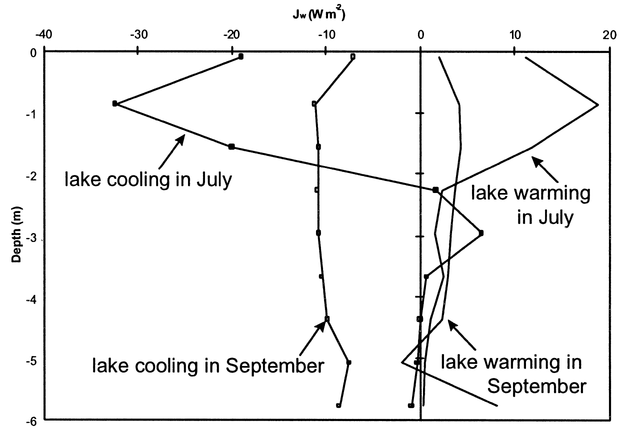

FIG. 4. Division of heat storage for different lake conditions in Jul and Sep 2000.

The release of lake heat at the end of both open-water seasons augmented the energy available from Q^* so that in September, on average, turbulent fluxes exceeded Q^*.

The water budgets (Table 3) show good closure in June. During the period of study, there was no surface outflow because the water level was always below the lake outlet elevation. Evaporation was the largest flux to or from the lake during the open-water season. It offset all rainfall inputs and lead to a large loss of storage. The unaccounted loss of water from the lake in July, as shown by a negative ε, may result, in part, from high rates of seepage loss from Skeeter Lake to Lower Carp Lake 500 m to the east. Seepage observed from springs located downslope from Skeeter Lake and adjacent to Lower Carp Lake appeared to peak in late June and July. It has not been determined where the water for this seepage originated, but if it is part of the same local groundwater system that contains Skeeter Lake, which is not an unreasonable assumption, it would suggest that the 0.5 mm day^{-1} groundwater loss is an underestimate during midsummer. A positive ε during September may be due to underestimating R_s, because high-

TABLE 2. The magnitude of energy fluxes and the division of available energy during 2 months in 2000 for periods when the lake was warming or cooling, J_{ws} and J_{wd} are heat storage in shallow (<2.3 m) and deep (>2.3 m) water, respectively.

	Jul		Sep	
Fluxes	Warming	Cooling	Warming	Cooling
Q^*	138.4	85.0	54.8	8.4
Q_h	16.9	28.8	−1.0	31.3
Q_e	71.5	119.7	26.9	64.0
J_{ws}	41.8	−71.4	10.5	−29.0
J_{wd}	8.3	7.9	18.4	−57.8
Division of available energy				
Q^* as a portion of available energy	1.0	0.54	1.0	0.09
J_{ws} as a portion of available energy	—	0.46	—	0.3
J_{wd} as a portion of available energy	—	—	—	0.61
Q_h/available energy	0.12	0.18	0.02	0.33
Q_e/available energy	0.52	0.77	0.49	0.67
J_{ws}/available energy	0.3	—	0.19	—
J_{wd}/available energy	0.06	0.05	0.34	—

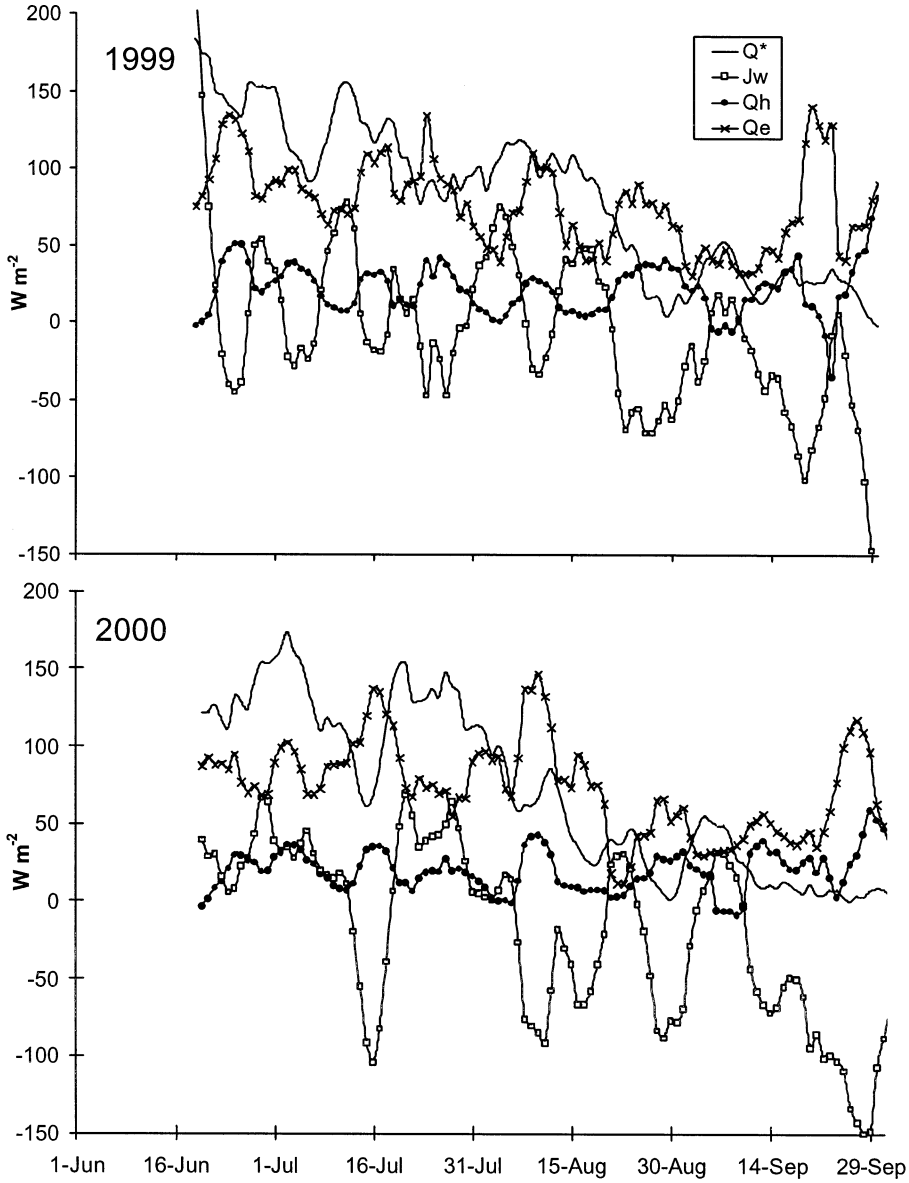

FIG. 5. The energy budget of Skeeter Lake in 1999 and 2000, beginning when the lake tower was deployed. Values presented are 5-day running means.

TABLE 3. Monthly water budget terms. Units: mm.

1999	P	R_s	E	G	O	ΔS (obs)	ε
Jun	1	0	50	7	0	−55	1
Jul	10	0	89	15.5	0	−118	−23.5
Aug	51	0	67	15.5	0	−52	−20.5
Sep	37	0	60	15	0	13	51
Open-water season	99	0	266	53	0	−212	8
2000							
Jun	23	0	44	8	0	−29	0
Jul	12	0	98	15.5	0	−143	−41.5
Aug	55	0	70	15.5	0	−12	18.5
Sep	32	0	52	15	0	−5	30
Open-water season	122	0	264	54	0	−189	7

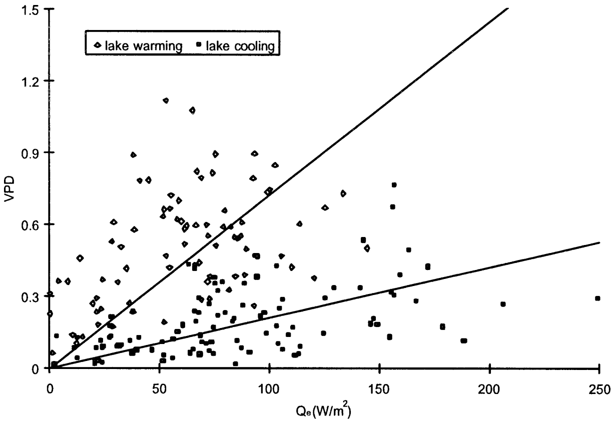

FIG. 6. Scattergram and regression lines illustrating the variation in VPD and Q_e for the periods when Skeeter Lake was warming and cooling.

er rainfall rates likely resulted in some runoff into the lake from outside the main inflow channel.

d. Turbulent fluxes

There is no relationship between Q^* and Q_h, and although there is a statistically significant linear regression of daily Q^* and Q_e, the relationship is not strong ($r^2 = 0.35$). Early in the summer when the lake is warming, Q_e follows Q^* (Fig. 5), but this relationship breaks down when the lake is cooling. When the lake is cooling, the turbulent fluxes will be largely controlled by temperature and/or vapor pressure gradients. The slope of the vapor pressure deficit (VPD) Q_e relationship flattens when the lake cools and releases heat, implying that the turbulent fluxes become more responsive to changes in temperature and vapor pressure gradients between the lake and atmosphere (Fig. 6). Even though there is a higher average temperature gradient between the lake and atmosphere when the lake cools in July than in September, the magnitude of Q_h does not change (Table 2). As lower air temperatures in September reduce the VPD, Q_e decreases significantly relative to Q_h.

The relationship between vapor pressure deficit and turbulent fluxes is logarithmic:

$$\beta = -0.2063 \cdot \ln(\text{VPD}) + 0.0814. \tag{8}$$

This empirical relationship may be site specific to Skeeter Lake, but because it reflects physical processes, it may be applicable to other lakes where the turbulent fluxes are controlled by temperature and vapor pressure gradients between the lake and atmosphere. Many cold northern lakes fall into this category (Rouse et al. 1997). Equation (8) underestimates Skeeter Lake 2001 open-water season evaporation by only 3%. When compared to Bowen ratio–energy budget evaporation estimates from the small shallow Golf Lake in the Hudson Bay Lowlands (Boudreau and Rouse 1995), the seasonal pattern is well represented, but Eq. (8) underestimates cumulative evaporation by 41 mm, or 14%. These differences may be due to the absence of a wind term in Eq. (8). As implied by similarity theory and the mass transfer approach (Oke 1978), a wind term is necessary to fully predict β.

e. CAGES

The open-water season of the CAGES water year at Skeeter Lake was characterized by a cool dry July (Table 1). The result was a higher frequency of lake-cooling events and a colder lake, as evidenced by the small magnitude of J_w (Fig. 5). With less of the energy heating the lake in July 1999 than July 2000, more was available for the turbulent fluxes; but the proportion of energy directed to latent heat was lower in 1999, and there was a decrease in evaporation (Table 3). However, seasonal evaporation may not experience much summer variance at lakes, such as Skeeter Lake, because higher-energy inputs during the warmer and sunnier summer of 2000 were directed toward lake heating. Because of the inability of radiation to penetrate to deep water, it is unlikely that even local extremes in air temperature and incoming solar radiation create the summer isothermal conditions that have been observed in southern Canadian Shield lakes (Barry and Robertson 1975), which allow more energy to be directed toward evaporation during the summer months. Such behavior is observed only when Skeeter Lake is isothermal in the fall and evaporation becomes more responsive than earlier in the year to changes in air temperature and the VPD (Tables 1 and 3). It is not known how many northern Shield lakes behave like Skeeter Lake. However, because similar small headwater lakes in this region are also characterized by high DOC concentrations (Pienitz et al. 1997) and occupy at least 35% of the freshwater area (Rouse et al. 2002), the energy budget processes identified at Skeeter probably play an influential role in the hydrometeorology of the region.

5. Conclusions

This study provides detailed information on the energy budget processes at a small lake in the subarctic Canadian Shield. High attenuation of incoming radiation at shallow depths and the sheltered location of Skeeter Lake allow a strong thermocline to develop during the summer months, which prevents deeper water from exchanging energy with the atmosphere. Only when the lake becomes isothermal in late August do deeper waters interact with the atmosphere. When the lake is warming, evaporation is controlled by net radiation, but when the lake is losing heat to the atmosphere, turbulent energy fluxes are mainly influenced by the vapor pressure deficit. An empirical logarithmic relationship was identified between the Bowen ratio and the vapor pressure deficit. It performed reasonably well, but underestimated evaporation, when applied to another northern lake. The

CAGES water year at Skeeter Lake was characterized by a cool dry July, which resulted in less of the available energy heating the lake. Because of the inability of radiation to penetrate to deep water in this lake, it is unlikely that even local extremes in air temperature and incoming solar radiation create the summer isothermal conditions observed in southern Canadian Shield lakes, which allow more energy to be directed toward evaporation during the summer months.

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