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(Running head: Artificial lake circulation model)

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MANAGEMENT PERSPECTIVE

Low wintertime levels of dissolved oxygen leading to fishkills is a perennial problem in some shallow lakes. We report on the thermal regimes of two small lakes located on the interior plateau of British Columbia as established from extensive winter observations. One of the lakes has a commercial artificial circulation device which is used to lift warmer and deeper water to the surface where it is used to melt a hole in the ice cover. Natural re-aeration of the surface waters in the hole maintains sufficient levels of oxygen in the lake. However, the cost is a loss of heat from the lake which may have adverse biological consequences.

The goal of our study is to construct a mathematical model of this artificial aeration process and use it to simulate the thermal regimes of the treated and untreated lakes. Improved understanding of this treatment process resulting from our field validated model could lead to improvements and reduced operating costs of winter aeration of lakes as well as design modifications resulting in less overall heat loss from the lake. Our field study has also stimulated related laboratory studies currently being conducted at the University of Western Ontario.

The lakes selected for study are particularly popular recreational fisheries in a provincial park. This generic study has wide applicability to other Canadian lakes. Our model is considered to be capable of being applied to predict to winter thermal regime of other lakes. This study was commissioned and supported in part by the British Columbia Ministry of Environment. It also was the basis of the graduate research of the first author which was co-supervised by the other two authors.

Abstract

A numerical model of the heat budget of a small mid-latitude ice-covered lake was extended to include the impact of an artificial circulation device. Two lakes located in the Southern Interior Plateau of British Columbia were selected for a field investigation to verify the model. The effects of the device include polynya development, and a substantial reduction in average lake temperature. An empirical surface velocity relationship derived from field measurements is used to estimate polynya size and turbulent heat transfer from the circulated water to the ice cover. Over the cooling period, the average heat lost from turbulent heat transfer between water and ice was three times that lost across the polynya surface. Lake temperature, polynya size and snow depth were well represented by the model. Further work is required to assess discrepancies between early winter ice thickness predictions and observations.

Introduction

Artificial disturbance of water is a common means of inhibiting ice formation in ports and marinas. Increasingly, it is also being used for the maintenance of water quality by facilitating the transfer of oxygen from air to water (Ward et al., 1986). To date, limited effort has been made in simulating the impacts on water temperature and the surficial extent of the ice-free zone known as a polynya by the various methods of generating disturbances. While the method of creating the polynya is important with regard to quantifying the impact on ice and water, a good model should be universal in terms of describing the heat transfer mechanisms involved. The only known models that predict the size of an artificially-generated polynya are those developed by Ashton (1979) and Helsten et al. (1995). Ashton's (1979) model simulates a point source bubbler system which induces a vertical flow of water, thereby melting the ice cover above. The emphasis in this model is the prediction of induced flow rates and plume temperature in a stratified body of water. The model uses empirical results of an axisymmetric impinging air jet on a flat plate (Gardon & Akfirat, 1966) to estimate the lateral variation of heat transfer between water and ice. The melting of ice is based on a simplified heat budget in which air temperature and wind speed are the only input variables. The simulation described, however, assumes a constant wind speed over a 24 day simulation period, and is not verified by field data. The Helsten et al. (1995) model is similar except that a mechanical jet lifts the deeper and warmer water to the underside of the ice instead of a bubbler. Their model is validated by observations of polynya growth in the laboratory.

We have developed a new model which is comprehensive in terms of describing the heat transfer mechanisms involved in the inhibition of ice formation. The model, in this case, is customized to predict the specific impact of a commercial artificial circulation device (ACD) commonly used for the re-aeration of small ice-covered lakes. Furthermore, the model is verified by field investigation. Simulation of this particular application is important because, depending on

Table 1: Morphometry of Menzies and Harmon Lakes

Parameter	Menzies Lake	Harmon Lake
elevation (m)	1250	1150
mean depth (m)	8.2	8.0
volume (m^3)	390 000	2 480 000
surface area (m^2)	47 500	311 000
maximum depth (m)	16.5	22.0
sheltering coefficient	0.68	0.82
Maximum Fetch (m)	500 (NE)	1100 (N)

The ACD at Menzies Lake is a commercial unit called the Air-o-lator ® (figure 1). It consists of a 0.75 kW axial flow pump fixed inside of a vertical draught tube which is attached to a floatation device. Water is drawn up through the draught tube, which extends 3.0 metres into the lake, and is projected horizontally just above the lake surface. The jet plunges back into the water and spreads radially. The area around the device remains ice-free out to a critical distance where the artificially-induced turbulence and thermal energy are insufficient to prevent freezing.

A weather station was installed on the ice-covered portion of Menzies Lake, at the location of maximum depth and data were collected from 13 December 1991 until 27 March 1992. The meteorological data are given by Rogers et al. (1995). Snow depth, ice thickness and lake temperature were measured during field trips to the lake, which took place about once every 2 weeks. Vertical temperature profiles were also monitored at an interval of 0.5 hours over the course of the study using a set of 6 thermistors and a datalogger contained within the weather station. An additional set of measurements were also made at 1.0 m intervals during each field trip using a portable temperature meter. Horizontal temperature variations were found to be negligible. Isotherms for both Menzies Lake and Harmon Lake are given in figure 2. (The period of partial ice cover at Harmon Lake [after 10 March] is excluded.) While the water below ice cover at Harmon Lake gradually, but consistently, heats up over the winter due to solar radiation and sediment heat transfer, the ACD at Menzies Lake causes the water to cool down to a minimum average temperature of about 1.4 ^{o}C. As early as late February, however, average air temperatures almost consistently above zero and increased solar heating rapidly drove the temperatures of both lakes up.

At the start of the monitoring period, a slight thermal stratification in Menzies Lake inhibited full circulation to a minor degree. The steady flow of water drawn up into the ACD, however, eroded this thermocline until virtually the entire lake volume was influenced by the unit. Therefore, the rate at which the isotherms dropped in December was more a function of pumping rate and lake morphometry than the rate of cooling. It should be noted that MLI is a bulk heat budget model and is therefore only appropriate for lakes which have no density stratification over the simulation period (Rogers et al., 1995). Average lake temperatures which are calculated by the model are compared with weighted average temperatures based on the observed vertical profiles. While temperature differences at Menzies Lake of almost 2.0 ^{o}C between 1 and 16.5 m (maximum depth) do occur over the monitoring period, most of the temperature change occurs below 12.0 m. The volume of water below this depth represents only about 5% of the lake volume. The errors associated with assuming isothermal conditions are considered negligible.

The size of the polynya, which, although irregular, is approximately circular in shape, was also measured during each field trip. A surveyor's chain was fixed to the ACD and unspooled from a boat to the polynya edge in 2 to 10 directions, depending of the time available. No significant changes in size were detected until spring when there was a rapid expansion leading to completely ice-free conditions within two weeks. The radius of the polynya was observed to remain about 20 m on average. The only significant evidence of variable radius in mid-winter was a thin ice layer, about 1 m wide on average, which was observed around the polynya perimeter when the lake was visited early one morning in cold weather. A diurnal contraction/expansion cycle is suspected as a result of this observation.

The radial velocity field created by the ACD was measured using a portable OTT meter. Velocities were measured at 13 stations between 1 and 7 metres from the ACD (beyond 7 metres, velocities were below the range of the meter). At each station, measurements were made at the surface, 10, 15 and 20 cm. The surface velocities measured using the current meter (figure 3) agree very well with turbulent radial jet theory (see Rajaratnam, 1976; Witze & Dwyer, 1976) which states that the velocity generated along the centerline of a submerged jet (which we assume to be equivalent to the surface velocity generated by the ACD) and:

$$U = \frac{k\,Q}{r} \qquad (1)$$

where U ($m\ s^{-1}$) is the surface velocity, Q (m^3/s) is the flow rate through the ACD, and r (m) is the radial distance. The field measurements indicate that, for the Air-o-lator® device complete with flow deflector, as shown in Figure 1 (item #1), $k = 6.13\ m^{-1}$. The below surface measurements were only sufficient enough to suggest a qualitative consistency with theory. As the jet entrains more water along its trajectory, the vertical velocity gradient reduces and at a radial distance of 7 m, the velocity is nearly uniform over the top 20 cm.

Model Development

The MLI model, described by Rogers et al. (1995), involves a one-dimensional balance of heat flux across an ice and snow cover. All fluxes are assumed to be uniformly distributed over the entire lake area. It has been modified, however, in order to account for the non-distributed nature of the Air-o-lator® device. The new version, called MLI-C (MLI-Circulator), is described here.

The new key variables which must be calculated at each time step are the radius of the polynya generated by the circulator, the heat flux across the polynya, and the turbulent heat flux from the water to the ice in the vicinity of the polynya. It is assumed that the polynya is circular at all times, with the circulator at the centre. Beyond its importance with respect to sensible and evaporative heat loss, the wind is neglected as far as the shape of the polynya and the surface currents are concerned. We feel this simplification is reasonable given that, upwind of the circulator, surface currents are impeded while downwind they are assisted by the wind. The lake morphometry may also play a role in the polynya shape and size, but this possibility has also been ignored.

Little information is available regarding the shape and other characteristics of the transition region between the open water and full ice and snow cover. The transition region may be of significance to the flow regime, and hence the heat transfer at the ice-water interface. Furthermore, the field study yielded no information regarding the velocity field in the vicinity of the transition region. We do not attempt, therefore, to predict the nature of the transition region. Instead, a simple model, based on the assumption that there is an abrupt change from open water conditions to some minimum ice thickness, will be employed to calculate the polynya radius. The approach is based on that taken by Patterson & Hamblin (1988) to account for the effect of partial ice cover on an undisturbed lake.

All heat fluxes across the lake surface, including the polynya and the ice at the polynya edge, are identified in figure 4. In this figure, H refers to the balance of meteorological energy at the lake surface, and q represents the heat fluxes from the water through to the surface of the ice and snow cover (see Rogers et al., 1995). In addition to the conduction of heat at the ice-water interface which exists under natural conditions (q_w), the ACD creates a turbulent heat flux, q_t, at this boundary which is a function of the flow field induced by its operation. Furthermore, the meteorological balance within the polynya itself, H_p, must be calculated and used to determine the total heat loss from the water body. The heat fluxes at the edge of the polynya must also be calculated independently, based on the minimum ice thickness described above, to determine changes in polynya size.

Turbulent heat transfer between water and ice

The turbulent heat transfer between water and ice can be described using a bulk aerodynamic formulation of Newton's law of cooling which has been used to describe heat flux in lakes with significant flow-through (Hamblin & Carmack, 1990):

$$q_t = C_t \rho c_p U (T_w - T_m) \qquad (2)$$

where, C_t is the turbulent heat transfer coefficient, ρ is the density of water, c_p is the specific heat of water, U is the flow velocity at some distance from the boundary, T_w is the water temperature, and T_m is the melt temperature (0 ^oC).

In this case, the flow velocity, U, is caused by the ACD. As described above, the surface velocity varies as r^{-1}, where r is the radial distance from the circulator. At the polynya edge, there is a thick layer of water moving below the ice at a relatively uniform velocity. From radial jet theory (Witze & Dwyer, 1976), at a distance of 20 m (typical polynya radius), the velocity one meter below the surface is about 85% of the surface velocity. Therefore, while the vertical velocity profile of the ACD flow regime and that of the natural lake with significant flow-through are bound to differ, we feel it is reasonable to suggest that, in both cases, shear is only significant at the ice-water interface, and equation 2 can be applied to the ACD regime, but only at significant radial distances.

From Figure 13 in Gilpin et al. (1980), C_t varies from 0.6 x 10^{-3} to 1.0 x 10^{-3} under experimental conditions depending on the ice roughness. As Hamblin & Carmack (1990) point out, however, the scales of turbulent motion associated with laboratory flow fields are generally not representative of lakes. Furthermore, Gilpin's (et al., 1980) use of cross-sectionally averaged velocities in equation 2, is also inappropriate for this application. Using under ice-current and temperature measurements (made at 1 m below the ice) in three large northern lakes with significant flow-through, Hamblin & Carmack (1990) found C_t to be in the slightly broader range of 0.5×10^{-3} to 1.1×10^{-3}. Given this wide range and the unique flow regime, C_t, is left as a calibration parameter in this study.

At this point we would like to comment on the heat transfer coefficient derived by Ashton (1979). The coefficient, in this case, is based on empirical results of Gardon & Akrifat (1966) involving an axisymmetric air jet (in air) impinging on a flat plate. The details of boundary layer development are not considered. Hirata et al. (1979), however, examined these details in a laboratory investigation of the steady state profile of an ice layer in a forced convection flow of water. It was found that the Nusselt Numbers throughout the turbulent regime were in the order of 35% larger than those given by the von Kármán correlation for turbulent flow over a flat plate. Gilpin et al. (1980) explain that the heat transfer rates for forced convection over an ice layer are greater that those predicted by flat plate boundary layer theory because of irregularities that will develop in the ice layer profile.

To quantify the total turbulent heat transfer to the ice-covered region of the lake, q_t must be integrated over the ice-covered region, from the ice edge to some radial distance, r_∞ away from the edge:

$$Q_t = \frac{2\pi}{A_L - A_p} \int_{r_p}^{r_\infty} q_t \, r \, dr = \frac{12.26\pi \, C_t \, \rho_w \, c_p \, Q \, (T_w - T_m) \, (r_\infty - r_p)}{A_L - A_p} \qquad (3)$$

where Q_t is the net turbulent heat transfer, A_p is the polynya area, A_L is the lake area, and r_p is the polynya radius. The parameter r_∞ could be defined by calculating the radius of a circle with the same area as the lake considered. Overestimates of heat loss would result, however, because the radial jet is constrained by friction along the under-side of the ice and by the lake boundaries (i.e. the lake constitutes a closed system in which significant adverse pressure gradients may be established due to the recirculation of water). These two problems could be dealt with simply by treating r_∞ as a calibration parameter. The degree to which the radial jet is constrained by friction, however, will depend on the size of the polynya. If we make the approximation that friction dissipates the velocity to laminar conditions over a constant distance under the ice, regardless of r_p, then the calibration parameter becomes Δr, where $r_\infty = r_p + \Delta r$. Given that the surface velocity gradient is small beyond the polynya edge, and the variation in polynya size has been observed to be small over most of the winter period, errors associated with the above assumption are considered to be minor.

Meteorological balance within the polynya

In addition to the fluxes applied in the ice and snow covered area (see Rogers et al., 1995), the energy balance at the air-water interface within the polynya is a function of cooling due to free convection and snowfall. A further consideration is the turbulence induced by the circulator at the air-water interface. Measurements made in the ocean, however, have shown that sensible heat transfer is a function of wind speed, but is independent of sea state (Kraus, 1972). Given this finding, it is assumed that the turbulence generated by circulator is only important insofar as it increases the heat transfer to the ice cover.

Free convection due to unstable humidity profiles, is considered important in cooling ponds, Arctic leads and polynyas where the air temperature is, on average, much less than the surface water temperature, and wind speeds are low (Ryan et al., 1974; Den Hartog, 1983). Its contribution to the evaporative heat loss is given as follows (Ryan et al., 1974):

$$Q_{fc} = \lambda \cdot (svp0 - svpd) \cdot \sqrt[3]{T_{wv} - T_{av}} \qquad (4)$$

where, svp0 is the saturation vapour pressure at the water temperature, T_w (mbars), svpd is the vapour pressure of the air (mbars), T_{wv} is the virtual surface water temperature (°C), T_{av} is the virtual air temperature (°C), and $\lambda = 2.7\ Wm^{-2}mbar^{-1}(^oC)^{-1/3}$.

Since water vapour is lighter than air, evaporation increases the driving buoyancy force driven by the temperature difference T_w - T_{air}. This effect is accounted for by employing the virtual temperature difference, T_{wv} - T_{av}. The virtual temperatures are calculated as follows:

$$T_v = \frac{T+273}{1 - \left(\frac{0.378 svp}{P_{atm}}\right)} - 273 \qquad (5)$$

where, P_{atm} is the atmospheric pressure (mbars).

Reservoir operators have often observed a reduction in water temperature following snowfall over open water (Ashton, 1986). The following equation may be employed:

$$Q_{sp} = L\, \rho_w\, I_s - C_{pi}\, \rho_w\, (T_{air} - T_m)\, I_s \qquad (6)$$

where, Q_{sp} is the heat removed from the water (W/m^2) and I_s is the snowfall rate (mm/hr, rain equivalent). The first term accounts for the latent heat of fusion, and the second for the heat used in warming the snow to the melting temperature.

The net heat flux, H_p, at the air-water interface is calculated as follows:

$$H_p = I_{wp} + R_{li} - R_{lop} - Q_{cp} - Q_{ep} - Q_{fc} - Q_{sp} \qquad (7)$$

where I_w is the non-reflected solar radiation, R_{lo} and R_{li} are the outgoing and incoming longwave radiation respectively, Q_c is the sensible heat transfer and Q_e is the evaporative heat transfer. Each of these terms is determined using standard bulk aerodynamic formulae. The subscript p refers to the polynya.

Polynya Radius

The polynya radius is determined at each time step in a manner similar to the calculation of the ablation and accretion of ice at the ice-water interface for a lake with full ice cover (Rogers et al., 1995). As described above, however, the minimum ice thickness, h_{min}, concept employed by

Patterson & Hamblin (1988) to account for partial ice cover is assumed to apply to the ice at the polynya edge. It will be treated as an additional calibration constant for the model.

Field observations indicate that, at the polynya edge snow does not accumulate, and the ice has the appearance of snow-ice. It is hypothesized that the surface turbulence in the polynya causes water to lap up onto the ice thereby saturating any snow which may exist there. Subsequent freezing creates snow-ice. All ice at the polynya edge will be assumed to be "white ice", as field observations have indicated. The assumption is supported by the fact that lake surface agitation (such as that produced by the ACD) will lead to granular white ice during freeze-up (Gray & Male, 1981). It is assumed that the properties of this white ice are the same as snow-ice, and hence, the ice at the polynya edge is considered uniform.

The model assumes that a polynya always exists (in fact, the operational procedure of the ACD is such that this assumption is correct). For the polynya size to increase, the entire white ice layer must be melted at the radius defined by the current location of the polynya edge. The change in ice thickness at the polynya edge is determined as follows:

$$\frac{dh}{dt} = \frac{(q_f)_{pe} - q_w - q_t}{\rho_e L} \qquad (8)$$

where, dh/dt is the time rate of change of ice thickness at the polynya edge, $(q_f)_{pe}$ = the flux of heat through the ice at the ice-water interface of the polynya edge, q_w is the conduction of heat from water to ice, ρ_e is the density of snow-ice, and L is the latent heat of fusion (see figure 4).

If equation 8 results in an ice thickness less than or equal to zero for the half-day time step, or if $H_p > 0$, then polynya expansion is underway, and equations 1, 2, and 8 are solved simultaneously for r, the new polynya radius. The above formulation implies that melting is assumed to proceed from the bottom of the ice cover. If equation 8 produces an ice thickness which is greater than zero, contraction of the polynya occurs and these equations are again solved simultaneously. In this case, however, equation 8 is modified reflect the fact that accretion can only occur on the face of the ice edge, where it is exposed to H_p:

$$\frac{dh}{dt} = \frac{-H_p - q_t}{\rho_e L} \tag{9}$$

We emphasize that there is no coupling between the ice at the polynya edge and the far-field ice beyond. The (far-field) ice thickness calculations are based only on meteorological fluxes and simple heat conduction as described by Rogers et al. (1995).

Integration with MLI

The above formulations have been incorporated into new subroutines which have been linked with the MLI model. These new subroutines affect the MLI computations by introducing the two new terms H_p and Q_t in the equation for the net heat transfer to or from the water, q_{net}:

$$q_{net} = H_p + I_w + q_{sed} - q_w - Q_t \tag{10}$$

where I_w is the solar radiation which penetrates through the ice-covered area to the water below, q_{sed} is the heat transfer from the lake sediments, and q_w applies to the entire ice covered region. Each component of q_{net} is scaled by a surface area ratio which depends on the part of the lake over which the specific heat transfer process is active.

Simulation Results

MLI-C was written in QuickBASIC 5.0 and run in 32 bit precision on an 80386 DX (25 MHz) PC equipped with an 80387 math co-processor. For 105 days of data, less than 10 seconds were required to produce results.

MLI-C results for snow depth, ice thickness and lake temperature using the Menzies Lake data set are given in Figure 5. All parameters used in MLI were set to their default values (see

Rogers et al., 1995). All of the trends in temperature are correctly predicted by MLI-C as substantiated by weather station thermistor data. Snow thickness predictions are also good notwithstanding a poor match between predicted and observed values on 7 January. There are, however, some significant discrepancies with respect to ice thickness, especially early in the simulation period. The problem of ice thickness predictions is considered later.

Figure 5 also includes ice and snow predictions for Harmon Lake, as well as results for Menzies Lake in the case of no artificial circulation (i.e. using the MLI model). All three results (Harmon, Menzies with ACD, Menzies without ACD) are nearly identical for snow cover, and only minor differences in ice thickness are predicted over the latter two-thirds of the simulation. Artificial circulation at Menzies Lakes results in cooler water temperatures and therefore less heat conduction from the water to the ice cover, leading to slightly greater ice thickness. Since both the snow cover results and observations at Menzies Lake are almost identical to those at Harmon Lake, it is unlikely that artificial circulation has any significant impact on snow cover. There are sound explanations, however, for the small differences observed, involving factors such as snow bearing capacity of ice, sheltering characteristics of the surrounding terrain, and to a very minor degree, the indirect influence of heat conduction through ice during periods of surface melt.

MLI-C correctly predicts a narrow range in the polynya radius as shown in figure 6. There is a sharp diurnal trend due to the effect of solar heating in the first time step. The trend cannot be confirmed since almost all observations were made near mid-day. The one early morning observation of the thin, narrow rim of ice around the polynya perimeter as described above, however, provides further evidence that a significant diurnal contraction/expansion cycle does exist. Aside from this diurnal variation, there are, at times, some significant day to day changes, notably during the January rainy period and near the end of the simulation. The sampling was insufficiently frequent to confirm any rapid day to day changes.

The errors involved in estimating the average polynya radius generally exceed its variability over the observation period. There continues to be good agreement, however, between predictions and observations when a significant increase in polynya radius finally occurs near the end of the simulation. The wide error bars shown in figure 6 reflect the irregular shape of the polynya and are dependent on the number of direct measurements made. As described above, anywhere from 2 to 10 measurements of radius were made on each field trip.

MLI-C Calibration Parameters

The results shown in figures 5 and 6 were achieved using the following parameter values: C_t = 1.1×10^{-3}, $h_{min} = 0.02$ m, and $\Delta r = 13$ m. Any reasonable change in the calibration parameters has virtually no impact on the lake ice and snow cover. The impact of each on lake temperature and polynya radius, however, is substantial. The above values produced a good match between the observed and predicted values of both of these variables, although the rate of lake warming in March is underestimated. The relatively poor simulation in late winter may be due to low radiation measurements resulting from a slight tilt which developed in the weather station during the late winter ice-melt period (see Rogers, 1992) or poor albedo representation associated with thin snow cover. Factors which are particular to the impact of the ACD include possible underestimations of the polynya radius and boundary effects. The latter factor may be of great importance given that, by the end of the simulation period, the polynya edge was only two to three metres from the north shore of the lake, in very shallow water.

The above value of C_t is at the high end of the range given by Hamblin & Carmack (1990). We suspect that this may be a reflection of the radial jet velocity distribution which may be characterized by relatively high velocities near the ice interface as compared to the case of river flow-through. Minimum ice thicknesses of approximately the same magnitude as the selected h_{min} have been observed at both Harmon and Menzies Lakes, both during freeze-over and around the perimeter of the Menzies Lake polynya. Patterson & Hamblin (1988) employed an h_{min} value of 10 cm for simulating partial ice cover at much larger lakes with significantly greater fetch lengths. The value of h_{min} should drop with reduced fetch length because the maximum wind speed and wave height development is limited, resulting in less turbulent energy available to inhibit the persistence of a thin ice layer. Although the ACD creates turbulence, it is quickly dissipated as the radial jet spreads, and the wave amplitudes produced are small. Therefore, a relatively thin ice sheet is able to persist around the polynya edge. The parameter Δr is, as expected due to friction and boundary effects, less than that which corresponds to the entire ice-covered area of the lake surface. Beyond about 33 m from the ACD ($r_\infty = r_p + \Delta r \approx 20 + 13 = 33$ m), turbulence should be negligible if the calibrated value of Δr is reasonable. Based on a length scale of 1m (as is assumed for the calibration of C_t), the Reynolds Number at this distance is about 10^4, suggesting transition flow nearing laminar conditions.

Components of the Heat Budget

The surface heat budget components for the ice-covered portion of Menzies Lake are given in Figure 7. The indirect effect of much cooler lake temperatures has virtually no effect on any of the components in relation to the Harmon Lake simulation (see Rogers et al., 1995). The heat fluxes to and from the lake water are also given in Figure 7. All of the fluxes shown (i.e. across the polynya and ice-covered areas) have been adjusted to apply over the entire lake surface in order to facilitate direct comparisons. From the start of the simulation until the end of January, when the minimum lake temperature was reached, Q_t (the turbulent heat transfer from water to ice), averaged about 7.6 W/m^2 over the entire lake area, or over three times the rate of cooling across the polynya, H_p, (adjusted to apply over the same area) for the same period. From the start of February until the end of March, there was, on average, a slight net transfer of heat into the lake across the polynya, while Q_t increased to an average rate of 8.6 W/m^2 due to elevated water temperatures. There are no significant diurnal variations in Q_t because this variable is more dependent on Δr (which is assumed constant) than the actual distance from the ACD to the polynya edge. Over most of the simulation, there is only about a 4 W/m^2 range in Q_t, mainly due to gradual changes in lake temperature. Sharp increases in Q_t do not occur at the end of the simulation in response to more rapidly increasing water temperature because the corresponding increase in polynya size is accompanied by a decrease in average velocity, or turbulence, underneath the ice-covered portion of the lake. It is likely, of course, that there is a dependency of Δr on r_p. That is, the distance over which the energy associated with the jet is dissipated decreases as the polynya radius increases. If this is so, then MLI-C would tend to overpredict the heat loss due to Q_t near the end of the simulation when the polynya is large. Overprediction of Q_t provides another possible explanation for the low rate of temperature increase predicted in March (figure 5).

H_p varies strongly due to diurnal changes in the meteorological balance, but average heat loss over the first two months is only in the order of about 3 W/m^2. In terms of heat loss from the entire lake, this means that H_p is only slightly more important than the simple conduction of heat from quiescent water to ice over the ice-covered region. When warmer conditions prevail, as early as the late January rainy period, the average daily heat exchange across the polynya is close to zero. Following a brief cooling period in mid-February, when average daily heat losses were only about 1 W/m^2, the direction of net heat transfer is reversed. At this stage, greatly increased solar energy penetrating through the ice-covered area more than offsets Q_t to produce warming of the lake water. The range and importance of H_p is shown to increase dramatically at the end of March because both polynya area and solar heating through the polynya also increase significantly. In terms of average daily heat exchange, however, H_p remains a modest term compared with both I_w and Q_t.

The trends in q_{sed} and q_w, although subtle, do not follow those associated with Harmon Lake (see Rogers et al., 1995), due to the significant difference in water temperature changes. The sediment heat transfer rate, q_{sed}, increases slightly as the lake cools, and then drops back down near the end of February as the water begins to warm. The opposite trend is observed in q_w. As the lake cools, there is a reduced thermal gradient between the lake water and the ice. As a result, the heat transfer rate goes down until a steady recovery begins as the lake warms up at the end of February. In general both q_{sed} and q_w vary little compared with the remaining sources and sinks of heat. The solar radiation which is able to penetrate the ice cover, I_W, increases with the depletion of the ice and snow cover, and as spring equinox is approached.

The components of H_p are plotted in Figure 8. (They have not been adjusted to apply over the entire lake area.) As the lake surface is relatively warm compared with the snow surface, net emission of long-wave radiation is much greater from the polynya than the rest of the lake. Net long-wave heat loss ranges from about 25 to 100 W/m^2 over the entire period. The greater temperature difference between the water and the atmosphere also translates into greater evaporative and sensible heat transfers. In this case, however, the sensible component removes heat from the polynya surface over most of the simulation (up to an occasional maximum of over 100 W/m^2). It is also clear that heat loss due to free convection, Q_{fc}, is much more important than the evaporative loss as quantified by the standard aerodynamic formula. Maximum heat transfer rates due to this mechanism are in the range of 25 to 35 W/m^2. Heat loss due to the cooling and melting of snow, Q_{sp}, falling into the polynya is also important when the total daily accumulation is greater than about 5 cm. For this amount of precipitation, about 10 W/m^2 of heat is lost on average over the time step.

By early February, solar heating begins to overcome all of the heat sinks described above. Following another brief cooling period later that month, only the net long-wave heat loss term is significant, but is no match for the solar heating which ranges from about 100 W/m^2 at the beginning of March to about 400 W/m^2 near the end of the simulation.

Ice thickness predictions

It is unlikely that errors were made in ice thickness observations given the simplicity of the measurement, as well as the fact that significant differences from the Harmon Lake observations were noted on almost half of the field trip dates. Inadequate or improper sampling may have led to poor estimates of average lake ice thickness. It is suspected that ice measurements may have been often made too close to the weather station, which probably served as a heat sink. A relatively high flux of heat from the water up through the weather station may have resulted in greater local ice thicknesses.

In terms of possible deficiencies in the model, the reader is reminded that, although the calibration parameters C_t, h_{min}, and Δr have a significant impact on lake temperature and polynya radius, they have virtually no effect on the ice cover. The greatest discrepancies between the predicted and observed ice thicknesses occur in the first month of the simulation when the lake water is experiencing its highest rate of cooling. If the observations are reliable, MLI-C must significantly underpredict the conduction of heat through the ice and snow cover. Based on the success of MLI in predicting ice thickness at nearby Harmon Lake, however, (see Rogers et al., 1995) we can discard the explanation that the conductivity of ice and snow is greater than what is assumed. We feel it is most likely that unsatisfactory ice thickness predictions are related to the lack of attention paid to the details of the radial jet thermodynamics which may lead to extensive horizontal variations in ice thickness as well as heat transfer rates.

Conclusions

The field observations at Menzies and Harmon Lakes coupled with the modeling results provide conclusive evidence of the severe impact that artificial circulation has on the temperature of a small mid-latitude lake. It has been confirmed that a gradual increase in temperature would likely take place at Menzies Lake if it were left in a natural state. Instead, significant cooling takes place, bringing the lake dangerously close to a temperature which is intolerable to aquatic life, even over the course of the uncharacteristically warm winter of 1991-92.

The MLI-C model provides good predictions of temperature, polynya size and snow depth at Menzies Lake throughout the simulation period. The deviations from the observations could be attributed to factors which are independent of the artificial circulation process, such as the difficulty of albedo prediction during periods of little or no snow cover (see Rogers et al., 1995). However, the reliability of the results are brought into question by the apparently poor ice predictions in early winter. The unsatisfactory match between predicted and observed ice thickness is considered to be due to insufficient sampling, and to the fact that the model does not reflect a direct dependence between the polynya and the heat transfer through the ice cover on the polynya.

Although MLI-C produces polynya size predictions which agree quite well with the observations, the lack of long term variations which exceed the expected error does not provide an adequate test of the model. Given the asymmetries in the jet and the potential impact of the lake boundaries on the hydrodynamics and the heat transfer processes, better results are not likely without increasing both the sophistication of the model, the input data requirements, and the observation requirements. Further fine-tuning of the calibration parameters are unlikely to produce more reliable results without making the model more sophisticated, or by providing better velocity field data. Although determined through calibration, the values of h_{min} and C_t are consistent with observations and previous studies.

The turbulent heat transfer from the water to the ice, Q_t, at an average of about 7.6 W/m^2, is over three times as important as the heat transfer across the polynya, H_p, over the lake cooling period. After the lake had reached its minimum temperature, there is, on average, only a slight net transfer of heat across the polynya until the end of the simulation. Meanwhile, Q_t increased in importance in the latter half of the simulation, with a lake average heat transfer rate of about 8.6 W/m^2.

The simulation results indicate that there is a delicate heat flux balance which results in lake temperatures that are just adequate in supporting aquatic life. For example, the heat which is provided to the lake by the sediments could, over cold winters, often constitute the difference between fish survival and fish mortality. Extremely windy conditions could also increase the importance of H_p through substantial gains in sensible heat loss. Furthermore, although snow cover does insulate the lake, its main impacts are to reduce the growth in ice thickness and to prevent solar radiation from penetrating into the water. Hence a winter characterized by consistently thick snow cover may deprive an artificially circulated lake of the solar heat it needs over the winter.

The results of this study suggest that some design changes in the ACD system may be appropriate in some cases. The most important finding is that, in terms of minimizing heat loss, it is less important to control polynya size than to minimize turbulence beneath the ice. A system of two or more smaller ACDs could produce the same polynya area while reducing the total turbulent heat loss to the ice. Although the same surface velocities must exist along the perimeter of the polynya for a given polynya radius and any system configuration, the use of several units should mean that the rate at which these velocities decrease beyond the polynya edge should be higher, thereby resulting in a reduced value of Q_t. This is explained by the inverse relationship between velocity and the radial distance from each individual circulator. Since the radius of the polynya was observed to be fairly stable, it would be feasible to install a curtain or a system of baffles at the polynya edge that would deflect the flow away from the underside of the ice, thereby reducing Q_t.

Further research is required in order to improve MLI-C. A re-evaluation of the MLI parameters and processes (such as snow properties, sediment heat transfer, snowmelt due to rainfall...etc.) is required (Rogers et al., 1995). Attention should be focused on the characteristics of the polynya edge and the hydrodynamic boundary layer which becomes established at the ice-water interface. Once the hydro/thermodynamics are better understood, it may be possible to abandon the h_{min} approach in favour of a more theoretical boundary layer heat transfer model in which the growth of ice from the polynya edge out the full ice thickness is also predicted. If this could be done, then there would also be no further need for the Δr calibration constant. The remaining parameter, C_t, would best be assessed in the field specifically for the Air-o-lator®, in a manner similar to that described by Hamblin (1990). Alternatively, C_t could be determined with better confidence by means of calibration once the hydrodynamic model is established.

More thorough ice thickness observations is also recommended to produce more accurate values of average thickness, and for providing more insight on spatial variations which may be dependent on the circulator. Additional observations may also allow for an indirect evaluation of the velocity decay below the ice, and Q_t. Finally, the impact the polynya has on the heat flux through the ice covering the remainder of the lake should be well established and quantified. A first attempt at solving this problem could involve the thermal resistance approach described above.

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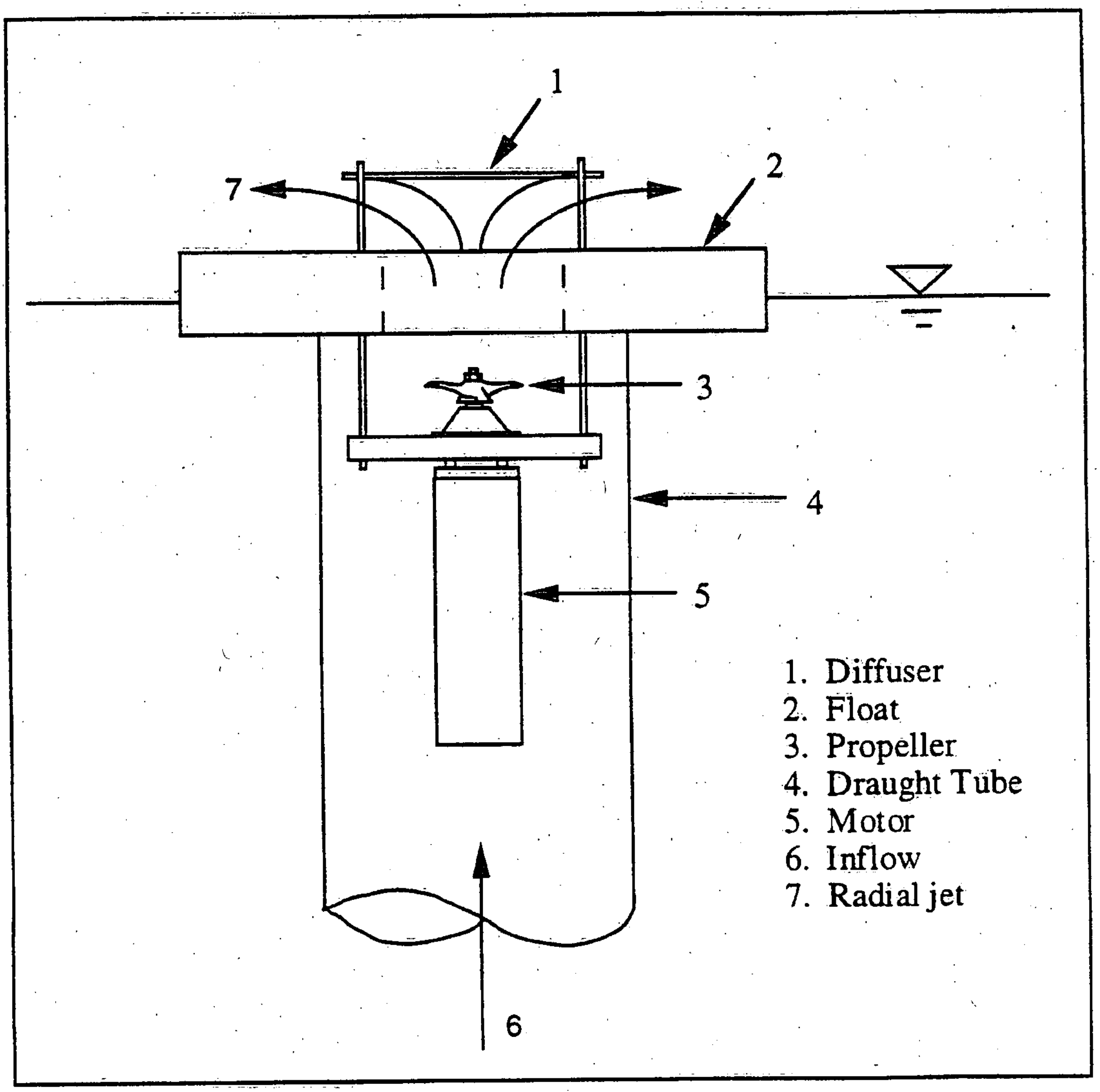

Fig. 1: The Air-o-lator ®

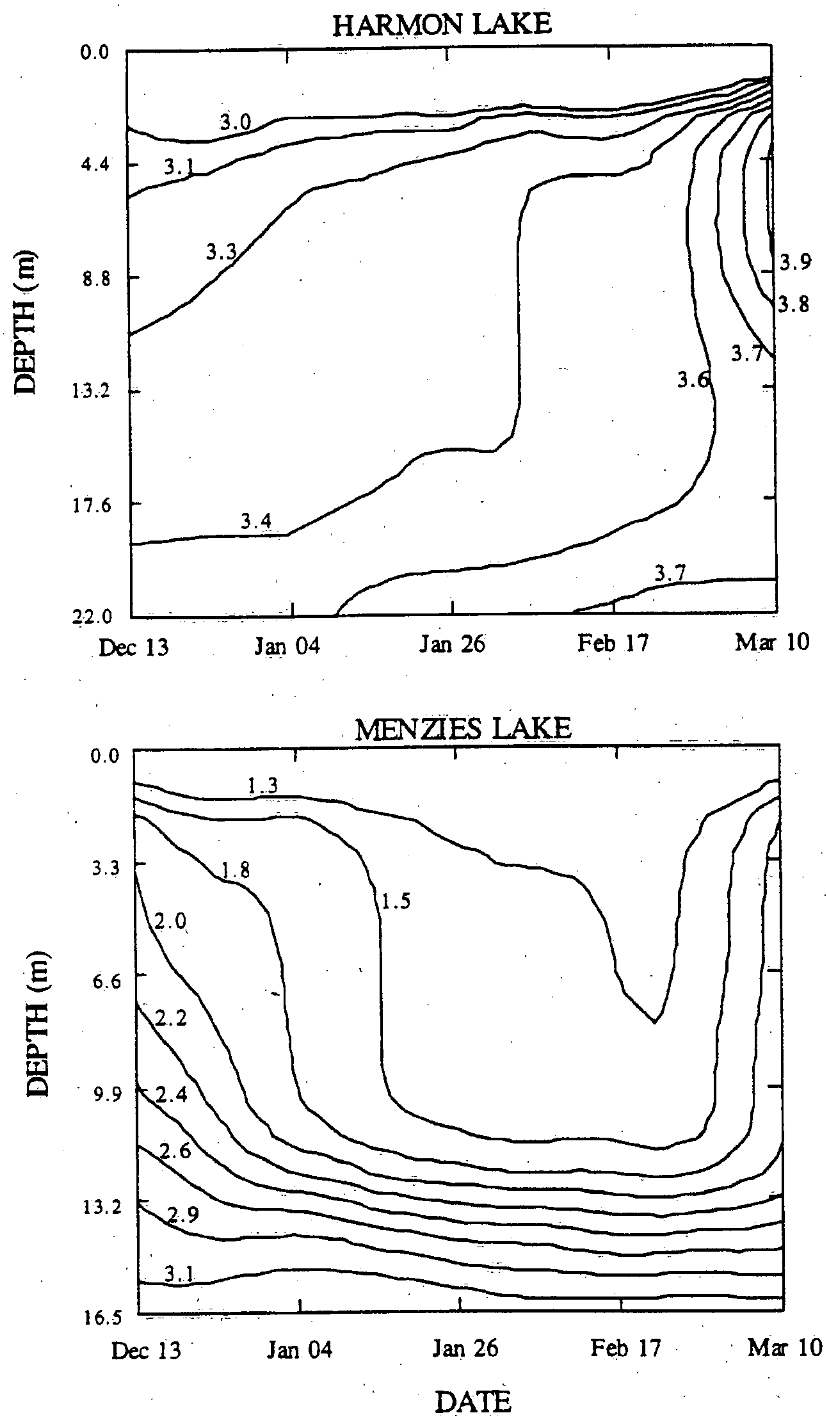

Fig. 2: Isotherms at Menzies and Harmon Lakes, December 13th - March 10th. For clarity, the isotherms in the vicinity of the ice-water interface have been omitted.

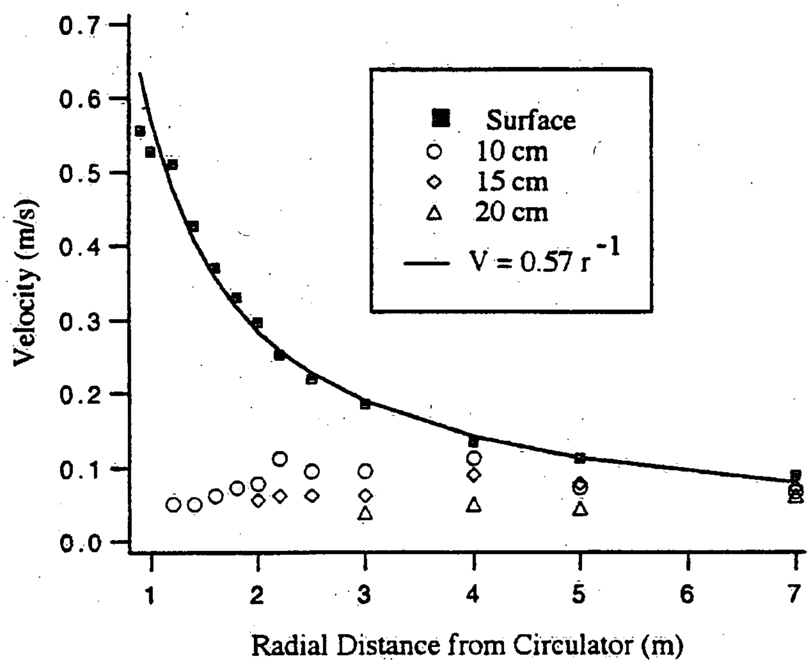

Fig. 3 Velocity Measurements in Vicinity of ACD

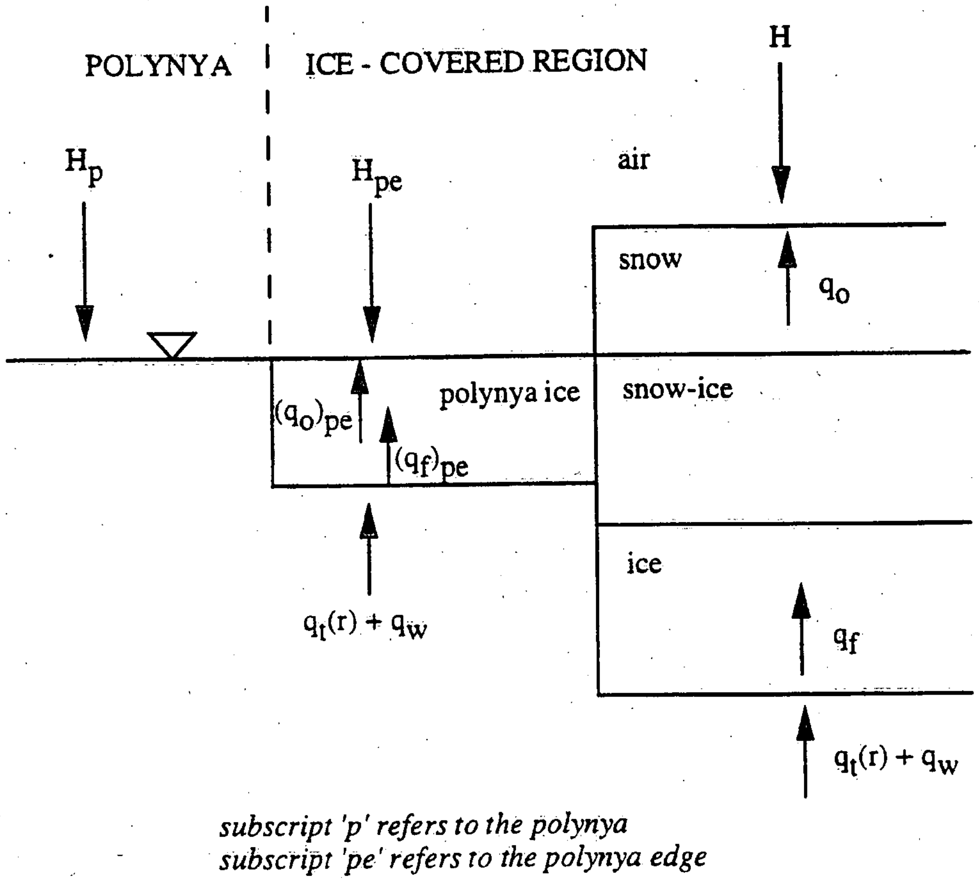

Fig. 4: Heat fluxes across lake surface with ACD-created polynya.

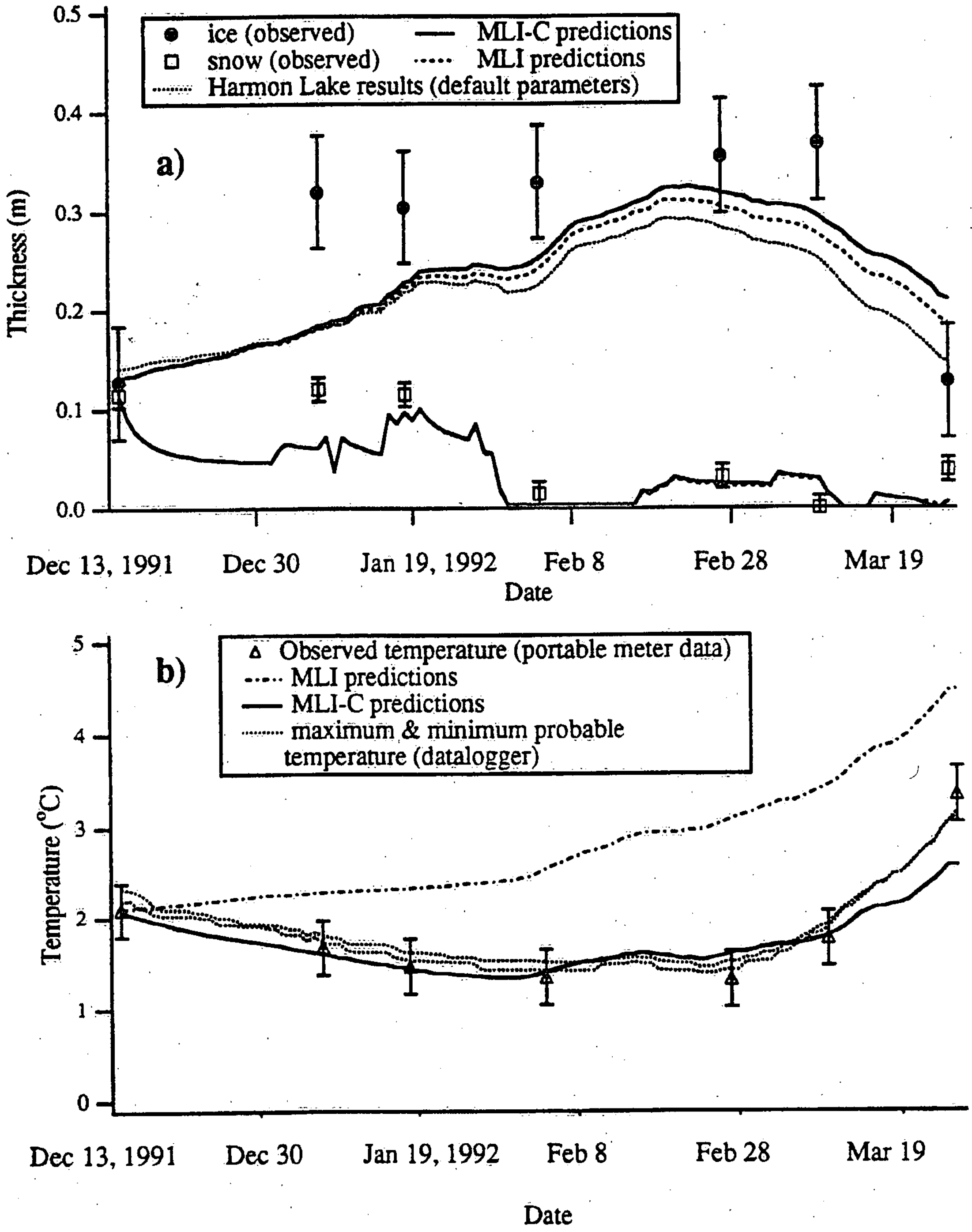

Figure 5 a) Snow and ice thickness predictions; b) Whole lake temperature predctions: a comparison of MLI and MLI-C ouput for Menzies Lake

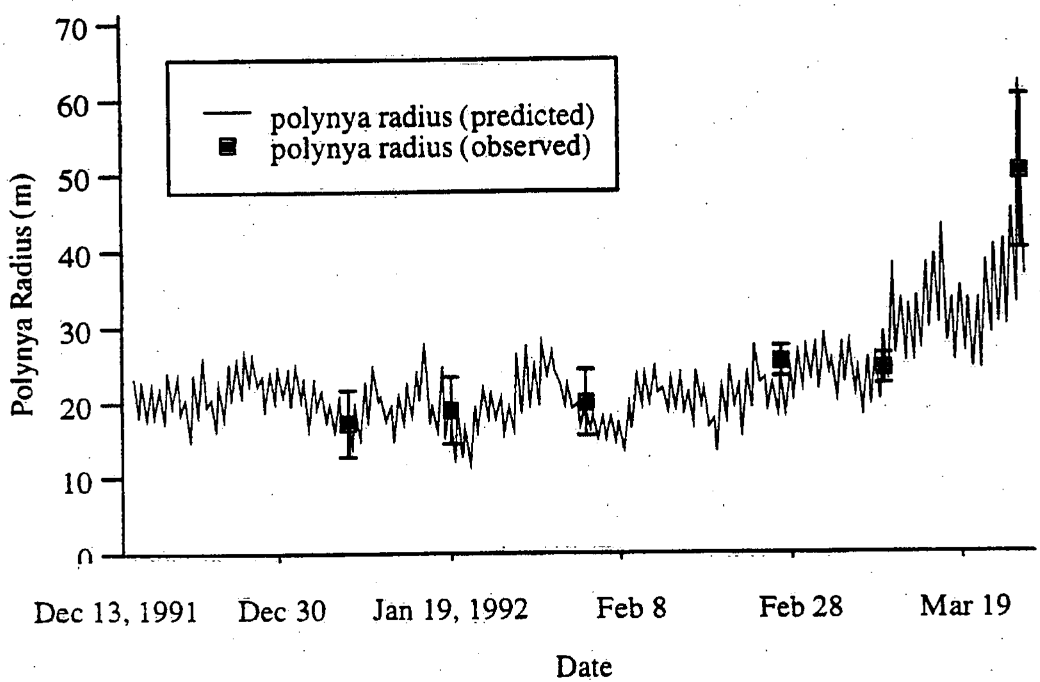

Fig. 6 Predicted and observed polynya radius at Menzies Lake

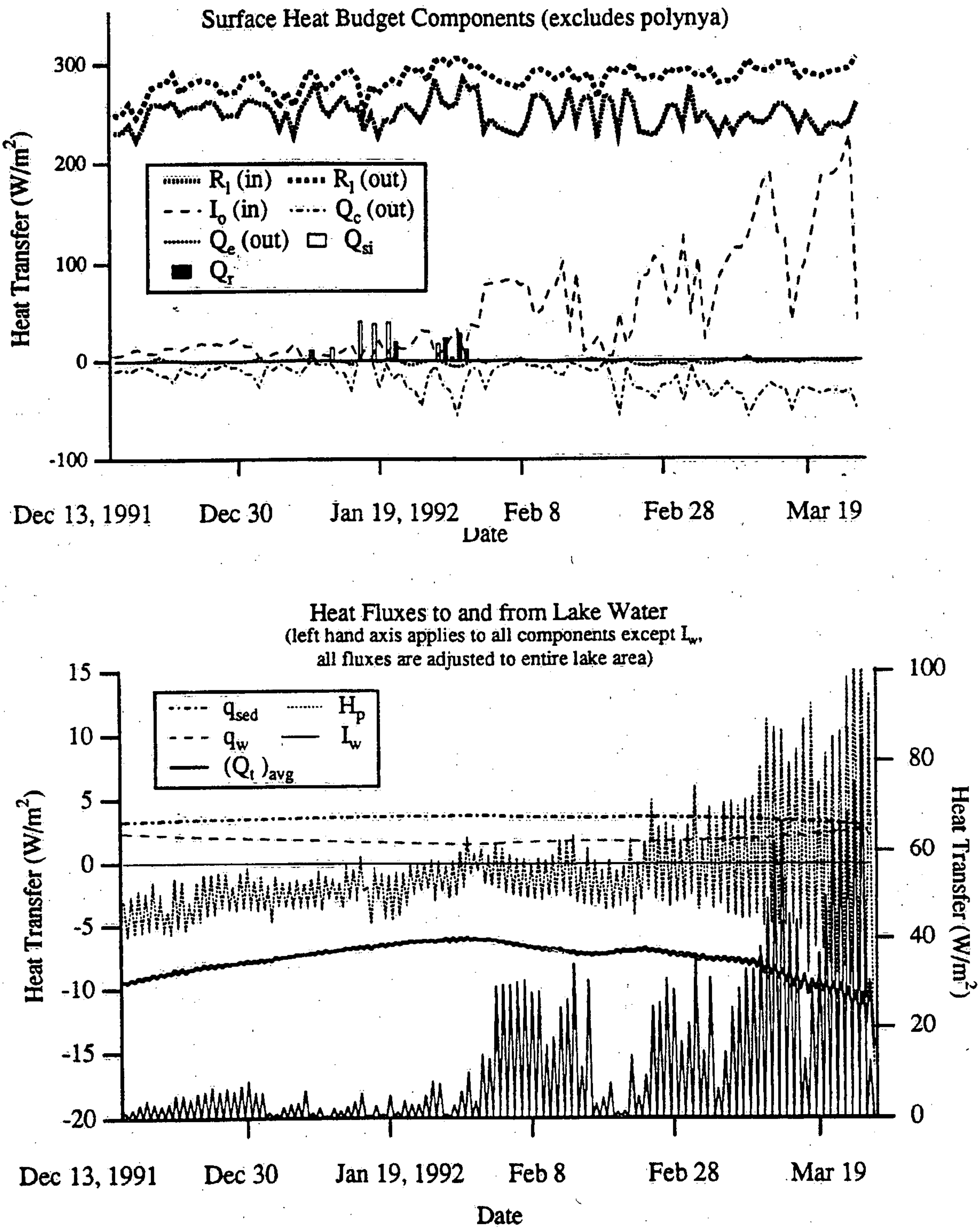

Fig. 7 MLI-C: Surface Heat Budget Components (excludes polynya) and Heat Fluxes to and from Lake Water at Menzies Lake

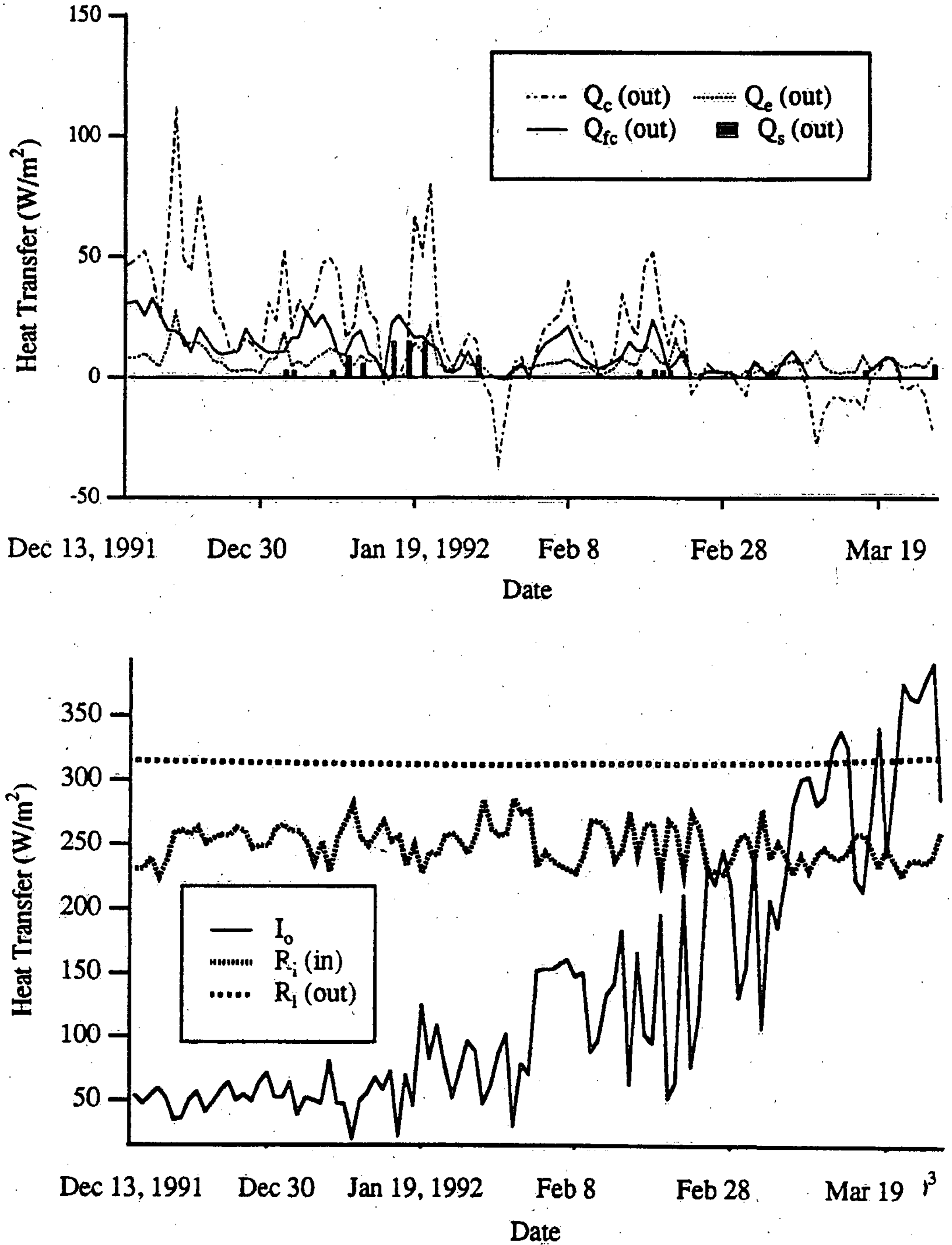

Fig. 8 Components of polynya heat budget, H_p, at Menzies Lake.

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