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The Use of Thermal Infrared Imagery in Surface Current Analysis of a Small Lake

Mapping and analysis of variations in surface temperatures are discussed for a conceptual model of lake circulation features.

Abstract: *Surface temperature detected by an airborne scanner is an invaluable data source for investigations into the mechanisms of surface circulations in small lakes. From 1979 to 1982, field experiments were conducted at the Chalk River Nuclear Laboratories in Chalk River, Ontario, to examine the role of remotely sensed imagery in two-dimensional studies of boundary layer processes over a small lake. These processes may control, in part, the three-dimensional circulation of the lake.*

Thermal imagery of Lower Bass Lake was collected in May and June of 1979, June of 1981, and in August of 1982. Micrometeorological measurements of the momentum flux over the lake surface were taken at the lake center for selected intervals in 1981 and 1982. To trace the surface currents, drifting drogues released from reference buoys were tracked both by survey triangulation and from periodic photography from a balloon centered over the lake. Rhodamine dye was used as a supplemental indicator.

The spatial variation of surface temperature over the lake is sufficient to have an influence on the transfer of momentum to the lake surface and, thus, affects the surface current velocities. In a small, closed system, the current patterns may also be affected by the resulting gradient of surface current velocity. The drogue trajectories reveal behavior consistent with theory.

Introduction

In micrometeorological and limnological studies, *in situ* measurement has often been restricted to selected sample points because of the complexity of instrumentation required. Remote sensing data provide insight into the spatial integrity of many phenomena and extend traditional one dimensional studies into two dimensions.

For example, analysis of thermal imagery may provide an accurate, synoptic account of temperature variations over the surface of the lake. This is not possible with sparse traditional sampling. The surface temperature distribution may contribute to explanations of lake circulatory features such as currents, zones of upwelling and downwelling, thermal fronts and bars, and discharge plumes (Scarpace *et al.*, 1975; Tonelli, 1978). Furthermore, because the surface temperature is the forcing function in many atmospheric processes, information on the spatial pattern of this parameter is also important in studies of boundary layer mechanisms. LeDrew and Reid (1982) coupled micrometeorological measurements at two locations over a small lake with a map of surface temperature derived from thermal imagery to estimate lake evaporation. They illustrated that evaporation based upon the typical single observation point may be in error by −6 to +10 percent

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when compared to an integrated areal average which includes the effect of variable thermal forcing.

The present study focuses on the incorporation of temperature patterns from infrared (IR) scanner data into an explanation of one driving mechanism of surface currents in a small lake. The actual configuration of the surface current may be a result of one or a combination of the spatial distribution of the atmospheric momentum flux to the surface, the ~~bottom~~ topography, shoreline geometry, bottom friction, and density patterns. We concentrate on the first factor using observational data and a simple conceptual model relating the momentum flux to the surface temperature and the surface current pattern.

SURFACE CURRENTS AND SURFACE TEMPERATURE

In a review of the patterns of the surface circulation of more than 40 constricted water bodies in the northern hemisphere, Emery and Csanady (1973) observed a characteristic counterclockwise gyre in all cases except one. The authors proposed an hypothesis based upon the influence of surface temperature on the overlying atmospheric stability and, consequently, on the momentum transfer to the surface. For a counterclockwise circulation to occur in a basin smaller than the scale of a synoptic weather pattern, there must be a cyclonic curl to the wind stress related only to the characteristics of the basin itself. With Ekman drift, there will be an accumulation of warm surface water to the right of the air flow trajectory and upwelling of cold water to the left, if mass continuity is to be maintained. The presumption is that the scale of the circulation is large enough for the Rossby number to be much less than one, and, therefore, the Coriolis effect is significant. Over the warm water, the atmosphere will be more unstable than over the cooler region. In an unstable regime the surface is 'coupled' to the atmospheric flow and momentum transfer is enhanced, whereas in a stable regime an 'uncoupled' situation prevails with less momentum exchange. The effect is accelerated surface flow to the right of the air flow trajectory in the 'coupled' region and a lower current velocity to the left. Within the constraints of a closed basin, the result is a counterclockwise surface current explained by a cyclonic curl in the wind stress (Figure 1).

While there have been notable theoretical and observational advances made in our understanding of the flow in these large lakes where the Coriolis effect is a major factor (e.g., Csanady, 1972a,b), there is a dearth of information regarding small lakes where other forces become important. In one study of a small coastal pond with a width of approximately 300 metres and length of approximately 1100 metres, Emery (1969) did note a dominant counterclockwise current.

Four years of field work at Chalk River Nuclear Laboratories near Chalk River, Ontario (Figure 2), have been directed towards the incorporation of remotely sensed imagery in studies of boundary layer processes over small lakes. At Lower Bass Lake, we have used thermal imagery in conjunction with measurements of the momentum flux within the atmospheric boundary layer and maps of surface current trajectories to explore the suitability of the Emery and Csanady hypothesis for a small lake where the Coriolis force and Ekman drift are negligible factors. The thermal gradients result from other mechanisms. Specific objectives are to determine whether there are spatial variations in the surface temperature of a lake of this size that may have significance in terms of the momentum flux and whether there are distinct modes in the patterns of surface currents over the lake.

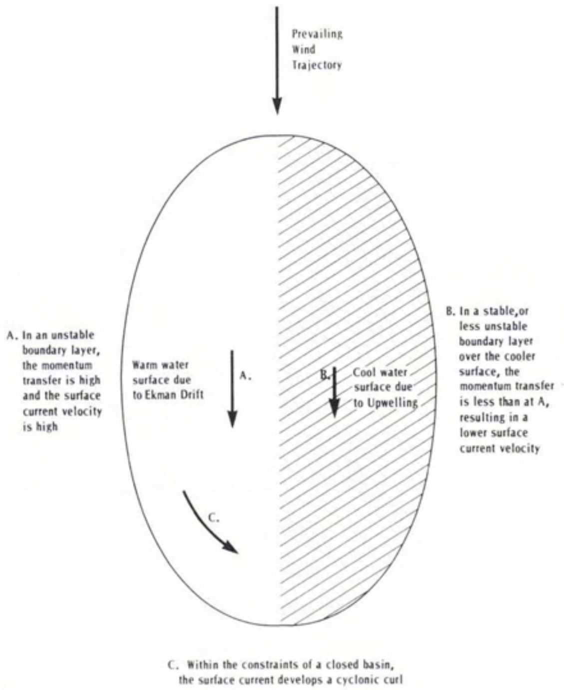

FIG. 1. Schematic illustration of the surface current curl resulting from a surface temperature gradient across a large lake with Ekman drift.

OBSERVATIONS AT LOWER BASS LAKE

Lower Bass Lake is approximately 0.11 square kilometres in area and has a maximum depth of 10.7 metres (Figure 3). On 17 May and 14 June 1979 thermal imagery was collected over the lake with a Daedalus IR line scanner (model DS-1260) at 1300 hours under clear skies and at a flight altitude of 1250 m above ground level by the Canada Centre for Remote Sensing (CCRS). The flight line was along the major axis of the lake and the path angle did not exceed 10 degrees across the minor axis. The

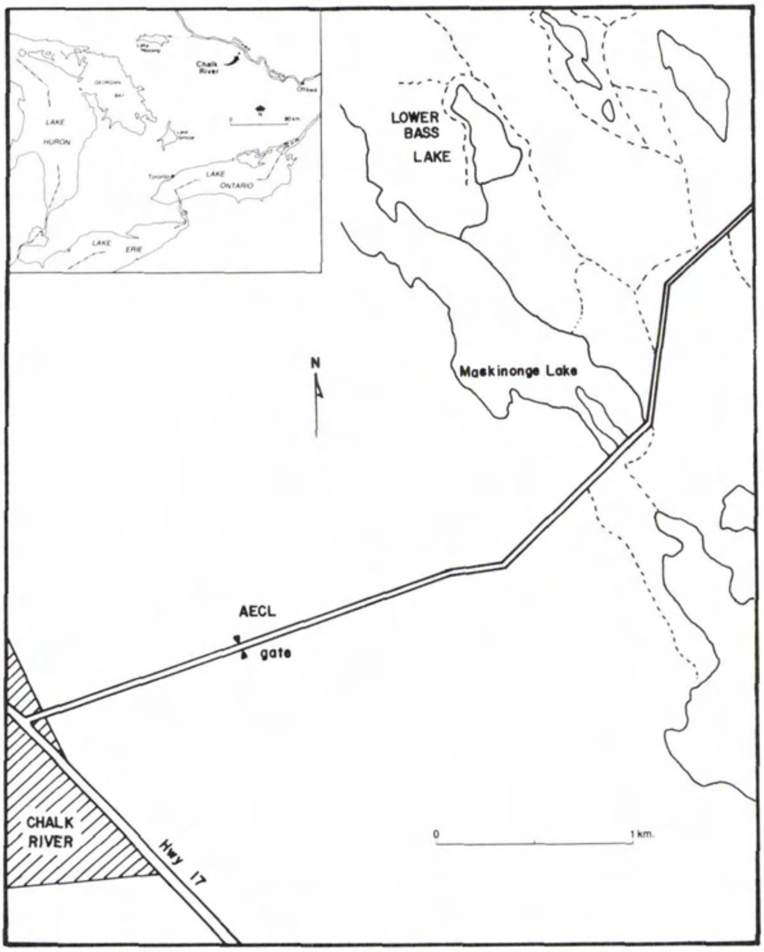

FIG. 2. Regional setting of Lower Bass Lake.

ground cell was 1.5 metres in width for the 17 May image and 2 metres for the 14 June image. Scanner gain and offset were fixed throughout each flight so that signal variations reflect absolute differences in blackbody temperature. Standard climatological data were recorded, and surface temperatures were measured with a handheld infrared thermometer and shielded thermisters at the water surface.

On 12 June 1981 video thermal imagery and normal color imagery of the lake were taken from a helicopter. Rhodamine dye was released from reference buoys. These observations were taken in conjunction with measurements of the surface currents using drogues tracked by survey triangulation from shore. Micrometeorological measurements of the wind and temperature profiles between 40- and 160-cm height were also made over the lake center at an instrument raft. The drogue surveys and micrometeorological observations were continued through the month of June to examine the typical current regimes.

From 13 August to 12 September 1982 the surface currents were again tracked using drogues painted so that they could be identified on imagery taken from a 35-mm camera system suspended from a tethered balloon at 300-metres altitude. This balloon-camera system was a modification of the design given by Petzinger (1977). A 28 cubic metre balloon was fitted with a gimbal to maintain an approximately normal aspect for the camera. A 35-mm Nikon camera with a data back was fitted with a radio exposure trigger modified from a hobby airplane control. Images were made every 10 to 15 minutes to track the drogue trajectories and to record the evolution of rhodamine dye plumes. With the minute of exposure imprinted on the slide, approximate calculations of drogue velocity could be made. These data were backed up by the survey observations.

Micrometeorological measurements were also taken regularly during this field season at the lake center. The Ontario Centre for Remote Sensing col-

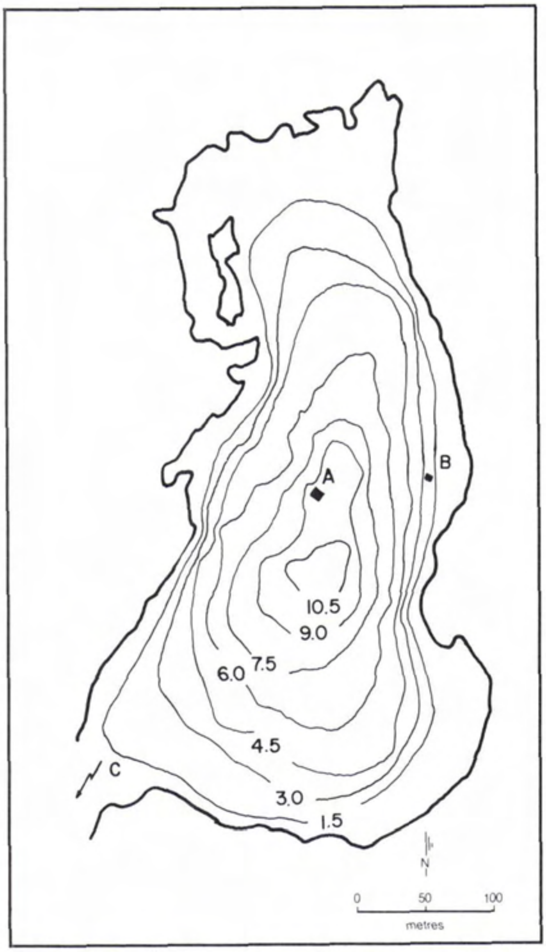

FIG. 3. Bathymetric map of Lower Bass Lake. Contours are in metres. Micrometeorological stations are at A and B and the outlet is at C.

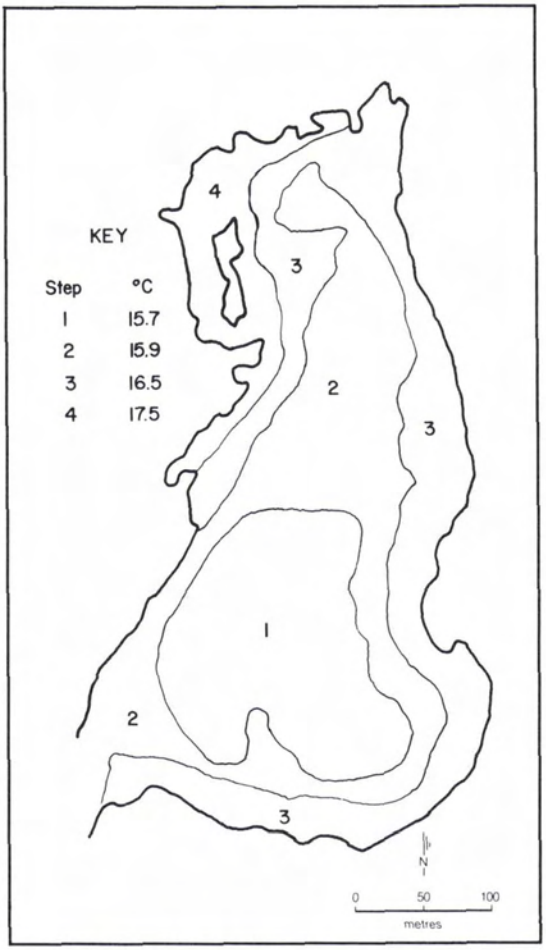

FIG. 4. Temperature patterns for 17 May 1979 at 1300 hours. The map is derived from a threshold edge detector passed across digital image brightness values. The step temperatures are areal mean corrected surface temperature.

lected IR line scanner imagery (Daedalus DS-1230) over the lake at 2000 hrs on 17 August and at 0000, 0900, and 1200 hrs on 18 August. Gain and offset were fixed throughout each flight. The objective was to determine whether the patterns evident in the spring imagery persisted into August.

IMAGE PROCESSING

The digital thermal IR data for the two dates in 1979 were used to determine the magnitude and range of temperatures across the lake and to identify and interpret the thermal features.

Radiometric correction of the imagery for atmospheric attenuation was accomplished using a modified version of the NOAA/NESS model RADCOM described by Weinreb and Hill (1980). Absorption coefficients for water vapor and the uniformly mixed gases were based upon profiles of temperature, pressure, and vapor content constructed from the regional weather analysis and nearby ground observations. The correction for the 8.5 to 12.7-μm band was +0.26C. Within the 10 degree viewing angle over the lake, adjustment for a variable path length can be neglected. A further correction of +0.5C was applied to adjust for emissivity effects. This figure is based upon empirical studies of water surfaces by Shaw and Irbe (1972). The total correction makes the scanner data consistent with *in situ* measurements on June 1979 when the surface temperature measured with a handheld infrared thermometer (assuming unit emissivity) was 21C and that measured at −1.0 cm with a shielded thermister was 22C while the uncorrected IR scanner temperature was 20.8C.

The digital images were enhanced using a parallelepiped classification which is equivalent to a digital density slice in a single channel. A modified

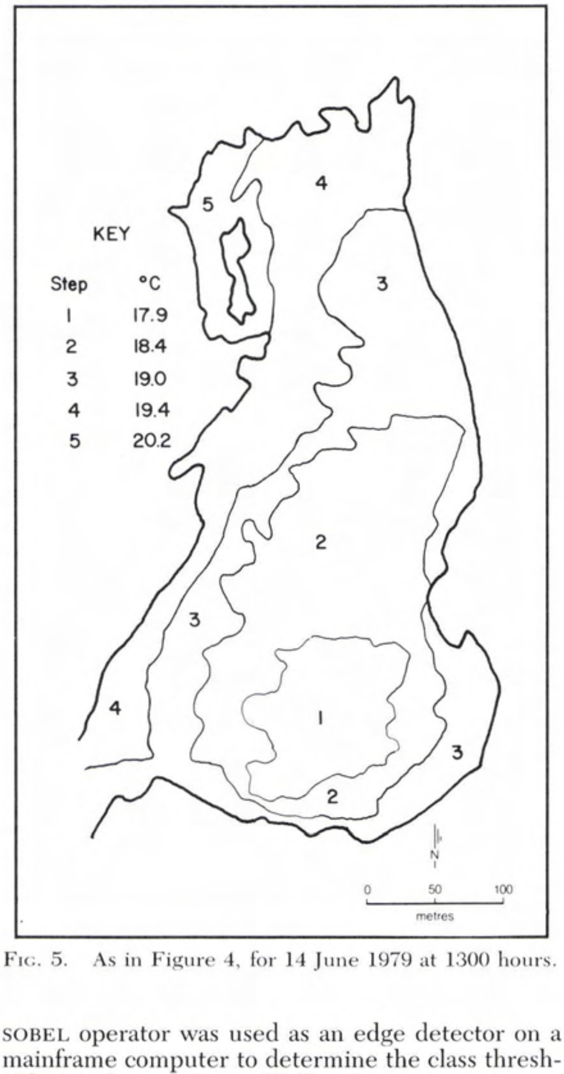

FIG. 5. As in Figure 4, for 14 June 1979 at 1300 hours.

SOBEL operator was used as an edge detector on a mainframe computer to determine the class thresholds (Duda and Hart, 1973). Data volumes were then reduced by application of a 5 by 6 and 4 by 4 skip factor for the May and June images, respectively. We found that an average procedure resulted in alteration of the radiometric integrity and created difficulties at the large gradients along the shorelines. The files were then downloaded to a color microcomputer for the classification and subsequent image display. The low overhead costs of the microcomputer enabled considerable experimentation to create a product which had maximum visual discrimination of the thermal features.

We wished to relate the thermal patterns to survey data of lake depths. The hardcopy enhanced images were optically registered to color infrared photographs taken at the same time using 12 ground control points. A more accurate geometric correction based upon digital techniques was not warranted in light of the five-metre spacing of the lake depth measurements.

Unfortunately, the August data were available in analog format only. These data were processed in double gain level slice mode across a range of 2.9C so that each density level represented 0.2C, which is the estimated system resolution. The data were subsequently color coded on a video image analyzer. Because the data for the August mission were nearly isothermal across the lake and surface temperatures were observed *in situ* at several sample points, correction for absolute temperatures on the imagery was irrelevant.

THE SURFACE TEMPERATURE AND THE MOMENTUM TRANSFER

The temperature patterns for the May and June, 1979, images are displayed in Figures 4 and 5. For the June data, the minimum temperatures in the cold core near the deepest sector of the lake were in the 17.8 to 18.2C range while the near shore values were in the 19.2 to 21.8C range. In these shallows, there is a broad correspondence between the surface temperature structure and the depth contours (cf. Figure 3). The relationship is readily apparent when the 1.5-metre contour line is followed. This is the thermal bar effect typical of the spring period (Carmack, 1979) which is related to solar heating of a limited volume with restricted circulation in the shallows. However, a simple one to one correspondence over the entire lake is complicated by processes in the deeper sector where there is a cool pool which is displaced over the topographic rise. A linear regression between 24 measured depths and surface temperature along transects throughout the lake for the images of both dates yields an explanation of variance of only 50 percent. This is significant at the 0.05 level.

This cool pool may be a feature of turbulent mixing. The wind on the days the images were recorded was from the northwest along the major axis of the lake. The warm shallows in the northwest of the lake were in a lee wind shadow of the surrounding mixed forest. It is conceivable that the turbulent mixing of the surface layer of the lake (the epilimnion) resulting from the atmospheric wind stress would become established only after a reasonable fetch down the lake. Because the boundary between the warm epilimnion and cooler sub layer (the hypolimnion) is relatively close to the surface (−1.5 m at the lake center), this turbulence may bring the cooler water towards the surface near the downwind sector of the lake to create the cool pool. In contrast, the August imagery does not illustrate a cool pool with a similar wind regime. The temperature boundary or thermocline was at −4.5 m. Further investigaton into the three-dimensional circulation regime is warranted.

The video thermal imagery of 12 June 1981 includes a thermal gradient from approximately 19.0C in the lake center to 20.7C along the shallows (not illustrated). The cool core is again clearly visible.

Given that there may be a temperature range of up to 4.0C across the main body of the lake in the spring period, it must be determined whether the effect of this difference in surface temperature on momentum transfer is significant.

The shear stress or momentum flux (τ) may be calculated from the wind profile with a correction of the neutral logarithmic profile for the diabatic atmosphere through the Monin-Obukhov parameter (Φ)

$$\tau = -\rho k^2 z^2 \left(\frac{\partial u}{\partial z}\right)^2 \frac{1}{\Phi} \qquad (1)$$

where ρ is the air density, k is the von Karman constant, z is the height, and u is the velocity. Typically, the Monin-Obukhov parameter is determined as a statistical function of the gradient Richardson Number (Ri):

$$\Phi = (a \pm bRi)^{\pm c} \qquad (2)$$

where a, b, and c are empirical coefficients derived for the stable and unstable case following Pruitt *et al.* (1973).

Using data for 1300 hrs on 12 June 1981, the time of the video thermal imagery, we calculate the shear stress at the lake center to have been 1.31×10^{-3} Pascals. If the surface temperature is 2C higher, representing the lake margins for this case, the shear stress increases to 2.28×10^{-3} Pascals if one assumes a linear extrapolation of the temperature profile to the surface. This is an increase of 75 percent.

Using 24 cases of micrometeorological data and drogue current velocities for August 1982, for which we have more complete data than for the previous year, a quadratic correlation between shear stress and surface current velocity explains 72 percent of the variance. This illustrates that shear stress does have an influence on surface current velocity in this lake. The high order relation includes a transition between two regimes of current response to the atmosphere that occurs with increasing wind speed and the change from a hydrodynamically smooth to rough water surface (Haines and Bryson, 1961). These data are based upon observations taken at different times and not at different locations across the lake at one time.

This estimate of the response of shear stress to surface temperature is more conservative than that of Emery and Csanady (1973) who used a model of synoptic scale processes. They suggested that a difference in surface temperature of only 1C was sufficient to account for the curvature in trajectory in a large lake resulting from variations in shear stress or the momentum flux to the surface.

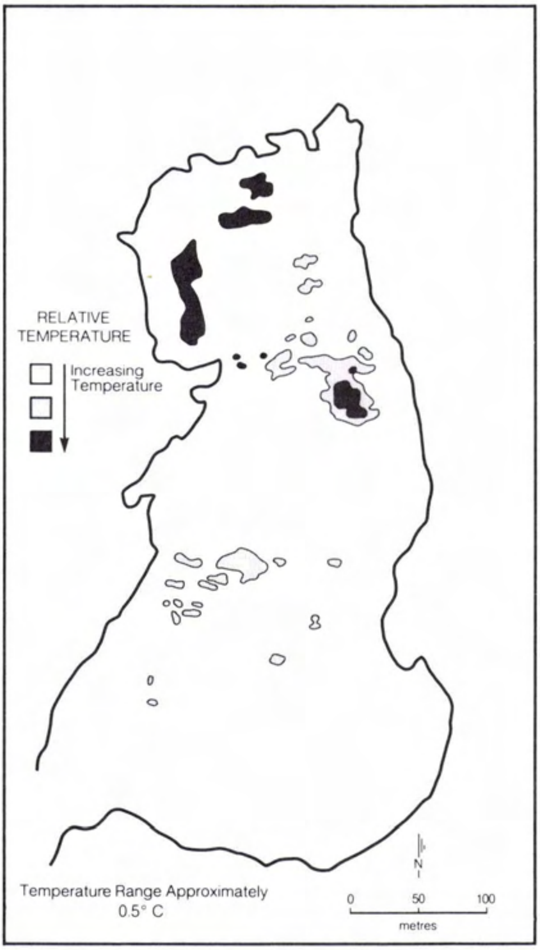

Fig. 6. Temperature patterns for 18 August 1982 at 1200 hrs. The map is derived from level-sliced analog film and only relative temperature patterns are mapped.

These temperature variations are not observed in the imagery for 17-18 August 1982 (Figure 6). The maximum temperature range across the lake surface is estimated to have been less than 0.5C and the patterns evident, which merge with scanner noise, can be cautiously interpreted as wind drift of a thin skin layer rather than a major feature of the circulation structure. This is not surprising this late in the heating cycle of the lake. The thermocline had been eroded down to a depth of 4.5 metres. We would expect the temperature of this large volume to be similar throughout.

The Surface Current Trajectories

The general characteristic of the June 1981 trajectories which were derived from survey triangulation of drifting drogues is that curvature is found in all cases with wind flow along the major axis of the lake. This curvature, however, is both the expected counterclockwise (approximately 30 percent of the 11 cases) and the unexpected clockwise direction (the balance of 70 percent). The curvature is most evident near the lake center where bottom topography would not be an obvious control. In some cases it is not found as the drogues approached

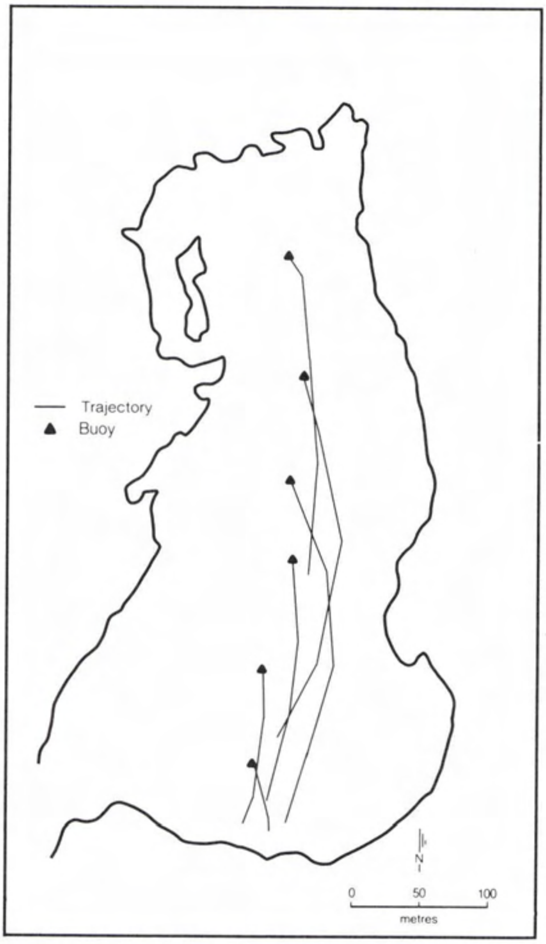

FIG. 7. Drogue trajectories on 17 June 1981 at 1022 hrs mapped from survey triangulation of drifting drogues. Wind direction was northerly at 2.3 m sec^{-1}.

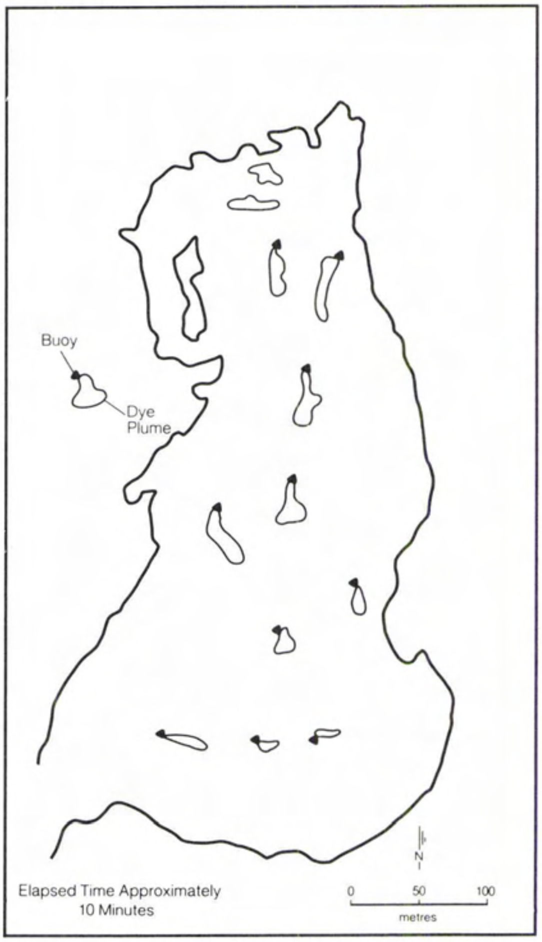

FIG. 8. Rhodamine dye plumes of 12 June 1981 photographed from a helicopter platform.

the shallows where the topography would be expected to exert an influence. Figure 7 illustrates this curl. For this case the wind direction was from the southeast along the main axis of the basin. The surrounding topography channels the wind along this axis.

An extreme example of this curvature may be seen in the direction of the rhodamine dye plumes photographed from the helicopter on 12 June (Figure 8). The wind was from the northwest and the plumes at the north end of the lake were aligned along this axis; but in the south, in the region of the cool pool, they are deflected in a counterclockwise direction.

The consistent feature of the August 1982 data is a comparatively linear trajectory. There are abberations, however, and these are most probably related to short term wind shifts during the episode, and they are short lived. Figure 9 illustrates an example of the drogue paths as determined from the balloon imagery with southerly wind flow. The linear characteristic is corroborated by the results of the survey triangulation and is found in all of the dye plumes photographed from the balloon.

DISCUSSION

The thermal imagery reveals a range of patterns in the surface temperature of the lake that may influence the control of atmospheric boundary layer processes on the surface current configuration. The hypothesis is that a variation of surface temperature over a lake surface will have an influence on the stability of the overlying atmosphere and consequently affect the downward momentum transfer which is one factor in the surface current regime. We have coupled the analysis of the thermal imagery with measurements of the surface currents and atmospheric boundary layer in an effort to confirm this hypothesis.

Statistical analysis of the shear stress at the lake center and the observed surface currents indicates

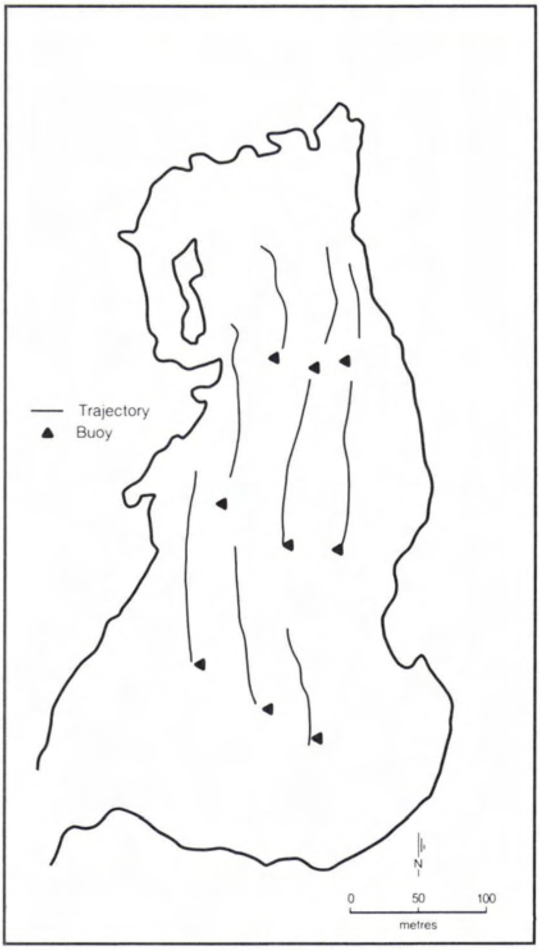

FIG. 9. Drogue trajectories on 12 September 1982 at 1350 hrs mapped from tethered balloon imagery of drifting drogues. Wind direction was south east at 2.4 m sec^{-1}.

that there is a significant relationship between the boundary layer processes and the current regime. Atmospheric forcing is a major factor governing mass water movements. This result has also been found in studies of other lakes where the explanation of variance in correlations between wind speed and surface currents has been as high as 93 percent (George, 1981).

In June, the epilimnion at Lower Bass Lake is less than 1.5 metres deep, and we may assume that factors affecting the surface currents are restricted to that warm surface layer. Only at the lake margins would the bottom topography exert a direct influence. The drogue trajectories indicate that there is actually little modification of the direction of flow as the drogues approach these areas. In the lake center, however, across which there is an observed thermal gradient that is sufficient to affect the shear stress or momentum flux, there is consistent curvature in the flow.

In August, the epilimnion extends close to the bottom of the lake in the center and reaches it elsewhere. We may expect the three-dimensional circulation within this volume to include the effects of the bottom contours, but the trajectories of the surface currents are essentially linear. Furthermore, there is not the thermal gradient across the surface that could force curvature if the hypothesis is to be accepted. Consequently, the lack of curvature with this regime is consistent with the hypothesis.

The results of this study are not sufficient to unequivocally confirm the hypothesis. Other models which include density stratifications due to varying inflows and heating, bottom topography and the associated three-dimensional friction stresses, as well as the shoreline constraints, must be considered. Inclusion of these factors is in the realm of numerical simulation, which is the next step. The results do indicate, however, that the processes considered in this study are plausible and should be considered in those simulations, and indeed may be a major factor.

It is clear that thermal imagery provides an invaluable data source in this type of analysis. It is the spatial patterns and relative magnitudes that often are of significance, rather than precise values at relatively few sample points. The linkage of these data with traditional *in situ* observations through conceptual and numerical models is providing new insights into problems which have been constrained by limited spatial information.

The balloon platform has proven to be very satisfactory, and in some instances to be more accurate than surface triangulation when instrument platforms on the lake obscure the surveyor's line of sight. The 35-mm camera data back provides a record from which to calculate current velocities with an accuracy of 7 to 10 percent for the sampling interval used in this study. Some difficulties include

- the tether line can obscure the drogue
- the rectangular film format must be aligned with the lake to ensure complete coverage with the 21-mm lens at 300-metres (an altitude limit imposed by flight regulations in our region). There is little room for error if the wind shifts the balloon orientation in mid-flight.
- there is some tilt distortion if the camera is buffeted with the wind, but this can be rectified satisfactorily in the mapping process by optical methods.

In most instances there was no problem lifting the balloon, even in moderate winds, because the launch was at the lake center away from major obstructions. In only one case was the turbulence so extreme as to prohibit taking the balloon from the shore storage area to the lake center. A rule of thumb is: if the balloon pulls the boat rather than vice versa, do not launch!

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