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Publisher's version / Version de l'éditeur:

<https://doi.org/10.1139/t65-047>

Canadian Geotechnical Journal, 2, 4, pp. 313-326, 1965-12-01

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WEATHER CONDITIONS**

by

G. P. WILLIAMS

Reprinted from
Canadian Geotechnical Journal
Vol. II, no. 4, November 1965, pp. 313-326

RESEARCH PAPER No. 275
OF THE
DIVISION OF BUILDING RESEARCH

Price 25 cents

Ottawa
December 1965

NRC 8793

CORRELATING FREEZE-UP AND BREAK-UP WITH WEATHER CONDITIONS

G. P. WILLIAMS*

ABSTRACT

The results of studies on the relation between freeze-up, break-up and weather conditions for a small fresh-water lake in the Ottawa area are reported. Techniques using air temperature records for estimating when a solid ice-cover will form on the lake are investigated. A formula using weather records is also developed for estimating the time taken for ice to melt from the lake. The usefulness of these relationships for estimating "freeze-up" and "break-up" dates for rivers and lakes is discussed.

SOMMAIRE

Cet article présente les résultats d'études faites dans le but d'établir le temps de prise et de débâcle des glaces en fonction des conditions atmosphériques pour un petit lac dans la région d'Ottawa. Les techniques d'estimation de la date de prise du champ de glace à partir des relevés de la température de l'air ont été examinées et une formule permettant d'estimer, à partir des données météorologiques, le temps requis pour la fonte de la glace sur le lac a été développée. L'utilité de ces relations servant à estimer les dates de prise et de débâcle des glaces sur les rivières et les lacs est discutée.

The first ice cover or freeze-up in early winter marks the end of water navigation and the end of the season when run-off from rainfall will increase the water supply in reservoirs. Spring break-up (defined as the complete clearing of ice covers from rivers, lakes, and harbours) marks not only the beginning of the navigation season, but also the time when depleted water reservoirs will be filled by spring run-off. Although the prediction of freeze-up and break-up would be of great value in planning construction, logging, navigation, and hydro-electric operations, it is only in very recent years that organized efforts have been made to assemble the basic information available in Canada on this problem (Meteorological Branch, DOT, 1959).

One approach to the prediction of freeze-up and break-up is through a statistical analysis of past records (MacKay, 1962a; Cote, 1950). With such an analysis it is possible to use past freeze-up or break-up records as a guide to what can be expected in the future. This approach has limitations, however, which can best be illustrated by an analysis of some available freeze-up and break-up records.

The results of statistical analysis of relatively long-term records from several lakes and rivers are tabulated in Table I. The difference, in days, between the dates of earliest and latest freeze-up and between the dates of earliest and latest break-up are shown. The 10 per cent level (one year out of ten) was used to define these dates. The difference for freeze-up varies from 14 to 37 days for the rivers and lakes analysed; that for break-up varies from 20 to 45 days. This type of statistical analysis of past records enables one to estimate only that freeze-up or break-up will probably occur within a period of several weeks.

Freeze-up and break-up records seldom show a cyclic pattern from which future trends can be established. For example, an analysis of 106 years of

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break-up records for Lake Mendota, Wisconsin (Ragotzkie, 1960), shows that in 1880–81 freeze-up occurred on 23 November and break-up on 3 May, a duration of ice cover of 161 days and one of the longest on record for that lake. The next winter season, 1881–82, freeze-up occurred on 2 January and break-up on 21 March, a duration of ice cover of 78 days and one of the shortest on record.

Attempts have been made to improve on this statistical type of prediction by correlating meteorological elements with ice conditions so that weather forecasts can be translated into ice forecasts. The usual procedure is to correlate accumulated degree days (the differences between air temperature and a given base temperature for a given period) with freeze-up and break-up dates. Stankiewicz (1947) used this degree-day technique for estimating from air temperature records the date when a river would be open for driving logs. Mackay (1961), in a study of freeze-up and break-up of the lower Mackenzie River, related a weighted air temperature, based on the estimated flow time of the river, to freeze-up. Burbidge and Lauder (1957), in a preliminary investigation of freeze-up and break-up, presented some relationships between degree days and freeze-up and break-up. More recently, Bilello (1964) presented an improved technique for forecasting river and lake ice formation using air temperature records, and MacKay (1962b) studied in some detail the factors that affect freeze-up and break-up on the Nelson River drainage system. The use of weather information for predicting freeze-up and break-up has limitations, however, which are considered in this paper.

In 1956 observations on initial ice formation, on the rate of ice growth in winter, and on the rate of ice melt in spring were initiated at McKay Lake, a small, sheltered lake located within the city of Ottawa. Ice thickness observations were used, along with ice thickness records from other lakes, in a statistical analysis of ice growth rates and maximum ice thicknesses (Williams, 1963b). In 1959 observations on water temperature in the fall cooling period were included in this program. Heat losses determined from these temperature measurements were shown to be approximately proportional to the difference in temperature between the water surface and the air, indicating that the energy gained by solar radiation equals that lost by evaporation (Williams, 1963a). These water temperature observations, together with observations on initial ice formation and ice melt, are analysed and used in this paper to establish relationships between freeze-up and break-up and weather.

ENVIRONMENTAL FACTORS AFFECTING FREEZE-UP AND BREAK-UP

Some background information on the environmental factors that affect freeze-up and break-up may be useful.

The formation of a solid ice cover at freeze-up is determined by the following factors: heat exchange with the atmosphere, heat stored in a water body, and inflow of warm or more saline water to a site.

1. Atmospheric heat exchange (the rate of heat loss from the water surface to the surrounding air) is determined by the weather conditions that prevail during the period prior to freeze-up. Air temperature, wind velocity, and solar

radiation are the most important weather elements affecting this rate of heat loss.

2. The heat stored in a water body is a function of water depth. In general, the deeper the lake, the deeper the convective mixing and the slower the rate of cooling for a given surface heat loss. In rivers the water is kept at nearly the same temperature by turbulent mixing, but the deeper the river the slower the rate of cooling for a given rate of heat loss.

3. Inflow of heat from upstream sources such as water flowing from a deep reservoir can delay or prevent sheet ice formation on a river. In salt-water harbours inflow of more saline water because of density currents can also retard the formation of an ice cover.

The clearing of ice from bodies of water at break-up is affected by the following factors: heat gain from the atmosphere, snow and ice conditions, wind and currents, and inflow of warm or more saline water to a site.

1. The heat gained from the atmosphere, principally from solar radiation, weakens and melts the ice; the reflectivity of the snow or ice surface determines the amount of solar radiation absorbed.

2. The thickness of the snow and ice determines the amount of ice to be melted, and this affects the duration of the break-up period.

3. Of great importance is the mechanical action of wind and currents in breaking up the ice and mixing it with warmer sub-surface water.

4. In salt-water harbours wind and current can break up the ice so that it is mixed with more saline water. Run-off water also from surrounding land areas can accelerate break-up, as can the flow from southern portions of a northward-flowing river affect the break-up of the northern section.

The mechanical breaking of solid cover by wind and currents can sometimes be more important in the break-up process than the heat gained from the atmosphere. To illustrate the difference between break-up due almost entirely to heat gained from the atmosphere and break-up resulting from wind or currents, some available break-up records for several lakes, rivers, and salt-water harbours in Canada were analysed (Meteorological Branch, DOT, 1959). The number of days from the time the ice thickness was last measured in the spring to the time when it was completely cleared was related to the total ice thickness at the time of the last measurement (Figure 1). The comparison shows the great variation in the rate at which ice disappears from different bodies of water. The lower limit, where the ice melt is due entirely to the heat from the atmosphere, is about 1 in./day. This is less than one tenth the upper limit where the ice is cleared from a river or harbour largely by wind and current effects.

Ice break-up caused only by heat from the atmosphere will probably occur for a relatively small percentage of lakes, rivers, and harbours. Even for quite small lakes, wind effects can be appreciable. After observing ice break-up for several years on lakes in New Brunswick, Smith (1951) stated: "With strong winds the ice disappeared simultaneously from several small lakes, but with calm weather, such as in 1943, a number of days may intervene between their break-up dates."

The factors that determine when an ice cover will form on a water body or

FIGURE 1. Comparison of number of days for ice to disappear with ice thickness at time of last measurement.

when it will melt, weaken, and disappear are complicated and interrelated. Of all these factors, however, the rate at which heat is gained or lost at the surface because of prevailing weather conditions is usually dominant. Even when wind and currents accelerate break-up by mechanically breaking the solid cover the ice has often been weakened previously by mild weather. A large part of forecasting freeze-up or break-up dates at any site is thus a problem of relating weather conditions to ice conditions. It is for this reason that the relation between freeze-up and break-up and weather conditions was investigated on a sheltered lake where atmospheric heat exchange was dominant and effects of wind and current were minor.

MCKAY LAKE FREEZE-UP

Figure 2 shows typical water temperature profiles at McKay Lake from the beginning of the fall cooling period in 1961 until freeze-up. The profiles obtained for other years were similar, although there were some differences in the thickness of the thermocline at any particular time. After the water became isothermal at 39 to 40 °F, the surface water remained at the surface and quickly cooled to 32 °F. With further cooling sheet ice started to form.

The observations show that the cooling of a fresh-water lake is divided into two stages: gradual cooling until all the water is at a temperature of about 39 °F, and cooling of a shallow layer of surface water from the time the water is isothermal at 39 °F until sheet ice forms. Predicting freeze-up dates is a two-fold problem: to predict when the water will become isothermal at 39 °F, and when ice will form after the water temperature has reached 39 °F.

FIGURE 2. Typical water temperature profiles, McKay Lake, 1961.

These two aspects can be illustrated by plotting changes in surface water temperature during several fall cooling periods (Figure 3). While the lake is cooling to 39 °F the rate of change of the water surface temperature parallels the rate of change of mean air temperature. During this period the lake has a large thermal inertia and surface heat loss cools it to a considerable depth. In McKay Lake the effects of cooling extend 15 to 20 feet below the surface and it thus takes considerable surface cooling to change the surface temperature

FIGURE 3. Surface water temperature, McKay Lake.

appreciably. When the lake water becomes isothermal at 39 °F, however, surface heat loss affects only a thin surface layer of water so that surface temperature is much more sensitive to the weather and fluctuations in it. Surface water may be quickly cooled to 32 °F and ice will form if cooling continues. This ice may melt again or freeze into a permanent cover, depending on the weather conditions.

The sensitivity of surface ice formation to variable weather conditions during this final stage of cooling is one reason why freeze-up dates fluctuate within rather wide limits (Table I). In 1962 the duration of the second stage of cooling

TABLE I
Difference in Days between the 10 per cent Level Early and Late Freeze-up and Early and Late Break-up for Some Lakes and Rivers

Body of water	Years of record	Difference between dates of earliest and latest freeze-up (10 per cent levels—days)		Reference
		Difference between dates of earliest and latest freeze-up (10 per cent levels—days)	Difference between dates of earliest and latest break-up (10 per cent levels—days)	
Charlottetown Harbour	37	22	37	Met Branch 1959
Christina L. BC	37	37	45	Met Branch 1959
L. Kenogami	31	25	20	Met Branch 1959
L. Mendota	107	28	31	Ragotzkie 1960
Port Arthur and Fort William	59	14	25	Met Branch 1959
South Bay (Coral Harbour)	29	16	22	Met Branch 1959
Miramichi R.	128	27	20	Met Branch 1959
North Saskatchewan R. (Edmonton)	56	20	21	Met Branch 1959
Coppermine R.	28	18	20	Met Branch 1959

was 28 days (14 November to 13 December); in 1963 it lasted only 5 days (30 November to 4 December).

Because surface water temperature change parallels air temperature change during the first stage of cooling, it should be possible to establish a relationship between air and water temperature. Such a relationship has been established for sea water where, because the maximum density of salt water depends on salt concentration, convective mixing is maintained until it cools to the freezing point, and there is generally no second stage of cooling. For example, Rodhe (1952) used a relationship between mean daily air temperature and water temperature for predicting ice formation in the Baltic.

The mathematical expression, based on the assumption that the rate of heat loss from a water surface depends on air-water temperature difference, is:

$$(1) \quad h_0 A (T_w - T_A) dt = ADs dT_w$$

where T_w = surface water temperature, which remains essentially constant to depth D (depth of convective mixing),

T_A = air temperature,

A = area of water,

s = specific heat of water,

h_0 = coefficient of heat transfer from a water surface.

This equation can be reduced to that used by Rodhe by letting $K = h_0/Ds$, which can for practical purposes be treated as a constant with the inverse dimensions of time. Equation (1) then becomes:

$$(2) \quad dT_w/dt = K(T_w - T_A)$$

Bilello (1961) used the technique developed by Rodhe to compute from daily air temperatures the date of ice formation at several locations in the Arctic. A value of K^{-1} was found by trial and error for each location. Once K was determined, it was possible to make a reasonably accurate estimate of the date of ice formation from daily air temperature records.

Using the computation procedure outlined by Bilello, K^{-1} was calculated to be 17.5 days for the period 1 October to 28 November 1961 for McKay Lake. With this value of K^{-1} mean air temperatures were used to compute synthetic water temperatures for the first stage of fall cooling for McKay Lake for the years 1959, 1960, 1962, 1963. Figure 4 shows the result of plotting the calculated water temperature against the measured water temperature. By this procedure the date when McKay Lake would become isothermal at 39 °F (obtained from synthetic water temperatures) agreed with the actual date within ± 3 days, an error about the same as that obtained by Bilello for estimating freeze-up dates in the Arctic.

The relationship between air temperature and surface water temperature cannot be applied after a sheltered fresh-water lake becomes isothermal at 39 °F because the water surface temperature is much more sensitive to the weather and may be quickly cooled to 32 °F. During this second cooling stage it was found that accumulated degree days, using 32 °F as a reference temperature, could be correlated with the time taken for a solid ice cover to form on the lake. The basis for this relationship is that during this final cooling stage the lake-water surface temperature is close to 32 °F, and the rate of heat loss is approximately proportional to $(T_A - 32)^\circ\text{F}$.

Accumulated degree days for McKay Lake were calculated for 1959 to 1963 from the time the lake water was isothermal at 39 °F until 4 to 6 in. of ice had formed. A solid cover of 4 to 6 in. was used as a reference because this thickness of ice will generally not melt during subsequent mild weather. Figure 5 shows that the accumulated degree days during this second stage of lake cooling varied from 70 to 100 for the five years studied. After the lake water became

FIGURE 4. Relation between water and weighted air temperature, McKay Lake (1959-63).

FIGURE 5. Accumulated degree days during period from when water temperature 39 °F until 4 to 6 in. of ice forms, McKay Lake.

isothermal at 32 °F the first sustained period of cold weather, usually from 3 to 5 days, would result in an ice growth of 4 to 6 in. By using this relationship the time taken for a solid ice cover of 4 to 6 in. to form could be estimated from air temperature records to within a day or two.

McKAY LAKE BREAK-UP RELATIONSHIPS

Predicting the date when a sheltered lake will be completely free of ice is somewhat different from predicting when a solid ice cover will first form. Prediction of freeze-up depends almost entirely on prediction of weather conditions, but prediction of break-up depends not only on weather conditions but also on the thickness of ice to be melted and the condition of the ice surface, including the depth of snow cover. In the fall the rate of heat loss from open water can be related to the air-water temperature difference because solar radiation approximately equals evaporation. During the spring melt period the heat from solar radiation is usually much greater than evaporative heat loss and, consequently, calculations of the heat gained at melting ice surfaces must include heat gained from solar radiation.

In a previous study on the use of dust to advance the break-up of ice on lakes and rivers (Williams and Gold, 1963) a simplified heat balance equation was used for estimating the heat gained at a melting ice surface. A modified form of this equation is:

$$(3) \quad Q_m = [(100 - \alpha) 3.69 R_{sw}] / 100 + 85 \Delta e + 37 \Delta T \text{ Btu/sq. ft./24 hr}$$

where

Q_m = net heat gain at melting ice surface,

α = albedo or reflectivity of surface (per cent),

$\Delta e = (e_s - e_a)$, e_s equals saturated vapour pressure of air at temperature of surface and e_a equals vapour pressure of air (mbs),

$\Delta T = (T_s - T_a)$, T_s temperature of surface, and T_a equals temperature of air ($^{\circ}\text{F}$),

R_{sw} = Incoming short-wave radiation (cal./sq. cm./24 hr).

Equation (3) was used to calculate the heat available for melting ice in each spring melt period at McKay Lake for the ten years from 1952 to 1961. In making the calculations the following assumptions were made, based on field observations in the Ottawa area from 1956 to 1963:

1. If the daily air temperature was above freezing the surface temperature was assumed equal to 32°F .
2. If the daily air temperature was below freezing, the surface temperature was assumed equal to the daily air temperature.
3. Values of albedo or reflectivity of the melting surface were assumed as follows:
 - (a) if air temperature was above 32°F , albedo equalled 50 per cent;
 - (b) if rain occurred, the albedo was assumed to be 40 per cent for the two days following the rain, then 50 per cent if air temperature was above 32°F ;
 - (c) if new snow occurred, the albedo was assumed to be 80 per cent on the first day after the snowfall, 70 per cent after the second day, and 50 per cent if air temperature was 32°F by the third day;
 - (d) in the late stages of melting, if the air temperature was above 40°F for several days, the albedo was assumed to equal 40 per cent.
4. The beginning of the effective melt period was assumed to start when the five-day average air temperature was above 35°F .
5. The end of the melting period was taken as the time when ice completely melted from the lake.

A check on the accuracy of the calculated total heat loss was obtained by comparing it with the heat required to melt the thickness of ice recorded at McKay Lake at the beginning of the break-up periods (prior to 1956 maximum ice thickness was estimated from ice thickness records on other lakes in the Ottawa area). The calculated heat is compared with the heat required to melt the observed thickness of ice in Table II. Considering the many assumptions made, the agreement is surprisingly good.

To show the relative importance of the different components of the heat exchange, these are tabulated in Table III as percentages of the total calculated melt. The importance of each component varied considerably from year to year. The short-wave radiative heat gain varied from 65 to 109 per cent, the evaporative heat loss from 2 to 29 per cent, and the combined long-wave and convective heat gain from 20 to 40 per cent of the total melt. It is considered that these percentages are representative of the relative importance of the different components of the heat balance in melting the ice cover of a sheltered lake in the Ottawa area.

These calculations illustrate the importance of solar radiation in the ice melting process. Because the albedo of the ice surface is highly variable, it will always be difficult to estimate accurately how much incoming solar energy goes

TABLE II
Comparison of Calculated Heat Gain to Heat Required to Melt Ice
Break-up period 1952-61, McKay Lake

Year	Calculated heat (Btu)	Heat required melt ice (Btu)	Per cent difference
1952	14,700	14,200*	-3.5
1953	12,900	12,700*	-1.5
1954	14,900	14,900*	0
1955	22,600	25,400*	+11.0
1956	16,200	17,200	+6.0
1957	14,600	14,200	-2.5
1958	13,500	14,200	+5.0
1959	15,700	17,200	+9.0
1960	18,400	20,200	+9.0
1961	19,000	21,000	+9.5

*Estimated.

TABLE III
Calculated Percentage of Total Melt Caused by Different Components of Heat Exchange
Break-up period 1952-61, McKay Lake

Year	Percentage of Total Melt		
	Short-wave radiation	Long-wave radiation and convection	Evaporation
1952	+86	+25	-11
1953	+65	+40	-5
1954	+67	+35	-2
1955	+77	+28	-5
1956	+81	+30	-11
1957	+109	+20	-29
1958	+92	+25	-17
1959	+82	+28	-10
1960	+84	+23	-7
1961	+77	+32	-9

to melt ice, unless actual measurements of albedo are made at several representative locations on a lake.

DEVELOPMENT OF A SIMPLIFIED ICE-MELTING FORMULA

As an outcome of the preceding analysis a simplified heat exchange formula was developed combining a solar radiation term with a degree-day term:

$$(4) \quad Qm = 0.5 \Sigma R_{sw} + 10 \Sigma \Delta T \text{ cal./sq. cm.}$$

where

Qm = heat available for melting lake ice,

ΣR_{sw} = accumulated short-wave radiation over break-up period (cal./sq. cm.),

$\Sigma \Delta T$ = $(Ta - 32)$ accumulated degree days over break-up period ($^{\circ}\text{F}$).

This formula assumes that the albedo of the ice cover equals 50 per cent during the entire break-up period. The term $10 \Delta T$ in equation (4) was derived from the combined long-wave radiation and convection equations previously developed in equation (3). The evaporation term is not included in this simplified formula. The units ($^{\circ}\text{F}$ and cal./sq. cm.) are used because air temperature and solar radiation are normally recorded at Canadian meteorological stations in these units.

In using this formula the active melt period is assumed to begin when the five-day average air temperature is 35°F or above. (Thus degree-day accumulations and solar radiation accumulations are started at this time.) This arbitrary rule has some physical basis as, judging from the McKay Lake observations, unless average air temperature is well above 32°F , melting of lake ice during the day is offset by freezing during the night.

The formula was checked by comparing the melt estimated from the reported decrease in ice thickness at several Canadian stations with the melt calculated by formula. Only those periods during which decrease of ice thickness was estimated to be entirely due to heat exchange from the atmosphere were considered; in most cases the period of calculation was for only part of the melt period. Solar radiation and air temperature records used in the formula were obtained from meteorological stations located near where ice thickness observations are made. Unfortunately, there are few stations in Canada where both radiation and ice thickness records are maintained. Those available, usually with quite short records, were Knob Lake, Churchill, Resolute, Moncton (McLaughlin Reservoir), and Ottawa (McKay Lake). In addition, radiation observations at Churchill were used to calculate the rate of melting at Brochet and Ennadai Lakes, two fresh-water lakes several hundred miles west of Churchill.

It was expected that the computed melt for Brochet and Ennadai Lakes would not be very satisfactory. The results of the analysis (Figure 6) indicate, however, that this simplified formula gives a reasonable estimate of the rate of melting of ice covers on sheltered lakes. Its accuracy will depend on how closely the necessary assumptions, such as that concerning the albedo, fit the actual situation at a particular lake. The accuracy of the formula should be greater the closer the radiation observation site is to the lake.

It should be emphasized that estimating the rate of ice melt with equation (4) is only part of the problem of estimating the date of break-up. For exposed lakes and rivers the influence of wind and currents must also be considered. There is some indication that break-up of ice on a river (Stankiewicz, 1947) or of ice on a large exposed lake (Richards, 1963) will occur after a specific amount of melting, and that equation (4) or some modification of it can be used to estimate the date when a river or large lake will clear. Studies would have to be made, however, at individual sites for a number of years before the value of such formulae for estimating break-up dates could be established.

CONCLUSIONS

The relation between freeze-up, break-up, and weather conditions was investigated for five winter seasons at a small fresh-water lake sheltered from wind

FIGURE 6. Heat required to melt ice vs. calculated heat.

action where heat exchange with the atmosphere is the dominant factor affecting ice formation at freeze-up and ice melting at break-up. The following conclusions were obtained:

1. Freeze-up occurs in two stages. During the first stage there is gradual cooling of water to a depth of 15 to 20 ft. below the surface until all the water is isothermal at a temperature of about 39 °F. During the second stage, from the time the water is isothermal at 39 °F until sheet ice forms, only a thin layer of surface water is cooled and thus surface temperature is much more sensitive to fluctuations in the weather.

2. During the first stage of cooling, air temperature can be correlated with surface water temperature. The rate of change of water temperature dT_w/dt can be equated with $K(T_w - T_a)$ where K is a constant and $T_w - T_a$ is air-water temperature difference. Using this relationship the date when a sheltered lake becomes isothermal at 39 °F can be calculated from air temperature records.

3. During the second stage of cooling accumulated degree-days (daily air temperature minus 32 °F) can be correlated with the time taken for a solid ice cover to form. Using this correlation the time taken for 4 to 6 in. of ice to form can be calculated from air temperature records.

4. Observations taken on the small fresh-water lake show that the rate at which ice melts during the spring break-up period can be estimated from the heat exchange formula

$$Q_m = 0.5 \Sigma R_{sw} + 10 \Sigma \Delta T$$

where Q_m = the heat available for melting lake ice,

ΣR_{sw} = the heat available from solar radiation accumulated over the break-up period,

$\Sigma \Delta T$ = accumulated degree days over the break-up period.

The formula can be used to estimate the time taken for ice to melt from a lake, provided wind or currents do not accelerate the ice break-up process.

5. The usefulness of the relationships developed will depend not only on the accuracy of radiation and air temperature forecasts, but also on the length of period in the future for which these forecasts can be made. The real challenge of predicting freeze-up and break-up dates is thus a part of the more general challenge of improving the accuracy of short-term and long-term (30-day) weather forecasts.

ACKNOWLEDGMENTS

The writer is indebted to several members of the Division of Building Research for assistance in obtaining water temperature measurements and analysing weather records. He is particularly indebted to Mr. D. Boyd and Mr. L. Gold for most helpful discussions during the preparation of this paper.

This paper is a contribution from the Division of Building Research, National Research Council, Canada, and is published with the approval of the Director of the Division.

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