# Freeze-up and Break-up of Lakes as an Index of Temperature Changes during the Transition Seasons: A Case Study for Finland

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## ABSTRACT

The statistical relationships between lake freeze-up/lake ice break-up dates and air temperature means over various time periods are analyzed for 63 lakes in Finland. Mean temperatures for the individual months before the lake event dates are strongly correlated with these dates; significant correlations hold for periods up to five months in length before freeze-up. Regression coefficients depend on location, but are consistent within regions. Latitude and distance from the coast are the most important sources of variation in the regression coefficients.

The regression coefficients are used to translate changes in lake freeze-up/break-up dates into estimated changes in air temperature. In southern Finland a five day change in freeze-up date would represent a 1.1°C change in November temperature of the same sign. A time series of November temperatures estimated from lake freeze-up dates is derived and compared with observations at Helsinki. The spatial pattern of temperature change over time is also examined using the freeze-up dates. Freeze-up/break-up dates provide a useful proxy for air temperature estimates in data-sparse regions of middle-high latitudes and could permit rapid satellite monitoring of climate perturbations.

## 1. Introduction

The monitoring of present global temperature trends is important in determining the possible atmospheric changes occurring due to the increase of $CO_2$ in the atmosphere. While excellent progress has been made with station temperature records, an often overlooked source of information is lake ice cover records. Tramoni (1985) has noted that lake freeze-up/break-up holds the possibility of being a useful detector of potential $CO_2$-induced warming, as it fulfills the requirements suggested by Barry (1982): 1) it is highly sensitive to one meteorological variable—temperature; 2) it responds rapidly to warming; 3) long-term observational series are available; 4) the lake ice data can be recorded using remote sensing techniques, ensuring extensive availability of data. Lake ice-cover data can be used to increase the spatial coverage of temperature data in the middle-high latitudes of the Northern Hemisphere, an area with a sparse coverage of meteorological stations. This region is thought to be susceptible to much larger $CO_2$-induced temperature increases than the global average, as albedo feedback mechanisms would be activated (National Research Council, 1982). Experiments for $CO_2$-doubling with the GFDL general circulation model (Manabe and Stouffer, 1980) indicate that around 65°N, the greatest warming would be in early winter, with a secondary peak in April. Therefore, it is likely that lake ice observations would provide temperature data in the most critical seasons for detection of a warming.

Considerable work has been completed in the study of lake ice growth and decay since 1960 (for a review, see Adams, 1981). Most of the resulting publications discuss the processes of lake ice cover evolution at a specific place and time. Several researchers have studied empirically the relationships between weather and the formation and decay of lake ice cover (e.g., Billelo, 1964, 1980; Williams, 1965, 1971). However, this was usually done for the purpose of predicting freeze-up and break-up dates for fresh water navigation.

A small but significant amount of research has been published specifically concerning the use of lake ice dates as a climate index. McFadden (1965) introduced the concept of studying lakes over a broad area with uniform, remotely sensed techniques (aerial photography) in Canada in order to determine the spatial character of lake ice–climate interactions. Unfortunately, data were collected for only a short time interval. Recently, DaSilva (1985) has used multiple regression techniques to study the importance of temperature, wind, and cloud to the freeze-up and break-up dates of a widely scattered selection of Canadian lakes. Monthly meteorological statistics were weighted to give values most representative of the 30 days before the average freeze-up/break-up date. Considerable variations in the regression coefficients were shown to exist for different latitudinal zones. A different linear regression approach was used by Tramoni (1985; et al., 1985), following the work of Simojoki (1940). Lake ice event dates were related to temperatures for periods of time attached to the freeze-up/break-up date itself (e.g., the temperature average for the 30 days before freeze-up date). With this method, the time periods change from year-to-year, resulting in interpretational difficulties that will be discussed below.

The possibility of calibrating lakes with exceptionally long ice cover records has been explored in the case of Lake Suwa, Japan. Gray (1974) used simple regression techniques to relate the modern lake freeze-up series to measured Tokyo winter temperature. She then used this equation to estimate winter temperatures for the period 1440–1953. Further work on Lake Suwa by Tanaka and Yoshino (1982) demonstrates that care must be taken in selecting meteorological data with which to calibrate lake records, as they may be affected by urbanization or station location change. It is also clear that modern content analysis techniques (Catchpole, et al., 1970) could be used to improve interpretation of indirect lake ice records.

In this study, Finland is of specific interest for two reasons: lake ice data are available for a spatially dense network of hydrological stations, and many of these have very long time series. Several important studies of climate–lake ice relationships have been completed by Finnish scientists. Simojoki (1939, 1940) has studied many morphologic, hydrologic, and meteorological factors in relationship to lake ice events. Simojoki used temperature averages for time periods fixed to the ice event date. Lemmelä and Kuusisto (1975) describe the natural variations in the lake ice formation/decay processes, especially those due to lake morphology. Laasanen (1982) analyzes the ice records for 19 Finnish lakes that are over 100 years duration in relation to the mean autumn, winter, and spring temperatures for the zone of 65°–85°N. The 19 lakes were averaged together and the deviations of freeze-up and break-up dates were regressed with the zonal temperature deviations. This resulted in very weak correlations, indicating the regional scale of temperature patterns at high latitudes.

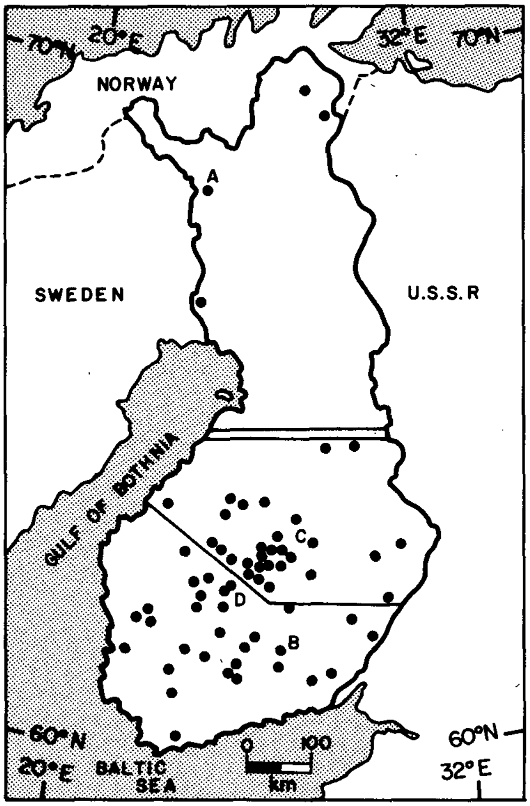


FIG. 1. Location of 63 lakes used in study. Coastal/south and inland/north subdivisions in southern Finland are demarcated. Letters A–D show the positions of meteorological stations used in regional regressions; D is Jyväskylä.

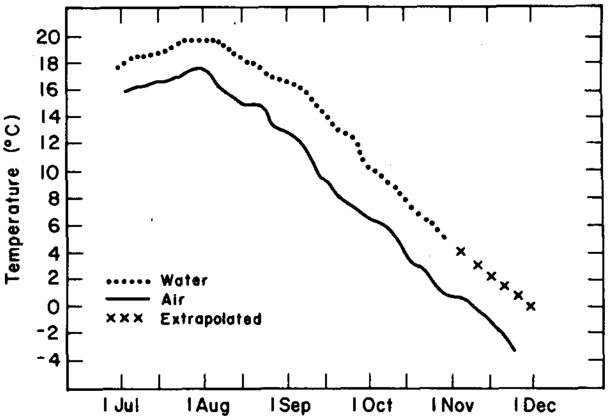


FIG. 2. Average trends of surface water temperature (1961–80) and air temperature (1959–82) for July through December at Lake Saimaa, Finland (61°05′N, 28°16′E).

The purpose of this study is to develop regressions between air temperature and ice cover for selected lakes in Finland (Fig. 1) in order to calibrate changes in lake freeze-up and break-up dates in terms of seasonal temperature anomalies. This is done with the realization that while air temperature will not explain all the variance in freeze-up/break-up dates, it is still the most important single factor that can be extracted for studying climate change. DaSilva (1985) has statistically confirmed this fact with his multiple regression study. The dates themselves have considerable value as climate indicators, but interpretation can be complicated by differences in lake location and morphology. This can lead to different means and variances for lakes in the same climate zones, undergoing the same climate change. Extraction of climate data using simple regression techniques is a way to make lake ice observations more useful.

## 2. Theory

The theory of lake ice freeze-up and break-up is discussed extensively by Michel (1971). It will be sufficient here to discuss the role of air temperature in these processes. During the fall, surface water temperature declines in parallel with the air temperature trend. Figure 2 shows a comparison of averaged water temperature

(1961–80) and air temperature (1959–82) trends for Lake Saimaa, Finland. Williams (1965) finds that heat loss from a large lake is proportional to the difference in air and water temperatures. The example shown demonstrates the expected relationship between surface water and air temperature trends (Williams, 1965; p. 317). Radiation and latent heat exchange between the lake and the atmosphere approximately cancel, leaving sensible heat exchange to dominate the cooling. The relationship between air temperature and the freeze-up date is strong because of this, although once the lake has cooled to 4°C, the actual freeze-up date is dependent on synoptic conditions. A cold, calm air mass must persist over the lake before solid ice cover is established.

The spring break-up processes are less directly dependent on air temperature. Once initial warming leads to snow melt, thereby reducing the surface albedo of the ice over the lake, more direct solar radiation is absorbed, weakening the ice. Since local air temperature is also dependent on the solar radiation, in the absence of pronounced warm air advection, there is a good relationship between the decay of the ice and air temperature. Nevertheless, the end process is very much dependent on synoptic conditions; windy weather greatly encourages mechanical break-up of ice, even if it has not yet rotted thoroughly.

While the physical processes of lake ice cover formation and break-up are quite complicated, regression coefficients appear to be consistent for lakes from the same regions of Finland. Results will be reported for northern Finland and southern Finland divided into two subregions (outlined in Fig. 1).

## 3. Data

Lake ice data for Finland were obtained from the Hydrological Office in the Water Research Institute of the National Board of Waters. Sixty-three observation sites were chosen that represent either small freshwater lakes or a subarea of a larger lake. Williams (1971) finds that using parts of large lakes for ice cover–air temperature studies is as effective as using smaller lakes. All sites have lengthy records of freeze-up and break-up observations, from 35 years at Iijärvi to 150 years at Kallavesi, with most records reaching about 70 years. The major requirement for site selection was the availability of local temperature data for each lake from digitized records of the Finnish Meteorological Institute. A total of 31 meteorological stations were used to provide the mean daily air temperature for nearby lakes, with the length of record varying between 19 and 24 years. The meteorological stations are all less than 75 kilometers from the lakes with which they were paired, most being closer than 25 kilometers. A lengthy meteorological dataset was provided for Jyväskylä, Finland, comprising 98 years of mean daily temperatures; this was used to test the stability of relationships derived over the shorter time period.

The lake ice observations record four types of freeze-up and break-up information each year. The freeze-up observations include the dates of ice formation on shore, ice cover on bays, ice within visible range, and final freeze-up. The break-up observations include dates of open water on shore, open water offshore, ice in movement, and the final break-up. These observations are made for a particular area of the lake in question that is usually smaller than the entire lake. For the purposes of this study, the dates of final freeze-up and final break-up are used, as these definitions are used consistently by Finnish observers and these events occur every year.

The lake ice and meteorological records are thought to be highly reliable. Urbanization effects on the temperature records are likely to be slight (Heino, 1978), and no discontinuities are apparent in the 19–24 year station records. The 98 year temperature record at Jyväskylä was examined graphically; it displays a similar trend to that shown for the 65°–85°N latitudinal zone by Kelly et al. (1982). The lake-ice event dates were recorded and/or collected by the Hydrological Office and its predecessors for over one hundred years (Laasanen, 1982). The definitions of final freeze-up and break-up have not changed over the years. Of the 63 lakes used in this study, only a handful showed some inconsistencies of an unknown nature. These did not affect the final results, since the lake data were pooled in most analyses reported here. We believe that these meteorological and lake ice data are reasonably homogeneous.

In addition to lake ice and air temperature data, information on lake elevation, surface area, and depth were available for a large percentage of the lakes used in the study. These data are helpful in interpreting the effect of lake location and morphology on lake ice–air temperature relationships. Knowledge of these effects will be useful in selecting lakes for future studies covering wider regions with fewer calibrated lakes.

## 4. Results

### *a. Method of analysis*

To explore the relationships between air temperatures and freeze-up/break-up dates, two different methods of calculating air temperature were tried. One approach utilized mean temperatures for calendar time periods, while the other utilized mean temperatures for time periods fixed to the annual dates of freeze-up or break-up. The first method is straightforward; calendar time period temperatures will be used in this study. The second method used by Tramoni (1985) and, in preliminary work, by these authors (Palecki et al., 1985) results in interpretational problems. Since the temperature time period moves every year, one is essentially studying the seasonal temperature trend rather than the lake ice response to seasonal temperature. In fact, the regression of the freeze-up date with the average temperature of 100 days before this date results in a regression coefficient of negative value that closely approximates the fall seasonal temperature trend in Finland of $-0.16°\mathrm{C\ day}^{-1}$. The use of calendar fixed time periods basically avoids these problems.

### *b. Correlation analysis*

The first statistical operation consisted of calculating for each lake the simple product-moment correlations of mean temperatures for various calendar time periods with the freeze-up and break-up dates. These dates are given in terms of days after July 1 for each ice year. All calculations were performed with the Statistical Package for the Social Sciences. The selection of calendar time periods included short, medium and long intervals. The shortest time intervals used were five day or pentad means. During the fall, thirty pentad means from 1 July to 27 November were used; during the spring twenty pentad means from 21 January to 30 April were used. The daily temperatures used to make the pentad means were then accumulated from the last to the first pentad in order to create mean temperatures for periods of increasing length ending 27 November and 30 April. In addition, traditional time periods of half months, months, and several months were used to create mean temperatures for analysis.

The individual pentad means pinpoint the period of highest correlation with freeze-up as usually residing between 8 and 17 November in the southern part of Finland, 15–25 days before the average freeze-up date. This usually approximates the time when local daily mean temperatures fall to $\leqslant 0°\mathrm{C}$. The northern Finnish lakes also show highest correlations between air temperature and lake freeze-up at approximately the time when the average daily means reach 0°C; however, this occurs three to four weeks earlier, in October. It follows that the November monthly mean is the most highly correlated with the southern Finnish lake freeze-up dates. The 15 October–15 November monthly mean is most highly correlated with the northern Finnish lake freeze-up dates. Additional longer time-period mean temperatures are reasonably well correlated with freeze-up dates in both northern and southern Finland, especially the cumulative means of daily temperatures for 4 October–27 November, September through November, and July through to November. Based on these findings, four regression equations of air temperature with freeze-up date have been calculated for each lake: the month closest to mean freeze-up date (November or 15 October–15 November), October–November (actually 4 October–27 November), September–November, and July–November.

The correlations between air temperature and break-up date are also dependent on the region. In southern Finland, high correlations are found with the first two pentad means, covering the period 21–30 April. This is roughly five to ten days before the average break-up day. In northern Finland, no reasonable correlations are found, as the latest individual pentad mean calculated, for 26–30 April, precedes the average break-up date by two to four weeks. Similar to the freeze-up case, the southern Finnish lakes are highly correlated with April mean temperature, while the northern lakes are more highly correlated with the monthly mean temperature in May.

Additional longer time period mean temperatures are not consistently correlated with break-up; the most useful temperature is the cumulative mean of the daily temperatures from 2 March–30 April. Based on these findings, two regression coefficients of air temperature with break-up have been calculated for each lake: April and March–April for southern Finnish lakes, and May and March–May for the northern Finnish lakes.

### *c. Regression analysis*

Differential behavior of lake ice covers due to location is expected. Any lake being used to supply regression coefficients for other lakes without adjacent temperature data must be situated in the same climate region. To demonstrate this, the northern Finnish and southern Finnish lakes were analyzed separately, with the group of southern Finnish lakes being further subdivided between coastal/south and inland/north zones (Fig. 1).

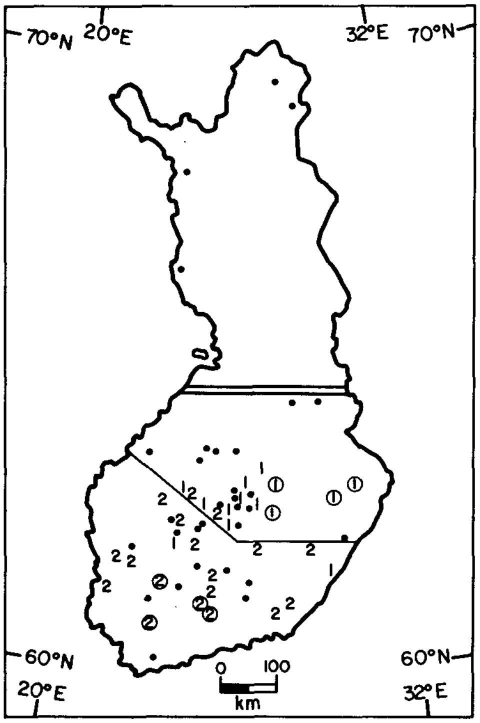


FIG. 3. The grouping of lakes by discriminant analysis of November and April temperature/lake ice date regression coefficients. The circled lakes were used to create the discrimination function.

TABLE 1a. Distribution of lakes by correlation coefficient for Northern Finland region.

| | Correlation | | | |
|---|---|---|---|---|
| | ≤0.49 | 0.50–0.59 | 0.60–0.69 | ≥0.70 |
| with freeze-up | | | | |
| 15 October–15 November | 1 | 2 | 1 | — |
| October–November | — | 2 | 2 | — |
| September–November | — | 3 | — | 1 |
| July–November | 2 | — | 1 | 1 |
| with break-up | | | | |
| May | — | 1 | — | 3 |
| March–May | 2 | 1 | 1 | — |

This division of the southern Finnish lakes was made by subjecting individual lake regression coefficients to discriminant analysis. Specifically, two discriminating variables were used: the November temperature/freeze-up date regression coefficient and the April temperature/break-up date regression coefficient. Only lakes with both regression coefficients highly significant were used in the discrimination (a correlation level of $r = 0.55$ was used as the cutoff, yielding a significance of 0.01). A total of 32 lakes was available for the analysis. Figure 3 displays the resulting classification. The circled lakes were used to create the discriminant function, separating the two groups of four lakes with a significance level of 0.04. This function objectively classified the remaining 24 lakes into the very coherent pattern delineated in Fig. 3, with only two lakes in each region misclassified.

All lakes within group boundaries were used in the regression analysis. The freeze-up and break-up dates of the individual lakes were averaged and then regressed with a single meteorological record from within the region. Regional regression equations were derived with lake ice data as the independent variable and temperature average as the dependent variable. Unlike studies mentioned earlier, lake ice dates are being used to predict temperature; therefore, the equations are calculated in this manner.

All regional lake ice equations displayed include the correlation coefficient; the uncertainties of the slope and intercept, expressed as twice the standard error; and the uncertainty of the equation prediction, expressed as twice the standard error of estimate. Equations with significance less than 0.01 are not displayed.

### 1) NORTHERN FINNISH LAKES

Four lakes with long ice cover and temperature records are available in a region between latitudes 66.9° and 69.4°N (Fig. 1). Table 1a groups the lakes by correlation coefficients for each temperature mean used in the analysis. The individual lakes are not consistently correlated with the temperature averages. Especially weak are relationships between long term temperature averages in the spring and break-up date. The resulting regression equations for the North Finnish region are listed in Table 1b. Using the composite lake ice record rather than individual lake ice records results in the development of stronger relationships between temperature and ice event date. For this region, the average monthly period preceding freeze-up date stradles October and November, while the month preceding break-up date is May. These monthly temperatures are strongly correlated with freeze-up and break-up dates, respectively. For example, a change in freeze-up date of three days indicates a change of 15 October–15 November temperature of about 0.9°C, using the regression coefficient 0.30.

### 2) SOUTHERN FINNISH LAKES

Fifty-nine lakes were analyzed in a latitudinal band between 60.2° and 64.3°N. Table 2a reports the distribution of individual lake correlations. The Southern Finland regional regression equations in Table 2b again display higher correlations when the composite of lake ice dates is related to a single temperature station. The March–April regression equation was derived from longer records spanning 70 years, as the shorter record equation was not significant. For this region, the average month preceding break-up date was April. As in the north region, these monthly temperatures are strongly correlated with ice event dates. A three day change in freeze-up date indicates a change of November temperature of about 0.6°C, using the regression coefficient 0.21.

Comparing the results for Northern and Southern Finland, one observes that the equation slopes are stronger for most of the Northern Finnish regional regression equations. An equivalent change in freeze-up date in both regions will indicate a larger magnitude shift of temperature in the northern Finnish region. This is related to differences in seasonality, with the

TABLE 1b. Regression coefficients and standard errors (SE) calculated for Northern Finland Region.

| Time period | Correlation | Equation | 2 × SE of estimate |
|---|---|---|---|
| 15 October–15 November | 0.73 | $y = 0.30\ (\pm 0.12)x - 43.1\ (\pm 15.3)$ | ±4.8 |
| October–November | 0.80 | $y = 0.24\ (\pm 0.08)x - 35.4\ (\pm 10.0)$ | ±3.2 |
| September–November | 0.78 | $y = 0.17\ (\pm 0.06)x - 22.6\ (\pm 7.4)$ | ±2.4 |
| July–November | 0.78 | $y = 0.10\ (\pm 0.04)x - 8.4\ (\pm 5.5)$ | ±1.8 |
| May | −0.80 | $y = -0.22\ (\pm 0.07)x + 78.3\ (\pm 24.1)$ | ±2.4 |
| March–May | −0.56 | $y = -0.13\ (\pm 0.08)x + 41.3\ (\pm 28.6)$ | ±2.8 |

TABLE 2a. Distribution of lakes by correlation coefficient for the Southern Finland region.

| | Correlation | | | |
|---|---|---|---|---|
| | ⩽0.49 | 0.50–0.59 | 0.60–0.69 | ⩾0.70 |
| with freeze-up | | | | |
| November | 10 | 16 | 21 | 12 |
| October–November | 12 | 15 | 17 | 15 |
| September–November | 16 | 13 | 16 | 14 |
| July–November | 14 | 15 | 19 | 11 |
| with break-up | | | | |
| April | 5 | 10 | 25 | 19 |
| March–April | 35 | 9 | 10 | 5 |

North Finnish region having a greater annual range in temperature than the southern Finnish region. Laaksonen (1977) has found that maritime flow influences temperature in southern Finland positively from September to April and negatively the rest of the year, causing this reduction in seasonality.

### 3) Coastal/South and Inland/North lakes of Southern Finland

Analysis of two separate areas of southern Finland has been used to gain insight into the areal behavior of regional regression equations. Table 3 indicates that the temperature regressions used to group the individual lakes demonstrate a clear differentiation between the composited groups in November and April. However, the two- to five-month regression equations tend to be nearly the same for both areas. It is likely that shorter time period temperature/lake ice regressions are more sensitive to small differences in regional climate. The longer time period temperature/lake ice regressions are valid over larger areas and may be more useful in areas of sparse meteorological data, especially for the fall season.

### *d. Use of a long meteorological record*

Temperature records for Jyväskylä, Finland, are available in digital form for the period 1883–1980. This location, noted as D on Fig. 1, is near the border of the inland and coastal zones in southern Finland. Table 4 compares the correlations and regression equations derived for seven sets of temperature averages using lake ice records composited for the years 1959–79 and 1909–79. The long record regression coefficients tend to be smaller than those of the short record for the temperature/freeze-up date relationships. However, the April temperature/break-up date regression equation is almost exactly the same. The fall regression difference is due to a significant population of outliers at the late freeze-up date limit. Figure 4a displays the November temperature/freeze-up date regression lines, with and without the outliers. Figure 4b shows the same regression done with the longer records. While the one outlier noted in Fig. 4b does not greatly affect the regression equation, the two outliers in Fig. 4a greatly reduce the slope of the line, from 0.21 to 0.14. As can be seen in Fig. 4b, the two outliers in the short record are not outliers in the long record. This slightly curvilinear relationship at late freeze-up dates flattens the linear regression slope.

The physical reason for this behavior is the lack of consideration of December temperatures in the fall analysis. The outliers represent years in which November temperatures are near normal, but December temperatures greatly above normal, delaying freeze-up in a way that is not accounted for by this regression model. This does not happen in the spring, as final break-up date is not affected by the temperature history late in the season. Including the December temperature in the regression analysis reduces correlation greatly; therefore, the nonlinearity problem has been moderated by cautious removal of outliers. The two outliers, 1972 and 1974, have been removed from the short record analysis, as has the outlier, 1929, been removed from the long record analysis.

## 5. Discussion

Strong statistical relationships between lake ice cover dates and various air temperature indices have been established. Other factors must now be examined to determine the utility of applying these results in substituting lake ice cover data for direct temperature data.

The 1941–70 average freeze-up and break-up dates for 41 lakes in southern Finland were analyzed to find any significant relationships with location and mor-

TABLE 2b. Regression equations and standard errors (SE) calculated for the Southern Finland region.

| Time period | Correlation | Equation | 2 × SE of estimate |
|---|---|---|---|
| November | 0.85 | $y = 0.21\ (\pm 0.06)x - 32.5\ (\pm 9.2)$ | ±2.4 |
| October–November | 0.91 | $y = 0.20\ (\pm 0.04)x - 28.2\ (\pm 6.7)$ | ±1.7 |
| September–November | 0.79 | $y = 0.14\ (\pm 0.05)x - 16.3\ (\pm 7.4)$ | ±1.9 |
| July–November | 0.63 | $y = 0.07\ (\pm 0.04)x - 2.3\ (\pm 6.4)$ | ±1.7 |
| April | −0.71 | $y = -0.20\ (\pm 0.09)x + 64.7\ (\pm 28.6)$ | ±1.6 |
| March–April* | −0.71 | $y = -0.18\ (\pm 0.04)x + 54.9\ (\pm 13.7)$ | ±2.4 |

* Longer records used for this statistic.

TABLE 3. Regression equations and standard errors (SE) calculated for the coastal/south and inland/north areas of the Southern Finland region.

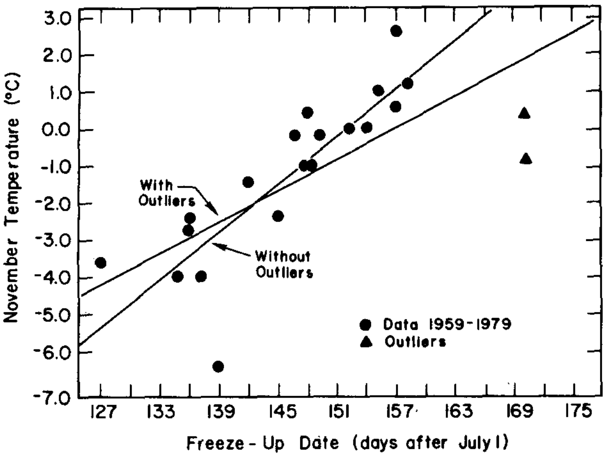
| Time period | Correlation | Equation | 2 × SE of estimate |
|---|---|---|---|
| | | *Coastal/South* | |
| November | 0.88 | $y = 0.24\ (\pm 0.06)x - 37.7\ (\pm 8.9)$ | ±2.2 |
| October–November | 0.86 | $y = 0.19\ (\pm 0.05)x - 27.7\ (\pm 7.6)$ | ±1.8 |
| September–November | 0.73 | $y = 0.12\ (\pm 0.05)x - 15.0\ (\pm 7.7)$ | ±1.9 |
| July–November | 0.61 | $y = 0.06\ (\pm 0.04)x - 1.6\ (\pm 5.7)$ | ±1.4 |
| April | −0.69 | $y = -0.16\ (\pm 0.07)x + 49.7\ (\pm 22.0)$ | ±1.6 |
| March–April | −0.62 | $y = -0.18\ (\pm 0.09)x + 53.8\ (\pm 30.3)$ | ±2.2 |
| | | *Inland/North* | |
| November | 0.81 | $y = 0.19\ (\pm 0.06)x - 28.8\ (\pm 8.8)$ | ±2.8 |
| October–November | 0.93 | $y = 0.18\ (\pm 0.03)x - 24.9\ (\pm 4.8)$ | ±1.5 |
| September–November | 0.85 | $y = 0.13\ (\pm 0.03)x - 14.4\ (\pm 5.0)$ | ±1.6 |
| July–November | 0.72 | $y = 0.07\ (\pm 0.03)x - 1.2\ (\pm 4.1)$ | ±1.3 |
| April | −0.69 | $y = -0.18\ (\pm 0.08)x + 57.2\ (\pm 25.7)$ | ±1.6 |
| March–April | −0.39 | ------------------------------ | |

phologic features. Figures 5a and 5b show the average dates of final freeze-up and break-up in Finland for the period 1960–79, compiled from many more lakes than examined here (Laasanen, 1982). The most striking feature of these figures is the pronounced deflection of isolines of average freeze-up and break-up date northward near the Baltic Sea coast. This maritime influence is also evident in the regression coefficients of individual lakes, as the same deflection northward is seen in the discriminant analysis grouping of Fig. 3. As can be expected from looking at the figures, both freeze-up and break-up dates are well correlated with latitude. Break-up dates are also somewhat correlated with longitude in the sample, although freeze-up is not. Mean lake depth is fairly well correlated with freeze-up dates. Lake area is more important in the determination of break-up dates, but is not as well correlated. Table 5 presents these individual correlations.

The correlation of freeze-up and break-up dates with latitude indicates that regions chosen for analysis should be limited in latitudinal extent. If the lakes considered together differ too much in ice cover dates, then regression coefficients with a particular monthly temperature will be too variable and not represent the region in question. This finding, combined with the earlier noted dependence of regression coefficients on continentality, indicates that the region over which a particular set of regression coefficients is usable may only be a few hundred kilometers in diameter in Finland. However, the extent of area with approximately

TABLE 4. Comparison of correlation ($r$) and regression equations ($a$) derived from short and long term records for the Southern Finland region.

| Time period | Correlation | Equation | 2 × SE of estimate |
|---|---|---|---|
| | | *Short records (1959–1979)* | |
| November | 0.85 | $y = 0.21\ (\pm 0.60)x - 32.5\ (\pm 9.2)$ | ±2.4 |
| October–November | 0.91 | $y = 0.20\ (\pm 0.04)x - 28.2\ (\pm 6.7)$ | ±1.7 |
| September–November | 0.79 | $y = 0.14\ (\pm 0.05)x - 16.3\ (\pm 7.4)$ | ±1.9 |
| July–Nov | 0.63 | $y = 0.07\ (\pm 0.04)x - 2.3\ (\pm 6.4)$ | ±1.7 |
| April | −0.71 | $y = -0.20\ (\pm 0.09)x + 64.7\ (\pm 28.6)$ | ±1.6 |
| Mar–Apr | −0.44 | ------------------------------ | |
| Mar–May | −0.28 | ------------------------------ | |
| | | *Long records (1909–1979)* | |
| November | 0.82 | $y = 0.17\ (\pm 0.03)x - 25.9\ (\pm 4.2)$ | ±2.7 |
| October–November | 0.78 | $y = 0.13\ (\pm 0.03)x - 17.6\ (\pm 3.7)$ | ±2.4 |
| September–November | 0.75 | $y = 0.10\ (\pm 0.02)x - 10.2\ (\pm 3.1)$ | ±2.0 |
| July–November | 0.63 | $y = 0.06\ (\pm 0.02)x + 0.4\ (\pm 3.5)$ | ±1.7 |
| April | −0.82 | $y = -0.20\ (\pm 0.03)x + 63.9\ (\pm 10.6)$ | ±1.9 |
| March–April | −0.71 | $y = -0.18\ (\pm 0.04)x + 54.9\ (\pm 13.7)$ | ±2.5 |
| March–May | −0.73 | $y = -0.16\ (\pm 0.04)x + 50.7\ (\pm 11.3)$ | ±2.1 |



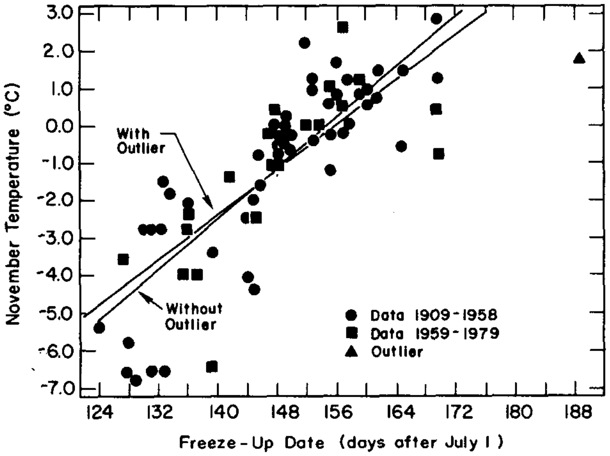


FIG. 4a. The regression of the short Jyväskylä November temperature record with the southern Finland composite lake freeze-up record.

FIG. 4b. The regression of the long Jyväskylä November temperature record with the southern Finland composite lake freeze-up record.

homogeneous response will be larger in regions where the climatic gradients are weaker.

The other results point out a few strengths and weaknesses in the regression analysis techniques discussed. The moderately strong relationship between lake depth and freeze-up date supports the earlier finding that lakes are more responsive to long time period temperatures in the fall than in the spring. Deeper lakes within each regional sample integrate temperature to depth over several months because they store more heat than shallower lakes. The freeze-up day for larger lakes is then sensitive to longer term heating as well as early winter cooling rates. On the contrary, break-up is more dependent on the surface area of the lake, indicating the importance of wind fetch in mechanical break-up. Because of this, break-up date is less sensitive to seasonal-length heating of the air. As soon as the ice is weakened by short-term heating and solar radiation, it is accessible to mechanical break-up.

Several rules-of-thumb are now available in choosing lakes for study that do not have many nearby meteorological stations. Lakes chosen should be clustered closely for spatial representativeness and to allow one set of regression coefficients to be used for all. If possible, several lakes in each region should have longer-term ice cover observational data in order to provide ground truth for satellite monitoring of lake ice freeze-up and break-up. Lakes should be several square kilometers in area, or larger, in order to be good thermal integrators and also be easily detected on satellite imagery. At least one meteorological station is needed to calibrate the ice cover-air temperature relationship in each region. Table 2b indicates that a single meteorological station can be successfully related to a rather large composited sample; therefore, it appears feasible that sparsely arranged meteorological stations would be adequate for this purpose.

Meteorological factors other than mean air temperature affecting the freeze-up and break-up dates can be considered to be related to synoptic conditions. Wind speed, wind direction, cloud cover and precipitation all affect the final stages of freeze-up and break-up, as noted earlier. Therefore, it is not realistic to expect the regression coefficients to be any more accurate than the two standard errors bounding them. The translation of changes in freeze-up or break-up dates to changes in temperature should be limited in range to small or medium oscillations around the mean.

The regression results may be applied to spatial or temporal data. Two examples of the translation of lake ice time series to temperature time series are given in Figs. 6a and 6b. Twenty-year moving averages of lake ice dates for Lake Kallavesi have been converted to November and April temperature anomalies, using the long term southern Finland regression coefficients of 0.17 and −0.20, respectively. The anomalies are referenced to the 1951–70 mean. The lake ice derived temperatures are compared to the 20-year moving average of measured air temperatures at Helsinki. The resulting agreement of the November and April temperature curves is very good, with correlations of 0.94 and 0.93, respectively. However, the significance of this correlation is not high due to the autocorrelation introduced by the 20-year moving average. Using the method of Quenouille (1952, p. 168), the correlations for both time series are not significant at the 0.05 level. Using a shorter moving average would likely result in a significant correlation. The location of Lake Kallavesi in central southern Finland results in some overestimate of the Helsinki temperature changes along the coast; this is due to the more continental regime inland. Any urban effects would be expected to have caused greater warming at Helsinki, and so probably are not a factor in this comparison.

An application of a spatial nature is shown in Fig. 7. For 33 lakes in southern Finland, the freeze-up date of the decade 1932–41 was subtracted from the freeze-up date of the decade 1962–71. The change of freeze-up date was converted to November temperature

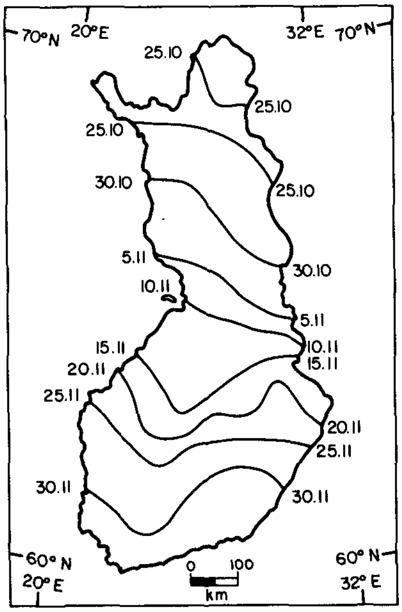


FIG. 5a. Average date of final lake freeze-up in Finland 1960–79 (Laasanen, 1982).

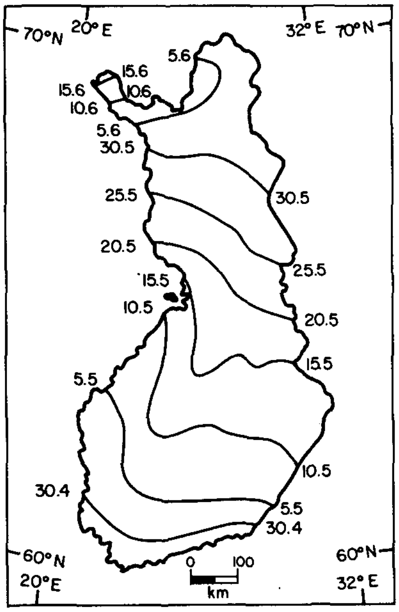


FIG. 5b. Average date of final lake ice break-up in Finland 1960–79 (Laasanen, 1982).

change using the long record regression coefficient of 0.17. To smooth the resulting spatial pattern, the individual lake temperature values were averaged onto a 100 km$^2$ grid. These values were then contoured. The pattern indicates stronger cooling toward the southwest coast, with weaker cooling inland. This is a coherent response to a change in mean atmospheric circulation between these decadal periods. Lamb (1972) shows that during the 1960s circulation was more meridional than during the 1930s. Deprived of the maritime airflow that is more usually associated with zonal flow, the southwest area of Finland underwent the greatest temperature change. Conversely, the area inland and to the northeast is only moderately influenced by maritime airflow, and so did not undergo as large a magnitude of cooling. While the magnitude of November temperature change is overestimated, the pattern of gradual decrease in the magnitude of change from southwest to northeast is quite plausible. This simple regression method tends to exaggerate real temperature changes over time because it accounts for all variance in lake freeze-up dates as being caused by air temperature changes. Undoubtedly, long term changes of other synoptic factors also occur.

TABLE 5. Factors affecting freeze-up and break-up dates.

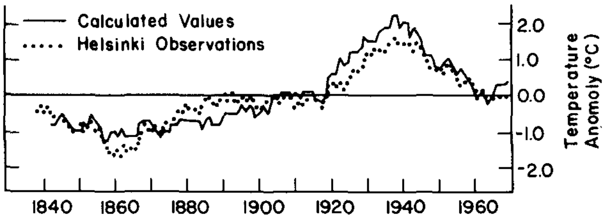
| Parameter | Correlation with freeze-up | | Correlation with break-up |
|---|---|---|---|
| Latitude | $r = -0.62$ | (41 cases) | $r = 0.80$ |
| Longitude | $r = -0.04$ | (41 cases) | $r = 0.51$ |
| Depth | $r = 0.55$ | (31 cases) | $r = -0.02$ |
| Area* | $r = 0.29$ | (34 cases) | $r = 0.45$ |

* Four lakes greater than 500 km$^2$ were excluded.

## 6. Conclusions

Records of lake ice observations are a previously untapped source of quantitative temperature information. Exploration of this method leads to the conclusion that temperature anomalies derived by regression coefficients are at least internally consistent, although some significant problems still exist.

At this point, the numerical conclusions reported



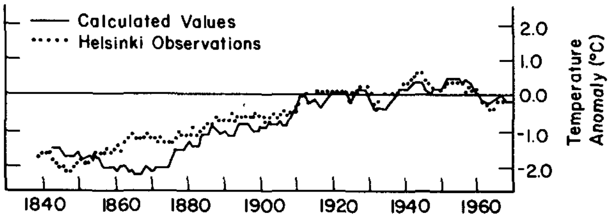


FIG. 6a. 20-year running mean of November temperature given as anomalies from the 1951–70 mean: calculated from freeze-up dates of Lake Kallavesi, 62°54′N 28°38′E (solid line) (Lemmelä and Kuuisto, 1975), using the long record southern Finland regression coefficient of 0.17; observed temperatures at Helsinki, 60°05′N 25°00′E (dotted line).

FIG. 6b. As in Fig. 6a, with April temperature anomalies calculated from break-up dates using the long record southern Finland regression coefficient of −0.20.

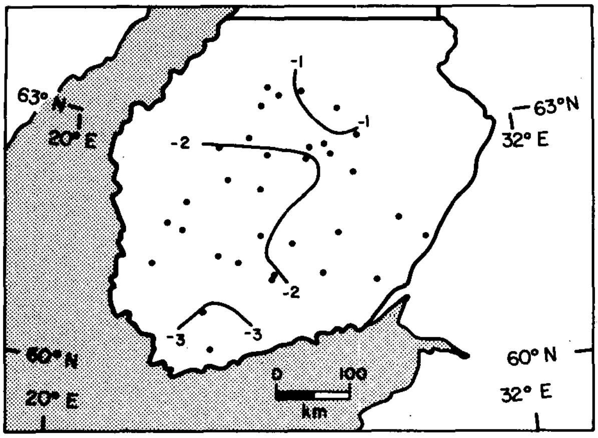


FIG. 7. November temperature differences between the decades 1932–41 and 1962–71, derived from the change in freeze-up dates of 33 lakes, using the regression coefficient of 0.17 for southern Finland. The contours were smoothed by averaging data on a 100 km$^2$ grid.

here can be used as a first approximation. Using the regression equations for southern Finland (Table 2b), a five day change in freeze-up date would represent a 1.1°C change in November temperature. Likewise, a five-day change in break-up date would represent a 1.0°C change in April temperature. These values will vary for different regions, as is seen in Tables 1–3. Refinement of procedures will be required to eliminate overestimation of temperature, probably by introducing additional synoptic variables into the analysis.

This method of analysis will be useful in studies of modern climatic change. By utilizing closely spaced lakes that cover large portions of the data sparse regions in middle–high northern latitudes, the spatial character of a changing climate will be more easily discerned. Satellite imagery can be used to monitor lake freeze-up and break-up dates on a consistent, regular basis with a uniform approach. When a sufficient number of cases is made available, the lakes can then be calibrated to the most representative meteorological station data and used for spatial analysis as described in the second example. If further testing proves the method robust, it should be applied to the $CO_2$-warming detection problem.

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