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THE DATE OF BREAK-UP OF LAKE ICE AS A CLIMATIC INDEX

by

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Abstract

The relationship between vernal weather conditions and the date of break-up of the winter ice cover on Lake Kallavesi in central Finland has been studied with a regression model. The formulation of the meteorological variable in the model is based on the energy balance equation of the ice cover.

The date of break-up can be explained quite satisfactorily by taking into account the air temperature only. Precipitation during the melting period may have some importance, too. On the other hand, radiation anomalies do not seem to contribute significantly to the date of break-up.

The observed climatological temperature changes and the ones deduced on the basis of the ice conditions are in good agreement. This encourages the usage of the dates of break-up as a climatic index. In using such an index, however, caution is required, since the date of break-up may also be affected by changes in the amount of precipitation and other meteorological parameters.

1. *Introduction*

This study explores the value of the date of break-up of lake ice as a climatic index in remote areas. Nowadays the date can easily be obtained from satellite observations. Therefore, its usefulness in climate monitoring is worth studying in those areas where time series of conventional climate variables exist together with those for the date of the break-up of ice. The latter is not significantly affected *e.g.* by urban effects. Where long series of ice observations are available, one can thus also investigate, whether the climatic changes which are indicated by conventional meteorological observations are real or not.

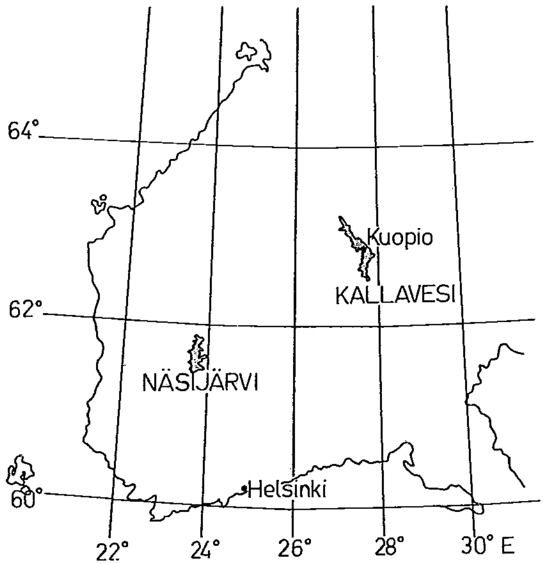

Fig. 1. The geographical locations of Lakes Kallavesi and Näsijärvi and the weather observing stations at Kuopio and Helsinki.

Changes in the ice conditions of lakes (SIMOJOKI (1940, 1959), TANAKA and YOSHINO (1982), PALECKI *et. al.* (1985), TRAMONI *et. al.* (1985))*), rivers RANNIE, 1983) and seas (ALENIUS and MAKKONEN, 1981) and their relationships with climatic changes have been rather widely investigated. In the papers mentioned the methods have been almost completely statistical. In most cases some variables describing the ice conditions are related with rather arbitrarily chosen variables describing the air temperature. However, when one uses statistical methods in order to clarify how climatic changes affect ice conditions, more attention should be paid to the physical significance of the meteorological variables included in the model.

The method used here consists of finding a regression equation between the date of break-up of ice and »weather» during the spring. The variable describing the mean spring weather is the date when the ice cover has received a certain amount of energy. The associated energy flux is parameterized in terms of meteorological variables.

The lake mainly used in this study is Kallavesi (see Fig. 1), which is suitable

*) See also: PALECKI, M.A. and R.G. BARRY, 1986: Freeze-up and break-up of lakes as an index of temperature changes during the transition seasons: A case study for Finland. J. Appl. Meteor., 25, 893–902. (Appeared when the present paper was in press.)

for this purpose in many ways. It is rather a big lake, break-ups have been observed continuously since 1834 and a weather station at Kuopio has been in operation near this lake since 1884. In this study, the period 1884–1914 has been used. This old period was chosen in order to minimize possible biases due to man's impact on the ice conditions. Some results are also shown for Lake Näsijärvi, the geographical location of which is also shown in Fig. 1.

2. *Parameterization of the energy balance equation of the ice cover*

The energy balance of the ice cover of a lake can be presented in the form:

$$\frac{dE}{dt} = Q_s - Q_I + Q_H + Q_L + Q_P + Q_G \tag{1}$$

where the term on the left is the rate of change of energy content of the ice cover, Q_s is the absorbed short-wave radiation, Q_I the net emission of infrared radiation and Q_H and Q_L the sensible and latent heat fluxes from the atmosphere to the ice. Q_P is the heat transfer by precipitation and Q_G the energy flux from the lake water below the ice.

In explaining the date of break-up, most attention must be paid to the terms which have large magnitudes and which vary considerably from year to year. The terms Q_I and Q_G can thus be neglected for the following reasons. Firstly, the infrared emissivity of the ice surface is practically constant and its temperature during the melting period always close to 0 °C. In addition, the infrared emission is mostly compensated by atmospheric counterradiation. The energy flux from below (Q_G) cannot be very strong, because the vertical gradient of water temperature is small in ice-covered lakes (see, for example, KUUSISTO, 1981). Furthermore, its value does not vary significantly from year to year, because the temperature distribution in a big lake with slow currents must be almost identical every spring.

Most of the anomalous energy flux which causes year-to-year fluctuations in the date of break-up of ice can be expected to come from the anomalous absorbed solar radiation and from latent and sensible heat fluxes from the atmosphere to the ice. The direct effect of heat transfer by precipitation can be shown to be less important. It is, however, easy to calculate and will therefore also be taken into account in this study. These energy fluxes can be roughly parameterized in terms of cloudiness, air temperature and humidity, amount of precipitation and wind. By integrating the parameterized energy fluxes from the beginning of the spring one can, in principle, decide when the ice has become fragile enough for the break-up to occur.

In the regression model developed in this study the dependent variable is the date of break-up of ice and the only independent variable the date when the integrated parameterized energy flux has attained a certain level. The independent variable used can of course be defined in several ways depending on the method of parameterization and weighting of various energy fluxes. Only one independent variable is used in each regression model. In experiments with several independent variables, the predictors often correlated strongly with each other and so the regression coefficients of some predictors got a sign opposite to that expected on a physical basis.

The formulation used for parameterizing absorbed solar radiation was (parameterized variables, whose unit is J/day, are marked with asterisk):

$$Q_S^{\star} = (1-a) \cdot Q_O \cdot f(N) \tag{2}$$

where a is the surface albedo, Q_O the total daily amount of solar radiation reaching the surface in clear sky conditions and N the total cloudiness. For function f, several alternatives were tested in this study (see, for example, KONDRATYEV, 1969, pp. 467–469). The amount of available solar radiation (Q_O) can, of course, be easily calculated knowing the latitude and time of year. The value 0.8 for the transmission coefficient of the atmosphere for a direct beam was used (see Fig. 7 in DEACON, 1969). Unfortunately, the absorbed radiation is decisively affected by the surface albedo, whose value is unknown. For early spring it was set equal to 0.9 (typical value for white snow). When a certain amount of energy had been received (several alternatives were tested), it was set equal to 0.2. (In some experiments a different types of parameterization of absorbed radiation, described in terms of the amplitude of daily temperature variation, was explored).

The sensible heat flux (integrated over a day) was depicted with a somewhat modified bulk-aerodynamical formula:

$$Q_H^{\star} = \alpha(1 + \beta v)(T_a - T_s) \tag{3}$$

where v is the wind speed, T_a and T_s the temperatures of air and ice-surface ($T_s \equiv 0\,^{\circ}\mathrm{C}$ during the melting period) and α and β empirical coefficients. In the experiments done, best results were attained by using the value $\beta \approx 0.1$ s/m. However, when using the value $\beta = 0$, only an insignificant amount of explained variance was lost. The explanation for this may be that the wind at the observing station is not necessarily the same as that on the lake. There is also good reason to think that the old wind observations used here are not reliable. So, from here on, wind observations will be omitted, *i.e.* in (3) β is set equal to zero. The value of the coefficient α will be discussed later.

The old humidity measurements were considered so unreliable that the latent heat flux was not parameterized explicitly. However, during the melting period the latent and sensible heat fluxes typically correlate positively (see, for instance, McKay and Thurtell, 1978).

The heat transfer by precipitation is written as:

$$Q_P^\star = c \cdot r \cdot T_a \tag{4}$$

where c is the specific heat of water and r the amount of daily precipitation (expressed in kg/m^2, which is practically equal to mm). However, if the daily mean air temperature is below +1 °C, the precipitation is considered to be snow, and the heat transfer by precipitation is assumed to be zero.

3. *Calculation of the independent variable*

The data used for calculating the energy fluxes comes from the weather station at Kuopio. The 31 years from 1884 until 1914 were used to develop the model. The air temperature observations were made at 7 am, 2 pm and 9 pm (local time); in (2) and (4) the arithmetic average of these three observations was utilized. For the cloudiness only the observation at 2 pm was used. It best describes radiation conditions around noon, when most radiation is received. The amount of precipitation was measured once a day.

In order to get a numerical value for the independent variable used in this model for each spring, one chooses a certain limit, which the sum of the parameterized energy flux must reach. Then, the day when this limit is attained will be the value of the independent variable for that spring. The limit is arbitrary and the best choice can be made using statistical methods.

The total daily energy received by the ice cover is written as:

$$Q^\star = C_1 Q_S^\star + C_2 Q_H^\star + C_3 Q_P^\star \tag{5}$$

where coefficients C_1, C_2 and C_3 are arbitrary. The best values for these coefficients will later be found experimentally. The amount of energy flux integrated over the spring is computed as the cumulative sum of $Q^\star$. Every day when $Q^\star$ is positive the sum increases and vice versa. Negative energy sums, however, are prohibited, *i.e.* if the sum would turn out to be negative, it is set equal to zero. The melting period is thus considered to begin only when the energy sum is permanently positive. Possible thaws before that date are followed by frosts, which eliminate the melting occured. The date of beginning of the melting period naturally varies from year to year: in warm years it already begins in early March, in cool years not until early May.

4. *The regression equations best explaining the date of break-up*

A large number of regression models were tested. In these experiments, the ways of parameterizing the absorbed radiation (Eq. (2)) and sensible heat flux (Eq. (3)), coefficients C_1, C_2 and C_3 in (5) and the limit of the energy sum were altered. In these experiments the best correlation between variables was obtained, when the radiation term was completely omitted, *i.e.* C_1 in Eq. (5) was set equal to zero. Yet this does not indicate that the role of radiative energy would be insignificant in the melting process. It appears that the parameterized solar radiation does not vary much from one year to another and that its small variations do not significantly correlate with the date of the break-up of ice. Furthermore, the absorbed radiation may also correlate negatively with the latent heat flux: clear days are dry, too (compare YLINEN, 1968).

It is clear that the parameterization of solar radiation with the total cloudiness, as done here, is insufficient. However, observations of separate cloud types were not available. The variations of surface albedo are also complicated, and can only poorly be described by the meteorological variables used: the colour of the ice surface varies because of fallen snow or rain, solid particles etc.. One must remember, too, that the cloudiness can vary during the day, and that the cloudiness at 2 pm is not necessarily representative for the whole day.

The best correlation between the variables in the regression model was obtained when only air temperature and precipitation were taken into account in (5). Even so, there still exist four free parameters in computing the independent variable: α, C_2, C_3 and the limit that the energy sum must attain. On the other hand, there are only two degrees of freedom in the model: the ratio of the energy fluxes of sensible heat and that due to precipitation, and the limit of energy sum. For the sake of convenience, the coefficients α and C_2 are set equal to one, whereby the unit of the »energy sum» is changed into degree days. The »daily energy gain» is thus computed as:

$$Q^* = T_a + \kappa \cdot r \cdot T_a = T_a(1 + \kappa \cdot r) \qquad (6)$$

The experiments done with the statistical model show that the best results are obtained, if $\kappa = 0.4$ m^2/kg. Other values of κ near this number gave almost as good results. If one integrates (6) until the value 175 degree days is reached and uses this date (t_S) as the value of the independent variable, a correlation coefficient 0.932 between t_S and the observed date of break-up (t_B) is obtained. Other limits of the energy sum gave slightly smaller correlations. The regression equation between variables is:

$$t_B = 0.897\ t_S + 8.75 \qquad (7)$$

in which day number one for t_S and t_B is April 1st.

It is rather surprising that the importance of precipitation seems to be as large as obtained here (according to (6), for instance, a daily precipitation of 2.5 mm means that the energy gain would be double that on days without precipitation). If one computes the amount of energy typically available from rain water, one sees that it can only melt an insignificant layer of ice. The indirect effects of warm precipitation (the surface albedo becomes lower and perhaps the ice becomes more fragile when water in liquid form penetrates into the ice) are probably more important than the direct one. The importance of precipitation in this regression model can be partly explained by the effect of the latent heat flux: when it is raining, the air is moist and the latent heat flux is strengthened.

5. *The model including temperature sums only*

If one wants to use the history of dates of break-up in order to study the possible warming or cooling of the climate, it is of course most advantageous to use a model including the air temperature alone. The value of the independent variable t_S is then obtained simply by adding the daily mean temperatures until a chosen temperature sum is reached. The highest correlation coefficient between t_S and t_B (0.910) is obtained by using as t_S the time, when the value of 140 degree days is obtained for the temperature sum. The regression equation:

$$t_B = 0.836\ t_S + 10.06 \qquad (8)$$

and the annual values of t_B and t_S are shown in Fig. 2. The roles of dependent and independent variables in the regression model can be interchanged, and one gets a regression equation:

$$t_S = 0.992\ t_B - 2.27 \qquad (9)$$

The coefficient of t_B in the regression equation is practically equal to one. Thus, if one knows the date of break-up of ice, one can deduce how early (that is, how warm) the spring has been.

The values for individual years show quite a large scatter. On the other hand, when one aims to evaluate the possibility of using the date of break-up of lake ice as a climatic index, attention should be focussed on averages over several years. In individual years several factors can make the results of a regression model worse; for instance, the thickness of the ice cover varies from one winter to another

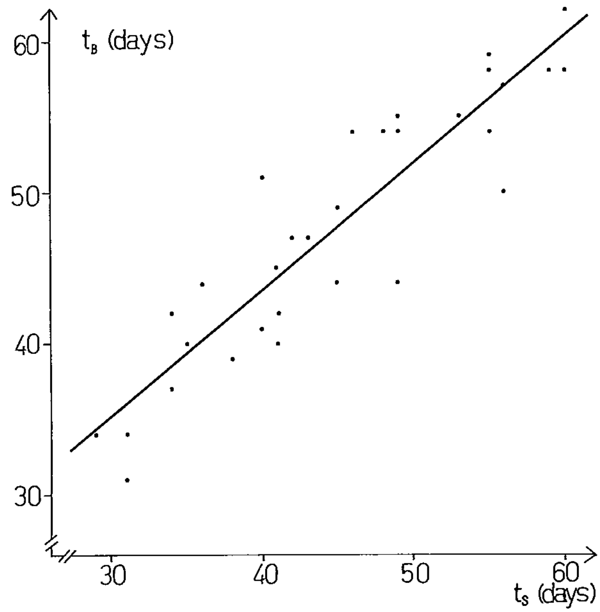

Fig. 2. Scatter diagram for the annual values of the date of break-up of the ice on Kallavesi (t_B) and the date of reaching the temperature sum of 140 degree days (t_S). The line shows the regression equation (8).

(observations of ice thickness were not available for the period investigated). However, when one investigates the averages over several years, these factors are partially eliminated.

Fig. 3 gives the decadal averages of anomalies of the dates of break-up for two lakes (Kallavesi and Näsijärvi, see Fig. 1) for the years 1840–1979. For comparison, the earliness of spring deduced from the April-May mean temperatures of Helsinki is also shown (because the difference between the mean temperatures of May and April in Helsinki is 6.4°, a rise of 1° in mean temperature implies an increase of 4.8 days in earliness). The monthly mean temperatures of Helsinki are chosen because no other series of observations exists in Finland for the whole period 1840–1979. In any case, the correlation between the dates of break-up and the vernal temperatures is still very good. Fig. 3 shows rather decisively that during the last 140 years, the spring in Finland really has become warmer. Spring begins nowadays on the average about 9–10 days earlier than in the 19th century. The dates of break-up are almost independent of the thermal pollution due to urban effects. Because the observed temperature changes and the ones deduced from ice conditions are in good agreement, the measured warming in Helsinki must also be

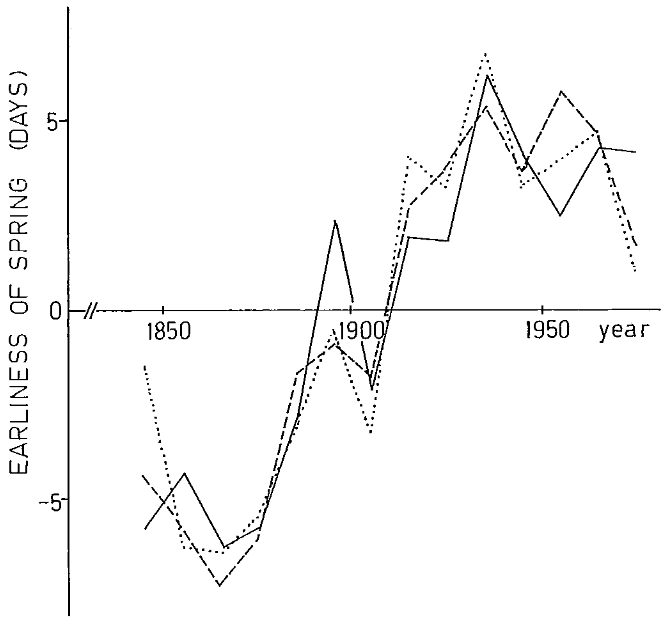

Fig. 3. Ten-year average anomalies (from the decade 1840–49 until 1970–79) of the date of break-up of ice on Kallavesi (------) and Näsijärvi (......). The solid line shows the earliness of spring in Helsinki (deduced from the mean temperatures of April–May). (Spring becoming warmer by 1° means an increase of 4.8 days in earliness).

to a major extent real.

There exist a couple of decades, when the measured spring temperatures have been distinctly warmer than those deduced from the dates of break-ups. The reason for this is probably the way the earliness of spring is here determined (April-May mean temperature). For instance, in the 1970s there were several springs, when the temperatures in late May were very high. Thus the May–April mean temperature was high, although the temperature during the melting period (April and early May) had been rather low.

6. *Concluding remarks*

In this study a statistical model has been developed to explain the relationship between the date of break-up of ice of a lake and weather conditions in spring. The meteorological variables employed in the model have been chosen on a physical basis, by using the parameterized energy balance equation of the ice cover.

It was found that the vernal temperature conditions alone explain the date of break-up rather well. The knowledge of precipitation also contributes to the explained variance. This latter result is in contradiction to that of SIMOJOKI (1940), who found that little correlation exists between the date of break-up and the amount of precipitation during the spring. In the present study rain in form of snow has been excluded and the temperature of rain water has been taken into account. However, because of the small number of years used in this study, the difference between the correlation coefficients 0.910 (the model without precipitation) and 0.932 (the model with precipitation) is not statistically significant, so the importance of precipitation in the melting process should be confirmed with a larger data base.

The radiation anomalies in spring do not seem to contribute to the interannual fluctuations in the date of break-up. This result may in part be due to the unsatisfactory parameterization of the absorbed radiation obtainable with the aid of the available observations. Neither does knowledge of the wind seem to be essential in parameterizing the sensible heat flux. This probably stems from the fact that the wind observations used do not well describe the wind conditions on the lake.

In the present study, the correlation coefficients obtained between the date of break-up and weather conditions during spring are higher than those obtained, for instance, by RANNIE (1983) and PALECKI *et al.* (1985). This is probably due to the more physical basis of the independent variables chosen in this study. The results would obviously further improve if the parameterization of energy fluxes were improved. For instance, a better description of the absorbed solar radiation would be obtained, if observations of different cloud types were available. The description of surface albedo could be improved, too. Furthermore, the latent heat flux is by no means unimportant in the melting process. Its sign can vary during spring (see, for example, MCKAY and THURTELL, 1978), but in the later stage of the melting period it is mostly positive, *i.e.* condensation of water occurs on the ice cover. Although sensible and latent heat fluxes correlate positively, taking into account the latent heat flux would most likely improve the model. In addition, the thickness of the ice, and the snow covering it naturally have a decisive effect on the amount of energy needed to melt the ice.

The dates of break-up correlate well with the spring-time mean air temperatures. Thus it is obviously possible to use this date as an index indicating climatic trends, as far as spring temperature is concerned. However, there can be some bias in this monitoring index if simultaneously with temperature change, the amounts of vernal precipitation also change significantly. Changes in the thickness of the ice cover, amount of snow, radiation and humidity in spring may have similar effects.

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REFERENCES

ALENIUS, P. and L. MAKKONEN, 1981: Variability of the annual maximum ice extent of the Baltic Sea. *Arch. Met. Geoph. Biokl., Ser. B,* 29, 393–398.

DEACON, E.L., 1969: Physical processes near the surface of the earth. In: Flohn, H. (ed.): *General climatology, 2 (World Survey of Climatology Volume 2),* Elsevier publishing company, Amsterdam.

KONDRATYEV, K.Y., 1969: *Radiation in the atmosphere.* Academic Press, New York, 912 pp.

KUUSISTO, E., 1981: Suomen vesistöjen lämpötilat kaudella 1961–1971 (Water temperatures of lakes and rivers in Finland in the period 1961–1975). *Vesientutkimuslaitoksen julkaisuja,* 44. Helsinki. 40 pp.

MCKAY, D.C. and G.W. THURTELL, 1978: Measurements of the energy fluxes involved in the energy budget of a snow cover. *J. Appl. Meteor.,* 17, 339–349.

PALECKI, M., BARRY, R.G. and F. TRAMONI, 1985: Lake freeze-up and break-up records as a temperature indicator for detecting climate change. *Third Conference on climate variations and symposium on contemporary climate 1850–2100. Extended abstracts.* American Meteorological Society, Boston, Massachusetts. 29–30.

RANNIE, W.F., 1983: Breakup and freezeup of the Red River at Winnipeg, Manitoba Canada in the 19th Century and some climatic implications. *Climatic Change,* 5, 283–296.

SIMOJOKI, H., 1940: Über die Eisverhältnisse der Binnenseen Finnlands. *Mitteilungen des Meteorologischen Instituts der Universität Helsinki-Helsingfors,* 43, 194 pp.

–»–, 1959: Kallaveden pitkä jäähavaintosarja (A long series of ice observations at Lake Kallavesi). *Terra,* 71, 156–161.

TANAKA, M. and M.M. YOSHINO, 1982: Re-examination of the climatic change in central Japan based on freezing dates of Lake Suwa. *Weather,* 37, 252–259.

TRAMONI, F., BARRY, R.G. and J. KEY, 1985: Lake ice cover as a temperature index for monitoring climate perturbations. *Zeitschr. Gletscherk. Glazialgeol.,* 21, 43–49.

YLINEN, J., 1968: Lumen vähenemisestä keväällä sateettomina päivinä (On the decrease of snow in spring in rainless days). *Ilmatieteen laitos, Tutkimusseloste 7.* Helsinki. 4 pp.