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Ice break-up on southern Lake Baikal and its relationship to local and regional air temperatures in Siberia and to the North Atlantic Oscillation

David M. Livingstone
Department of Environmental Physics, Swiss Federal Institute of Environmental Science and Technology (EAWAG), Überlandstrasse 133, CH-8600 Dübendorf, Switzerland

Abstract

The calendar date of ice break-up on southern Lake Baikal has been recorded uninterruptedly since 1869. A strong trend to earlier thawing up to around 1920 (1 d per 3.3 yr) is followed by the lack of any significant trend thereafter. For the period 1931–1994, the timing of break-up is related to local surface air temperatures integrated over periods of 1–3 months. Although highest unimodal correlations are with the 3-month mean air temperature, a bimodal relationship between break-up and air temperature exists at shorter integration times, with break-up date being related not only to the air temperature prevailing during thawing (April) but also to that prevailing during the time of ice formation, when air temperatures are lowest (February). High-frequency (interannual) fluctuations in the timing of break-up appear to be influenced mainly by the air temperatures prevailing during thawing, and low-frequency (interdecadal) fluctuations by those prevailing during ice formation.

Whereas correlations with April air temperatures are always significant, those with February air temperatures are only significant during the latter part of this century, i.e., after cessation of the tendency toward earlier thawing. The high correlation between break-up date and integrated air temperature is not merely local but extends over most of Siberia and parts of northern China. Because air temperatures in Siberia contain a strong winter NAO (North Atlantic Oscillation) signal, so does the Lake Baikal break-up date, with up to 14% of the variance in the observed date of break-up being explained by the seasonal NAO index from January to March. As in the case of the air temperature data, a significant NAO signal in the break-up date can be detected only during the latter part of this century, implying that the influence of the NAO on the thawing of Lake Baikal during the early part of this century was probably negligible.

Lake Baikal (Fig. 1), situated at 456 m above sea level in the Baikal Rift Zone of eastern Siberia, extends about 636 km from southwest to northeast, with an average breadth of 49 km (Shimaraev et al. 1994). The lake is estimated to be over 25 million yr old and is the deepest freshwater lake on earth (~1,650 m maximum depth) and the largest by volume (~23,000 km^3), containing no less than 20% of all liquid fresh water on the surface of the earth. It is so large that it exerts a significant tempering influence on local climate (e.g., Woeikof 1900; Hutchinson 1957). Lake Baikal, which was declared a United Nations World Heritage Site in 1996, has the highest biodiversity of any lake now existing and supports a unique ecological system with about 1,500 floral and more than 3,500 faunal species and subspecies (Timoshkin 1997). About 35% of the floral and 54% of the faunal species are endemic (Martin 1994). This makes it imperative that efforts be undertaken to understand this system and build up a knowledge base so that the local and international communities can react responsibly to any potential threat to it which may emerge.

Ecologically, one of the most important aspects of the physical environment of Lake Baikal is the fact that it is frozen over during 4–5 months of the year. A description of the freezing and thawing of the lake has been given by Verbolov et al. (1965) and Shimaraev et al. (1994). Because of the difference in climate along the more than 4° of latitude spanned by the lake, there is a north–south gradient in both the time of freeze-up and the time of break-up. Freezing begins in late October, and most of the northern basin is usually frozen over by early December; the southern basin, however, does not freeze over until about a month later. Maximum ice thickness varies from about 1 m in the northern basin to <80 cm in the southern basin. Ice decay in the southern basin begins in late March or early April and by the middle of May the southern basin is generally free of ice. Break-up in the northern basin occurs 2–3 weeks later.

Because the presence or absence of ice cover on a lake critically affects mixing processes, and hence lake chemistry and biology, climatic control of the timing of freeze-up and break-up is of great limnological interest. Shimaraev et al. (1991), for instance, have demonstrated a relationship between freeze-up date and phytoplankton and zooplankton biomass in Lake Baikal. Break-up, with which this paper is

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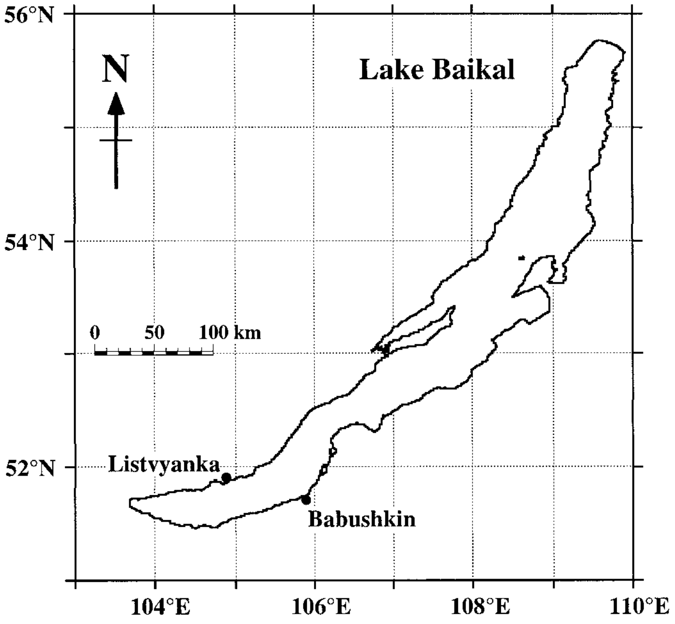

Fig. 1. Outline map of Lake Baikal, showing the locations of the ice observation point (Listvyanka limnological station) and the local air temperature measurements (Babushkin meteorological station).

concerned, represents a temporally integrated response to the weather conditions to which the lake is subjected during a period of several weeks in spring. Although thawing processes are extremely complex and involve many meteorological and nonmeteorological variables (see e.g., Leppäranta 1983; Gu and Stefan 1990; Vavrus et al. 1996), air temperature appears to be by far the most important of these variables (Ruosteenoja 1986; Vavrus et al. 1996), and air temperature alone is often able statistically to explain 60–70% of the variance in break-up date (Palecki and Barry 1986; Livingstone 1997). Thus, not only can historical air temperature data be used to estimate the time of break-up of a lake, but also historical observations of the timing of break-up can be employed as proxy data for integrated local and regional air temperatures or temperature changes (e.g., Pfister 1984; Palecki and Barry 1986; Ruosteenoja 1986; Skinner 1986, 1993; Kuusisto 1987, 1993; Robertson et al. 1992; Assel and Robertson 1995; Livingstone 1997), and it has been suggested that satellite remote sensing of ice cover may be of value for estimating air temperatures in sparsely populated areas (Palecki and Barry 1986; Maslanik and Barry 1987; Barry and Maslanik 1993; Hall 1993; Wynne and Lillesand 1993; Wynne et al. 1996). For both limnological and climatological reasons it is therefore important to investigate those few long time-series of historical observations of lake ice break-up that exist with a view to clarifying the relationship between break-up date and air temperature and establishing the significance of ice break-up as a climate indicator. This paper presents the results of a study relating an uninterrupted 128-yr record of observations of the break-up date of Lake Baikal to local and regional air temperatures in Siberia and to the North Atlantic Oscillation (NAO).

Data and methods

Historical observations of break-up on southern Lake Baikal—The date of break-up on southern Lake Baikal has been registered continuously at the same point of observation, the Listvyanka limnological station (51°52′N, 104°51′E; Fig. 1) since 1869 (Shimaraev 1977; Shimaraev et al. 1994). The term break-up date as used here refers to the first day on which the lake opposite the observation point was observed to be ice-free. It should be borne in mind here that the necessarily restricted field of view is likely to limit the representativeness of the observed break-up date for the southern basin as a whole (Lake Baikal is about 30 km wide at Listvyanka). Depending on wind strength and direction, for instance, ice floes may be carried into or out of the field of view. Despite this reservation, the series of observed break-up dates (Fig. 2) represents a valuable historical record. Break-up has been known to occur any time between 19 April and 20 May, but on average (1869–1996) it occurs on 4 May, with a standard deviation of ±8 d. This degree of long-term interannual variability is typical for the break-up of lake ice regardless of lake size or geographical location: some examples of the standard deviation of the calendar date of break-up for other lakes are 8 d for Lej da San Murezzan, Switzerland (Livingstone 1997); 9 d for Lake Kallavesi, Finland (Simojoki 1940); 10 d for lakes in northern Sweden (Williams 1971); and 11 d for Lake Mendota, Wisconsin (office of the state climatologist, Wisconsin).

It is apparent from Fig. 2 that long-term changes have been occurring in the timing of break-up on Lake Baikal. Taking the entire record into account, the mean square successive difference test (von Neumann et al. 1941; Moore 1955) confirms the existence of a significant ($P < 0.05$) overall trend to earlier break-up. The mean rate of change of break-up date from 1869 to 1996 is 0.052 d yr^{-1} or 1 d per 19.3 yr (95% C.I. [confidence interval] = ±0.035 d yr^{-1}). However, it is clear that this rate is not characteristic of the entire period. Based on Fig. 2, subjectively the series can be roughly split into two subseries at around 1920. Linear regression of these subseries suggests a shift toward earlier break-up from 1869 to 1920 at the rate of 0.30 d yr^{-1}, or 1 d per 3.3 yr ($r^2 = 0.33$, $P < 0.001$, 95% C.I. = ±0.12 d yr^{-1}). In contrast to this, the slight shift toward later break-up from 1920 to 1996 visible in Fig. 2 (0.036 d yr^{-1} or 1 d per 27.7 yr) is statistically indistinguishable from zero ($P > 0.3$).

Trends in break-up date can also be interpreted in terms of abrupt changes between homogeneous thawing regimes (Robertson et al. 1992; Assel and Robertson 1995). This hypothesis requires identification of the most likely significant change-points between stationary subseries. One method of accomplishing this is by using Pettitt's nonparametric change-point test (Pettitt 1979). Livingstone (1997) has already used this approach in a hierarchical fashion to determine change-points in the break-up series of Lake Baikal and of other lakes. The principal change-point for the Lake Baikal series is 1910, with a shift from 8 May to 2 May. Repeating the test on the two subseries revealed only one further significant change-point, from 12 May to 6 May in

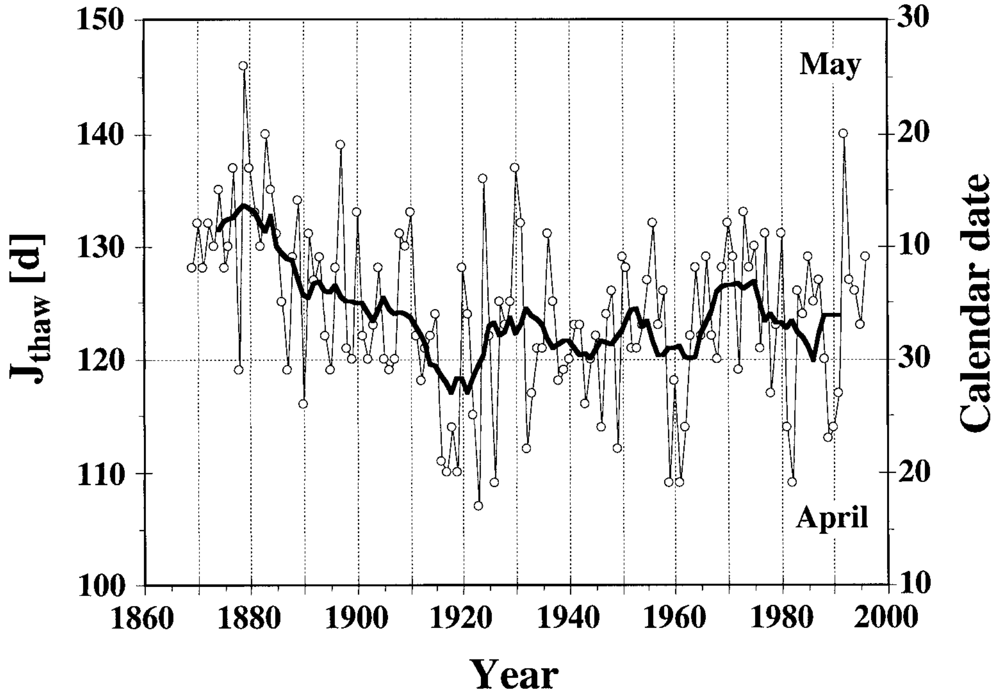

Fig. 2. Break-up dates of lake ice on southern Lake Baikal (open circles) with 11-yr running means (thick solid lines). Data from M. N. Shimaraev (pers. comm.).

1885. The Pettitt test thus supports the contention that there has been essentially no shift in the mean break-up date of the southern basin of Lake Baikal over approximately the last 80 yr.

Local air temperatures—For various lakes, the timing of break-up has been shown to be related strongly to local and regional air temperatures averaged over a few weeks prior to the mean break-up date (e.g., Palecki and Barry 1986; Robertson et al. 1992; Assel and Robertson 1995; Livingstone 1997). The relationship between the timing of break-up on the southern basin of Lake Baikal and local air temperatures was investigated using daily air temperature data from the meteorological station at Babushkin (51°41′N, 105°54′E), located about 70 km ESE of Listvyanka on the opposite shore of the lake (Fig. 1). At this station, daily minimum air temperatures (T_n) have been measured since 1896 and daily maximum air temperatures (T_x) since 1931, allowing the daily mean air temperature (T_m) from 1931 onward to be estimated as $(T_n + T_x)/2$. The progression of the air temperature at Babushkin during the period of the year most relevant to lake ice break-up, viz. January–May, is summarized in Fig. 3a. On average, daily mean air temperatures decrease during January, when the southern basin of the lake first freezes over, to reach an annual minimum around the beginning of February. With an overall mean monthly air temperature (1931–1994) of -16.2°C, February is usually the coldest month of the year; in no year during the period 1931–1994 did the February monthly mean air temperature exceed -11°C. During March, however, temperatures rise rapidly, passing through 0°C usually about the middle of April.

The fixed-period regression method—Empirical relationships between break-up date and air temperature are commonly described using some form of either the fixed-period regression method (e.g., Palecki and Barry 1986) or the accumulated degree-day method (e.g., Bilello 1961). According to Barry and Maslanik (1993), the direct use of air temperature data (i.e., the fixed-period regression method) is generally preferable to the accumulated degree-day method for predicting break-up dates. This opinion is supported by the results of Livingstone (1997), who noted in the case of three Swiss Alpine lakes that no improvement in the relationship between break-up date and local air temperature resulted if the accumulated degree-day method was used instead of the more direct fixed-period regression method. For Lake Baikal, the fixed-period regression method was therefore preferred for the empirical analysis of the relationship between break-up date and air temperature. The underlying assumption of this method is that the timing of break-up of lake ice is associated with the local air temperature integrated over some fixed period in spring; i.e., that the day of the year J_{thaw} on which break-up occurs is correlated with the mean local air temperature, $\overline{T}_{J,N}$, defined in discrete form as

$$\overline{T}_{J,N} = \frac{1}{N} \sum_{j=J-N/2}^{J+N/2} \overline{T}_{j,1}, \qquad (1)$$

where the location parameter J is the day of the year on which the averaging is centered, the integrating parameter N is the number of days over which the mean is calculated, and $\overline{T}_{j,1}$ is the daily mean air temperature ($=T_m$) on day j. The best linear relationship between J_{thaw} and $\overline{T}_{J,N}$ is then

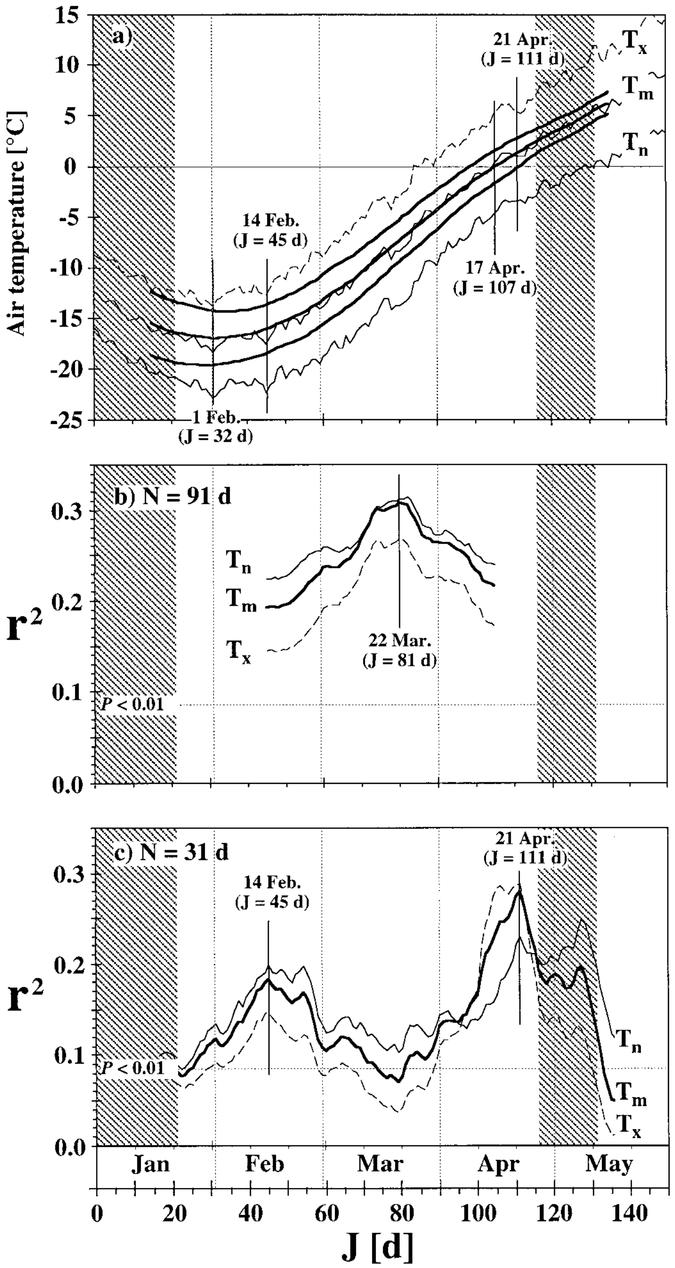

Fig. 3. (a) Seasonal progression of the air temperature at Babushkin, based on data from 1931 to 1994. Thin lines: T_n = mean daily minimum; T_x = mean daily maximum; T_m = mean daily mean = $(T_n + T_x)/2$. Thick lines: mean 31-d daily mean ± 1 standard deviation. (b) Coefficients of determination (r^2) between the break-up date of southern Lake Baikal and the mean air temperature at Babushkin on day J as a function of J for an averaging time N = 91 d. The maximum value of r^2 occurs on day J = 81 d (22 March). (c) As b, but for an averaging time N = 31 d. The coefficient of determination exhibits two maxima, viz. on days J = 45 d (14 February) and J = 111 d (21 April). These days closely follow the annual minimum air temperature (J = 32 d, i.e., 1 February) and the intersection of the air temperature curve with the 0°C line (J = 107 d, i.e., 17 April), respectively. Shaded areas represent the usual ranges of freeze-up date and break-up date (mean break-up date ± 1 standard deviation). Significance levels ($P < 0.01$) are shown as horizontal dotted lines in b and c.

obtained by finding the values of J and N that maximize r^2, the proportion of variance explained (e.g., Palecki and Barry 1986; Livingstone 1997).

Results and discussion

The timing of break-up related to local air temperatures—Values of r^2 between J_{thaw} and $T_{J,N}$ were computed for 1 d ≤ J ≤ 151 d (i.e., J ranging from 1 January to 31 May) at daily intervals and for 1 d ≤ N ≤ 91 d at 10-d intervals. The maximum explained variance in J_{thaw} (r^2 = 31%) was obtained with $T_{81,91}$, i.e., with the air temperature averaged over 91 d and centered on day 81 (22 March) (Fig. 3b). Reducing the averaging time N reduced the maximum proportion of variance explained. However, this reduction was not uniform: as the averaging time was reduced from 91 d, the unimodal curve of r^2 with a maximum in March (Fig. 3b) metamorphosed gradually into a bimodal curve with maxima in February and April (Fig. 3c). Maximum r^2 values of this bimodal curve occurred at an averaging time N = 31 d, with mean air temperatures $T_{45,31}$ (r^2 = 17%) and $T_{111,31}$ (r^2 = 27%). For the sake of simplicity, $T_{45,31}$ and $T_{111,31}$ will henceforth be referred to as T_{45} and T_{111}, respectively. T_{45} and T_{111} are essentially uncorrelated with one another (Table 1), so a multiple linear regression (MLR) of J_{thaw} on these two temperatures explains substantially more of the total variance (r^2 = 39%) than a simple linear regression on either one of them alone. Prediction of J_{thaw} based on both T_{45} and T_{111} (Fig. 4) also yields a greater proportion of shared variance than prediction based on $T_{81,91}$. The reason for the unusually large 91-d averaging time for the best correlation between J_{thaw} and mean air temperature now emerges: the unimodal peak of Fig. 3b is in a sense an artefact; $T_{81,91}$ includes the smoothed effect of both T_{45} and T_{111}.

In an attempt to improve on the proportion of variance explained, the sensible heat transfer model of Robertson et al. (1992) and Assel and Robertson (1995) was applied to the Lake Baikal J_{thaw} data over the same period as the fixed-period regression method (1931–1994). Although this method has been shown in at least two cases to yield better predictions of break-up date from air temperature than the fixed-period regression method (Robertson et al. 1992; Assel and Robertson 1995), and despite the use of three fit parameters (determined by a Nelder–Mead simplex procedure), this more complex model performed less well in this case than the simple fixed-period regression method, yielding an r^2 value of only 21% and a root-mean-square error of 8.7 d, as opposed to 39% and 5.1 d for the bimodal fixed-period regression method that was therefore deemed to be the best descriptive model available.

It is not surprising that the timing of break-up in May is correlated with mean air temperatures in April. Figure 3a shows that, on average, the 31-d mean air temperature at Babushkin rises through 0°C on 17 April (J = 107 d), so ice decay will be directly influenced by the positive daily mean air temperatures prevailing during the second half of the month. Ice decay, however, actually begins during late March or early April (Shimaraev et al. 1994), when mean air temperatures are negative (Fig. 3a). Both the melting and

Table 1. Correlation coefficients between variables relevant to the timing of break-up on Lake Baikal, based on 64 yr of data (1931–1994). J_{thaw} = day of the year on which break-up occurs; $\bar{T}_{45}$ = 31-d mean air temperature centered on day 45 (14 February); $\bar{T}_{\mathrm{amin}}$ = annual minimum of the 31-d mean air temperature; $\bar{T}_{111}$ = 31-d mean air temperature centered on day 111 (21 April); J_{-1}, J_0, J_1 = day on which the 31-d mean air temperature rises through −1°C, 0°C, and 1°C, respectively. All air temperatures measured at Babushkin (Fig. 1). Correlation coefficients marked with an asterisk are significant at the $P<0.01$ level; those not so marked are not significant at the $P<0.1$ level.

	J_{thaw}	$\bar{T}_{45}$	$\bar{T}_{\mathrm{amin}}$	$\bar{T}_{111}$	J_{-1}	J_0
$\bar{T}_{45}$	−0.4275*					
$\bar{T}_{\mathrm{amin}}$	−0.3853*	0.8202*				
$\bar{T}_{111}$	−0.5279*	0.1360	0.1137			
J_{-1}	0.5188*	−0.1745	−0.1475	−0.8190*		
J_0	0.5490*	−0.1944	−0.1634	−0.8616*	0.9098*	
J_1	0.5631*	−0.1915	−0.1807	−0.8572*	0.8461*	0.9300*

sublimation of snow at negative mean air temperatures, but high incident solar radiation, have long been known to be characteristic of the Lake Baikal area (Verbolov et al. 1965). Ice decay during the first half of April, therefore, can only occur during daylight hours as a result of increasing incident solar radiation and positive daytime temperatures (see the curve of T_x in Fig. 3a), but still contributes to the correlation between J_{thaw} and $\bar{T}_{111}$ because of the necessarily high degree of correlation between incident radiation, daily maximum air temperature, and daily mean air temperature.

It is perhaps not so immediately clear why the timing of break-up should be related to mean air temperatures in February. However, Fig. 3a may yield a clue to this also. On 14 February (J = 45 d), the 31-d mean air temperature is very close to its seasonal minimum (the difference between the two is only 1.8°C) and the two are very highly correlated (Table 1). Anomalously high air temperatures at this time of year are therefore likely to be associated with anomalously low rates of conductive heat loss through the ice, resulting in low rates of ice formation at the water–ice interface and a comparatively thin ice layer; for anomalously low temperatures, the reverse will be the case. Because of the insulating effect of snow cover, a positive correlation between air temperature and precipitation will enhance this effect. It is therefore likely that the thickness of the ice sheet immediately prior to the start of the thawing process in April will be controlled to a large extent by the mean air temperatures prevailing during February. This effect is likely to be particularly strong in Lake Baikal because the water–ice interface is not well insulated from atmospheric influences. Snow cover is not thick and snow is often blown off the ice on parts of the lake by strong winds (R. Kipfer, pers. comm.), so that parts of the ice sheet are directly exposed to atmospheric influences. In addition, the ice sheet itself is relatively thin (about 80 cm: Shimaraev et al. 1994). This implies that ice formation processes at the water–ice interface are likely to react much more sensitively to changes in air temperature and/or solar radiation in the case of Lake Baikal than, for instance, in the case of European Alpine lakes, where personal observations of the author suggest that 1.5 m of ice overlain by over 2 m of snow is not uncommon. During March, when air temperatures are on the increase and the ice layer is thicker than in February, the air temperature is usually neither low enough to result in much ice growth at the ice–water interface nor high enough to allow thawing at the air–ice interface; air temperatures in March are therefore largely irrelevant to the timing of break-up. This interpretation is supported by the fact that break-up is more strongly related to daily *maximum* air temperatures in April, when the ice is decaying, but to daily *minimum* air temperatures in February, when the ice is growing in thickness (Fig. 3c). An MLR of J_{thaw} on $\bar{T}_{45}$ and $\bar{T}_{111}$ yields slightly higher r^2 values (r^2 = 42%) when daily minimum instead of daily mean air temperatures are used for $\bar{T}_{45}$, and daily maximum instead of daily mean air temperatures for $\bar{T}_{111}$; in the reverse situation, the r^2 values obtained are substantially lower (r^2 = 32%).

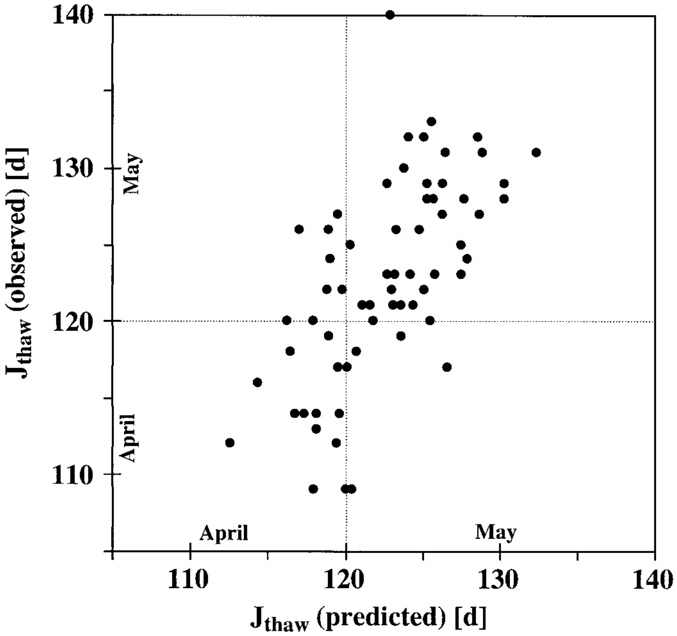

Fig. 4. Relationship between observed and predicted break-up dates (J_{thaw}) on southern Lake Baikal. Predictions are based on a multilinear regression of J_{thaw} on the 31-d mean air temperatures $\bar{T}_{45}$ and $\bar{T}_{111}$ at Babushkin from 1931 to 1994, centered on 14 February and 21 April, respectively (cf. Fig. 3c).

Based on the above interpretation, two other variables

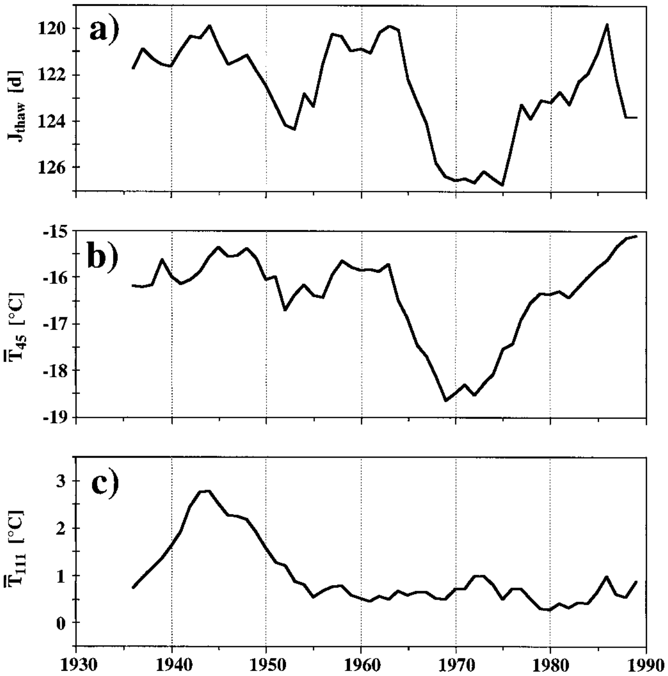

Fig. 5. Comparison of the 11-yr running means of (a) the break-up date of southern Lake Baikal (J_{thaw}) with those of (b) the 31-d mean air temperature at Babushkin centered on 14 February (T_{45}) and (c) the 31-d mean air temperature at Babushkin centered on 21 April (T_{111}).

come into question as possibly useful empirical determinants of the timing of break-up as substitutes for T_{45} and T_{111}: viz. (1) the annual minimum T_{amin} of the 31-d mean air temperature; and (2) the day J_0 on which the 31-d mean air temperature rises through 0°C. T_{amin} is highly correlated with T_{45}, and J_0 (or indeed the day on which the 31-d mean air temperature rises through any specific temperature between -1°C and $+1$°C) is highly correlated with T_{111} (Table 1). The use of these variables for prediction purposes, instead of mean temperatures centered on specific days of the year, has the advantage of taking into account long-term shifts in seasonality that might render T_{45} and T_{111} less effective as empirical determinants of J_{thaw}. J_{thaw} is slightly less strongly related to T_{amin} than to T_{45}, but slightly more strongly related to J_0 than to T_{111} (Table 1). An MLR of J_{thaw} on T_{amin} and J_0 explained only 2% less variance than the MLR on T_{45} and T_{111}. The similarity of the results implies that the prediction of J_{thaw} based on February and April air temperature data is robust with respect to the variable chosen and that T_{amin} and J_0 also represent useful empirical determinants of J_{thaw}.

Despite the fact that J_{thaw} is more highly correlated with T_{111} than with T_{45} (Fig. 3c), comparison of 11-yr running means (Fig. 5) reveals a strong similarity only between J_{thaw} and T_{45}. This intriguing phenomenon was investigated in more detail by applying low-pass and high-pass elliptical filters (Rabiner and Gold 1975) with a cut-off at 10 yr to all three data series and computing the proportion of shared variance. After low-pass filtering, the proportion of variance shared between J_{thaw} and T_{45} was found to be 56%, whereas that shared between J_{thaw} and T_{111} was only 12%. This difference is even more striking in view of the likelihood that part of the latter may be a result of persistence within the air temperature series, because the proportion of variance shared between T_{45} and T_{111} after low-pass filtering was 9%. After applying a high-pass elliptical filter with the same cut-off to the original data, the situation was reversed, with only 13% of the variance shared between J_{thaw} and T_{45}, but 44% shared between J_{thaw} and T_{111} (in this case, the amount of variance shared between T_{45} and T_{111} was <1%). Thus, on a decadal scale, fluctuations in J_{thaw} are more closely related to fluctuations in T_{45} than to fluctuations in T_{111}. As a corollary to this, interannual fluctuations in J_{thaw} are more strongly related to T_{111} than to T_{45}. This would seem to imply that long-term (interdecadal) fluctuations in break-up date are related to fluctuations in annual minimum air temperatures, whereas short-term (interannual) fluctuations are related more to fluctuations in air temperature during the thawing phase (or, perhaps better, to fluctuations in the date upon which thawing air temperatures are reached).

The timing of break-up related to regional mean air temperatures and to the NAO—The availability in the Global Historical Climatology Network dataset (Vose et al. 1992) of historical monthly mean air temperature data from many meteorological stations in Siberia and other areas of Asia close to Lake Baikal allowed the timing of break-up on the lake to be related not only to air temperatures on a local scale but also on regional to continental scales. Analogously to the case of the daily mean air temperatures (T_m) above, the monthly mean temperature ($\overline{T}_m$) was computed from the monthly mean daily minimum ($\overline{T}_n$) and monthly mean daily maximum (T_x) as $T_m = (T_n + T_x)/2$. A total of 170 meteorological stations (90 in Russia, 22 in Kazakhstan, 33 in China, and 25 in Japan) were selected for which T_n and T_x were available from at least 45 out of the 54 yr from 1936 to 1989 (this period was chosen because of the availability of data from many Russian stations during this time). Correlation coefficients were calculated between the date of break-up of Lake Baikal (J_{thaw}) and the monthly mean air temperature (T_m) at each of the 170 stations for the months of February, March, and April. Contour plots of these correlation coefficients are presented in Fig. 6. In agreement with Fig. 3c, Fig. 6 shows that J_{thaw} is more highly correlated with air temperatures in February and April than with those in March. However, Fig. 6 shows additionally that these correlations are not merely local but extend over large areas of northern Asia. In February, the area of significant negative correlation between J_{thaw} and T_m at the $P < 0.05$ level ($r < -0.23$) extends from European Russia to the mainland coast of the Sea of Japan, and from the north China coast to northern Siberia. In March, although J_{thaw} and T_m are substantially less well correlated, the area of significant correlation still encompasses the whole of central Siberia and much of northeast China. In April, correlation coefficients are as high as or higher than in February, but the area of significant correlation is confined essentially to Siberia, extending neither into European Russia nor very far southward into China. In fact, a significant ($P < 0.05$) positive correlation is found between J_{thaw} and the mean April air temperatures measured in southern Japan (Kyushu and the Ryukyu Islands), imply-

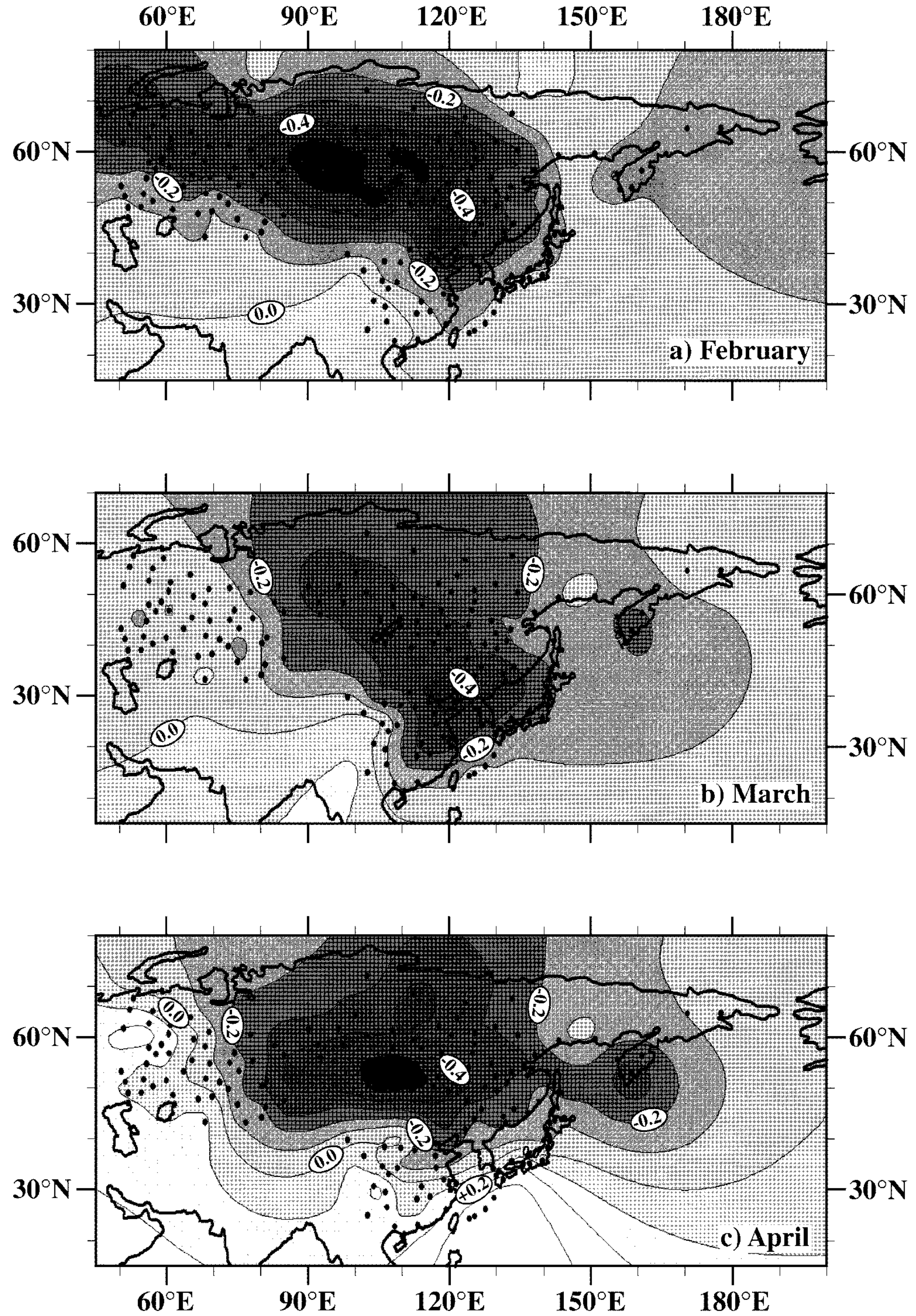

Fig. 6. Contour plots of the correlation coefficient between the calendar date of break-up on southern Lake Baikal (Fig. 2) and monthly mean air temperatures at 170 stations distributed over Russia, Kazakhstan, China, and Japan (1936–1989) in (a) February, (b) March, and (c) April. Correlation coefficients less than -0.23 are significant at the $P < 0.01$ level.

ing the existence of an inverse relationship between air temperatures in the Lake Baikal area and air temperatures over the South China Sea during the thawing period.

For lakes in central North America, there is statistical evidence that the extent and duration of ice cover may be associated to some extent with the El Niño-Southern Oscillation (ENSO) cycle (Robertson 1989; Anderson et al. 1996; Assel and Rodionov 1998; Robertson et al. 1999). The large spatial scale of the correlations between the date of break-up of Lake Baikal and air temperatures in Siberia and even further afield suggests that the thawing of this lake may also be influenced by climatic phenomena occurring on scales up to and including that of planetary waves. However, the ENSO cycle does not dominate in Siberia. Instead, the zonal extent of the region of significant correlation with mean February air temperatures (Fig. 6a) suggests that the time series of break-up dates may contain a signal associated with the NAO, which is known to have a significant effect on air temperatures throughout the Northern Hemisphere (Hurrell 1996). The NAO, representing a large-scale meridional alternation in the air pressure difference between the Azores High and the Iceland Low, is the dominant mode of atmospheric behavior in the North Atlantic region and accounts for over a third of the variance in sea-level pressure there (van Loon and Rogers 1978; Wallace and Gutzler 1981; Barnston and Livezey 1987). It is usually characterized in terms of indices based on the difference in sea-level pressure measured either on the Azores or in mainland Portugal on the one hand, and in Iceland on the other (e.g., Hurrell 1995). Especially in winter, it is known to have a strong influence on the weather not only in land areas bordering the North Atlantic, but also over much of Eurasia, including Siberia (Hurrell 1995, 1996; Hurrell and van Loon 1997). It is known to influence the level of the Caspian Sea (Rodionov 1994) and the degree of ice cover of the Baltic (Koslowski and Loewe 1994; Loewe and Koslowski 1998). High winter NAO indices tend to be associated with strong westerly winds blowing across Europe from the North Atlantic, bringing warm conditions to northern Europe and much of central Asia, while low winter NAO indices tend to be associated with the reverse situation (Hurrell 1995, 1996; Hurrell and van Loon 1997). Winter reversals of the normal pressure distribution over the North Atlantic result in meridional instead of zonal circulation, leading to extremely cold conditions (Moses et al. 1987). Variations in air temperature associated with the NAO account for 31% of the interannual variance in the mean Northern Hemisphere air temperature from 1935 to 1994 (Hurrell 1996). Figure 3a of Hurrell (1996) shows that winter air temperatures (December–March) in the Lake Baikal region are strongly affected by the NAO, so that, in view of the association described above between the timing of break-up and mean February air temperatures at Lake Baikal, an NAO signal might also be expected to manifest itself in the break-up date of the lake.

Based on data from 1936 to 1989, correlation coefficients were computed between J_{thaw} and monthly and seasonal (3-monthly) NAO indices during the year of break-up and the preceding year (Fig. 7a). J_{thaw} is seen to be correlated significantly with the monthly ($P < 0.05$) and seasonal ($P < 0.01$) NAO indices during the winter immediately preceding thawing. The highest correlation with a monthly index is with that for February, and the highest correlation with a seasonal index is with that for January to March. The latter index explains 14% of the variance in J_{thaw}, which is surprisingly high in view of the simplicity of the NAO index as a representation of the complex climatic effects of the NAO. The high correlation with the February NAO index might seem to imply that the NAO signal enters the J_{thaw} time series solely indirectly, via the processes determining the maximum thickness of the ice sheet, rather than directly,

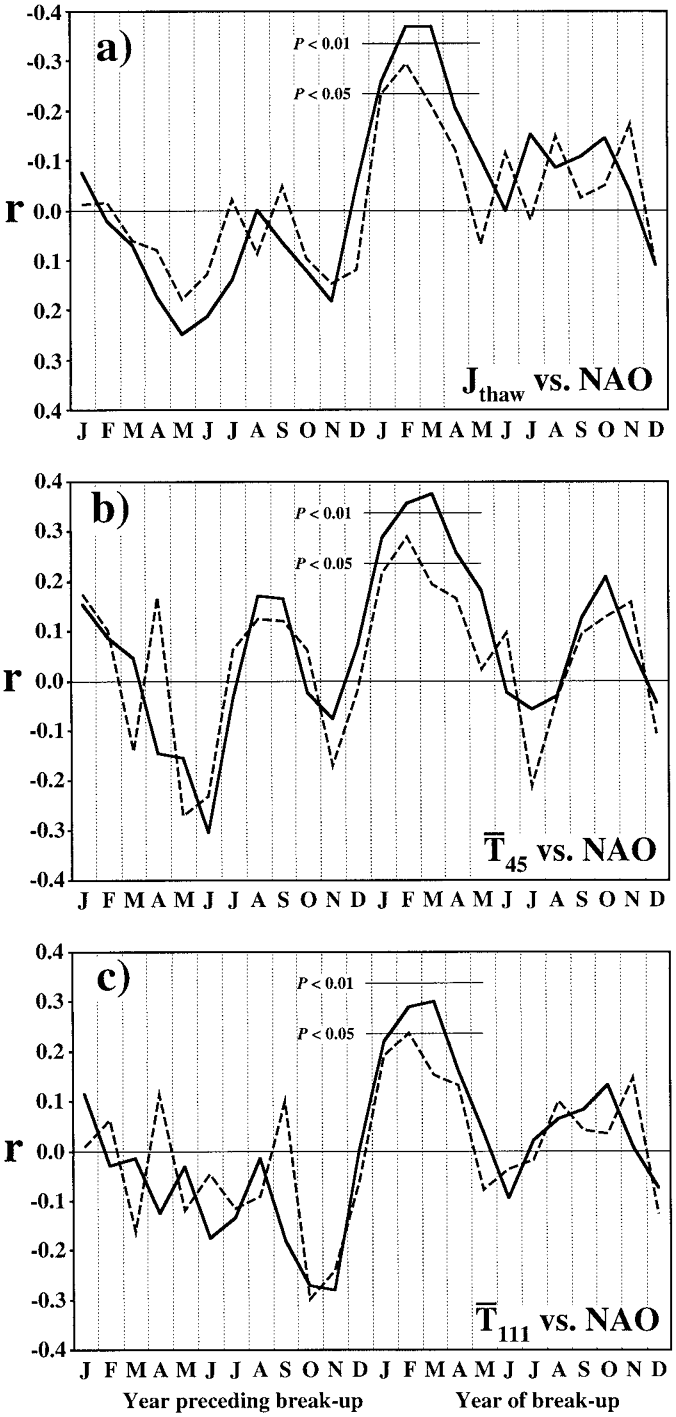

Fig. 7. (a) Correlation coefficients (r) between the date of break-up on southern Lake Baikal (J_{thaw}) and indices of the North Atlantic Oscillation (NAO) during the year of break-up and the preceding year, based on data from 1936 to 1989. (b) As a, but between the 31-d mean air temperature $\overline{T}_{45}$ centered on day 45 (14 February) and indices of the NAO. (c) As a, but between the 31-d mean air temperature $\overline{T}_{111}$ centered on day 111 (21 April) and indices of the NAO. Dotted lines: correlations with monthly NAO indices. Solid lines: correlations with seasonal (3-monthly) NAO indices. Significance levels ($P < 0.01$ and $P < 0.05$) are shown as horizontal lines. Note the reversed ordinate in a.

via the thawing processes themselves. This hypothesis was tested by searching for NAO signals in the two air temperatures T_{45} and T_{111}. If the NAO signal enters the J_{thaw} time-series solely indirectly, through processes of ice growth, an NAO signal should be found in T_{45} but not in T_{111}. However, comparison of Fig. 7b and c shows this not to be the case: not only is T_{111} correlated significantly with the NAO index, it is correlated most strongly with the February rather than the April index. Repeating the correlations of Fig. 7b using T_{amin} instead of T_{45} and those of Fig. 7c using J_{-1}, J_0, and J_1 instead of T_{111}, essentially the same results were obtained. Thus, although the NAO signal found in the time-series of Lake Baikal break-up dates is predominantly that of the NAO prevailing during the winter, this signal enters the time-series not only via the processes of ice growth during February but also via the April thawing processes, because air temperatures during thawing also contain a signal from the February NAO.

Temporal variations in the relationship between break-up and air temperature—This study of the relationship between break-up and air temperature has been confined up till now to the time subsequent to 1930, i.e., to the time of no significant long-term trend in break-up date. There is no guarantee that the empirical relationship found during this period is either representative of any relationship that may have existed earlier, when a strong trend in break-up date existed, or of any relationship that may exist in the future. However, the existence of 35 yr of daily minimum air temperature measurements at Babushkin prior to the first available measurements of daily maximum air temperature in 1931 allowed at least a limited investigation to be conducted into the stationarity of the relationship. Curves of r^2 for J_{thaw} and T_n, similar to the curves illustrated in Fig. 3c, were computed for various time windows back to 1896. A total of 50 such curves were computed, each based on 50 yr of data (31-d means), covering the periods 1896–1945, 1897–1946,. . . 1945–1994. All 50 curves showed a tendency to enhanced r^2 values in February and April compared to the other months. The first part of each of these r^2 curves (1 January–15 March) always showed a maximum somewhere between 6 February and 23 February, and the second part (16 March–31 May) always showed a maximum somewhere between 2 April and 29 April. Figure 8 illustrates how these peak February and April r^2 values changed with time from the 1896–1945 to the 1945–1994 window. Running r^2 values between J_{thaw} and the monthly mean values of T_n for February and April were also computed; these are slightly smaller than the peak r^2 values illustrated in Fig. 8, but the forms of the curves obtained are essentially the same, so that the following conclusions, drawn on the basis of the illustrated peak r^2 values, are robust with respect to the air temperature parameter chosen.

February: The peak r^2 values in February are only significant at the $P < 0.05$ level from the 1902–1951 data window onward, and at the $P < 0.01$ level from the 1918–1967 window onward. This suggests that, although enhanced correlations between J_{thaw} and February air temperatures are detectable in all 50-yr windows, climatic forcing in February was of no practical relevance to J_{thaw} during the earlier part of the series, possibly because of the insulating effects of thicker ice cover during the colder winters still prevailing last century during the recovery from the Little Ice Age. Approximately in the middle of the series (the computation of shorter-period running correlations suggests possibly during the mid-1920s), the relationship between break-up date and February air temperatures began to become increasingly stronger and r^2 increased rapidly. All 15 of the 50-yr windows within the period 1928–1991 exhibit high r^2 values (>0.3), suggesting that climatic forcing in February made an important contribution to J_{thaw} during most of this period. The abrupt drop in r^2 subsequent to 1991 was almost entirely due to the unusual lateness of break-up in 1992 ($J_{\mathrm{thaw}} = 140$ d, i.e., 20 May). Evidence implying that global volcanic activity can affect lake break-up dates (Livingstone 1997, 1999) suggests that the lateness of break-up of Lake Baikal in 1992 may have been a result of sensitivity to the climatic effects of the 1991 eruption of Pinatubo (e.g., Hansen et al. 1992; Minnis et al. 1993). Setting the 1992 value of J_{thaw} to the series mean was found to eliminate almost all of the abrupt drop in r^2, so that it is likely that the influence of February climatic forcing on J_{thaw} is continuing past the "Pinatubo blip." The r^2 curve based on running correlations of J_{thaw} with T_{amin} (not shown) exhibits the same characteristics as the curve based on the February peak values, supporting the conclusions drawn and emphasizing their robustness.

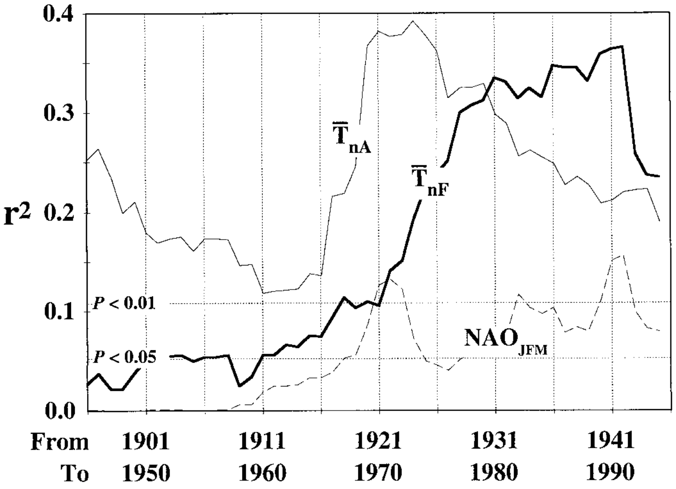

Fig. 8. Coefficients of determination (r^2) computed from 50-yr running correlations of the calendar date of break-up of Lake Baikal with the peak 31-d mean daily minimum air temperature at Babushkin in February (T_{nF}) and in April (T_{nA}) and with the seasonal North Atlantic Oscillation Index for January–March ($\mathrm{NAO_{JFM}}$). Significance levels ($P < 0.01$ and $P < 0.05$) are shown as horizontal lines.

April: The peak April r^2 values are significant at the $P < 0.01$ level for all data windows but vary greatly with time, decreasing from 25% (1896–1945) to a minimum of 12% (1911–1960), then increasing abruptly again to 39% (1924–1973) before falling almost monotonically to 19% (1945–1994). Climatic forcing in April, because it is associated directly with ice-thawing processes, is thus always an important determinant of the timing of break-up on Lake Baikal. However, after having reached a maximum during the 1924–1973 window, its importance now seems to be on the wane.

In addition to investigating the relationship between J_{thaw} and local air temperatures, r^2 curves similar to those described above were computed for J_{thaw} and $\mathrm{NAO}_{\mathrm{JFM}}$, the seasonal NAO index for January, February, and March (Fig. 8). A significant NAO signal ($P < 0.05$) was first detected in the 1918–1967 window and since then between about 5% and 15% of the variance in J_{thaw} can be associated with the NAO. The strongest association between the NAO and J_{thaw} is apparent in the 1942–1991 window; again, the abrupt decrease in r^2 subsequent to this window is a result of the extreme lateness of break-up in 1992 following the eruption of Pinatubo.

The lack of an NAO signal in the J_{thaw} time series during the first part of this century shows some agreement with the results of Osborn et al. (1999), who found no significant correlation to exist between extratropical Northern Hemisphere mean winter air temperatures and winter indices of the NAO between the 1893–1942 and 1933–1982 data windows, although they did find such a correlation previous to the 1893–1942 window and subsequent to the 1933–1982 window. The presence in Fig. 8 of a significant correlation between J_{thaw} and $\mathrm{NAO}_{\mathrm{JFM}}$ centered on the 1922–1970 window, which would not be expected in the light of the results of Osborn et al. (1999), is associated not with air temperatures in February but rather with those in April, which, as mentioned above, are also correlated with $\mathrm{NAO}_{\mathrm{JFM}}$.

Summary and conclusions

The available time-series of observations of break-up date on southern Lake Baikal (1869–1996, Fig. 2) can be divided roughly into two parts. Up to around 1920 there is a definite trend to earlier break-up of about 1 d per 3.3 yr; subsequently, no significant long-term trend is detectable. Based solely on data from the second part of the time-series, the break-up date of the lake appears to be related not only to the mean air temperature prevailing during the thawing phase (April) but also to that prevailing during the coldest time of the year (February) (Fig. 3). This latter relationship is presumably due to the dependence of the maximum thickness of the ice sheet on the annual minimum air temperature, perhaps enhanced by precipitation effects. Long-term (interdecadal) fluctuations in break-up date tend to be related to fluctuations in the 31-d mean air temperature during the coldest part of the year and shorter-term (interannual) fluctuations to fluctuations in the 31-d mean air temperature during the thawing phase.

A tendency to enhanced correlation between break-up date and local air temperature in February and April as compared to other months is present in all data considered in this study. However, although the peak correlations with the April air temperature data are always significant, those with the February air temperature data are only significant during the latter part of this century. Running correlations using a 50-yr data window reveal that the influence of February air temperatures on break-up date was slight prior to the 1918–1967 window but increased sharply between the 1918–1967 and the 1928–1977 windows, explaining from 30% to as much as 35% of the variance in break-up date in the windows between 1928–1977 and 1942–1991 (Fig. 8). The subsequent reduction in the proportion of variance explained by the February air temperatures is due to the exceptional lateness of break-up in 1992, possibly a result of the 1991 Pinatubo eruption, suggesting that global volcanism may also need to be taken into account when investigating large-scale climatic effects on lake ice cover (Livingstone 1997, 1999). The influence of April air temperatures on the break-up date has also varied considerably during the last hundred years, accounting for between 12% and 39% of the variance. During the second part of this century up until 1991, the proportion of variance explained by February air temperatures underwent a continual increase, while that explained by April air temperatures underwent a continual decrease (Fig. 8); it remains to be seen whether the decrease in the proportion of variance explained by the February air temperature subsequent to 1991 will be maintained or not.

The high correlation between break-up date and mean air temperature is not merely local, but extends over most of Siberia and parts of northern China (Fig. 6). The work of Hurrell (1995, 1996) and Hurrell and van Loon (1997), showing that air temperatures in this area of the world contain a strong winter NAO signal, suggests that such a signal might also be expected in the Lake Baikal break-up date. This was found to be the case, with about 14% of the variance in the observed date of break-up from 1936 to 1989 being explained by the seasonal NAO index from January to March (Fig. 7a). However, as in the case of the air temperature data, a significant NAO signal in the break-up date, explaining about 5–15% of the variance, can be detected only during the latter part of this century (Fig. 8), so that the influence of the NAO on the thawing of Lake Baikal during the early part of this century can probably be assumed to have been negligible.

Among other things, this study has shown that a major source of large-scale climatic variability, the NAO, leaves a detectable interdecadal signal in the timing of break-up of a lake situated 90° of longitude and several thousand kilometers from the NAO's immediate center of action. The presence of an NAO signal can be assumed in the timing of break-up of many other lakes within the area in which air temperatures are known to be affected by the NAO, i.e., north of about 45°N from western Europe to eastern Siberia and (inversely) northeastern Canada (Hurrell 1995, 1996; Hurrell and van Loon 1997), and recent work has shown this to be the case (Livingstone 1999). The NAO is not the only large-scale climatic phenomenon known to affect lake break-up: ENSO signals, for example, have been detected in ice cover data from North American lakes (Robertson 1989; Anderson et al., 1996; Assel and Rodionov 1998; Robertson et al. 1999). The break-up of lake ice represents only one of many physical determinants of lake behavior likely to be affected by large-scale climatic forcing. Therefore, although lakes in many respects can and do exhibit very individual physical responses to local meteorological forcing, this study suggests that similarities in physical lake forcing on a continental scale may exist that might merit investigation, especially in view of the probable effects of global climatic change on lakes (e.g., Schindler et al. 1996; Schindler 1997) and of their increasing importance in a world in which the demand for high-quality water is rapidly outstripping supply. Internationally based comparative studies, both empirical and process-based, involving suites of lakes within the extended areas of influence of the NAO and ENSO, might be one way of gaining some understanding of the role played by these major sources of climatic variability in determining the future physical, chemical, and biological reactions of lakes to global climatic change.

References

ANDERSON, W. L., D. M. ROBERTSON, AND J. J. MAGNUSON. 1996. Evidence of recent warming and El-Niño-related variations in ice breakup of Wisconsin lakes. Limnol. Oceanogr. **41:** 815–821.

ASSEL, R. A., AND D. M. ROBERTSON. 1995. Changes in winter air temperatures near Lake Michigan, 1851–1993, as determined from regional lake-ice records. Limnol. Oceanogr. **40:** 165–176.

———, AND S. RODIONOV. 1998. Atmospheric teleconnections for annual maximum ice cover on the Laurentian Great Lakes. Int. J. Climatol. **18:** 425–442.

BARNSTON, A. G., AND R. E. LIVEZEY. 1987. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Monthly Weather Rev. **115:** 1083–1126.

BARRY, R. G., AND J. A. MASLANIK. 1993. Monitoring lake freeze-up/break-up as a climatic index, p. 66–79. *In* R. G. Barry, B. E. Goodison, and E. F. Ledrew [eds.], Snow Watch 92—detection strategies for snow and ice. Glaciological data rep. GD-25, World Data Center A.

BILELLO, M. A. 1961. Formation, growth and decay of sea-ice in the Canadian Arctic archipelago. Arctic **14:** 2–25.

GU, R., AND H. G. STEFAN. 1990. Year-round temperature simulation of cold climate lakes. Cold Reg. Sci. Technol. **18:** 147–160.

HALL, D. L. 1993. Active and passive microwave remote sensing of frozen lakes for regional climate studies, p. 80–85. *In* R. G. Barry, B. E. Goodison, and E. F. Ledrew [eds.], Snow Watch 92—detection strategies for snow and ice. Glaciological data rep. GD-25, World Data Center A.

HANSEN, J., A. LACIS, R. RUEDY, AND M. SATO. 1992. Potential climate impact of Mount Pinatubo eruption. Geophys. Res. Lett. **19:** 215–218.

HURRELL, J. W. 1995. Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. Science **269:** 676–679.

———. 1996. Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperatures. Geophys. Res. Lett. **23:** 665–668.

———, AND H. VAN LOON. 1997. Decadal variations in climate associated with the North Atlantic Oscillation. Clim. Change **36:** 301–326.

HUTCHINSON, G. E. 1957. A treatise on limnology. V. 1: Geography, physics and chemistry. Wiley.

KOSLOWSKI, G., AND P. LOEWE. 1994. The western Baltic sea ice season in terms of a mass-related severity index: 1879–1992. Part I. Temporal variability and association with the north Atlantic oscillation. Tellus **46A:** 66–74.

KUUSISTO, E. 1987. An analysis of the longest ice observation series made on Finnish lakes. Aqua Fenn. **17:** 123–132.

———. 1993. Lake ice observations in Finland in the 19th and 20th Century: Any message for the 21st?, p. 57–65. *In* R. G. Barry, B. E. Goodison, and E. F. Ledrew [eds.], Snow Watch 92—detection strategies for snow and ice. Glaciological data rep. GD-25, World Data Center A.

LEPPÄRANTA, M. 1983. A growth model for black ice, snow ice and snow thickness in subarctic basins. Nord. Hydrol. **37:** 59–70.

LIVINGSTONE, D. M. 1997. Break-up dates of Alpine lakes as proxy data for local and regional mean surface air temperatures. Clim. Change **37:** 407–439.

———. 1999. Large-scale climatic forcing detected in historical observations of lake ice break-up. Verh. Int. Verein. Limnol. **27:** In press.

LOEWE, P., AND G. KOSLOWSKI. 1998. The Western Baltic sea ice season in terms of a mass-related severity index 1879–1992. (II) Spectral characteristics and associations with the NAO, QBO, and solar cycle. Tellus **50A:** 219–241.

MARTIN, P. 1994. Lake Baikal. Arch. Hydrobiol. Beih. Ergebn. Limnol. **44:** 3–11.

MASLANIK, J. A., AND R. G. BARRY. 1987. Lake ice formation and breakup as an indicator of climate change: Potential for monitoring using remote sensing techniques, p. 153–161. *In* S. I. Solomon, M. Beran, and W. Hogg [eds.], The influence of climate change and climatic variability on the hydrologic regime and water resources. IAHS publ. no. 168.

MINNIS, P., E. F. HARRISON, L. L. STOWE, G. G. GIBSON, F. M. DENN, D. R. DOELLING, AND W. L. SMITH, JR. 1993. Radiative climate forcing by the Mount Pinatubo eruption. Science **259:** 1411–1415.

MOORE, P. G. 1955. The properties of the mean square successive difference in samples from various populations. J. Am. Statist. Assoc. **50:** 434–456.

MOSES, T., G. N. KILADIS, H. F. DIAZ, AND R. G. BARRY. 1987. Characteristics and frequency of reversals in mean sea level pressure in the North Atlantic sector and their relationship to long-term temperature trends. J. Climatol. **7:** 13–30.

OSBORN, T. J., K. R. BRIFFA, S. F. B. TETT, P. D. JONES, AND R. M. TRIGO. 1999. Evaluation of the North Atlantic Oscillation as simulated by a climate model. Clim. Dyn. In press.

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. Clim. Appl. Meteorol. **25:** 893–902.

PETTITT, A. N. 1979. A non-parametric approach to the change-point problem. Appl. Statist. **28:** 126–135.

PFISTER, C. 1984. Klimageschichte der Schweiz 1525–1860. Das Klima der Schweiz von 1525–1860 und seine Bedeutung in der Geschichte von Bevölkerung und Landwirtschaft. Verlag Paul Haupt.

RABINER, L. R., AND B. GOLD. 1975. Theory and application of digital signal processing. Prentice-Hall.

ROBERTSON, D. M. 1989. The use of lake water temperature and ice cover as climatic indicators. Ph.D. thesis, Univ. Wisconsin, Madison.

———, R. A. RAGOTZSKIE, AND J. J. MAGNUSON. 1992. Lake ice records used to detect historical and future climatic change. Clim. Change **21:** 407–427.

———, R. H. WYNNE, AND W. Y. B. CHANG. 1999. Variability in ice cover across the Northern Hemisphere associated with El Niño events in the 1900's. Verh. Int. Verein. Limnol. **27:** In press.

RODIONOV, S. N. 1994. Global and regional climate interaction: The Caspian Sea experience. Kluwer.

RUOSTEENOJA, K. 1986. The date of break-up of lake ice as a climatic index. Geophysica **22:** 89–99.

SCHINDLER, D. W. 1997. Widespread effects of climatic warming on freshwater ecosystems in North America. Hydrol. Proc. **11:** 1043–1067.

———, AND OTHERS. 1996. The effects of climatic warming on the properties of boreal lakes and streams at the Experimental Lakes Area, northwestern Ontario. Limnol. Oceanogr. **41:** 1004–1017.

SHIMARAEV, M. N. 1977. Elements of the heat regime of Lake Baikal. Nauka. (In Russian).

———, L. N. KUIMOVA, AND V. V. TSEKHANOVSKII. 1991. Long-term variations of ice and thermal regime of Lake Baikal, p. 64–70. *In* Monitoring and evaluation of the environment in Lake Baikal and Pribaikaly. Gidrometeoizdat. (In Russian).

———, V. I. VERBOLOV, N. G. GRANIN, AND P. P. SHERSTYANKIN. 1994. Physical limnology of Lake Baikal: A review. Baikal International Center for Ecological Research, Irkutsk.

SIMOJOKI, H. 1940. Über die Eisverhältnisse der Binnenseen Finnlands. Ann. Acad. Sci. Fenn. A **52:** 1–194.

SKINNER, W. R. 1986. The break-up and freeze-up of lake and sea ice in Northern Canada. Canadian Climate Centre rep. 86-8, Atmos. Environ. Serv., Downsview, Ontario.

———. 1993. Lake ice conditions as a cryospheric indicator for detecting climate variability in Canada, p. 204–240. *In* R. G. Barry, B. E. Goodison, and E. F. Ledrew [eds.], Snow Watch 92—detection strategies for snow and ice. Glaciological data rep. GD-25, World Data Center A.

TIMOSHKIN, O. A. 1997. Biodiversity of Baikal fauna: State-of-the-art (preliminary analysis), p. 35–76. *In* E. Wada, O. A. Timoshkin, N. Fujita, and K. Tanida [eds.], New scope on boreal ecosystems in east Siberia. DIWPA Series, v. 2. Siberian Branch, Russian Academy of Sciences.

VAN LOON, H., AND J. C. ROGERS. 1978. The seesaw in winter temperatures between Greenland and Northern Europe. Part I: General description. Monthly Weather Rev. **106:** 296–310.

VAVRUS, S. J., R. H. WYNNE, AND J. A. FOLEY. 1996. Measuring the sensitivity of southern Wisconsin lake ice to climate variations and lake depth using a numerical model. Limnol. Oceanogr. **41:** 822–831.

VERBOLOV, V. I., V. M. SOKOL'NIKOV, AND M. N. SHIMARAEV. 1965. The hydrometeorological regime and heat balance of Lake Baikal. Nauka. (In Russian).

VON NEUMANN, J., R. H. KENT, H. R. BELLINSON, AND B. I. HART. 1941. The mean square successive difference. Ann. Math. Statist. **12:** 153–162.

VOSE, R. S., R. L. SCHMOYER, P. M. STEURER, T. C. PETERSON, R. R. HEIM, T. R. KARL, AND J. K. EISCHEID. 1992. The Global Historical Climatology Network: Long-term monthly temperature, precipitation, sea-level pressure, and station pressure data. Environ. Sci. Div. Publ. 3912, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory.

WALLACE, J. M., AND D. S. GUTZLER. 1981. Teleconnections in the geopotential height field during the Northern Hemisphere winter. Monthly Weather Rev. **109:** 784–812.

WILLIAMS, G. P. 1971. Predicting the date of lake ice break-up. Water Resour. Res. **7:** 323–333.

WOEIKOF, A. 1900. Temperatur und Bewölkung am Ufer des Baikal und auf den benachbarten Höhen. Meteorol. Z. **17:** 28–32.

WYNNE, R. H., AND T. M. LILLESAND. 1993. Satellite observation of lake ice as a climate indicator: Initial results from statewide monitoring in Wisconsin. Photogrammetric Engineering and Remote Sensing **59:** 1023–1031.

———, J. J. MAGNUSON, M. K. CLAYTON, T. M. LILLESAND, AND D. C. RODMAN. 1996. Determinants of temporal coherence in the satellite-derived 1987–1994 ice breakup dates of lakes on the Laurentian Shield. Limnol. Oceanogr. **41:** 832–838.

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