# BREAK-UP DATES OF ALPINE LAKES AS PROXY DATA FOR LOCAL AND REGIONAL MEAN SURFACE AIR TEMPERATURES

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**Abstract.** The calendar date of ice break-up on Lej da San Murezzan, a high-altitude (1768 m a.s.l.) lake in the Swiss Alps, has been recorded uninterruptedly since 1832. Based on this record and on shorter, interrupted records from two neighbouring lakes, the potential use of the timing of spring break-up as a proxy for local and regional surface air temperatures in the European Alpine region is investigated. Lej da San Murezzan exhibits an overall trend to earlier thawing (7.6 days per century) comparable to that of lakes in other parts of the Northern Hemisphere. Part of this trend may be due to shifts in mean break-up date around 1857 and 1932. The timing of break-up on all three lakes is strongly related to local and regional surface air temperatures centred on the middle of April and integrated over 4–8 weeks. Three empirical methods of relating break-up date to local air temperature yielded essentially the same proportion of shared variance (about 64%). Comparisons of break-up dates with surface air temperature data from Switzerland, the Netherlands and the United Kingdom suggest that the thawing of Alpine lakes is determined to a large extent by synoptic-scale meteorological processes. The timing of break-up on Lej da San Murezzan also tends to follow an index of global explosive volcanism with a time lag of about two years, volcanically quiescent periods being associated with early break-up, and volcanically active periods with late break-up. This suggests that modulation of incident radiation by stratospheric aerosols of volcanic origin may significantly affect the timing of break-up of high-altitude lakes.

## 1. Introduction

The timing of break-up of lake ice and its dependence on local and regional meteorological parameters are of both limnological and climatological interest. Modelling break-up dates from meteorological data is of limnological interest because of the importance of the duration of ice cover and the date of break-up for lake oxygenation (Stewart, 1976; Livingstone, 1993), fish winterkills (Greenbank, 1945; Barica and Mathias, 1979), phytoplankton production, species composition and abundance (Rodhe, 1955; Maeda and Ichimura, 1973; Smol, 1988) and several other aspects of lake ecology (Assel, 1991). With respect to its relevance to climate studies, the decay and eventual break-up of lake ice represents a temporally and (in the case of larger lakes) spatially integrated response to the weather conditions prevailing during a period of several weeks in spring. This period, which varies with latitude (Palecki and Barry, 1986), distance from the coast (Williams, 1971; Palecki and Barry, 1986), lake morphometry (Stewart and Haugen, 1990) and altitude, is fairly well defined for any one lake. One of the most important meteorological variables affecting both the formation and degeneration of lake ice is air temperature (Williams, 1971; Palecki and Barry, 1986). Consequently, historical information on

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both freeze-up and break-up dates can represent a valuable source of proxy data for air temperature (Arakawa, 1954; Simojoki, 1940; Gray, 1974; Tanaka and Yoshino, 1982; Pfister, 1984; Gordon et al., 1985; Tramoni et al., 1985; Palecki and Barry, 1986; Ruosteenoja, 1986; Skinner, 1986, 1993; Kuusisto, 1987, 1993; Robertson et al., 1992; Assel and Robertson, 1995). Some authors (e.g., Robertson et al., 1992; Assel and Robertson, 1995) are of the opinion that historical lake ice records may be a more reliable indicator of past local and regional climatic changes than even air temperature records themselves, since the latter are frequently subject to inhomogeneities and bias resulting from station alterations and observer changes. In addition, for lakes with known morphometry, satellite remote sensing of ice cover is potentially of value for estimating local and regional surface air temperatures in sparsely populated areas (Palecki and Barry, 1986; Maslanik and Barry, 1987; Barry and Maslanik, 1993; Hall, 1993; Wynne et al., 1996).

Long series of lake ice break-up dates with few or no interruptions have been employed with some success as regional climate indicators in Finland (Simojoki, 1940; Palecki and Barry, 1986; Ruosteenoja, 1986; Kuusisto, 1987, 1993), the Lake Michigan area (Robertson, 1992; Assel and Robertson, 1995) and various regions of Canada (Williams, 1971; Tramoni et al., 1985; Skinner, 1986, 1993). This paper presents the results of a study relating an uninterrupted 163 yr record of the break-up date of a small alpine lake to local and regional spring air temperatures in a region for which this has not previously been conducted: Switzerland.

In the environmental sciences, one of the most serious general problems involved in attempting to relate supposed causes to supposed effects is the fact that relationships between the two tend to be neither simple nor linear. This is especially evident in the case of the presumed dependence of the thawing of lake ice on air temperature. While air temperature may be an important factor affecting the decay and break-up of lake ice, it is certainly not the only one (Gu and Stefan, 1990). The success of any attempt to relate break-up date to air temperature – or to any other single meteorological variable for that matter – is thus necessarily limited by the multiplicity and complexity of thawing processes in the environment. The timing of break-up of lake ice depends essentially on the thickness and condition of the ice layer and on the wind stress acting on the ice surface (Williams, 1965). The thickness and condition of a layer of ice covering a lake at any point in time depend on many processes, each involving several environmental variables which are frequently difficult to measure or otherwise quantify. The processes involved include, for instance:

- surficial and internal ice melting due to direct and diffuse short-wave solar radiation and to diffuse long-wave radiation from clouds and gases in the atmosphere;
- surficial ice melting due to the exchange of sensible heat with the atmosphere;
- internal structural changes, ice decay and internal melting due to penetration of rain, melted snow or runoff;

- variations in surface albedo caused by new snowfall, rainfall, melting, the deposition of wind-borne plant remains, pollution and the presence or absence of air bubbles in the ice;
- variations in the insulating properties of the snow cover as a result of new snowfall, rainfall, compaction, melting at the air-snow interface, surficial and internal melting and refreezing;
- ice fracturing due to snow load;
- ice growth and decay at the ice-water interface.

It should be emphasized that this list of relevant processes is not exhaustive, and it is also evident that non-linear interactions between these processes will further complicate the problem. The degree of complexity resulting from this multiplicity of mutually interacting processes necessitates at least a partially empirical approach to lake ice modelling, especially during thawing. In most lake ice simulation models, heat fluxes are expressed as empirical functions of meteorological variables such as air temperature, wind speed and precipitation (e.g., Williams, 1965; Gu and Stefan, 1990). Although break-up date can depend significantly on wind stress (Williams, 1971) and precipitation (Ruosteenoja, 1986; Vavrus et al., 1996), air temperature is by far the most important of these variables (Ruosteenoja, 1986; Vavrus et al., 1996). Air temperature is not only an important meteorological variable in its own right, but can also act as an indicator for other meteorological variables with which it is correlated. In a situation like this, in which the number of processes (non-linear, mutually interactive and difficult to characterize) substantially exceeds the number of relevant variables contributing to them (especially if these variables are correlated to some extent), an empirical approach is justified. However, the conceptual impossibility of obtaining an exact determination of lake ice break-up dates from air temperature data alone, or *vice versa*, should be evident from the above. A prerequisite of any study employing proxy data should be to estimate the functional utility and reliability of any such artificially constructed one-on-one empirical relationship for which deterministic legitimation is lacking.

## 2. Break-Up Dates of the Upper Engadine Lakes

For the majority of Swiss lakes, no long-term information on ice break-up dates is available. Notable exceptions to this are Lej da San Murezzan (1768 m a.s.l.; surface area $A_0 = 0.78$ km$^2$; maximum depth $z_m = 44$ m), Lej da Silvaplauna (1791 m a.s.l.; $A_0 = 2.71$ km$^2$; $z_m = 78$ m) and Lej da Segl (1797 m a.s.l.; $A_0 = 4.11$ km$^2$; $z_m = 71$ m), a chain of small, relatively deep lakes strung out along a valley in the mountainous Upper Engadine region of south-east Switzerland (Figure 1). A long, unbroken series of break-up dates exists for Lej da San Murezzan beginning in 1832 (Figure 2a); shorter series, with interruptions, exist for the other two lakes (Figure 2b, c). Lütschg-Loetscher et al. (1954) have published the data available from all three lakes up to 1945 (listing the original sources); the complete series of

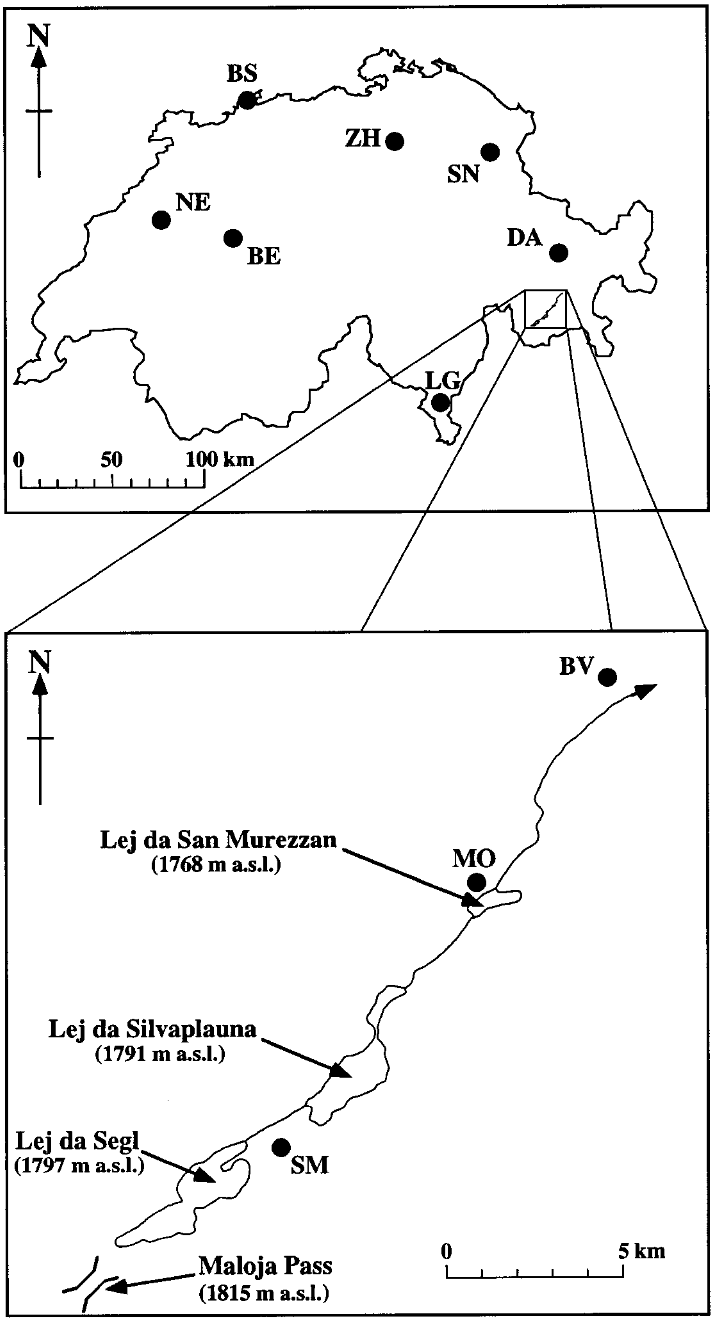

*Figure 1.* Location of Lej da San Murezzan, Lej da Silvaplauna and Lej da Segl in the Upper Engadine region of south-eastern Switzerland, and of the meteorological stations in Switzerland at which air temperature data were measured (Basle, BS; Berne, BE; Bever, BV; Davos, DA; Lugano, LG; Neuchâtel, NE; St. Moritz, MO; Mt. Säntis, SN; Sils-Maria, SM; Zurich, ZH).

break-up dates from Lej da San Murezzan from 1832 updated to the current year is listed every year in a local newspaper (Schaffner, 1994). The term 'break-up date' as used here refers to the first day on which the lake is observed to be completely ice-free (Lütschg-Loetscher et al., 1954; H. R. Schaffner, pers. comm.).

Because of its length, the Lej da San Murezzan data series is potentially of value for providing proxy spring air temperature data for the European Alpine region, if a relationship can be found linking the date of break-up to air temperature. The data from Lej da Segl and Lej da Silvaplauna are unfortunately too limited to be of use as long-term proxy air temperature data; their function here is to provide evidence to support the use of the Lej da San Murezzan data and to put the employment of lake break-up as a proxy for regional air temperature in perspective by giving an idea of the degree of local variability in break-up date (the lakes lie within 15 km of one another).

All three lakes usually thaw in May (Table Ia), and break-up dates are highly correlated (Table Ib). On average, Lej da San Murezzan thaws first, with Lej da Segl and Lej da Silvaplauna, which are separated by a mere 2 km of flat alluvium, thawing almost simultaneously about a week later (Table Ia). Because the three lakes are in close proximity and their surface altitudes differ by less than 30 m (Figure 1), the meteorological conditions to which the lakes are exposed can be assumed to be roughly similar. However, they are not identical, since, depending on wind conditions, a tongue of cold, moist air often penetrates part-way into the valley from the Maloja Pass to the south-west. When this happens, a horizontal gradient in local weather along the valley is noticeable, with cold, wet and windy conditions in the south-west (Lej da Segl) and relatively warm, dry and calm conditions in the north-east (Lej da San Murezzan) (M. Sturm, pers. comm.). This phenomenon may be a contributory cause of the delay in thawing experienced by Lej da Segl and Lej da Silvaplauna relative to Lej da San Murezzan. Coefficients of determination ($r^2$) between the break-up dates of the three lakes vary from 58% to 71% (Table Ib). The above-mentioned local meteorological differences, coupled with lake-specific factors such as lake morphometry (Stewart and Haugen, 1990) and wind fetch (Palecki and Barry, 1986) may be responsible for much of the unexplained variance. Whatever the reason, it is unlikely that synoptic meteorological data will be more highly correlated with the break-up date of any one of these lakes than are the lake break-up dates among themselves, since differences in the break-up dates of lakes only a few kilometres apart can only be the result either of local differences in meteorological forcing (owing, for example, to different degrees of topographical sheltering from wind and/or radiation) or of physical differences between the lakes themselves. This suggests that in this rugged mountainous area, where local weather can be very heterogeneous, the amount of variance in break-up date potentially explainable in terms of synoptic meteorological data is unlikely to exceed 60–70%.

Since break-up dates tend to be normally distributed, the standard deviation ($\sigma$) is a good measure of their variability (Williams, 1971). Variability in the break-up

Table Ia

Mean ($\overline{J}_{\text{thaw}}$, in Julian days) and standard deviation ($\sigma$) of ice break-up dates for the Upper Engadine lakes, based on the 58 years for which data exist for all three lakes (see Figure 1 for locations of lakes)

| Lake | $\overline{J}_{\text{thaw}}$ | $\sigma$ [d] |
|---|---|---|
| Lej da San Murezzan (LSM) | 132 (12 May) | 8 |
| Lej da Segl (LSG) | 139 (19 May) | 9 |
| Lej da Silvaplauna (LSP) | 139 (19 May) | 9 |

Table Ib

Coefficient of determination ($r^2$), mean ($\Delta$) and standard deviation ($\sigma_\Delta$) of the differences between the break-up dates of the Upper Engadine lakes taken in pairs, based on the 58 years for which data exist for all three lakes. All correlations are very highly significant (ANOVA $F$-test: $p < 0.001$)

| Lake pair | $r^2$ [%] | $\Delta$ [d] | $\sigma_\Delta$ [d] |
|---|---|---|---|
| LSM and LSG | 58 | –7 | 6 |
| LSM and LSP | 66 | –7 | 5 |
| LSP and LSG | 71 | 0 | 5 |

dates of the Upper Engadine lakes ($\sigma = 8$–9 d: Table Ia) is comparable to that of other continental lakes regardless of geographical location. It is very similar to the variability in the break-up dates of lakes in northern Sweden ($\sigma = 10$ d: Williams, 1971); of Lake Kallavesi, Finland ($\sigma = 9$ d: data from Simojoki, 1940); of Lake Baikal, Siberia ($\sigma = 8$ d: data from Shimaraev, 1977); of Lake Mendota, Wisconsin ($\sigma = 11$ d: data from Knox, 1992); and of other continental North American lakes ($\sigma = 7$ to 11 d: Williams, 1971). Variability in the break-up date of coastal lakes tends to be significantly greater (Williams, 1971).

On average, Lej da San Murezzan thaws within about a week either way of 12 May. However, from Figure 2a it is obvious that the time series of break-up date is non-stationary: a trend to earlier break-up with time is apparent. Application of the mean square successive difference (MSSD) test (von Neumann et al., 1941; Moore, 1955) to the data from 1840–1994 (the earliest data were omitted to avoid the possibility of distorting the results by including the unusually late break-up dates of 1836–1837, treated separately below) confirms the existence of a significant trend (unless otherwise stated, the significance level referred to here and in the following is $p < 0.05$). The concept of trend is vague; consequently, trend is difficult to define precisely (Brillinger, 1994). Without having first advanced a hypothesis relating the observed data to underlying mechanisms, trends in a stochastic time series

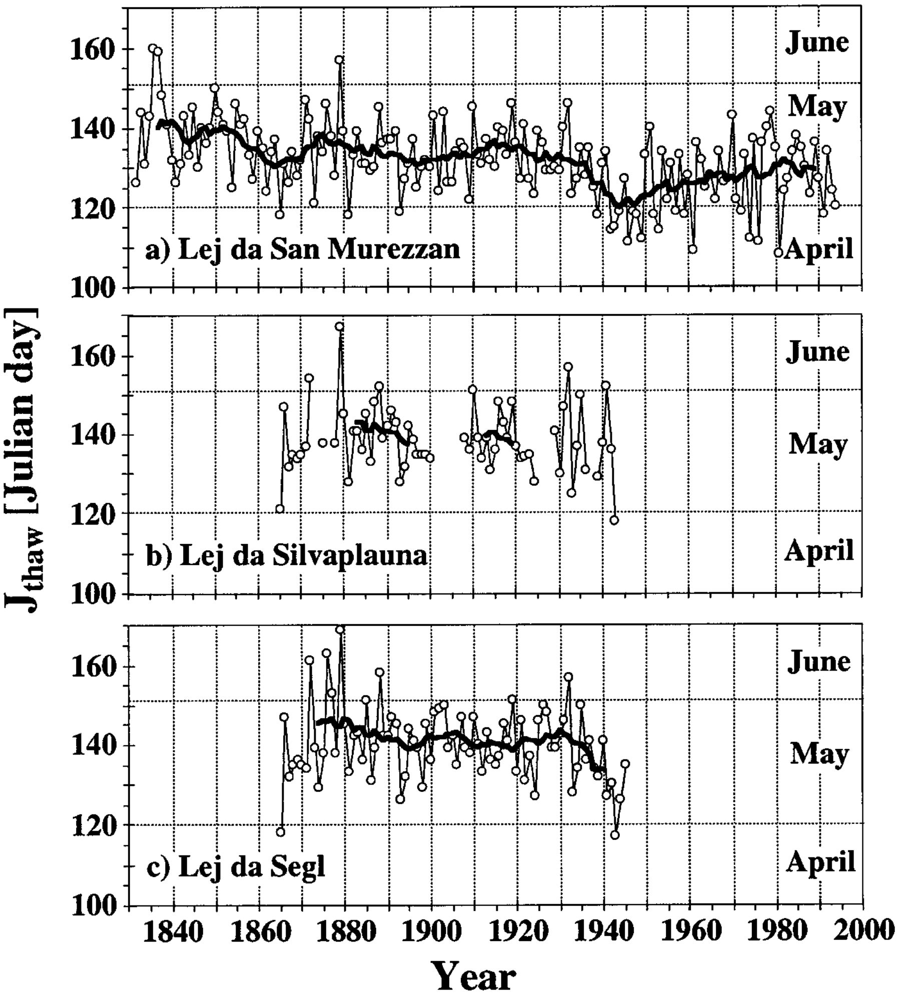

*Figure 2.* Break-up dates of lake ice on Lej da San Murezzan, Lej da Silvaplauna and Lej da Segl (open circles) with 11-yr running means (thick solid lines).

cannot be explained, but only described (or modelled) statistically. Such statistical descriptions can then help in the search for plausible hypotheses. Observed trends in stochastic time series can be described in several ways, two of the simplest and most common being gradual secular change and abrupt step-wise transition. Under the assumption of gradual secular change, regression techniques are appropriate. Estimation of the magnitude of an assumed secular trend by linear regression suggests that the break-up date has been moving forward in time since 1840 at a mean rate of 7.6 d per century (95% confidence interval = ±3.0 d per century); i.e., from about 18 May in the 1840s to about 5 May in the 1990s. In contrast, if trends in break-up date are assumed to be the product of successive abrupt changes between homogeneous climate regimes (e.g., Robertson et al., 1992; Assel and Robertson, 1995), methods of identifying the locations of the most likely change-points between stationary regimes are more appropriate. Application of Pettitt's (1979) non-parametric change-point test to the Lej da San Murezzan break-up dates suggests the most likely change-point location to have been in 1932, with a decrease in the mean break-up date from 14 May (1840–1932) to 6 May (1933–1994). Dividing the series into two segments at 1932 and repeating the Pettitt test reveals one further significant change-point at 1857, from 18 May (1840–1857) to 13 May (1858–1932). Cursory inspection of the 11-yr running mean (Figure 2a) confirms that a rough division of the time series into three regimes with change-points at 1857 and 1932 appears reasonable. An examination of the fine structure of each of these regimes, however, suggests that they are probably not stationary. This is especially true of the 1933–1994 segment, which exhibits a continual trend towards earlier break-up from 1933 to the mid-1940s, and towards later break-up from then until the late 1970s, a pattern similar to that shown by spring air temperature in Switzerland (Pfister, 1984). Subsequent to 1980, there are indications of a return to earlier break-up, a not unexpected occurrence in view of the increase in sunshine duration and air temperature registered in Switzerland since 1980 as a consequence of the increase in the frequency of blocking high pressure events in central Europe (Beniston et al., 1994). Further application of the Pettitt test to the data after removal of the overall linear trend revealed no significant change-point. Equally, no significant linear trend remains after having removed the abrupt changes identified by the Pettitt test. Either model – secular change or abrupt change – thus offers a valid statistical description of the long-term trend.

Long-term trends towards earlier break-up have been observed in both lakes and rivers in various parts of the Northern Hemisphere. In Finland, a trend towards earlier break-up on Lakes Kallavesi and Näsijärvi, among others, has been noted by Simojoki (1940), Ruosteenoja (1986) and Kuusisto (1987, 1993) from the 1870s up to the 1940s. In addition, Kuusisto (1993) has demonstrated a clear long-term trend in the break-up date of the River Tornionjoki, Finland, with break-up dates today being about 10 days earlier than 3 centuries ago. In the southern basin of Lake Baikal, Siberia, a clear trend to earlier ice break-up is apparent from the 1870s to the 1910s; thereafter, however, no clear trend is apparent (Shimaraev et al., 1994). Long-term records from North American lakes show a trend to earlier break-up from about 1870–1940 (Williams, 1970). Rannie (1983) has found that the Red River at Winnipeg, Manitoba, now breaks up about 10 days earlier than it did last century. Robertson et al. (1992) and Assel and Robertson (1995) have identified long-term trends towards earlier break-up in Lake Mendota, Wisconsin, and Grand Traverse Bay, Michigan, which they interpreted as a series of abrupt transitions between homogeneous climate regimes. In addition to these long-term trends, several studies have demonstrated the existence of shorter-term trends to earlier break-up over the last two or three decades, for which more data exist (e.g., Schindler et al., 1990; Hanson et al., 1992; Skinner, 1993; Anderson et al., 1996).

Three of the above examples for which published data on break-up dates are readily available – Lakes Kallavesi, Baikal and Mendota – were subjected to the Pettitt test to identify likely change-points:

(i) For the Lake Kallavesi data (1835–1934) listed by Simojoki (1940), the most likely significant change-point was found to be in 1886. No further significant change-points were identified in the two segments separated by this change-point.

(ii) Historical data on the break-up dates of Lake Baikal from 1869 to the present (Shimaraev, 1977; Shimaraev et al., 1991, 1994) show a significant trend to earlier break-up (MSSD test). Linear regression suggests a secular trend with a mean rate of 5.6 d per century (95% C.I. $= \pm 3.6$ d per century). The Pettitt test identifies the location of the most likely significant change-point as being 1910. Dividing the series into two segments at 1910 and repeating the test identifies a further significant change-point in 1885. Both change-points involve a change towards earlier break-up.

(iii) In the case of historical data from Lake Mendota (Ragotzkie, 1960; Knox, 1992), although the MSSD test surprisingly does not detect a very significant long-term trend ($p < 0.2$), linear regression does imply a significant trend towards earlier break-up at the mean rate of 7.7 d per century (95% C.I. $= \pm 4.5$ d per century). Thorough analyses of the Lake Mendota data by Robertson et al. (1992) and by Assel and Robertson (1995) imply that abrupt changes in break-up date, rather than secular change, are most likely to be responsible for the trend over the last 1.5 centuries. Using the intervention analysis method of Box and Tiao (1975), they identified two change-points in the Lake Mendota series; viz. 1888 and 1980. Application of the Pettitt test identifies the most likely significant change-point as being slightly later than 1888, viz. in 1901. After dividing the series into two segments at 1901 and repeating the test, no further significant change-points were identified. However, although not very significant ($p < 0.3$), the most likely location of a change-point in the 1902–1993 segment was found to be 1980, in exact agreement with Robertson et al. (1992) and Assel and Robertson (1995). As in the case of Lej da San Murezzan and Lake Baikal, both change-points in Lake Mendota involve a change towards earlier break-up.

The long-term tendency for ice on inland waters to thaw earlier is thus not confined to any particular region of the Northern Hemisphere, and might therefore be interpreted as yet more evidence for globally increasing surface air temperatures. As in the case of Lej da San Murezzan, on the one hand, no significant change-points were detected in the time series of break-up date from Lakes Kallavesi, Baikal and Mendota after having removed the overall linear trend; on the other hand, no significant linear trend remained after having removed the abrupt changes identified by the Pettitt test. It is therefore not clear whether the long-term trends can be best viewed statistically as gradual secular changes or abrupt step-wise transitions. In the latter case, the evidence from Lakes Kallavesi, Baikal and Mendota points to a transition to earlier break-up having occurred between 1885 and 1910. However, there is no evidence of a change-point having occurred in the Lej da San Murezzan data at this time; these data point rather to a transition having occurred in the early 1930s.

Tacit assumptions about the time-scale on which changes are taking place underlie both of the practical trend-analysis methods employed here. Linear regression methods test for secular change occurring on time-scales similar to or longer than that of the data window, whereas change-point tests test for abrupt change occurring on time-scales similar to or shorter than that of the sampling interval (i.e., 1.5 centuries and 1 yr, respectively, in this case). However, changes actually occurring in the physical world are unlikely to be either purely secular or purely abrupt, since both these terms are defined subjectively. They may lie almost anywhere along a continuous, infinite spectrum of time-scales associated with the processes responsible for the observed phenomenon. It should therefore be kept in mind that the statistical tests employed here cannot elucidate the true nature of any changes which may be occurring in the break-up series (only a process-based approach might accomplish this), but can only describe such changes from the viewpoints of two different hypotheses.

## 3. Local and Regional Air Temperature Data

The break-up dates of the Upper Engadine lakes were compared with local air temperature data in order to confirm that information on the thawing of lake ice can actually constitute usable proxy data for air temperature, and to determine the response time involved. To accomplish this requires the analysis of daily local air temperature data, since monthly mean data do not offer the required degree of resolution. The main data set employed for this purpose was that from the Bever (BV) meteorological station, located 7 km north-east of Lej da Murezzan (Figure 1). Daily air temperature data are available from this station in machine-readable form for the period 1901–1982 (the station was closed down in 1982).

The Swiss Meteorological Institute computes daily mean air temperatures as a weighted mean of the daily minimum and three observations conducted at fixed times during the day (the daily maximum being disregarded). In 1971, alterations were made to the observation times and to the computational method. To eliminate the possibility of these changes resulting in inhomogeneities in the time series of daily means, it was judged preferable for the purposes of this paper to estimate the daily mean air temperature in terms of the daily minimum and maximum, without taking the three daily observations into account. This not only avoids any discontinuity at 1970/71, but has the added advantage of removing much of the dependence of observation time on observer reliability, which will presumably vary in an unpredictable fashion as observers are replaced through time. Accordingly, corresponding to the convention adhered to in many international studies, the daily mean will be defined here as the arithmetic mean of the daily minimum and daily maximum. Because of diurnal asymmetry in the air temperature probability density function, the actual mean air temperature over any given time period will differ from the mean as computed here. However, this simple definition is useful to guarantee consistency between data sets and to avoid the possible introduction of statistical artefacts and inhomogeneities.

The location and exposure of the BV meteorological station were altered on at least three occasions during the period under discussion (Schüepp, 1968). Based on comparisons with measurements from the station at Davos (DA), located in a valley 30 km north of BV (Figure 1), Schüepp (1968) concluded that the BV temperature minima and maxima exhibited a certain degree of temporal inhomogeneity, which he attributed partly to the station alterations and partly to the existence of temperature inversions with a high degree of local variability. Here we are interested only in the situation pertaining to spring. Segment-by-segment regression analysis of the mean April BV and DA air temperature data revealed no significant change in the regression coefficients with time. The influence of station alterations on the local (BV) data was therefore not considered great enough to justify the risk of introducing distortion into the data set by making possibly erroneous corrections based on data from stations located outside the valley in which the lakes are situated.

Some air temperature data are available, however, from other stations in the valley itself. The meteorological station of St. Moritz (MO) is directly adjacent to Lej da San Murezzan, and the station of Sils-Maria (SM) is located on the flat land between Lej da Silvaplauna and Lej da Segl (Figure 1). Machine-readable daily air temperature data series from these stations are unfortunately too short to allow meaningful direct comparisons with lake break-up dates (MO 1959–1982; SM 1978–1994). However, these short series can be used to estimate the degree to which the BV data are representative of the air temperatures prevailing close to the lakes. In all months of conceivable relevance for break-up studies, strong linear relationships exist between the daily mean air temperatures computed for the three stations MO, SM and BV (Table II). It will be shown below that the lake break-up dates are most strongly related to air temperatures from March to May. Coefficients of determination (i.e., adjusted $r^2$ values) in these months are at least 88% between stations BV, MO and SM, taken pairwise. Local heterogeneity in air temperature is therefore unlikely to account for more than about 10% of any unexplained variance between the break-up dates of the Upper Engadine lakes and measured air temperature.

For the period during which data are available from the Bever (BV) station, daily minimum and maximum air temperatures are also available in machine-readable form from a further seven Swiss meteorological stations located between 30 km and 230 km from the lakes (Basle, BS; Berne, BE; Davos, DA; Lugano, LG; Neuchâtel, NE; Mt. Säntis, SN; Zurich, ZH: see Figure 1 for station locations). The eight stations are exposed to a variety of different local meteorological conditions. Five are lowland stations (NE, BE, ZH, LG, BS: 250–500 m a.s.l.), two are relatively high-altitude valley stations (BV, 1712 m a.s.l.; DA 1580 m a.s.l.) and one is a mountain-top station with maximum exposure to the free atmosphere (SN, 2500 m

Table II

Coefficients of determination (in %) between daily mean air temperatures measured at three meteorological stations in the Upper Engadine, January to June (BV, Bever; MO, St. Moritz; SM, Sils-Maria: see Figure 1 for station locations). All correlations are very highly significant (ANOVA $F$-test: $p < 0.001$)

| Station pair | Jan. | Feb. | Mar. | Apr. | May | June |
|---|---|---|---|---|---|---|
| BV & MO (1959–1982) | 77 | 85 | 89 | 90 | 88 | 91 |
| BV & SM (1978–1982) | 84 | 86 | 89 | 90 | 91 | 89 |
| MO & SM (1978–1982) | 84 | 89 | 90 | 94 | 95 | 92 |

a.s.l.). Five are situated north of the Alps (NE, BE, ZH, BS, SN), one south of the Alps (LG) and two in the midst of the Alps themselves (BV, DA). Because of their location in or close to large towns, some stations are subject to urban warming (BE, ZH, BS); others (e.g., SN) are most definitely not. The influence of anthropogenic aerosols and/or secular changes in cloud cover on the air temperature (Kukla and Karl, 1993) is likely to be greater at station LG than at the other stations because of the greater exposure of the south-facing slope of the Alps to the emissions of the industrial region of northern Italy; in contrast, air temperatures at the mountain-top station SN are unlikely to be affected at all by lower troposphere aerosols (Weber et al., 1994). Daily mean air temperatures at these very different stations were used to assess the relevance of lake ice break-up dates as proxy air temperature data not only with respect to local climate, but also with respect to regional climate, and to confirm the validity of the results based on the local (BV) data. The dependence of break-up date on even larger-scale (synoptic) processes was investigated using the well-known monthly mean air temperature data sets from central England (Manley, 1974, extended by Parker et al., 1992) and the Netherlands (the De Bilt series), situated 1100 km and 700 km, respectively, from the Upper Engadine valley. Finally, the Northern Hemisphere mean surface air temperature data of Jones et al. (1986) were employed to investigate any dependence of break-up date on hemisphere-scale processes.

## 4. Empirical Relationships Break-Up Date and Air Temperature

Relationships between break-up date and air temperature are commonly described using one of three empirical methods: the ‘fixed-period regression’ method of Palecki and Barry (1986), the ‘accumulated degree-day’ method of Bilello (1961), and the ‘sensible heat transfer’ method of Bilello (1964). The first two of these, plus a modified version of the second, will be employed here.

### 4.1. THE 'FIXED-PERIOD REGRESSION' METHOD

The fixed-period regression method attempts to relate the calendar date of break-up of lake ice to mean air temperature by correlating the two directly (e.g., Palecki and Barry, 1986). The underlying assumption is that high (low) mean air temperatures over some period in spring are associated with early (late) break-up. Conceptually, it would be more satisfactory to correlate the calendar date of break-up with the calendar date on which a particular mean air temperature is attained (e.g., the date of 'onset of spring': see Ruosteenoja, 1986), but practically, an estimate of mean air temperature is usually more useful. Assuming, then, that the timing of break-up can be used as a proxy for the mean local air temperature $\overline{T}_{t',\Delta t}$, where averaging is over a time period of duration $\Delta t$ centred on a point in time $t'$, the question of the determination of optimal values for $t'$ and $\Delta t$ arises: in other words, what is the response time of the 'ice thermometer'? Where $T(t)$ is the instantaneous temperature as a function of time $t$, the mean local air temperature $\overline{T}_{t',\Delta t}$ can be expressed as:

$$\overline{T}_{t',\Delta t} = \frac{1}{\Delta t} \cdot \int_{t'-\Delta t/2}^{t'+\Delta t/2} T(t) \cdot \mathrm{d}t\,, \tag{1}$$

or, in discrete form:

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

where the location parameter $J$ is the Julian day number corresponding to $t'$, the integrating parameter $N$ is the number of days corresponding to $\Delta t$, and $\overline{T}_{j,1}$ is the daily mean air temperature on Julian day $j$. For the Julian day of break-up, $J_{\mathrm{thaw}}$, to be a useful proxy for the mean air temperature $\overline{T}_{J,N}$, it must be significantly correlated with it. This will normally be the case over some (initially unknown) range of values of $J$ and $N$ defining a range of time periods. Although the break-up date can in principle be used as a proxy variable for the mean air temperature during any of these time periods, it yields the best proxy data for $\overline{T}_{J,N}$ when $J$ and $N$ are chosen to maximise the coefficient of determination, $r^2$, between $\overline{T}_{J,N}$ and $J_{\mathrm{thaw}}$.

Figure 3 shows the ranges of $J$ and $N$ for which $J_{\mathrm{thaw}}$ in each of the three Upper Engadine lakes can be employed as a proxy for $\overline{T}_{J,N}$ at Bever. Because the decay and break-up of a thick layer of ice is an integrated rather than an instantaneous response to meteorological forcing, small values of $N$ are associated with relatively low $r^2$ values. Equally, low $r^2$ values result if $N$ is large enough so that the range $J \pm N/2$ includes periods of little or no relevance to thawing (e.g., the previous winter's freezing period or the time subsequent to break-up). Within these limits, depending on $J$, a broad range of values of $N$ can yield high $r^2$ values. The rapidity at which the $r^2$ values fall off as $J$ deviates from its optimal value, in contrast to the comparatively small changes in maximum $r^2$ values effected by variations in

$N$, demonstrates that the coefficient of determination is much more sensitive to the location parameter $J$ than to the integrating parameter $N$. The former should therefore be established as precisely as possible, whereas the latter need only be established to within about $\pm 10$ d. The most reliable and most useful results are those from Lej da San Murezzan, since these are based on considerably more data than those from the other two lakes. Results from the other two lakes, however, are useful in supporting – or contradicting – conclusions drawn from the Lej da San Murezzan data.

(i) Results from Lej da San Murezzan (Figure 3a) reveal that $J$ must lie near the middle of April, and $N$ between 4 and 8 weeks. The percentage of variance explained reaches a maximum of 64% when $J = 108$ d and $N = 51$ d. The break-up date of Lej da San Murezzan is therefore most strongly related to a 51-day mean air temperature centred on 18 April, i.e., to the mean air temperature from 24 March to 13 May. Other combinations of $J$ and $N$ also yield high $r^2$ values: A monthly mean air temperature ($N = 31$ d) centred anywhere from 3–17 April, or a 2-monthly mean air temperature ($N = 61$ d) centred anywhere from 8–27 April, will yield $r^2$ values in excess of 50%. It is therefore possible to employ $J_{\text{thaw}}$ as a proxy for the local mean April air temperature ($J = 105.5$ d, $N = 30$ d), which is useful for comparison purposes in view of the fact that monthly mean air temperature data from most meteorological stations are usually more readily available than daily means. However, it can be seen from Figure 3 that $J_{\text{thaw}}$ is not nearly so suitable as a proxy for spring mean air temperature (defined as the mean air temperature from 1 March to 31 May), since $J = 105$ d and $N = 91$ d yields $r^2 = 37\%$, which is substantially less than values obtained for shorter averaging periods.

(ii) Results from Lej da Silvaplauna (Figure 3b) support those from Lej da San Murezzan. Highest $r^2$ values occur for averaging times of 31–61 d, and the break-up date is most strongly related to a 51-day mean air temperature centred on 21 April, i.e., to the mean air temperature from 27 March to 16 May ($r^2 = 68\%$). This period is almost identical to that found for Lej da San Murezzan, and the proportion of variance explained is similar.

(iii) Results from Lej da Segl (Figure 3c), however, are much less satisfactory, $r^2$ values attaining a maximum of only 40%. To exclude the possibility of this comparatively low degree of correlation being an artefact associated with the differing lengths of the data series, $r^2$ values for Lej da San Murezzan were recalculated using only the years for which data were available from Lej da Segl. Although slightly lower $r^2$ values resulted for all averaging times (e.g., a decrease of the $r^2$ value for $\overline{T}_{108,51}$ from 64% to 57%), the magnitude of the reduction is insufficient to explain the difference between the two lakes. Since mean air temperatures are very highly correlated among stations in the valley (Table II), factors other than air temperature – perhaps the above-mentioned prevalence of more changeable, wetter and windier weather in the south-west of the valley – are likely to be responsible for the fact that break-up on Lej da Segl correlates much

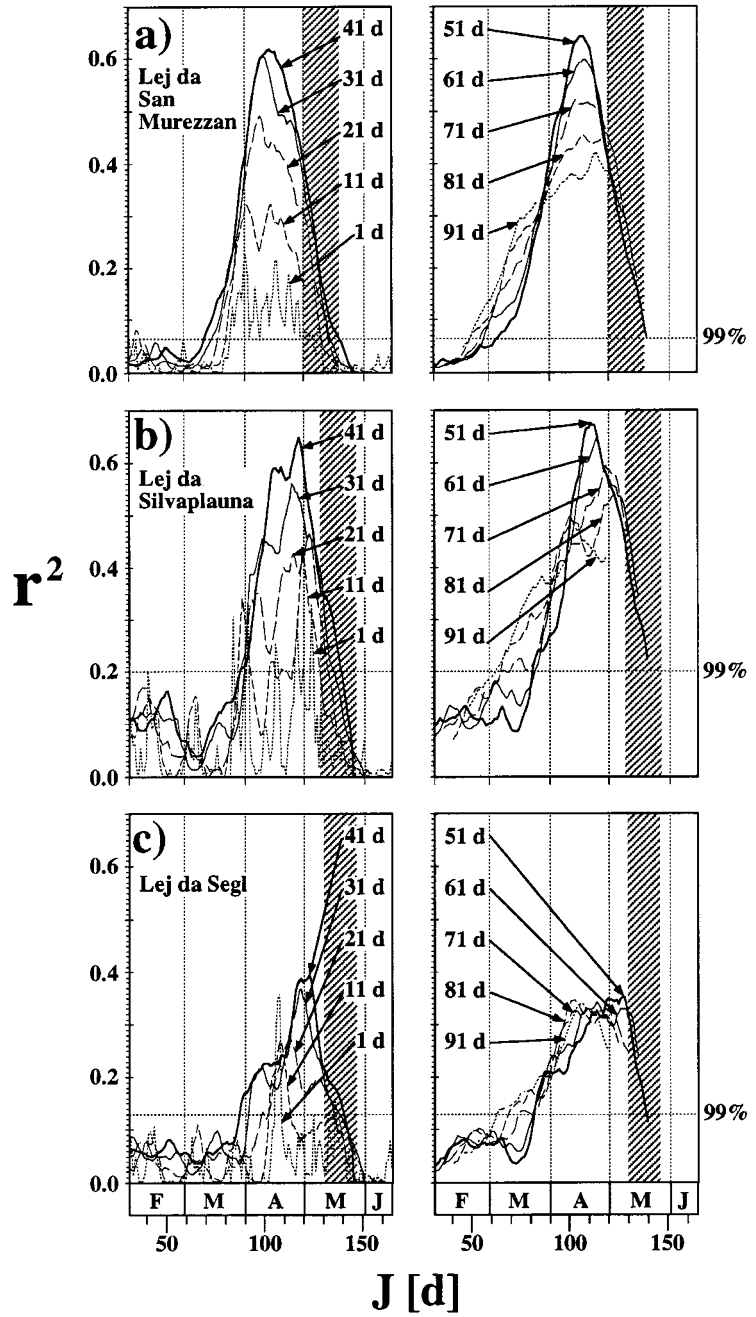

*Figure 3.* Coefficients of determination ($r^2$) between break-up date and mean air temperature at the Bever (BV) meteorological station on Julian day $J$ as a function of $J$ for various averaging times $N$ between 1 d and 91 d. (a) Break-up date of Lej da San Murezzan; (b) Break-up date of Lej da Silvaplauna; (c) Break-up date of Lej da Segl. Shaded areas represent the usual ranges of break-up date (mean break-up date ± one standard deviation). 99% significance levels are shown as horizontal dotted lines.

less well with BV air temperatures than does break-up on either of the other two lakes.

### 4.2. THE 'ACCUMULATED DEGREE-DAY' METHOD

The fixed-period regression method allowed 64% of the variance in the break-up date of Lej da San Murezzan to be explained on the basis of a linear relationship with the 51-day mean air temperature. To investigate the possibility of improving upon this without introducing additional meteorological variables, the 'accumulated degree-day' method of Bilello (1961) was also tried out. This method is based on the premise that ice thickness diminishes proportionally to the number of degree-days accumulated, counting only those days on which the mean daily air temperature exceeds the melting temperature of the ice. For lake ice melting at 0 °C, this is simply the number of positive degree-days accumulated between days $J_0$ and $J$:

$$A(J) = \frac{1}{2} \sum_{j=J_0}^{J} \{|\overline{T}_{j,1}| + \overline{T}_{j,1}\}\,, \tag{3}$$

where $J_0$ is the Julian day corresponding to some arbitrary point in time before the ice thickness begins to diminish and $\overline{T}_{j,1}$ [°C], as in Equation (2), is the daily mean air temperature on Julian day $j$ (the apparent dimensional inconsistency of this equation is due to the fact that the right-hand side tacitly includes a multiplier of 1 d). It is presumed that lake ice will thaw (on Julian day $J = J_{\text{thaw}}$) when $A(J)$ attains a certain critical value during the period of increasing air temperatures. This critical value can be estimated as the mean of $A(J_{\text{thaw}})$, i.e., $\overline{A}(J_{\text{thaw}})$. The success of this method rests on the fact that ice is not a good heat conductor, implying that the lower boundary of an ice layer, where ice growth takes place, is to a large extent insulated from the effects of the atmosphere. This is of course not the case for the upper boundary, where most thawing processes occur. An ice layer will therefore generally thaw faster at positive air temperatures than it grows at corresponding negative air temperatures.

The high degree of correlation between the air temperatures measured at stations BV, MO and SM (Table II) allowed the MO and SM air temperatures from 1901–1982 to be estimated from the corresponding BV air temperatures by linear regression. Taking account of the altitudes of the stations and the lakes, the corresponding air temperatures prevailing at each of the lakes could then be estimated, allowing $\overline{A}(J_{\text{thaw}})$ to be calculated for each lake from 1901–1982. The values obtained for $\overline{A}(J_{\text{thaw}})$ were 133 °C · d for Lej da San Murezzan, 134 °C · d for Lej da Silvaplauna and 137 °C · d for Lej da Segl (cf. 140 °C · d for Lake Kallavesi: Ruosteenoja, 1986). All three Swiss lakes require approximately the same number of positive degree-days for break-up; the fact that Lej da Silvaplauna and Lej da Segl usually thaw about a week later than Lej da San Murezzan (Table Ia) is therefore associated with the generally colder conditions to which the former two

Table III

Pairwise coefficients of determination ($r^2$) between the break-up dates of the Upper Engadine lakes and air temperature data from the Bever (BV) meteorological station using (i) the fixed-period regression method, (ii) the accumulated degree-day method and (iii) the modified accumulated degree-day method

| | Lej da San Murezzan ($n = 163$) | Lej da Silvaplauna ($n = 80$) | Lej da Segl ($n = 59$) |
|---|---|---|---|
| (i) Fixed-period regression method (51-day mean) | 64.3% | 67.5% | 34.7% |
| (ii) Accumulated degree-day method | 63.0% | 65.4% | 34.2% |
| (iii) Modified accumulated degree-day method | 63.1% | 63.6% | 36.4% |

are subjected in spring. Especially in the case of Lej da San Murezzan and Lej da Silvaplauna, the break-up date $J_{\text{thaw}}$ is highly correlated with the day on which the critical value $\overline{A}(J_{\text{thaw}})$ is attained. However, the proportion of variance explained is very similar to that explained by a linear dependence of $J_{\text{thaw}}$ on the 51-day mean Bever air temperature (Table III), and so use of the accumulated degree-day method represents no improvement over use of the fixed-period regression method.

## 4.3. THE MODIFIED ‘ACCUMULATED DEGREE-DAY’ METHOD

Another approach was tried by combining the accumulated degree-day method with aspects of the fixed-period regression method. Coefficients of determination ($r^2$) were calculated by setting $J_0 = 0$ and correlating the break-up date $J_{\text{thaw}}$ of each of the three lakes with the number of positive degree-days $A(J)$ accumulated up to each day from $J = 1$ (1 January) to $J = 165$ (14 June). In all three cases, $r^2$ attained its maximum within a few days of the respective mean break-up date $\overline{J}_{\text{thaw}}$, and was still very high on $\overline{J}_{\text{thaw}}$ itself (Figure 4). The current break-up date $J_{\text{thaw}}$ is thus highly correlated with the number of positive degree-days $A(\overline{J}_{\text{thaw}})$ accumulated up to the mean break-up date $\overline{J}_{\text{thaw}}$. Again, the modified accumulated degree-day method yields $r^2$ values similar to those obtained using the fixed-period regression method (Table III).

The $r^2$ values obtained using the three methods tested here agree well not only with each other (Table III), but also with the $r^2$ values obtained when correlating break-up dates between the lakes themselves (Table Ib). For instance, $J_{\text{thaw}}$ for Lej da Silvaplauna can be modelled for all practical purposes equally well in terms of $J_{\text{thaw}}$ for Lej da San Murezzan ($r^2 = 66\%$), $\overline{T}_{J,N}$ at Bever ($r^2 = 68\%$), $\overline{A}(J_{\text{thaw}})$ ($r^2 = 65\%$) or $A(\overline{J}_{\text{thaw}})$ ($r^2 = 64\%$). This suggests that no significant improvement in $r^2$ is likely to be achieved without including more meteorological variables (e.g., precipitation: Ruosteenoja, 1986) in the chosen model.

In contrast to the fixed-period regression method, further manipulation is required to convert a relationship involving accumulated degree-days into one involv-

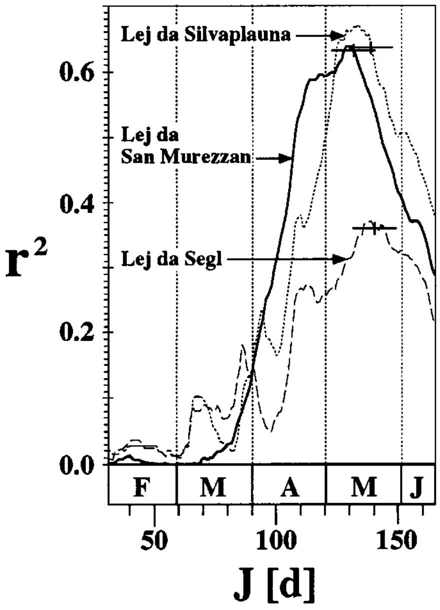

*Figure 4.* Coefficients of determination ($r^2$) between break-up date ($J_{\mathrm{thaw}}$) and number of positive degree-days $A(J)$ on Julian day $J$ as a function of $J$ for the three Upper Engadine lakes. Crosses represent means ($\overline{J}_{\mathrm{thaw}}$) and standard deviations of break-up dates.

ing mean air temperatures explicitly. As any manipulation which does not preserve the degree of linearity of the relationship completely will result in a reduction in the proportion of variance explained, in the specific case considered here neither version of the accumulated degree-day method can improve on the results obtained using the fixed-period regression method, which was accordingly considered to be the most suitable for the task in hand. This supports the opinion of Barry and Maslanik (1993) that 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.

## 5. Break-Up on Lej da San Murezzan as a Proxy for Regional Mean Air Temperatures

Having established the utility of the Lej da San Murezzan break-up date as a direct proxy for the *local* mean air temperature over a period of one to two months in spring (Figure 3), the further question arises of its utility as a proxy for the *regional* mean air temperature during the same period. In other words, to what extent is the thawing of lake ice a response to regional meteorological forcing? Using the fixed-period regression method, the break-up dates of Lej da San Murezzan were related to integrated daily mean air temperature data from the seven additional Swiss

Table IV

Integration time ($N$), Julian day ($J$) and percentage of variance explained ($r^2$) for optimal correlation between the break-up date of Lej da San Murezzan and the air temperature at each of eight meteorological stations in Switzerland (based on data from 1901–1982; see Equation (2) and Figure 5)

| Station | $N$ [d] | $J$ [d] | $r^2$ [%] |
|---|---|---|---|
| Bever (BV) | 51 | 108 (18 April) | 64.3 |
| Neuchâtel (NE) | 51 | 103 (13 April) | 61.0 |
| Berne (BE) | 31 | 96 (6 April) | 60.1 |
| Zurich (ZH) | 31 | 97 (7 April) | 55.9 |
| Lugano (LG) | 41 | 103 (13 April) | 55.0 |
| Davos (DA) | 31 | 97 (7 April) | 55.0 |
| Basle (BS) | 31 | 96 (6 April) | 54.5 |
| Mt. Säntis (SN) | 31 | 97 (7 April) | 50.4 |

meteorological stations for which daily air temperature data are also available from 1901–1982 (Figure 5). As was the case for the local (BV) air temperatures, integrating periods of 31–51 days yielded the highest $r^2$ values for all seven stations (Table IV). As mentioned above, the eight stations of Figure 5 and Table IV are exposed to a variety of different local climatic conditions. Despite this, the form of the dependence of $r^2$ on $J$ and $N$ illustrated in Figure 5 varies little among these stations. The maximum percentage variance explained varied from 50% at the Mt. Säntis station to 64% at Bever, implying that the thawing of Lej da San Murezzan – and, by analogy, of other Alpine lakes – is primarily a response to meteorological forcing on a regional scale. Interestingly, air temperature data from Neuchâtel (NE), the station furthest from the lake (230 km), exhibit higher correlations with the break-up date ($J = 103$ d, $N = 51$ d, $r^2 = 61\%$) than the data from all other stations except BV, possibly because the NE station surroundings and measuring equipment have been subject to comparatively little change through the years (Schüepp, 1961, 1968), so that the NE data are particularly homogeneous (Weber et al., 1994). Palecki and Barry (1986) obtained maximum correlation coefficients of 0.82, implying 67% explained variance, when correlating long-period (1909–1979) composite lake break-up data based on 7 lakes with mean air temperatures from the Jyväskylä meteorological station in southern Finland. In view of the fact that compositing the break-up data will tend to average out interannual fluctuations related to local weather effects (meteorological variables such as wind stress and precipitation tend to be much more spatially heterogeneous than air temperature), the Neuchâtel $r^2$ value of 61% compares well with this figure.

The relationship between the Lej da Murezzan break-up dates ($J_{\mathrm{thaw}}$) and the 51-day mean air temperatures at Bever ($\overline{T}_{108,51}$) and Neuchâtel ($\overline{T}_{103,51}$) is illustrated in Figure 6. It is evident from the scatter of the points that even local air temperatures

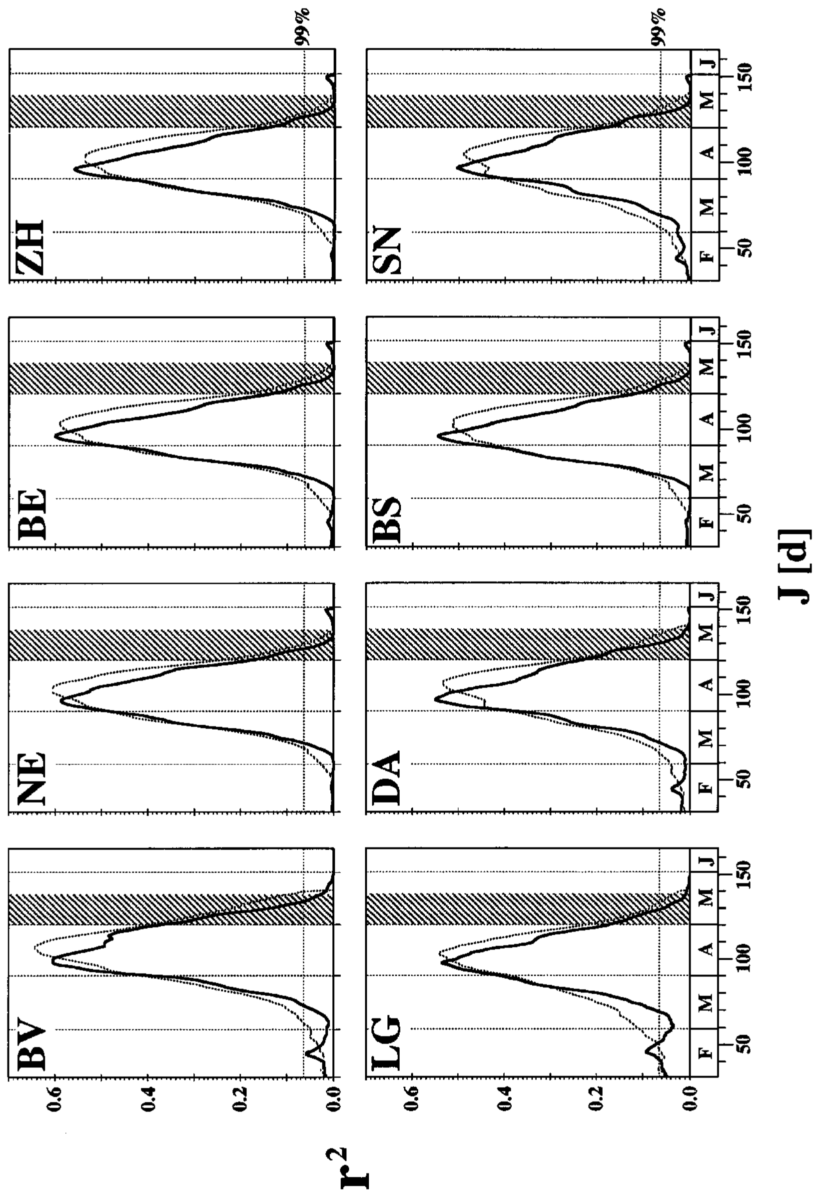

*Figure 5.* Coefficients of determination ($r^2$) between the break-up date of Lej da San Murezzan and the 31-day (solid line) and 51-day (dotted line) mean air temperatures at eight meteorological stations in Switzerland as a function of Julian day $J$ (data from 1901–1982). Shaded areas represent the usual range of break-up date (mean break-up date ± one standard deviation). See Figure 1 for the locations of the meteorological stations Bever (BV), Neuchâtel (NE), Berne (BE), Zurich (ZH), Lugano (LG), Davos (DA), Basle (BS) and Mt. Säntis (SN). 99% significance levels are shown as horizontal dotted lines.

cannot be predicted with great certainty solely on the basis of the thawing of lake ice, since, as illustrated in Figure 5, over a third of the variance remains unexplained. In spite of this, because it is the result of purely physical processes, the thawing of lake ice is probably still superior to most phenological indicators of air temperature based on biological processes. The linear regression lines expressing $J_{\mathrm{thaw}}$ in terms of $\overline{T}_{J,51}$ and vice versa

are also displayed in Figure 6 (Equations (i) and (ii), respectively). From Equation (i), a change of 1 K in $\overline{T}_{108,51}$ at Bever is predicted to correspond to a shift of 5.7 (±0.9) d in $J_{\mathrm{thaw}}$, whereas from Equation (ii) a shift in $J_{\mathrm{thaw}}$ of 1 d is predicted to correspond to a change of 0.11 (±0.02) K in $\overline{T}_{108,51}$ (95% confidence intervals in parentheses); results for $\overline{T}_{103,51}$ at Neuchâtel are very similar. Other authors have obtained results comparable to these. For lakes in southern Finland, for instance, Palecki and Barry (1986) found a 5 d shift in break-up to correspond to a change of about 1 K in April mean air temperature. For the Canadian Great Slave Lake region, Skinner (1993) found an 8 d shift in break-up date to represent a change of approximately 3 K in the May mean air temperature. According to Robertson et al. (1992), the mean break-up date of Lake Mendota shifts by 3.3 (±0.7) d per 1 K change in the January–March mean air temperature, and a shift of 1 d in the break-up date represents a change of 0.15 (±0.03) K in mean air temperature.

Relationship (ii) of Figure 6 was used to hindcast $\overline{T}_{108,51}$ at Bever and $\overline{T}_{103,51}$ at Neuchâtel from 1832–1994 (Figure 7). Many features of the measured data are reproduced quite well in the reconstructed series. This is especially true of the Bever data from 1915–1950. However, there are also several spurious features, e.g., the general underestimate of the amplitude of high-frequency (interannual) variations and (in the case of Bever, but not Neuchâtel) the underestimate of the rate of cooling which occurred during the 3 decades following the 1940s warm period. Such spurious features emphasize the fact that the existence of the unexplained variance must not be ignored in interpreting proxy data such as those presented here.

Having established a strong relationship between the Lej da San Murezzan break-up date and air temperatures all over Switzerland, the question arises of how strong the relationship is with air temperatures measured at sites even further afield. For comparison purposes, the Lej da San Murezzan break-up dates were therefore correlated with a further three air temperature data series, well-known from the literature: viz. the central England data series of Manley (1974) as extended by Parker et al. (1992); the Netherlands De Bilt series; and the mean Northern Hemisphere data of Jones et al. (1986). These data series are only available in the form of monthly means; therefore, to permit valid comparisons to be made the correlations of Figure 5 were repeated for the eight Swiss stations, but replacing the variable integrating time with the respective mean April air temperatures. This of course results in a substantial reduction in the amount of variance explained (e.g., from 64% to 51% for BV), but the correlations are still good (Figure 8). It is immediately obvious from Figure 8 that the interannual variation in the Lej da San Murezzan break-up

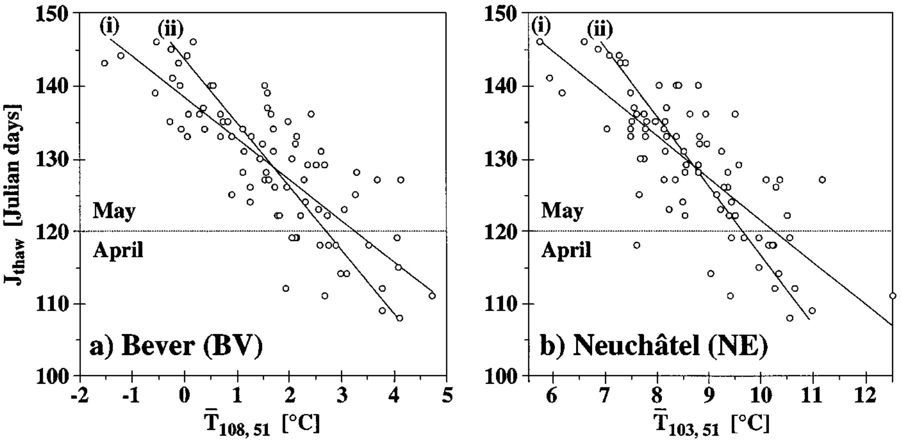

*Figure 6.* Least squares regressions relating the break-up date of Lej da San Murezzan ($J_{\text{thaw}}$) to the 51-day mean air temperature $\overline{T}_{J,51}$ at (a) Bever (BV), 7 km from the lake, and (b) Neuchâtel (NE), 230 km from the lake, based on 82 years of data (1901–1982). Equation (i) minimises the least-square error in $J_{\text{thaw}}$, and Equation (ii) minimises the least-square error in $\overline{T}_{J,51}$. All regressions are significant at the $p < 0.001$ level (ANOVA $F$-test).

(a) *BV*: $J = 108$, i.e., 18 April. $\overline{T}_{108,51}$ is the 51-day mean air temperature centred on 18 April, i.e., the mean air temperature from 24 March to 13 May:

(i) $J_{\text{thaw}} = 138.5\ (\pm 2.0) - 5.66\ (\pm 0.94)\ \overline{T}_{108,51}$ ($r^2 = 64.3\%$; $s = \pm 5.7$ d);

(ii) $\overline{T}_{108,51} = 16.3\ (\pm 2.4) - 0.114\ (\pm 0.019)\ J_{\text{thaw}}$ ($r^2 = 64.3\%$; $s = \pm 0.8$ °C).

(b) *NE*: $J = 103$, i.e., 13 April. $\overline{T}_{103,51}$ is the 51-day mean air temperature centred on 13 April, i.e., the mean air temperature from 19 March to 8 May:

(i) $J_{\text{thaw}} = 179.4\ (\pm 9.1) - 5.79\ (\pm 1.04)\ \overline{T}_{103,51}$ ($r^2 = 61.2\%$; $s = \pm 6.0$ d);

(ii) $\overline{T}_{103,51} = 22.2\ (\pm 2.4) - 0.105\ (\pm 0.019)\ J_{\text{thaw}}$ ($r^2 = 61.2\%$; $s = \pm 0.8$ °C).

$J_{\text{thaw}}$ is in d and $\overline{T}_{J,51}$ in °C; the figures in parentheses are 95% confidence intervals; $r^2$ = coefficient of determination; $s$ = standard error of the estimate.

date is governed primarily by large-scale, though not hemispherical-scale, climatic processes. Although, as expected, the highest proportion of variance explained is associated with the Swiss air temperature data ($r^2 = 37\%$ to 51%), the amount of variance explained by the United Kingdom and Netherlands data ($r^2 = 27\%$ to 29%) is substantial. Pfister (1992) has already shown that Manley's (1974) data correlate fairly well with monthly Swiss temperature indices; nevertheless, it is perhaps surprising that the amount of variance explained by the central England data is only about 10% less than that explained by the Mt. Säntis data, despite the fact that the Upper Engadine is over 1000 km from central England, but less than 100 km from Mt. Säntis. Even the Northern Hemisphere April mean air temperature data of Jones et al. (1986) are correlated significantly with the Lej da San Murezzan break-up dates, but explain only 4% of the variance (this significant correlation is presumably due to the fact that data from European stations are well-represented in the composite Northern Hemisphere series). Thus the thawing of the lakes of the Upper Engadine, and presumably, by analogy, the thawing of other Alpine lakes, depends principally on mesoscale climate. The break-up dates of Alpine lakes are

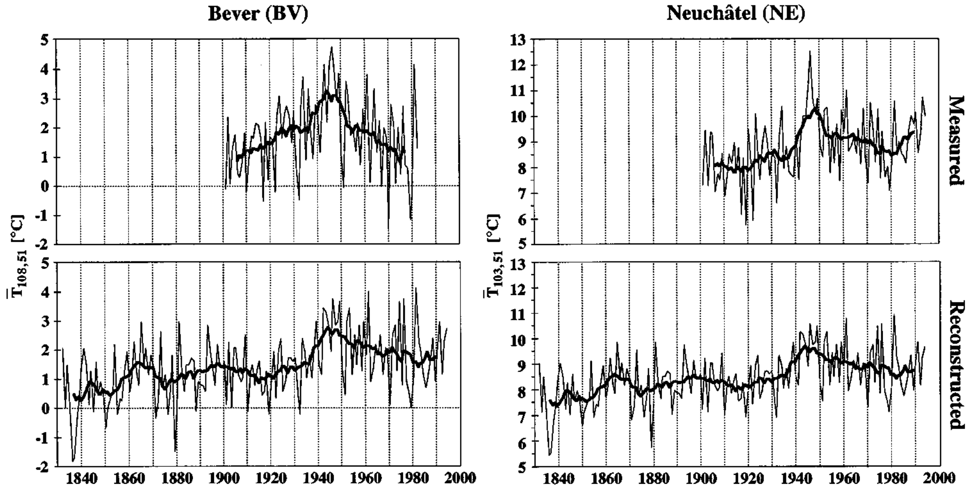

*Figure 7.* Time-series of 51-day mean air temperatures at Bever ($\overline{T}_{108,51}$: 24 March–13 May) and Neuchâtel ($\overline{T}_{103,51}$: 19 March–8 May) computed from measured data (above: 1901–1982) and reconstructed (below: 1832–1994) from the break-up dates of Lej da San Murezzan (Figure 2a) using Equations (ii) of Figure 6. The thick solid lines represent 11-yr running means.

therefore likely to comprise a useful set of proxy data for synoptic-scale, but not hemisphere-scale, meteorological processes.

## 6. The Possible Influence of Global Volcanic Activity on Break-Up Dates

A variety of empirical studies (Oliver, 1976; Mass and Schneider, 1977; Bray, 1978; Taylor et al., 1980; Self et al., 1981; Angell and Korshover, 1985; Mass and Portman, 1989) have demonstrated the occurrence of hemisphere-scale surface cooling lasting from 1–5 years subsequent to major volcanic eruptions. Such cooling occurs primarily because the increase in stratospheric sulphate aerosol concentrations known to follow many violent eruptions (Mossop, 1964; Castleman et al., 1974; Pollack et al., 1976; Hammer, 1977; Hammer et al., 1980, 1981; Pueschel et al., 1994; Zielinski et al., 1994) leads to increased backscattering of solar radiation, and consequently to a reduction in the amount of solar radiation entering the lower troposphere (Baldwin et al., 1976; Hansen et al., 1978; Rampino et al., 1985; Song et al., 1996). On 20 January 1835, an unusually violent eruption blew the top off Mount Coseguina, Nicaragua, ejecting large amounts of material into the atmosphere (Williams, 1952; Lamb, 1970). The resulting dust-veil index is the highest computed for any individual volcanic eruption from 1680 to 1970 (Lamb, 1970, 1972), including those associated with the much better known eruptions of Tambora (1815) and Krakatau (1883). In a statistical study of the effects on surface air temperatures of the six major volcanic episodes occurring from 1780–1980, Angell and Korshover (1985) concluded that the temperature decreases in the

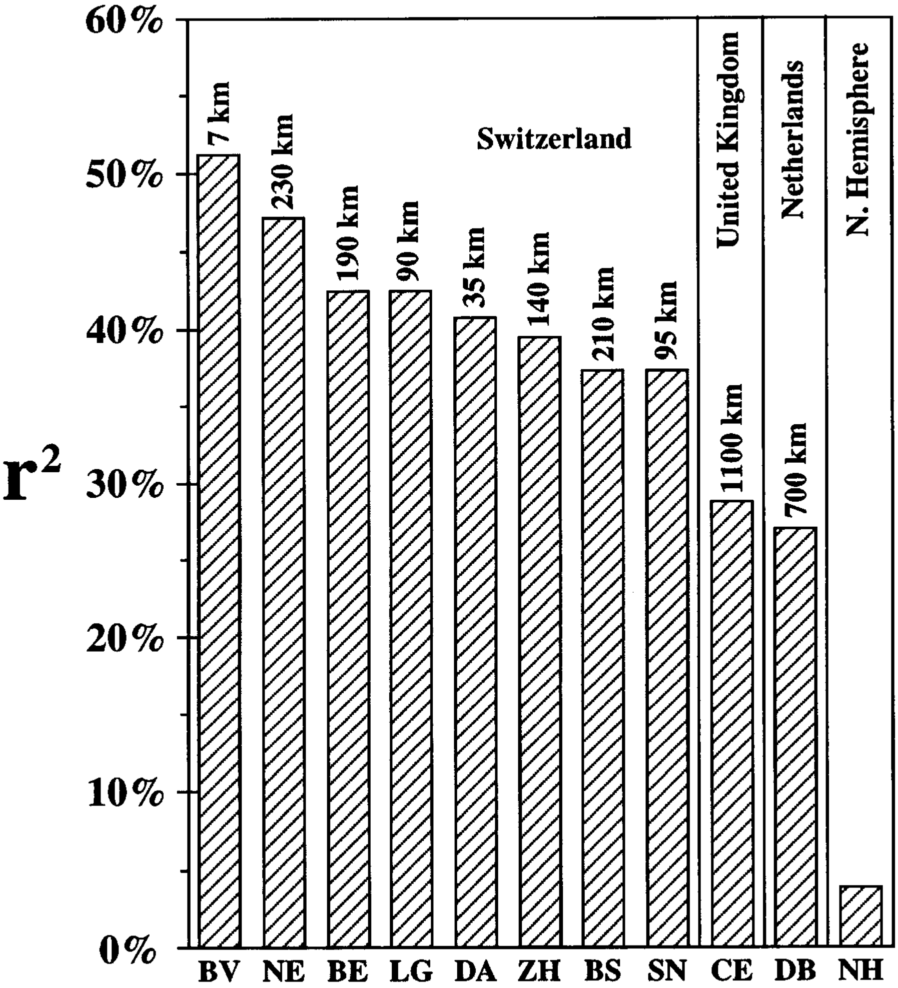

*Figure 8.* Coefficients of determination ($r^2$) between the break-up dates of Lej da San Murezzan and the mean April air temperature at the Swiss meteorological stations of Bever (BV), Neuchâtel (NE), Berne (BE), Lugano (LG), Davos (DA), Zurich (ZH), Basle (BS) and Mt. Säntis (SN), the central England mean April air temperatures of Manley (1974) as extended by Parker et al. (1992) (CE), the mean April air temperature at De Bilt in the Netherlands (DB) and the Northern Hemisphere mean April air temperatures of Jones et al. (1986) (NH), based on data from the period 1901–1982. Distances from the lake are given for each station.

Northern Hemisphere following the Coseguina eruption were substantially greater than those following the Tambora and Krakatau eruptions, being second only to those following the comparatively high-latitude Laki (Iceland) and Asama (Japan) eruptions of 1783. The cooling following the Coseguina eruption was sufficient to cause frost damage to bristle-cone pines over large areas of the western U.S.A. in 1837 (LaMarche and Hirschboek, 1984).

Documentary evidence from ships' log-books has shown that the most severe summer ice conditions in the western approach to Hudson Bay during the period 1750–1889 occurred during the year subsequent to the Coseguina eruption (Catchpole and Hanuta, 1989). Figure 2a suggests that this eruption may also have influenced the break-up date of Lej da San Murezzan, the only one of the lakes considered here for which relevant data exist. The latest break-up dates during the entire 163 years for which data from this lake are available occurred in 1836 and 1837 (8 June in both years*). These dates are 4 weeks later than the mean break-up date for the whole series (12 May) and 3 weeks later than the 11-yr running mean centred on these years; they translate to 51-day mean temperatures 2–3 K lower than usual in the middle of last century (Figure 7). Even in 1838 the break-up date (28 May) was still significantly later than average.

Self and Rampino (1988) and Self et al. (1989) suggest that the climatic significance of the Coseguina eruption may have been overestimated. Therefore, in view of the possibility that the lateness of break-up following the eruption may have been merely coincidental, further evidence linking break-up date to climatically relevant volcanic eruptions was sought. Simkin et al. (1981) have rated over 8000 historic and prehistoric volcanic eruptions in terms of a volcanic explosivity index (VEI) ranging from 0 to 8. From 1830–1980, 5336 eruptions were registered, of which 66 had a VEI of 4 or more (Newhall and Self, 1982). For the purposes of the present paper, a volcanicity index V for each year (counted from 1 April to 31 March of the following year) from 1832–1980 was constructed based on the list of eruptions with VEI $\geq 4$ given by Newhall and Self (1982) (after having corrected the eruption dates given for Novarupta, Tungurahua and Sheveluch from 1911, 1905 and 1969 to 1912, 1918 and 1964, respectively). V was assigned the value 1 if an eruption with VEI $\geq$4 occurred in that year and 0 otherwise, under the assumption that only eruptions with VEI $\geq$4 are climatically relevant, as only such eruptions are estimated to have definitely resulted in the injection of material into the stratosphere (Newhall and Self, 1982). This index was extended to 1993 by including additional information on eruptions occurring subsequent to 1980 given by Simkin and Siebert (1994). According to Newhall and Self (1982), the increase with time in the number of eruptions registered is an artefact due to an increase in the number of eruptions reported rather than in the frequency of eruptions actually occurring. The long-term increasing trend in V was therefore removed by linear detrending. The 11-yr running mean of the detrended time series of V (Figure 9b) gives a qualitative idea of the climatically relevant volcanism over a scale of decades.

Investigations of the acidity of Greenland ice cores have shown that periods of frequent and violent volcanic eruptions usually coincide with cold climatic conditions (Hammer et al., 1980, 1981). Comparison of the 11-yr running mean of the detrended time series of the break-up date $J_{\text{thaw}}$ (Figure 9a) with that of the

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[*] The one-day difference visible in Figure 2a is due to the fact that 1836 was a leap-year.

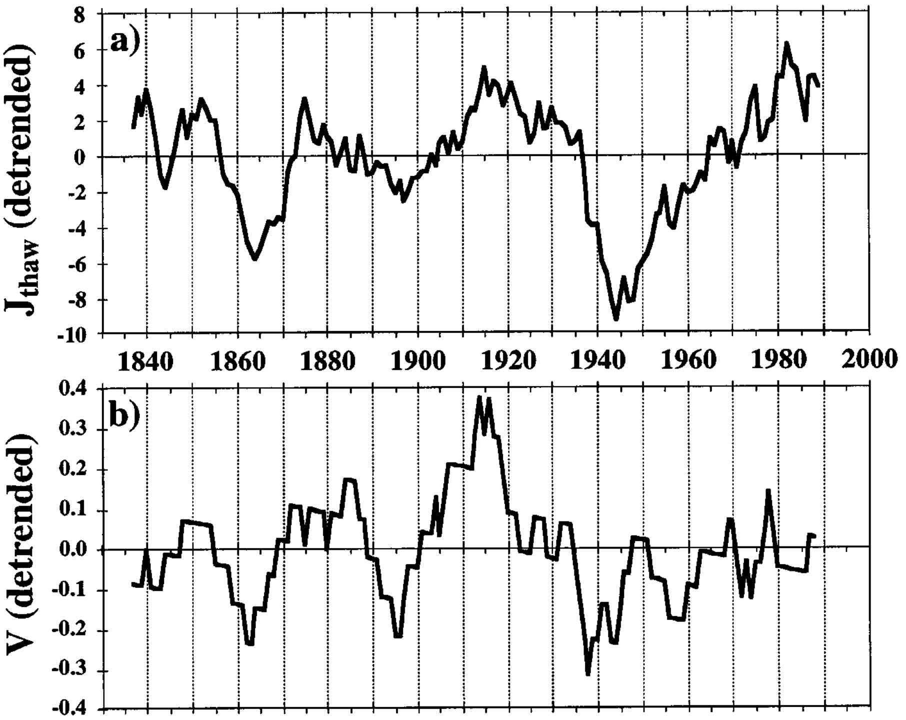

*Figure 9.* 11-yr running means of linearly detrended time series of (a) the break-up date of lake ice on Lej da San Murezzan ($J_{thaw}$) and (b) an index V of global volcanicity derived from the volcanic explosivity index (VEI) as described in the text.

corresponding time series of the volcanicity index V (Figure 9b) reveals a great degree of similarity between the two. Periods of earlier-than-average break-up date (e.g., during the 1840s, 1860s, 1890s and 1940s) tend to be associated with periods of low volcanic activity, during which sulphate aerosol concentrations in the stratosphere can be assumed to be low. Conversely, periods during which break-up date occurred later than average tend to be associated with higher volcanic activity. The similarity between the two series is especially pronounced during the first part of the series, but is much less so after about 1950. In particular, the period of low volcanic activity in the late 1950s is not well reflected in the Lej da San Murezzan break-up date.

If the lake break-up date is causally dependent to some extent on an enhanced concentration of sulphate aerosols in the stratosphere following climatically relevant volcanic eruptions, the detrended series of $J_{thaw}$ should lag the detrended series of V by about one to three years. This is because of the time necessary for the global dispersion of the sulphurous volcanic gases and for their photochemical conversion to sulphate aerosols (Castleman et al., 1974), and because of the continued presence of these aerosols during the few years subsequent to the eruption. Wendler and Kodama (1986) found the 1982 El Chichón eruption, for example, to have influenced the radiative regime in Alaska substantially during about 18 months, and Sedlacek et al. (1983) found the $e$-fold removal time of sulphate aerosols from the stratosphere following the 1974 Fuego eruption to have been 11.2 ± 1.2 months. Goodman et al. (1994) found an $e$-fold time of 216 days for the decay of sulphate aerosols from the 1991 Pinatubo eruption, with maximum concentrations 15 months after the eruption and sulphate mass loading still an order of magnitude higher than background values 2 yr after the eruption. Comparing Figures 9a and 9b, postulation of the existence of a 1–3 yr time lag between V and $J_{\mathrm{thaw}}$ does not appear unreasonable. Considering only the first part of the series, where the relationship between $J_{\mathrm{thaw}}$ and V is strongest, the cross-correlation function has its maximum at a lag of 2 yr (Figure 10). This time lag is the only one to yield a 99% significant correlation between the two series. Taking the entire series into consideration, however, reduces the correlation coefficient to the point where it is no longer significant at this level. Thus, if a relationship between break-up date and volcanism does in fact exist, the significance of this relationship is now markedly less than it was a century ago. If real, this may be the result of masking by increased anthropogenic effects. According to Sedlacek et al. (1983), although at least 58% of the sulphate aerosol present in the lower stratosphere between 1971 and 1981 was of volcanic origin, the anthropogenic contribution to stratosphere sulphate is increasing at a rate of 6–8% per year.

In contrast to Lej da San Murezzan, no clear relationship was found between the break-up dates of either Lake Kallavesi, Lake Baikal or Lake Mendota and the index V. It can be speculated that high-altitude lakes like Lej da San Murezzan may respond more sensitively to fluctuations in incident radiation associated with stratospheric aerosol concentrations than lakes at lower altitudes, where any such signal is liable to be masked to a certain extent by processes occurring in the lowermost troposphere. High-altitude lakes may therefore be sensitive indicators not only of climatically-relevant changes in stratospheric sulphate aerosols associated with volcanic eruptions, but also of those associated with human activities.

## 7. Summary and Conclusions

Since the first half of last century, Lej da San Murezzan has exhibited a long-term trend to earlier thawing of, on average, 7.6 days per century. Purely statistically, this trend can be viewed equally well either as the result of gradual secular change or of abrupt changes between homogeneous climate regimes. In the latter case, three such regimes can be distinguished: 1832–1857; 1857–1932 and 1933–1994. The fact that trends of an overall magnitude similar to that found in the Lej da San Murezzan break-up dates are exhibited by series of break-up dates from other lakes and rivers in various parts of the world suggests that a long-term alteration in thawing patterns has been and is now occurring on a global scale. Because

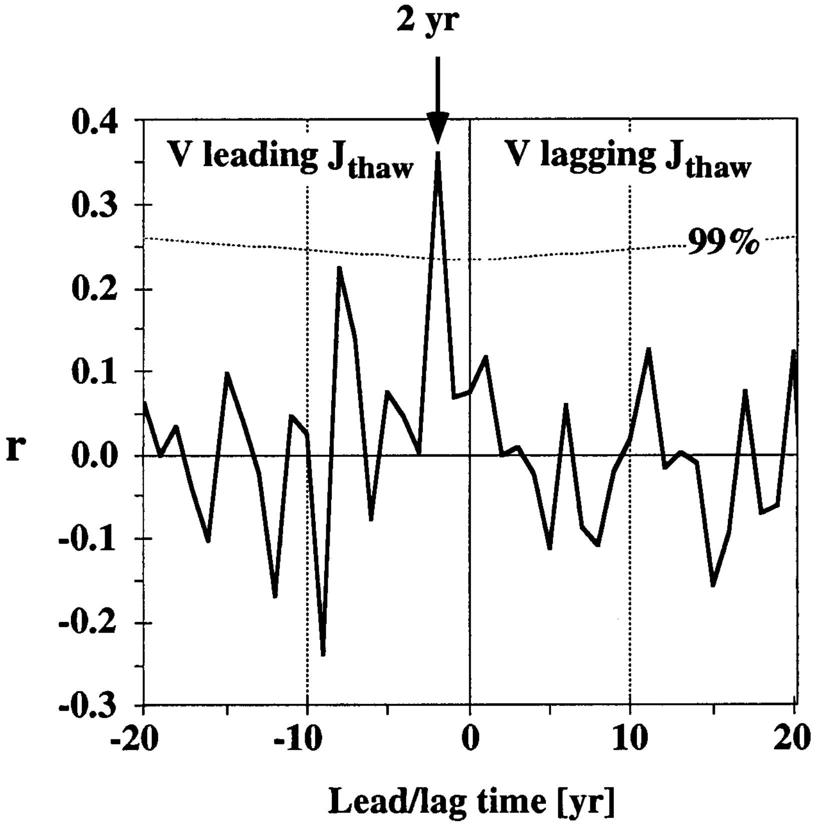

*Figure 10.* Cross-correlation function $r$ between linearly detrended time series of the index V of global volcanicity and the break-up date of lake ice on Lej da San Murezzan ($J_{\text{thaw}}$) for the first 100 yr of the series (1832–1931), showing the 2-yr lag between volcanicity and break-up date. The 99% significance level for $r$ (one-tailed $t$-test) is represented by the dotted line.

the presence or absence of ice cover radically affects atmosphere-lake coupling, shifts in freeze-up and break-up will result in shifts in the seasonal patterns of lake circulation and stratification. This is likely to have important consequences for aquatic ecosystems (e.g., George and Harris, 1985; Schindler et al., 1990).

Although the thawing of lake ice is governed by a multiplicity of (mainly) meteorological processes, purely empirical relationships involving some long-term integrative function of air temperature have often been found to explain much of the interannual variance in break-up date. In the case of the Upper Engadine lakes, break-up dates are highly correlated with integrated local surface air temperature centred approximately on the middle of April and integrated over 4–8 weeks; the best estimate of the response time of the 'lake ice thermometer' is 51 days for Lej da San Murezzan, with the proportion of shared variance being 64%. Since three empirical methods of relating break-up date to air temperature resulted in essentially the same proportion of explained variance, it is unlikely that this proportion can be increased substantially without taking further meteorological parameters into account. The fact that shared variance between pairs of neighbouring lakes is only 60–70% (Table Ib) suggests that the effect of factors such as local weather, degree of sheltering and lake morphometry on the timing of break-up of individual lakes should not be neglected.

Despite this caveat, comparisons of the Lej da San Murezzan break-up dates with mean surface air temperatures from various stations in Switzerland and northwest Europe suggests that the thawing of Alpine lakes is determined largely by synoptic-scale meteorological processes. This underlines the usefulness of break-up dates as proxy data in the investigation of such processes. However, it is evident that even on a local scale, problems may arise in reconstructing air temperature series solely on the basis of break-up dates, suggesting that a multi-proxy approach to air temperature reconstruction should be adopted whenever feasible to reduce the likelihood of spurious features appearing in the reconstructed series.

There is some evidence, especially in the early part of the record, that the timing of break-up on Lej da San Murezzan may be linked to changes in the radiation balance brought about by enhanced sulphate aerosol concentrations in the stratosphere following explosive volcanic eruptions. Break-up tends to be early (late) during periods of low (high) global volcanic activity, lagging the eruptions by about 2 yr. These results agree with investigations into the acidity of Greenland ice cores (Hammer et al., 1980, 1981), which suggest that cold climatic conditions are often associated with periods of frequent and violent volcanic eruptions. If break-up on Lej da San Murezzan is in fact reacting to stratospheric sulphate aerosol concentrations, this may highlight the importance of current research being conducted into high-altitude lakes as sensitive indicators of climatic change (e.g., Psenner and Schmidt, 1992).

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