ber 1999 in the Lootsberg Pass region and around the town of Bethulie using Jacobs staff. Interpretations of sedimentary facies were made in the field and transferred to the measured sections. Fossil material was collected at that time by the authors and by members of the South African Museum field teams. Stratigraphic sections include those of Lootsberg Pass, Old Lootsberg Pass, Wapatsberg Pass, Tweefontein, Bethulie, and Twin Rivers game park. Data on the occurrence of fluvial facies types from Precambrian river systems were derived from literature sources.

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Historical Trends in Lake and River Ice Cover in the Northern Hemisphere

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Freeze and breakup dates of ice on lakes and rivers provide consistent evidence of later freezing and earlier breakup around the Northern Hemisphere from 1846 to 1995. Over these 150 years, changes in freeze dates averaged 5.8 days per 100 years later, and changes in breakup dates averaged 6.5 days per 100 years earlier; these translate to increasing air temperatures of about 1.2°C per 100 years. Interannual variability in both freeze and breakup dates has increased since 1950. A few longer time series reveal reduced ice cover (a warming trend) beginning as early as the 16th century, with increasing rates of change after about 1850.

Calendar dates of freezing and thawing of lakes and rivers were being recorded by direct human observation well before scientists began to measure, manipulate, and model these freshwater ecosystems (*1*). The early observations were made for religious and cultural reasons (*2, 3*), for practical reasons concerned with transportation over ice or open water (*4*), and, apparently, simply out of curiosity. These simple records provide a seasonally integrated view of global warming from regions where early temperature measurements are sparse.

Here, we present and analyze the trends from time series that are longer than 100 years on lakes and rivers around the Northern Hemisphere. Thirty-nine time series are available for the 150-year period from 1846 to 1995 (*5*); three sites from Russia, Finland, and Japan with records beginning before 1800 are also available. The "freeze date" is defined as the first date on which the water body was observed to be totally ice covered, and the "breakup date" is the date of the last breakup observed before the summer open-water phase (*6*).

Between 1846 and 1995, 38 of 39 records change in the direction of later freeze dates (14 of 15) and earlier breakup dates (24 of 24) (Fig. 1 and Table 1) (*7*). The single exception, Lake Suwa, Japan, freeze dates, was not significant ($P = 0.25$). Individual slopes (9 out of 15 for the freeze date and 16 out of 24 for the breakup date) were statistically significant ($P < 0.05$). Linear trends over the 150 years averaged a freeze date that was 5.8 days/100 years later (±1.9 days, confidence interval 95%) and a breakup date that was 6.5 days/100 years earlier (±1.4 days, confidence interval 95%).

Slopes did not differ statistically between freeze and breakup dates (matched pair t test; $n = 12$; $P = 0.37$), among latitudes, between North America and Eurasia, nor between rivers (7.8 days/100 years) and lakes (5.9 days/100 years) (t test; $n = 7, 30$; $P > 0.25$). The overall rate of change for the Northern Hemisphere has been 6.2 days/100 years between 1846 and 1995, including all records except Toronto Harbor (Table 1) and giving equal weight to freeze and breakup.

The few records before 1846 suggest that long-term changes toward later freezing and earlier breakup dates were already occurring, but at slower rates, at sites as far apart as Europe and Japan. Three time series (one lake and two rivers) have records that are long enough to provide annual information on ice phenology trends before 1846 (Fig. 2 and Table 1).

For Lake Suwa, Japan, freeze dates became later over the 550-year record by 2.0 days/100 years ($P < 0.0001$) (Fig. 2). Slopes indicating later freezing for relatively unbroken windows of time ranged from 3.2 days/100 years (1443 to 1592) to 20.5 days/100 years (1897 to 1993). Additional evidence from Lake Suwa comes from the ice cover occurrence data. Lake Suwa was ice covered for 240 out of 243 winters (99%) from 1443 to 1700 but only for 261 out of 291 winters

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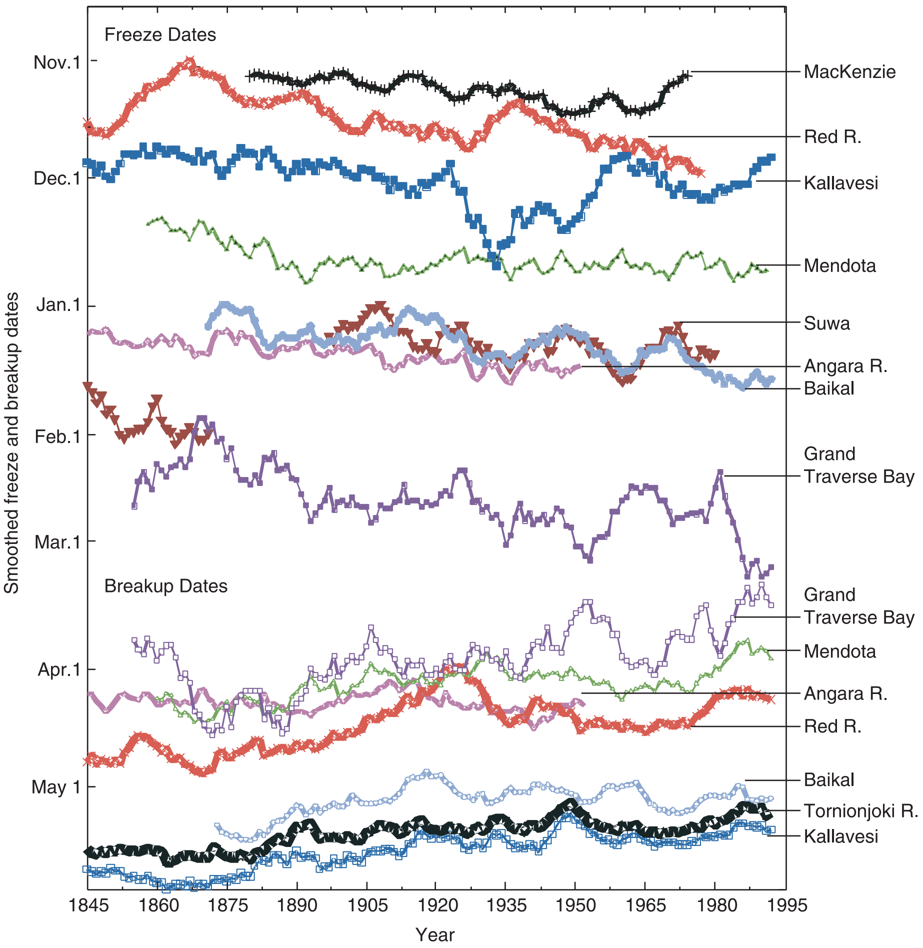
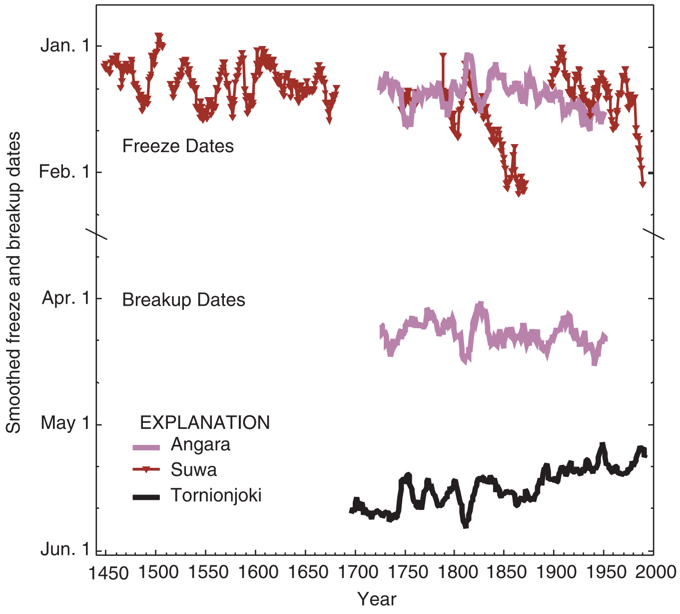


Fig. 1. Time series of freeze and breakup dates from selected Northern Hemisphere lakes and rivers (1846 to 1995). Data were smoothed with a 10-year moving average. Locations and related information are in Table 1.

Fig. 2. Time series of freeze and breakup dates for Lake Suwa (Japan), the Angara River (Russia), and Tornionjoki River (Finland), with records beginning before 1800. Data were smoothed with a 10-year moving average.



(90%) from 1700 to 1985 (χ^2 test; $P < 0.0001$). A reversed trend toward earlier freezing dates is apparent from about 1872 to 1897 (Fig. 2) and produces the single exception for slopes (Table 1) for the 150-year period from 1846 to 1995. This period is inconsistent with the trends toward later freezing dates for the rest of the Lake Suwa time series. The period includes 25 years of missing data, a time of social change, adjustments to the Japanese calendar, and, perhaps, anthropogenic influences.

Tornionjoki River, Finland, has a persistent long-term trend toward earlier breakup dates throughout the entire record (1692 to 1995) (Fig. 2). Slopes were significant for each 150-year interval tested, and they ranged from 3.7 days/100 years (1701 to 1850) to 6.6 days/100 years (1846 to 1995). Human influence on this record should be small; a single power plant is located on a tributary that represents only 3% of the catchment area.

Data for the Angara River, Siberia, suggest that the trend for later freezing began near 1850 (Fig. 2). Breakup data exhibited no long-term trend.

An additional data set of total ice cover is available for Lake Constance in central Europe from the 9th through the 20th centuries (*2*); it indicates cooler winters from the 13th through the 16th centuries. The criterion for "total ice cover" was a walk across the ice of the main basin to transport a Madonna figure between two churches: one in Germany, the other in Switzerland. The figure remained on one side of the lake until the next ice-covered winter, when it was possible to carry it back again. The number of winters with ice cover increased from 1 out of 100 years to 7 out of 100 years from the 12th through the 15th centuries, decreased from 7 out of 100 years to 1 out of 100 years from the 16th through the 18th centuries, and was 0, 1, or 2 out of 100 years in earlier and later centuries. The recent 150-year trends of later freeze and earlier breakup dates are not detectable with this coarser level of data.

The change in freeze and breakup dates over the 150 years from 1846 to 1995 corresponds to an increase in air temperature of ~1.2°C/100 years. Typical values for conversions of the change in ice cover to the change in air temperature are near a 0.2°C per day change in the phenological date for many lakes and rivers around the Northern Hemisphere (*8*–*15*).

Ice phenologies integrate change over an 8-month window (October through May). Ice freeze and breakup dates correlate most strongly with air temperatures in the month or two before the event (*9, 16*–*18*). In more northern areas, such as Lake Kallavesi, Finland, freeze dates reflect the climate prevailing around October to November (Fig. 1, freeze dates). However, in more southern areas such as Grand Traverse Bay, whose connection to the large Lake Michigan also delays freezing (*19*), freeze dates reflect the climate from January to February (Fig. 1, freeze dates). Similarly, breakup dates reflect February to March climates in more southern areas, such as Lake Mendota in Wisconsin,

Table 1. Linear trends in freeze and breakup dates for lakes and rivers in the Northern Hemisphere with >100 years of data from 1846 to 1995. Trends are for all available data in the 150 years. All sites are lakes unless specified. I.D., identification number. Location abbreviations are as follows: NT, Northwest Territories; MB, Manitoba; MN, Minnesota; WI, Wisconsin; ON, Ontario; NY, New York; ME, Maine; and NB, New Brunswick.

I.D.	Site	Location	Freeze date				Breakup date			
			Number of years	Years	Trend (later) (days/100 years)	*P* value	Number of years	Years	Trend (earlier) (days/100 years)	*P* value
				North America						
1	MacKenzie River	Canada, NT	10	1876 to 1978*	6.1	0.007				
2	Red River	Canada, Southern MB	16	1799 to 1981*	13.2	<0.001	180	1799 to 1993*	10.6	<0.001
3	Detroit	U.S., MN					101	1892 to 1994	12.9	0.003
4	Osakis	U.S., MN					121	1866 to 1989	4.3	0.086
5	Minnetonka	U.S., MN					112	1854 to 1989	2.0	0.444
6	Mendota	U.S., WI	14	1853 to 1995*	6.0	0.008	142	1852 to 1995*	7.5	0.001
7	Monona	U.S., WI	14	1851 to 1995	7.2	0.008	142	1851 to 1995	12.2	<0.001
8	Rock	U.S., WI					107	1886 to 1992	1.9	0.544
9	Geneva	U.S., WI					134	1862 to 1995	2.3	0.511
10	Grand Traverse Bay	U.S., MI	14	1850 to 1995*	11.4	0.006	146	1850 to 1995*	11.8	0.004
11	Toronto Harbor	Canada, Southern ON	11	1822 to 1920	36.9	<0.001	111	1822 to 1920	7.4	0.213
12	Oneida	U.S., NY					151	1845 to 1995	0.2	0.930
13	Otsego	U.S., NY	14	1849 to 1995	4.8	0.087	154	1842 to 1995	6.5	0.004
14	Schroon	U.S., NY					107	1872 to 1995	5.6	0.014
15	Cazenovia	U.S., NY	10	1844 to 1995	3.6	0.057	113	1838 to 1995	4.0	0.125
16	Moosehead	U.S., ME					149	1847 to 1995	5.6	<0.001
17	Miramichi River	Canada, NB					127	1822 to 1955	7.3	0.002
				Europe						
18	Tornionjoki River	Finland					304	1692 to 1995*	6.6	<0.001
19	Vesijärvi	Finland	10	1885 to 1995	0.7	0.874	110	1885 to 1995	7.1	0.005
20	Paijanne	Finland	10	1885 to 1995	1.9	0.697	108	1885 to 1995	8.3	0.002
21	Kallavesi	Finland	16	1833 to 1995*	5.3	0.038	163	1833 to 1995*	9.2	<0.001
22	Näsijärvi	Finland	16	1836 to 1995	5.7	0.055	161	1835 to 1995	8.8	<0.001
23	Lej da San Murezzan	Switzerland					164	1832 to 1995	8.1	<0.001
				Asia						
24	Angara River	Eastern Russia	23	1720 to 1955*	8.5		236	1721 to 1956*	2.1	0.465
25	Baikal	Eastern Russia	12	1868 to 1995*	11.0	<0.001	128	1868 to 1995*	5.1	0.004
26	Suwa	Japan	40	1443 to 1984*	−4.5	0.247				

*Shown in Fig. 1.

and April to May climates in the more northern areas, such as Kallavesi (Fig. 1, breakup dates).

Interannual variability in ice phenology dates also increased during the last half of the 20th century. For 184 lakes and rivers around the Northern Hemisphere (*20*), variability was 12% greater for freeze dates and 5% greater for breakup dates from 1971 to 1990 than during the period from 1951 to 1970. At Lake Mendota, the two earliest breakup events occurred in 1983 and 1997 during intense El Niño–Southern Oscillation events (*1, 21*).

For rivers and even for lakes with substantial stream inflow, the breakup date is strongly influenced by the timing, magnitude, and rate of spring runoff as well as by the nature of the freezing process and ice stratigraphy (*15, 22, 23*). Such processes, which are active during breakup, could explain why trends in ice phenology dates for Russian rivers from the 1930s to 1994 (*24*) were significant for the freeze date but not for the breakup date. For lakes, snow cover influences breakup dates (*25*); our observed trends toward earlier breakup dates may suggest some decline in snowfall.

Analysis of lake and river ice phenologies has a long history (*1, 26–28*). Their strengths as a climate proxy include the broad spatial distribution of sites, the annual resolution of the data, a longer record than other direct measures such as air temperature, and the relative ease and precision of measuring freeze and breakup dates both directly and by satellite (*29*). Their greatest weakness may be the absence of metadata for older records.

These long-term trends in observed lake and river ice phenologies provide evidence that freshwater ecosystems are responding to warming trends, and they increase confidence in the patterns of climate changes and global warming over the past 150 years. These increases are generally consistent with scenarios for greenhouse gas–forced climate warming (*30, 31*), but they may be related to other drivers, such as changes in solar activity (*30, 32*). The increased variability in ice dates may be related to greenhouse gas warming as well; scenarios from some climate models demonstrate an intensification of El Niño–like conditions with greenhouse gas forcing (*33*).

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5. The 39 time series from the 26 lakes and rivers in the Northern Hemisphere (Table 1) extend from 42.3° to 61.1°N in North America (Canada and the United States) and from 36.2° to 65.8°N in Eurasia (Finland, Switzerland, Russia, and Japan). The 150-year window (1846 to 1995) was chosen to maximize both the length of record and the overall number of sites with available data. The data from 1996 to 2000 are not available yet. Most of the water bodies are located in central or eastern North America or in Finland. Altitudes (above mean sea level) range from 3 to 1768 m, but only one site is above 1000 m. The lakes range in area from 0.8 to 31,500 km^2 (median, ~27 km^2) and in mean depth from 5 to 740 m (median, ~12 m). These time series are the longest records from a database that we aggregated from 746 lakes and rivers in the Northern Hemisphere. Data have been transferred to the World Data Center for Glaciology at the National Snow and Ice Data Center, affiliated with the U.S. National Oceanic and Atmospheric Agency (for additional information, see http://nsidc.org). Other analyses of these data related to El Niño, interdecadal changes, and other features will be published in a symposium (*1, 34*). The time series for Lake Suwa has been published in tabular form up to the winter of 1953–54 (*8*). More recent Lake

Suwa data are from various sources (*3*) [T. Kobayashi (National Research Institute of Fisheries Science, Kanagawa, Japan), personal communication in 1996].
6. For rivers and large lakes, the freeze and breakup dates are at the location of observation and not necessarily for the river drainage system or lake as a whole. Several definitions of freezing and breakup are used for rivers. The transition between ice on and ice off is usually rapid, at least in the smaller lakes. The measurement error should be relatively small when compared to the observed rates of change. In the few winters when a water body did not freeze over, we set the freeze date to the latest observed freeze date for that water body and the breakup date to the earliest observed breakup date for that water body. All time series have been corrected for calendar changes.
7. These series do not all cover the entire 150 years because missing data occur in many of them. We analyzed linear trends to facilitate synthesis. However, some of the changes also can be interpreted as abrupt steps. In Lake Mendota, rather abrupt changes were detected in the late 1800s at the end of the Little Ice Age (*8, 14, 16*) and again in the 1970s with the interdecadal shift in the strength of the Aleutian low (*1, 35*). Toronto Harbor was not included in any estimates of average rates of change nor in statistical tests, except for sign tests concerning the consistency in direction of change; the slope for its breakup was extreme (3.3 standard deviations from the mean slope). This urban harbor may have been influenced by local factors.
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36. D.M.R. produced the graphics, B.J.B. developed and managed the database, J.J.M. and R.H.W. organized the workshops, and all authors contributed data and improved the analyses, interpretations, and quality of the manuscript. We thank J. W. Mingle for assistance with manuscript preparation, those who contributed lake ice phenology data to the Lake Ice Analysis Group, the U.S. NSF's Division of Environmental Biology for supporting the research through grants DEB9632853 and DEB9416810, and W. Geller (Magdeburg, Germany) for calling attention to the Lake Constance data.

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Northridge Earthquake Damage Caused by Geologic Focusing of Seismic Waves

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Despite being located 21 kilometers from the epicenter of the 1994 Northridge earthquake (magnitude 6.7), the city of Santa Monica experienced anomalously concentrated damage with Mercalli intensity IX, an intensity as large as that experienced in the vicinity of the epicenter. Seismic records from aftershocks suggest that the damage resulted from the focusing of seismic waves by several underground acoustic lenses at depths of about 3 kilometers, formed by the faults that bound the northwestern edge of the Los Angeles basin. The amplification was greatest for high-frequency waves and was less powerful at lower frequencies, which is consistent with focusing theory and finite-difference simulations.

The usual expectation is that damage to buildings from an earthquake in an urban area will be greatest near the epicenter and will decrease steadily with increasing distance. Traditionally, anomalous large damage has been attributed to site effects, such as amplified shaking of compliant soil structures (*1*, *2*). For the Northridge earthquake (magnitude 6.7), soil effects in Santa Monica were found to be inadequate to explain the damage (*3*), because areas that had identical soils and were equidistant from the epicenter experienced less damage (Fig. 1).

The localized concentrations of high amplitudes of ground motion from the aftershocks of the Northridge earthquake suggested that focusing by deep geologic structures, which act like acoustic lenses, was likely to have caused the concentrated damage (Fig. 1) in Santa Monica during the main event (*4*).

Models have been proposed to test whether focusing can explain the aftershock amplitudes or the ground shaking from the main event (*5–11*). These models have used published cross sections (*12*) of the geology beneath Santa Monica, and although they confirm that focusing may occur, they either give amplitudes that are too small (*7*) or the presumed site of the focus is located too far south (*13*). The need to model high frequencies at fine grid spacing (10 m) is so computationally intensive that such simulations have been restricted to two-dimensional (2D) structures and to unacceptably low frequencies (*6*, *11*). Iterative inversion of the data is not yet feasible. However, the concentration of damage and the patterns of high aftershock amplification indicate that the proper treatment of the problem must take high frequencies into account, as well as the 3D subsurface structure. Our mapping of the underground geology is not sufficiently detailed to know, a priori, whether or not 3D focusing is important at any wavelength, much less at wavelengths on the order of 100 m. The geological cross sections are derived from logging of widely separated bore holes in the region (*12*, *13*) and from extrapolation from the surface geology. We turned the problem around by attempting to identify focusing structures from an inversion of the aftershock data. To do this, we have developed a 3D forward model of deep basin focusing, albeit a simple one, that is suitable for iterative inversion.

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