

Coherence of long-term lake ice records

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Introduction

Lake ice records are important in studies of climate (ASSEL & ROBERTSON 1995) and aquatic ecosystems (MAGNUSON et al. 1997). Further analysis of historical lake ice records is needed to improve knowledge of global cryospheric trends (FITZHARRIS 1996). An International Workshop on Lake Ice and Climate was held at the University of Wisconsin in 1996 (MAGNUSON et al. 2000) with the general goal of establishing a lake ice database and using it to analyze and interpret long-term ice data for their climatic and ecological content. The analysis described here is made under the auspices of an international "Lake Ice Analysis Group" (LIAG) established at that workshop. In this paper we present a preliminary analysis of 1) variations of long-term average ice-on, ice-off, and ice duration with latitude, and 2) an index of the coherence of ice event dates among five sites over the Northern Hemisphere with relatively continuous records from 1850 to 1995. Our objective is to provide information useful for the assessment and analysis of climate variability, climate change, and aquatic systems.

Data

Sites with 70 years or more of ice event dates, with no more than 10 years of missing data, were selected from the LIAG database. These criteria insured relatively long-term averages at each site for ice-on and/or ice-off dates. Some sites had ice-on dates only, some ice-off dates only, and some both ice-on and ice-off dates. The majority of the sites were located in eastern North America and Finland. The sites in western North America were rivers, and there were four sites in Russia and one in Japan. The majority of North American sites are south of 45 °N and the Finnish sites, which make up the majority of all sites, are located north of 60 °N.

Results and discussion

Variation of long-term average ice event dates with latitude

Long-term average dates were calculated for each ice event at each site (not shown for the sake of brevity). Regression analysis of latitude vs. ice event date (Table 1) shows a statistically significant linear trend (95% level), consistent with that noted by WYNNE et al. (1998). Ice-on dates are 1.7 days earlier, ice-off dates 1.4 days later, and ice duration 3.4 days longer per degree increase from about 40–65 °N. The linear regression analysis is biased by the larger number of sites in Finland relative to North America. For this reason, a linear regression analysis of ice event values with latitude for all North American (NA) sites were combined in one group, and for all Finnish and Russian (F&R) sites in another group. The results (Table 1), with the exception of the ice duration, lend credence to the results using all sites. The cause of the large differences between regional values and those determined using the values of ice duration from all sites is not known.

ASSEL et al. (1995) found that within a relatively small latitude range (43–47 °N) site physical limnology characteristics (water depth, water motion) and influence of the Laurentian Great Lakes were responsible for large local variation in ice-on and ice-off dates. Thus, local variations from the general linear trend in ice event dates with latitude can be large and lower the correlation of ice event dates with latitude. If we consider the standard error (S.E.) of estimate for the linear regression trend line as an index of the coherence of ice event date with latitude (Table 1), the coherence of the ice-on

Table 1. Regression analysis of ice-on, ice-off and ice duration with latitude.

Ice event	Coefficient of latitude*	Coefficient of intercept	R	S.E.	No
Ice-on	1.72	435.6	0.66	13.7	71
Ice-on NA	2.27	456.6	0.62	22.0	15
Ice-on F&R	2.55	488.7	0.73	9.5	56
Ice-off	1.39	407.7	0.88	6.3	94
Ice-off NA	1.23	415.6	0.42	8.9	38
Ice-off F&R	1.98	374.1	0.77	3.6	56
Ice-duration	3.36	-43.6	0.82	16.1	58
Ice-duration NA	6.11	-162.9	0.62	27.5	12
Ice-duration F&R	6.91	-264.5	0.90	7.55	46

R, % sum of squares accounted for by regression; S.E., the standard error of estimate; No, the number of observations; NA, North American sites; F&R, Finland and Russian sites; *coefficients significant at the 95% level.

dates with latitude is lower (S.E. 13.7) than that of ice-off dates with latitude (S.E. 6.3). The significance of the lower coherence for ice-on dates with latitude is that the process of ice formation, primarily heat loss by the water mass of each site, is dependent upon local site factors (bathymetry distribution, water motion), while the physical processes involved in ice-off (primarily energy balance of the ice mass) are less site dependent.

Coherence of ice event dates

A five-site mean and variance were calculated for ice-on, ice-off, and ice duration (Red River, Lake Mendota, Lake Otsego, Lake Kallavesi, and Lake Baikal) for each winter from 1850 to 1995. These five sites were chosen because they have relatively complete records of *both* ice-on and ice-off dates, and Kallavesi and Baikal are located far from the North American sites and thus represent different geographic regions in the Northern Hemisphere within the scope of available data. Missing data was filled in using long-term means or data from nearby sites. The variance is an index of inter-site coherence during a winter, and the year to year change in variance represents inter-annual changes in inter-site coherence.

A 10-year moving average of the variance (Fig. 1) shows that the 1850–1995 inter-annual changes in inter-site coherence (variance) is smallest for ice-off dates, increases for ice-on dates, and is largest for ice duration. A different

set of sites may have shown some differences in trends due to differences in climate and site characteristics. Given this caveat, only the broad trends in Fig. 1 are discussed because they are more likely to be general in scope. The large decline in the variance of ice duration in the 1860s to the early-1870s and the lower average inter-site variance during the 20th century compared to the last half of the 19th century may be artifacts of the end of the little ice age. A similar trend was not observed in the ice-off date. An overall increase in variance (decrease in inter-site coherence) in ice-on, ice-off, and ice duration (starting in the 1960s for ice-off and in the 1970s for ice-on and ice duration) may reflect differential regional and seasonal warming in the overall contemporary Northern Hemisphere global warming trend (JONES et al. 1994) of the last 25–30 years.

Summary and conclusions

Long-term average ice-on dates, ice-off dates, and days of ice duration at lakes and rivers in the Northern Hemisphere show a significant linear trend with latitude. This is expected because of the general decline in surface air temperature going from lower to higher latitudes, and has been noted by other researchers (WYNNE et al. 1998). Local site factors (water depth, local climatic influences such as proximity to large bodies of water) contribute to the variability in the general latitudinal linear trends. These factors, corroborated in an earlier study (ASSEL & HERCHEL 1998), have a larger effect on ice-on dates

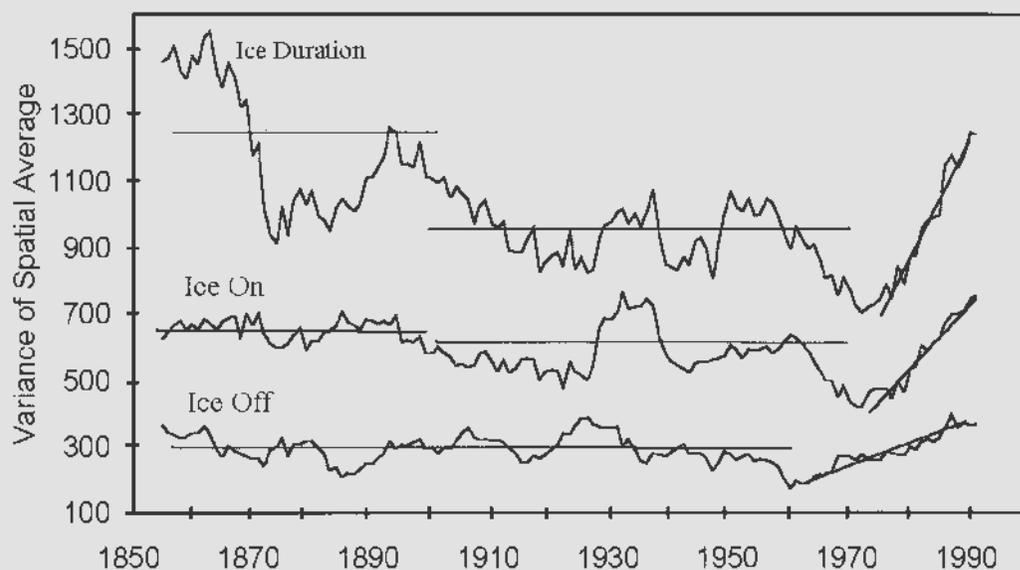


Fig. 1. Ten-year moving averages of inter-annual change in spatial variance from five-site averages of ice-on date, ice-off date, and ice duration. The five sites are: Red River (49.90 °N, 97.23 °W), Lake Mendota (43.10 °N, 89.40 °W), Lake Otsego (42.69 °N, 74.93 °W), Lake Kallavesi (62.83 °N, 27.67 °E), and Lake Baikal (51.66 °N, 105.00 °E). The horizontal straight lines show estimates of means, the diagonal straight lines show trends during the past 25–30 years.

relative to ice-off dates because the associated physical processes of ice formation have a greater dependence on water depth and site exposure. Analysis of the inter-annual change in inter-site coherence of ice-on, ice-off, and ice duration indicates ice duration has the largest variance and thus the weakest coherence (on a hemispheric scale) and the greatest inter-annual changes in coherence. The coherence of ice-off dates is the largest (variance is the smallest) and it changes the least over the period of record. This is likely due to the fact that processes of ice loss may be less sensitive to local site factors and more a function of local climate.

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