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Ice in Surface Waters

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Ice-on, ice-off, and ice duration for lakes and rivers with long-term records

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ABSTRACT: Decadal to century trends in ice event dates and ice duration are summarized from previous studies. The climatology of ice-on dates, ice-off dates, and ice duration are analyzed for several selected lakes and rivers in the northern hemisphere having long-term records. Long-term averages and standard deviations are summarized for each site and comparisons are made among sites to identify climate influence on ice event dates over the northern hemisphere.

1 INTRODUCTION

Lake ice is a sensitive indicator of climate and climate trends. Ice formation and loss are indices of integrated air temperature over late-fall-to-winter, and winter-to-spring periods (Assel & Robertson 1995, Skinner 1993, Palecki & Barry 1986). Lake ice also affects the ecosystem of lakes by acting as a filter for transmission of photosynthetically available radiation (Bolsenga et al. 1992), by effecting biological activity under the ice, and by affecting the lake fishery (Magnuson et al. 1997, Schindler 1990, Vanderploeg et al. 1992, Taylor et al.1987, Meisner et al. 1987). The impact of lake ice on aquatic systems in North America has been discussed in a recent (1994) symposium on regional assessment of freshwater ecosystems and climate change and presented in special issues of two journals: *Limnology and Oceanography* (vol. 41, No. 5 1996), *Hydrological Processes* (vol. 11, 1997). Changes in lake ice during the 20th Century, its sensitivity to climate change, the impact of future climate change on lake ice, and its impact on lake ecosystem and human activity, were discussed in the 1995 International-Governmental Panel on Climate Change Report, (Fitzharris 1996). Future work recommended by Fitzharris (1996) included the need for further statistical analysis of existing databases to improve knowledge of cryospheric trends. More recently (October 1996), an International Workshop on Lake Ice and Climate was held at the Trout Lake Biological Station of the University of Wisconsin (John Magnuson, - pers. comm.). The objectives of that workshop [namely: 1) to develop a database on lake ice phenology for the northern hemisphere, 2) assess lake ice records as indicators of climate variability and change, as well as the pattern of those changes across the northern hemisphere, 3) determine the relative impacts of lake location, elevation, morphometry, and local climate on ice thermodynamics using both empirical and process modeling approaches, and 4) to gain a fuller understanding of how changes in climatic forcing may affect aquatic ecosystems globally through changes in ice cover] directly address the need identified by Fitzharris (1996). The work presented here has its origins in a Lake Ice Analysis Group (LIAG) that was established at that workshop. In this paper decadal to century trends in ice event dates are reviewed from previous studies. The long-term average ice-on dates, ice-off dates, and ice duration are analyzed for several selected lakes and rivers in the northern hemisphere from the LIAG data base. A comparative analysis is made of the influence of site geographic position relative to the other sites, and by implication of climate, on the long-term average ice event dates and variation of those dates.

2 REVIEW OF PREVIOUS STUDIES

Analysis of the river and lake ice records in Europe, Asia, and North America demonstrate a general trend of later ice-on and earlier ice-off dates going from the 19th to 20th centuries. The end of the 'Little Ice Age'

(LIA) during the 19th century and subsequent warming during the 20th century is the primary cause of this trend. The LIA refers to a period of below-normal air temperatures that started in the mid-15th to mid-16th century (depending upon location), lasted until the mid-19th century, and was not continuous in its temporal or spatial domains. Differences in the temporal and spatial pattern of lake ice formation and loss trends over the northern hemisphere are due to differences in: 1) regional warming, and 2) the physical characteristics and exposure of each site within a region.

2.1 *Specific Studies*

Williams (1970) found ice-off dates were 10-to-15 days earlier in the mid-20th century compared to the 1870s at four distant sites: 1) the River Neva (in the Former Soviet Union), 2) Lake Kallavesi (in Finland), 3) Lake Mendota (USA- in Wisconsin), and 4) Saint John River (Canada in New Brunswick). Kuusisto (1987), analyzing ice-on and ice-off records starting in the 1830s found the duration of ice cover decreased around 1900 at two Finnish lakes and at 1920 at a third lake in Finland. Assel et al. (1995) and Assel and Robertson (1995) found that for the Laurentian Great Lakes of North America ice-on dates became 8-12 days later and ice-off dates became 7-11 days earlier after 1890, a secondary decrease in ice-off dates of about 7 days occurring during the 20th century. The second decrease occurred during the 1940s at deep embayments of the Great Lakes and in the 1980s at shallow embayments and at smaller inland lakes in the region. Shimaraev et al. (1994) observed a trend for shorter ice duration in the long-term (1869-1994) record of ice-on and ice-off dates for Lake Baikal during the 20th century and especially during the last 20-30 years. Zachirsson (1989) found that decadal average ice-off dates for the Torenalven River (Finland) was 4 days above the long-term mean (LTM) from 1700 to 1740, fluctuated above (+4 days) and below (-3 days) the LTM average from 1750 to 1870, and were below the LTM (-2 to > -5 days) from 1880 to 1990; the LTM, May 16, was a 100-year average (1801-1900). Hutchinson (1957) observes that Lake Suwa Japan, did not freeze-up 27 of the 254 winters between 1700 and 1954 while it did not freeze-up in only 13 of the previous 257 winters (1443-1700); 1505-1515 was a mild period and it only froze over once, while between 1557 and 1700 it froze over every year. Rennie (1983) found that for the Red River at Winnipeg, Canada the median ice-on date was 12 days earlier, and the median ice-off date was 10 days later in the 19th century (1815-1900) relative to the 20th century (1901-1981). While Catchpole et al. (1976) found a general trend for earlier ice-on and earlier ice-off dates in the 18th century and a trend for later ice-on dates during the 19th century for sites in Hudson Bay based on ice-on and ice-off dates for winters 1714-1871.

3 THE ICE COVER DATA

The ice-on and ice-off dates used here were obtained from the LIAG database established at the International Workshop on Lake Ice and. These data came from a wide variety of sources and were contributed by workshop participants for the exclusive use of the LIAG for a period of 2 years, after which they will be made available to the public at large. The exact definition of ice-on (freeze-up) and ice-off (break-up or ice loss) was not available at most sites, therefore it was not feasible to adjust ice-on and ice-off dates to a common definition of these terms. Thus, by necessity, our analysis is qualitative in nature even though we use quantitative methods to identify similarities and differences. The data consists of ice-on and ice-off dates (year, month, day) and duration of ice. A second metadata set contains information on site type (river or lake, country, latitude, longitude, elevation, mean depth, maximum depth, and other ancillary data). In most cases the metadata was of limited use because it was incomplete. The location and mean lake depth (when available) are given in Table 1. We limited our analysis to sites with long-term records or portions of long-term records (on the order of 100 years or more) with only minor amounts of missing data (less than 5% of the record under study). Long-term mean ice event dates and standard deviation are compared among the sites using graphical methods.

4 LONG-TERM AVERAGE ICE EVENT DATES

The long-term mean ice-on and ice-off dates are given in Table 1. It must be noted that because the sites have different base periods, changes in climate may have affected long-term mean ice event dates differently at each site in Table 1. Despite this caveat and within the scope of the sites in Table 1 climatic and local site influences on the long-term mean ice event dates are evident as discussed below.

4.1 *Ice-on Dates*

In general ice-on dates are earlier at higher latitudes (Fig.1). Site depth and proximity to moderating effect of ocean are also important factors affecting ice-on dates. The earliest mean ice-on dates occur at the two sites in south central Canada followed by Lake Kallavesi (greatest northern latitude of the sites under study). In the case of Lake Kallavesi, surface level atmospheric circulation from the Atlantic Ocean toward Finland provides a moderating influence on air temperatures and a later ice-on date relative to the sites in south central Canada (see page 138, Peioxoto & Oort 1991). Lake Baikal, at about the same latitude as the Canadian sites, does not form ice until about 8 weeks later. The Angara River and the large heat storage capacity of Lake Baikal (average depth is 731 m) are the likely causes of this later ice-on date. The latest mean ice-on dates for the sites in Table 1 is for Grand Traverse Bay and is likely due to the combination of moderating effect of Lake Michigan on air temperatures and relatively large mean depth of the Bay itself.

Table 1. Long-term average and standard deviation of ice-on and ice off-dates and ice duration.

Location	Ice On* Avg. Sd	Ice Off* Avg. Sd	Duration* Avg. Sd	Period Record	Avg.*** Depth
Lake Otsego 42.69N 74.91W	377 15	468 12	91 21	1849-1995	25
Toronto Hbr. 43.65N 79.45W	353 20	453 18	100 33	1823-1919	<10
Grand Traverse Bay** 44.76N 85.62W	407 16	461 15	54 32	1851-1995	46
Lake Mendota 43.66N 89.40W	353 11	458 11	105 17	1856-1995	12
Red River 49.88N 97.15W	319 11	471 10	152 16	1860-1995	--
N. Saskatchewan Ri. 53.21N 105.68W	321 9	474 7	153 12	1899-1994	--
Lake Kallavesi 62.13N 24.91E	334 13	502 9	168 17	1833-1995	9
Lake Baikal 51.66N 105.0E	375 11	489 7	114 14	1866-1995	731

* Rounded to the nearest day, and days are since beginning of year, thus day 366 is January 1 of the next year.

** Winters in which Grand Traverse Bay did not freeze-up were not included in the mean.

***Mean depth rounded to nearest meter.

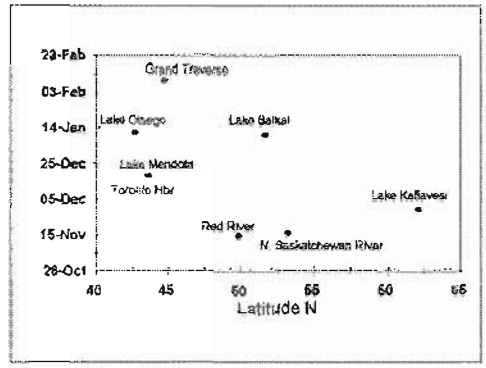

Figure 1. Ice-On Dates

4.2 *Variation in Mean Ice-on Dates*

The standard deviation of the ice-on dates from their long-term mean is on the order of 9-20 days. The lowest variation (9 and 11 days, Table 1), occurs at the sites with the most continental climate (Lake Mendota, Red River, North Saskatchewan River, and Lake Baikal). The larger variation in ice-on date (13-20 days) at other sites is likely due to greater variability in the frequency and intensity of continental and polar air masses in these regions due in part to their proximity to the Atlantic Ocean and Great Lakes.

4.3 *Ice-off Dates*

Ice-off dates are a function of the ice cover and the late-winter-early-spring energy budget of the ice cover. This is different than the ice-on dates, which are dependent upon the energy balance of the entire water mass. Thus, the ice-off dates exhibit a stronger correlation with latitude than ice-on dates (Fig. 2) and a lower range of dates for the sites under study. The latest mean ice-off date occurs on calender day 502 (L. Kallavesi) and earliest at Toronto Harbor, calendar day 453. The mean ice-off dates are about 2-6 weeks earlier for the lakes of North America compared to the sites in Finland and Siberia because of the lower latitude of the North American lakes.

4.4 *Variation in Mean Ice-off Dates*

The variation of ice-off dates is lowest at the higher latitude sites of Lakes Kallavesi, Baikal, and the North Saskatchewan River. The highest variation of ice-off dates occurs at sites connected to large bodies of waters (Toronto Harbor, Grand Traverse Bay) at the lower latitudes where the interannual variability of large scale weather patterns favorable for ice-off in combination with local climate and hydrodynamic

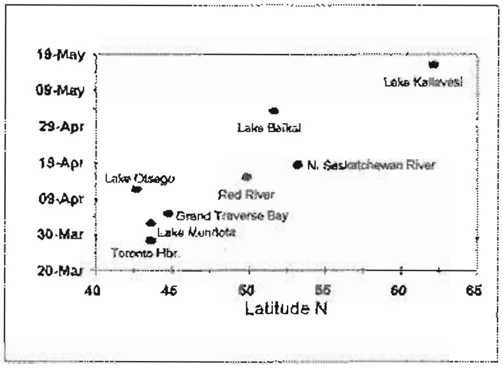

Figure 2. Ice-Off Dates

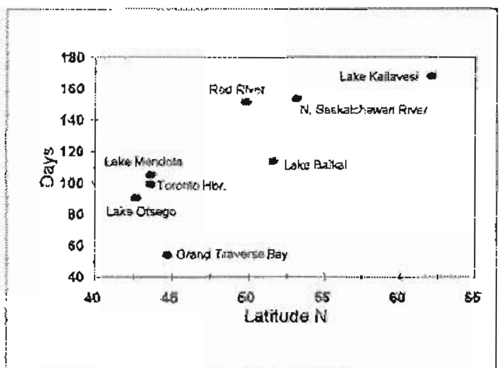

Figure 3. Ice Duration

influence of the larger body of water on ice-off dates are the likely causes (of the greater variability).

4.5 *Ice Duration*

The duration of ice cover at most sites also exhibits a correlation with latitude similar to that for ice-off dates (Fig. 3). The further north the longer the ice cover lasts. The large variation in duration at sites with similar latitude (Grand Traverse Bay vs Mendota, Toronto, Otsego) or (Baikal vs Red River, North Saskatchewan River) are due primarily to differences in ice-on date. Both Grand Traverse Bay and Lake Baikal are deep water sites that have later ice-on dates due to their greater heat storage capacity.

4.6 *Variation in Ice Duration*

The variation in ice duration is larger than either that for ice-on or ice-off dates. It is largest (21-33 days) for Grand Traverse Bay, Toronto Harbor, and Lake Otsego. These are deep water sites (Toronto Harbor is connected to Lake Ontario) exposed to milder air temperatures (all three sites are located south of 45°N). Variation of ice duration at the remaining sites range from 12-17 days. Most of these sites, with the possible exception of Lake Kallavesi have a continental climate.

5. SUMMARY AND CONCLUSIONS

Coherent trends in ice-on ice-off dates that are hemispheric in scale include earlier ice-on dates, later ice-off dates, and greater ice cover duration with increasing latitude. The variation of these trends for a given latitude is attributed to differences in regional climate and local site characteristics. Local site characteristics determine the sensitivity or reaction of a site to the hemisphere scale and regional scale climatic forcing. Thus, although ice-on and ice-off dates have a strong latitude component, site proximity relative to the oceans or large land mass, has a significant affect on ice-on dates with results such as the moderating effect of the Atlantic Ocean on winter air temperatures in Finland relative to lower air temperatures in south central Canada. The Canadian sites in this study are at a lower latitude than Lake Kallavesi in Finland, but they have earlier ice-on dates because of their continental climate. Local site physical characteristics influencing ice event dates include lake depth and water motion. Grand Traverse Bay has much later ice-on dates relative to Lake Mendota because of its greater depth and the moderating effect of Lake Michigan on air temperatures. The results presented here are more in the way of a first look at these data. We plan to make a more detailed analysis of the relationship between climate and lake ice and the coherence of lake ice records over the northern hemisphere in future studies.

6. ACKNOWLEDGMENTS

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