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LAKE ERIE ICE COVER CLIMATOLOGY -- BASIN AVERAGED ICE COVER: WINTERS 1898-2002

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TABLE OF CONTENTS

1. Introduction 4

2. Data and Analysis Methods 5
   2.1 Daily Ice Concentration 5
   2.2 Basin Average Ice Concentration 5
   2.3 Monthly Ice Concentration 5
   2.4 Annual Average Ice Concentration 5
   2.5 Dates of First Ice, Last Ice, and Ice Duration 6

3. Results and Discussion 6
   3.1 First Ice 6
   3.2 Last Ice 6
   3.3 Ice Duration 8
   3.4 Seasonal Average Ice Cover 8
   3.5 Monthly Ice Cover 10
   3.6 Daily Ice Cover 13

4. Summary 15

5. References 15

LIST OF TABLES

Table 1. Lake Erie Basins 5

Table 2. Statistics for Winters 1973-2002 7

LIST OF FIGURES

Figure 1. Lake Erie basins: west (WB) center (CB), east (EB), and bathymetry 4

Figure 2. Dates of first ice, 5-year centered running mean 7

Figure 3. Dates of last ice, 5-year centered running mean 8

Figure 4. Ice duration, 5-year centered running mean 9

Figure 5. Annual average ice cover, 5-year centered running mean 9

Figure 6. Monthly ice cover, 5-year centered running mean for the month of a) December, b) January, c) February, d) March, and e) April 10

Figure 7a. Seven-day moving average of daily median ice cover for west (WB), center (CB), and east (EB) basins of Lake Erie 13

Figure 7b. Seven-day moving average of observed daily maximum and minimum ice cover for west (WB), center (CB), and east (EB) basins of Lake Erie 14

Lake Erie Ice Cover Climatology – Basin Averaged Ice Cover: Winters 1898-2002

Raymond A. Assel

1. Introduction

Ice cover impacts the water balance of the lakes and lake flora and fauna by affecting energy and mass transfers from and to the lakes. Improved understanding of ice cover climatology is therefore needed for an improved understanding and forecasts of the winter lake ecosystem. The duration and extent of ice cover on the Great Lakes also has a major impact on the economy of the region by impeding and eventually stopping commercial navigation, interfering with hydropower production and cooling water intakes, and damaging shore structures. Assel (2003a) presents a climatology of Great Lakes ice cover for each Great Lake over the winters: 1973-2002 on a nominal spatial resolution of 2.5 km grid cells. The purpose of this report is to provide a different aspect of that climatology for Lake Erie, primarily, basin averages of ice concentration for the east, central, and west basins of that lake. This work is being done under the auspices of the Climatology of the Physical Environment in Lake Erie Project (http://www.glerl.noaa.gov/res/Task_rpts/ppschwab01-4.html) and as such is part of a coordinated effort to provide improved data for retrospective and interdisciplinary analyses of the relative roles of physical, chemical, and biological factors on the ecology of Lake Erie. Lake Erie is a good candidate for this research because it has a high population density, availability of long term data sets, a variety of physical, chemical, and biological forcing functions (including invasive species), and a wide variety of concerns including water quality (hypoxia/anoxia, harmful algal blooms,) water quantity (levels), and fisheries.

Spatial averages of ice concentrations for the west, center, and east basins of Lake Erie (Figure 1) are presented for the winter seasons 1898-2002. Daily basin-averaged ice concentrations are based on modeled data for winters 1898-1972 and on observed data for winters 1973-2002. Daily, monthly, and annual basin-averaged ice cover concentration, dates of first ice, dates of last ice, and ice season duration are calculated for each basin for each winter

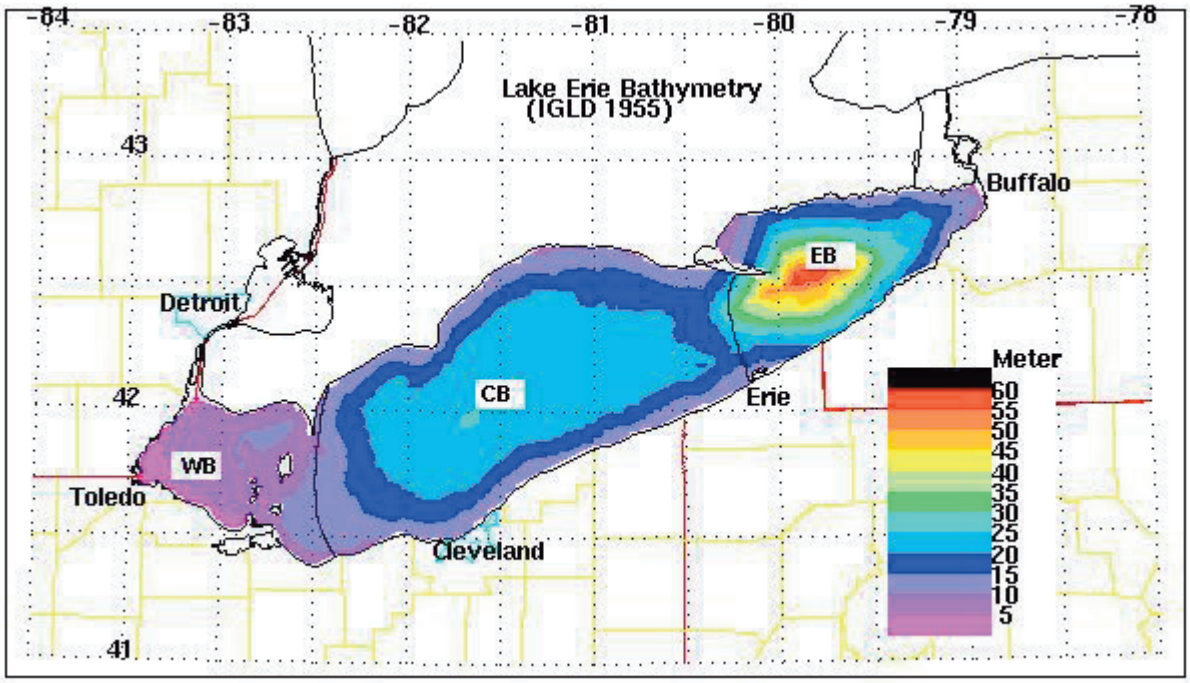

Figure 1. Lake Erie basins: west (WB) center (CB), east (EB), and bathymetry.

season from 1898 to 2002, as are computer animations that portray spatial patterns of the seasonal progression of ice cover extent for the 30 winters 1973–2002. All of these data are accessible as ASCII files and graphs on the Internet at: http://www.glerl.noaa.gov/rsch/erie/data/Spatial/Ice/Ice.html as part of the Climatology of the Physical Environment in Lake Erie Project, and are considered as part of this report although not shown here. In this report we summarize the data sources and methods used to create these data and present and discuss the results of a graphical analysis of selected spatial and temporal data characteristics.

2. Data and Analysis Methods

2.1 Daily Ice Concentration

ASCII grids of daily ice cover concentration for winters 1973–2002 are available at http://www.glerl.noaa.gov/data/ice/atlas/ice_charts/index.html, see Assel et al. (2002) for metadata. The daily ice concentration grids, nominal 2.5 km spatial resolution, were calculated by linear interpolation of ice concentration for each given grid cell between consecutive ice charts for a given winter season. No extrapolation was made prior to the first ice chart or after the last ice chart of each winter season. Daily ice chart observations usually start in the last half of December and usually end during late April to mid May (see Table 1 in Assel et al. 2003). The daily-averaged ice concentration grids for each winter season were used to create a computer animation of each winter from 1973 to 2002 as described in Assel and Norton (2001).

2.2 Basin Averaged Ice Concentration

An ASCII mask file was used to partition the daily ice concentration grids into a west, a center, and an east basin (Figure 1). Daily spatial-averaged ice concentration was then calculated for each lake basin. The average for the entire lake was calculated as the area weighted basin averages. The number of grid cells and average depth, rounded to the nearest meter, for each lake basin is given as Table 1.

Table 1. Lake Erie Basins.

	Number of Grid Cells	Average Basin Depth
West	708	8 m
Center	2039	19 m
East	830	26 m

The daily basin averages for winters 1898–1972 were abstracted from Assel (1990). These basin averages are based on a statistical empirical freezing degree-day model. Since these data are modeled, there are daily basin-averaged ice concentrations for each day of the winter from December 1 to April 30 for each winter season.

The ice cover model was also used to estimate potential Lake Erie ice cover under double CO_2 atmospheric concentration using data from GCM global warming scenarios. Needless to say, the average Lake Erie ice cover under double CO_2 warming scenarios is much less, ice duration is less, and the occurrence of winters without ice cover is greater. Readers interested in the results of this analysis are referred to Assel (1991) and Lofgren et al. (2002).

2.3 Monthly Ice Concentration

Monthly ice concentrations were calculated from the daily values for all winters (1898-2002). For the winters with observed ice cover concentration (1973–2002) if there were less than 25 days with data for a given month, no monthly average was calculated. This occurred most during the months of December and to a lesser degree for April during these winters.

2.4 Annual Average Ice Concentration

Two products were created for annual average ice concentrations, (1) average as the sum of the daily ice concen-

trations for a given winter (total ice) divided by the duration of ice cover, and (2) the total ice divided by 182 days (days between December 1 to May 31). Each average may be significant in analysis of the winter lake ecosystem. The total ice divided by the duration of days with ice is a metric of the total winter severity for only those days with ice, while the total ice divided by 182 days is a measure of mean daily ice cover severity over a standardized temporal base period and can be used more readily to compare different winter seasons.

2.5 Dates of First Ice, Last Ice, and Ice Duration

Computer files of the dates of first ice, last ice, and ice duration for winters 1973 -2002, and for winters 1898-1972 are abstracted from Assel (2003b) and Assel (1990), respectively, and used to calculate spatial basin averages for the first (last) date the spatial average ice cover concentration is greater or equal to 10% each winter season.

A 10% threshold is used because the original observations are only considered accurate to the nearest 10%. In addition, the term "open water" was used on many ice charts to indicate that less than 10% of the area was covered by ice. In some cases the lake was virtually ice free. Therefore, the 10% threshold value is a conservative estimate of the date of first reported ice. In addition, the standard error of estimate of the modeled ice cover data for each of the three lake basins was greater than 10% (Assel 1990).

The duration of ice cover (days) is the difference between the first date and the last date that the ice concentration is greater than or equal to 10%. If the first and last reported date of ice occurred on the same date, the duration of ice cover is set to 1. If no ice cover greater or equal to 10% was present for a given basin on a given winter, the duration is set to 0.

3. Results and Discussion

Temporal variations in basin-averaged ice concentrations for the 105 winters 1898 –2002 are portrayed by 5-year running means for dates of first/last ice, ice duration, annual averaged ice cover, and monthly averaged ice cover in Figures 2, 3, 4, 5, and 6, respectively. The first 5-year mean (1898-1902) is plotted on 1900, and the last 5-year mean (1998-2002) is plotted on 2000 in these figures. The differences in these variables among the three basins are discussed within the context of mean basin bathymetry, and winters in which some of the basins did not have ice cover (center basin: 1953, 1998, eastern basin: 1932, 1933, 1949, 1953). This resulted in local extremes in the smoothed data as described below.

3.1 First Ice

The shallower west basin is the first to form ice, Figure 2. The extreme late dates of first ice in the 1930s, the late 1940s to early 1950s, and late 1990s and early 2000s are due to winters without ice, the date of first ice for these winters was arbitrarily set to May 31. The cause of the gradual increase to a later date of first ice in the west basin from the late 1950s to the 1970s is not known, it may be an artifact of the blending of modeled and observed data. Dates of first ice in the west basin generally occur in the second half of December while dates of first ice in the center and east basins usually occur in January. Average dates for the contemporary 30-winter period 1973-2002 are given in Table 2. Dates of first ice trend toward later dates in the center and east basin from the late 1970s to 2002. The late 1970s and early 1980s was a period of above-average seasonal maximum ice cover in the Great Lakes (Assel et al. 2003). The winters in the 1980s and 1990s had several strong warm El Niño events (1983, 1987, 1992, 1998) and an exceptionally mild (non-El Niño) winter occurred in 2002. The combination of severe ice cover in the late 1970s and milder winters in the 1980s and 1990s explains the trends in the center and east basins. A similar trend is not observed in the west basin, because ice formation requires shorter periods of low air temperatures in the west basin due to its shallower depth and lower heat storage.

3.2 Last Ice

The effect of winters without ice cover in the early 1930, early 1950s, and late 1990s to early 2000s are associated with trends toward earlier ice loss dates as portrayed in Figure 3. Loss of ice cover occurs first in the west lake basin, followed by the center basin, and last in the east basin. The average date of last ice during the winters

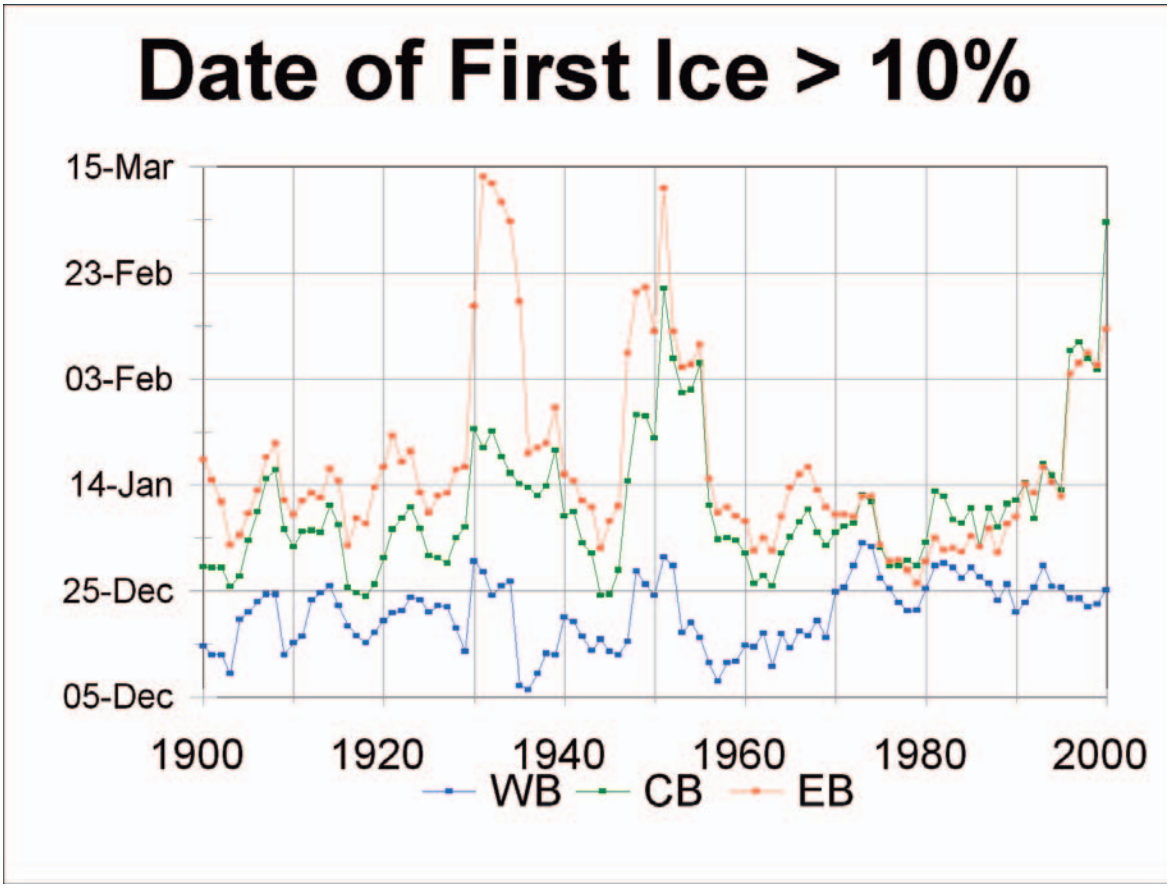

Figure 2. Dates of First Ice, 5-year centered running mean.

Table 2. Statistics for Winters 1973-2002*.

		Lake Basins		
		West	Center	East
First Ice	Average	25-Dec	07-Jan	06-Jan
	Std. Dev.	9.8	15.0	14.3
Last Ice	Average	15-Mar	23-Mar	31-Mar
	Std. Dev.	17.5	13.5	19.5
Duration	Average	80.3	69.9	82.3
	Std. Dev.	21.4	29.5	34.8
January	Average	61.7	39.3	36.6
	Std. Dev.	24.1	32.8	30.4
February	Average	69.0	65.9	64.9
	Std. Dev.	24.5	28.9	30.6
March	Average	30.8	36.7	50.4
	Std. Dev.	24.1	27.9	31.5
April	Average	3.5	4.3	11.8
	Std. Dev.	4.8	6.0	14.2
Season**	Average	29.1	24.5	27.6
	Std. Dev.	11.6	13.7	16.5
Season***	Average	61.5	54.8	51.5
	Std. Dev.	15.8	22.0	21.3

* Units for first/last ice and ice duration are days.
Units for ice cover data is percent ice cover concentration.
** Seasonal total ice divided by 182 days.
*** Seasonal total ice divided by duration of days with ice cover.

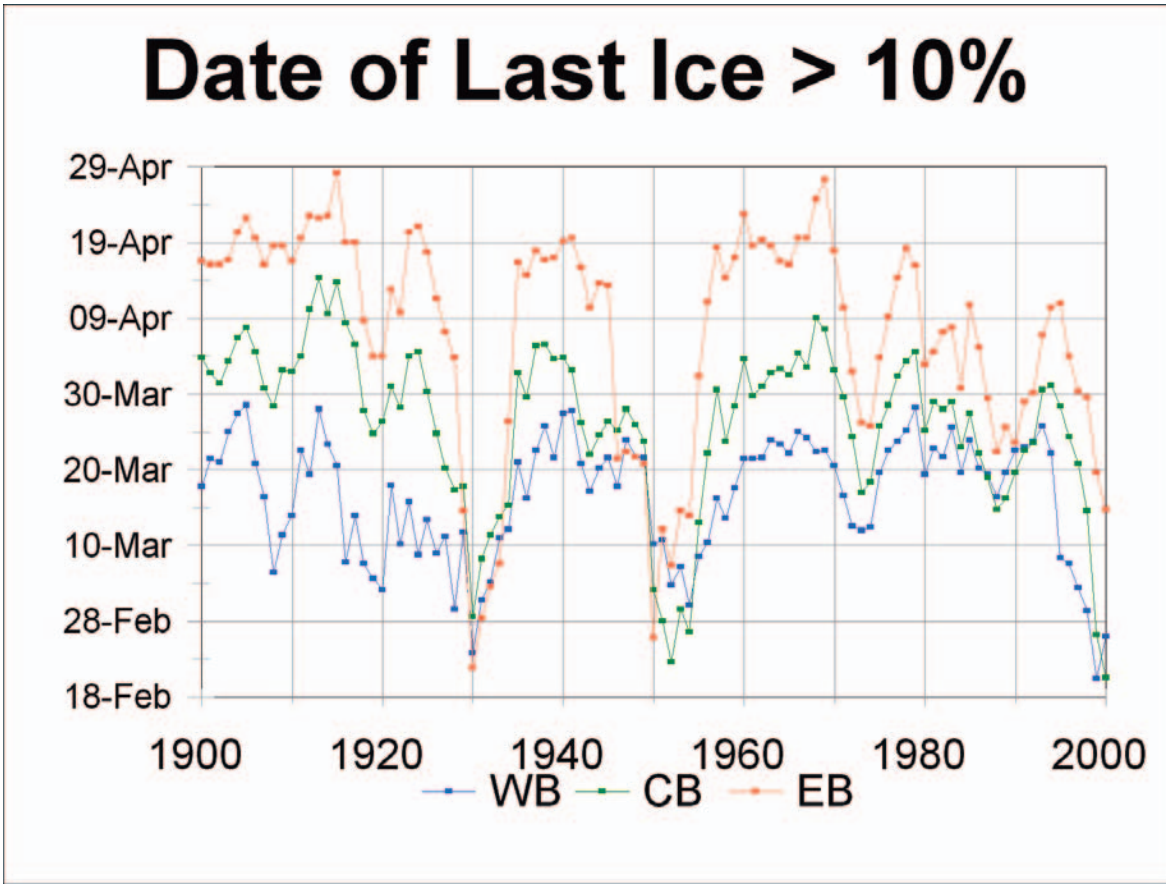

Figure 3. Dates of Last Ice, 5 year centered running mean.

1973-2002 occurred during the last half of March (Table 2), i.e., around mid-March in the west basin to the end of March in the east basin. Variations around these dates indicated by the standard deviation are on the order of 2 to 3 weeks. There is a marked trend toward earlier dates of last ice starting in the late 1960s and continuing through the end of the century. This decline is associated with a general increase in spring temperatures and earlier ice out dates in the Great Lakes during the last 40 winters (Hanson et al. 1992). This is part of a century scale trend toward earlier ice loss dates in the Northern Hemisphere that started in the mid 1800s marking the end of the little ice age (Magnuson et al. 2000).

3.3 Ice Duration

The earlier ice formation in the west basin tends to be offset by earlier ice loss there, so the duration of ice cover, unlike dates of formation and loss, appears to be similar among the three basins (Figure 4). Some exceptions occurred from 1900 to about 1915 and 1960 to about the mid 1980s where the east basin tended to have greater duration of ice cover. In terms of temporal trends, there is a marked trend for lower ice cover duration over the century, with a notable decline from the early 1960s onward with some reversal in the early and late 1970s. During the winters 1973-2002 it averaged near 80 days in the east and west lake basins and near 70 days in the center basin. The variation about these averages increases going from the west basin, where it is 3 weeks, to the east basin where is closer to 5 weeks (Table 2).

3.4 Seasonal Average Ice Cover

The effects of mild winters, e.g., winters without ice cover in center and east lake basins noted earlier and others with low ice cover, manifest themselves as local minimums on the plots of seasonal average ice cover on all three-lake basins (Figure 5). The winters of the early 1930s and early 1950s are more prominent on the east basin in the duration based seasonal averaged ice cover because the 182-day based seasonal averaged ice cover includes the default date for no ice cover, i.e. May 31. However, other local minimums in the curves and by implication mild

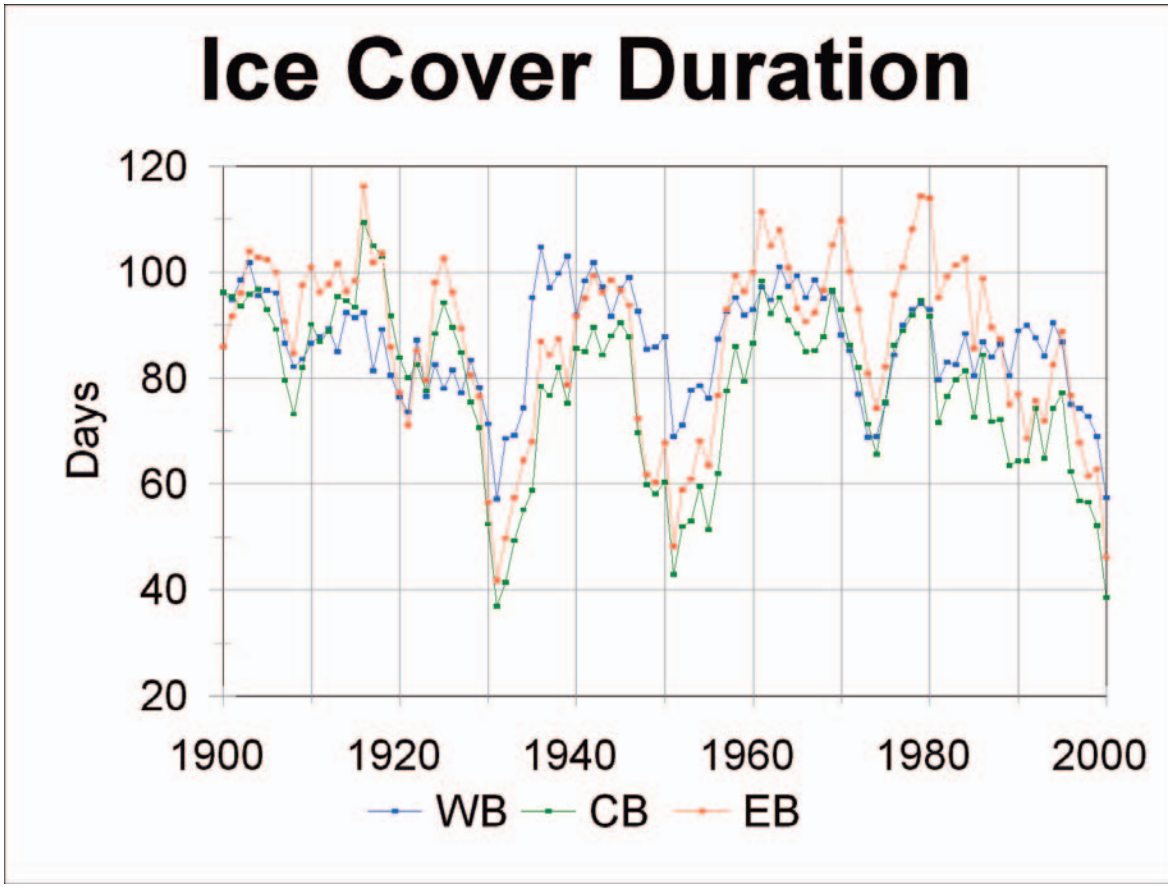

Figure 4. Ice Cover Duration, 5 year centered running mean.

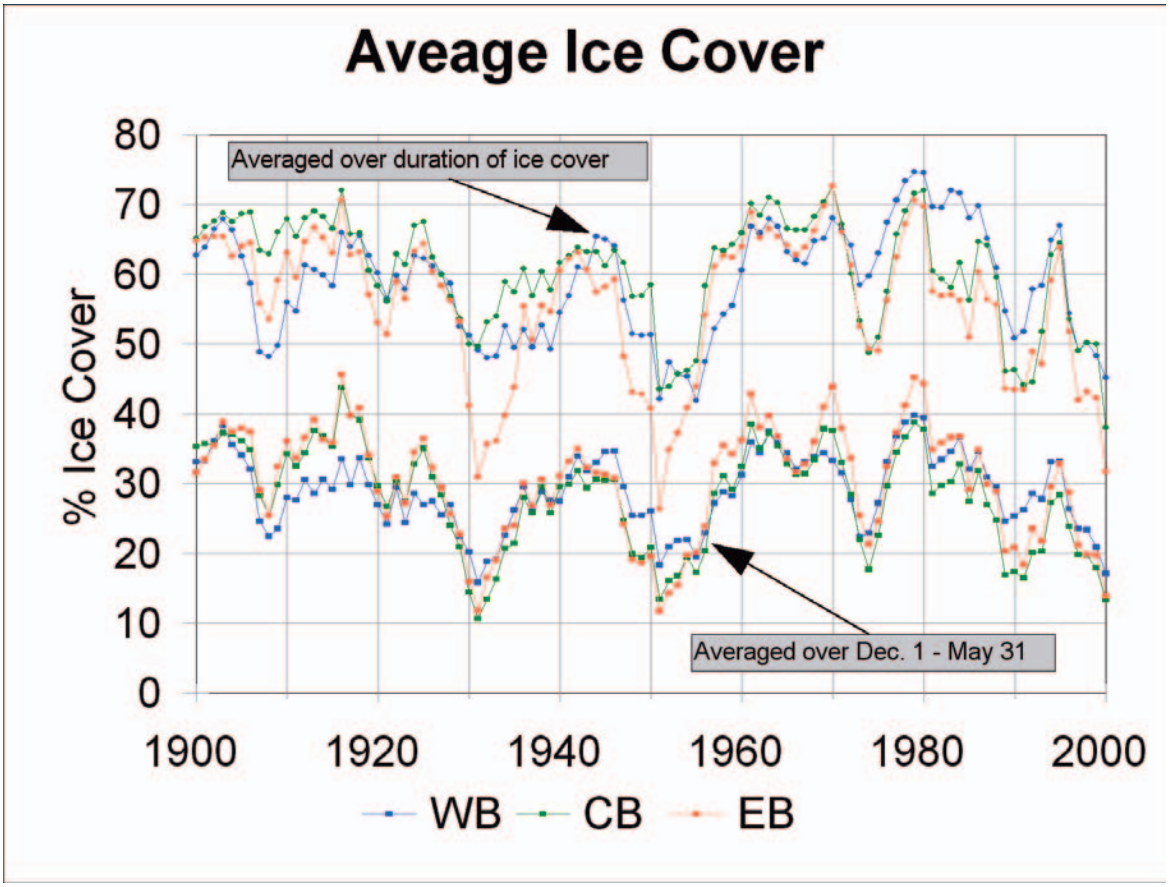

Figure 5. Seasonal Averaged Ice Cover, 5 year centered running.

winters occurred the last half of the 1900s, around 1920, in the mid 1970s, the late 1980s to early 1990s, and the late 1990s to 2002. The contemporary 30-winter averages (Table 2) range from 24% to 29% for the 182-day season and from 51% to 61% for the period of ice duration, with the west basin having the highest values. Variations around the contemporary period were also lowest for the west basin (11.6% for 182 day period to 15.8% for the period of ice duration). A prominent decline in seasonal average ice cover is observed from the late 1970s to 2002. These trends are similar to those described for the dates of first/last ice and ice duration and for the same reasons.

3.5 Monthly Ice Cover

Trends in monthly averaged ice cover over the period of record are similar to those noted above for first ice, last ice, ice duration, and seasonally averaged ice cover and are portrayed in Figure 6a-e. The greatest ice cover in December occurs in the west basin (Figure 6a), the center basin has less, and east basins almost nil ice cover. The west basin still has the greatest ice cover in January, (Figure 6b). The 30-winter contemporary averages are 61.7%, 39.3%, and 36.6% for the west, center, and east basins respectively (Table 2). There is a large increase in ice cover in the center and east basins in February (Figure 6c) as the ice cover approaches its seasonal maximum value, and the difference between the three basins approaches a minimum. February 30-winter contemporary averages are 69%, 65.9%, and 64.9% for west, center, and east basins, respectively. In March, (Figure 6d) the west basin now has less ice than the center basin, and the east basin has the greatest amount of ice. This is due to the prevailing westerly winds, milder temperatures, and river inflow into the west basin (Detroit, Maumee, Portage, Sandusky, Huron, Vermilion, and Black Rivers) during March. In March, the 30-winter contemporary averages are 30.8%, 36.7%, and 50.4% for west, center, and east basins respectively. In April, (Figure 6e) the ice

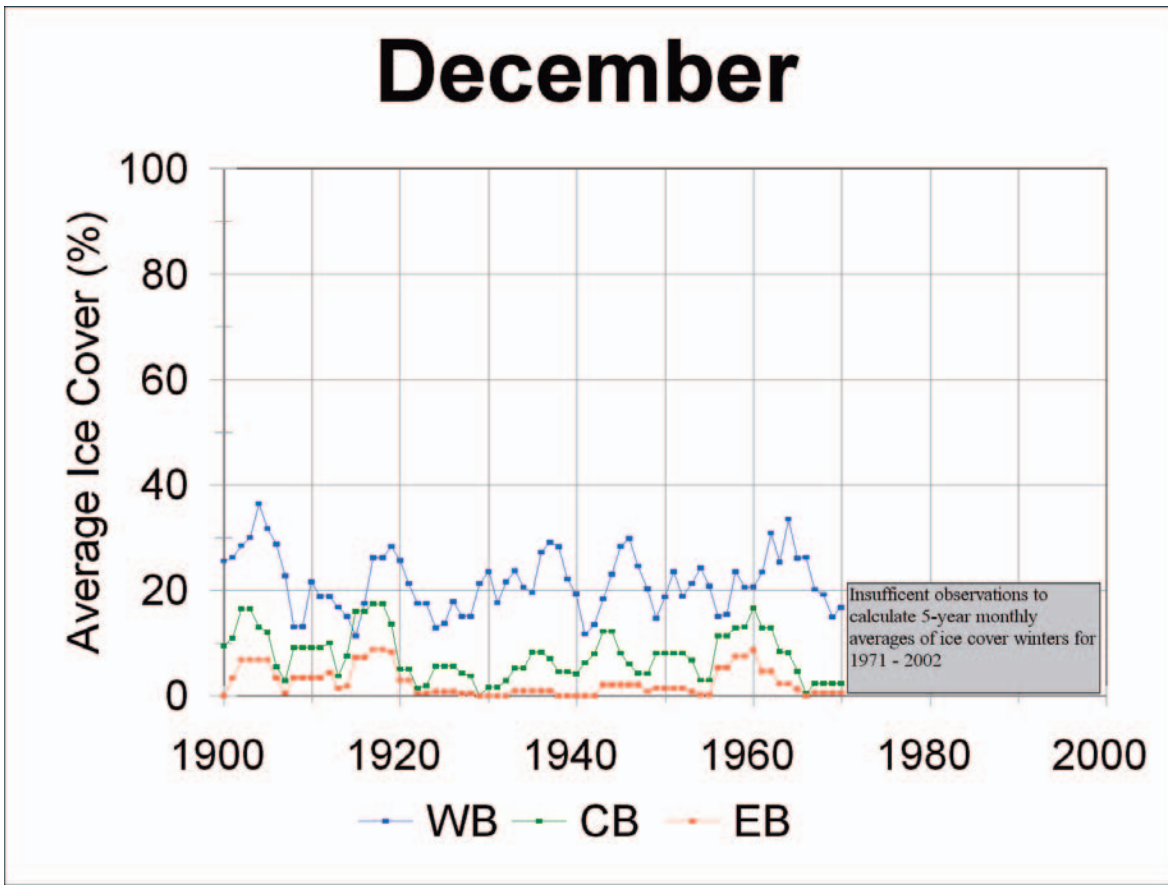

Figure 6a. Monthly averaged ice cover, 5 year centered running mean for December.

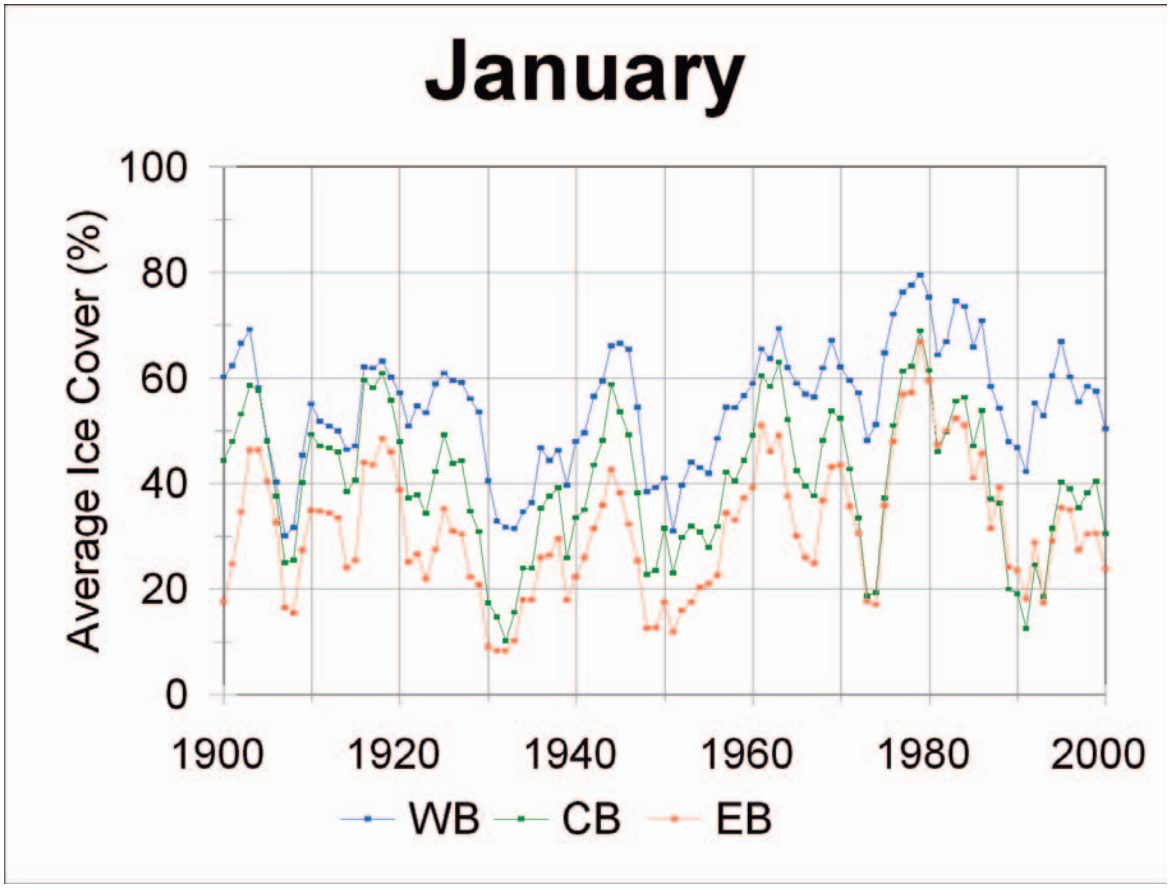

Figure 6b. Monthly averaged ice cover, 5-year centred running mean for January.

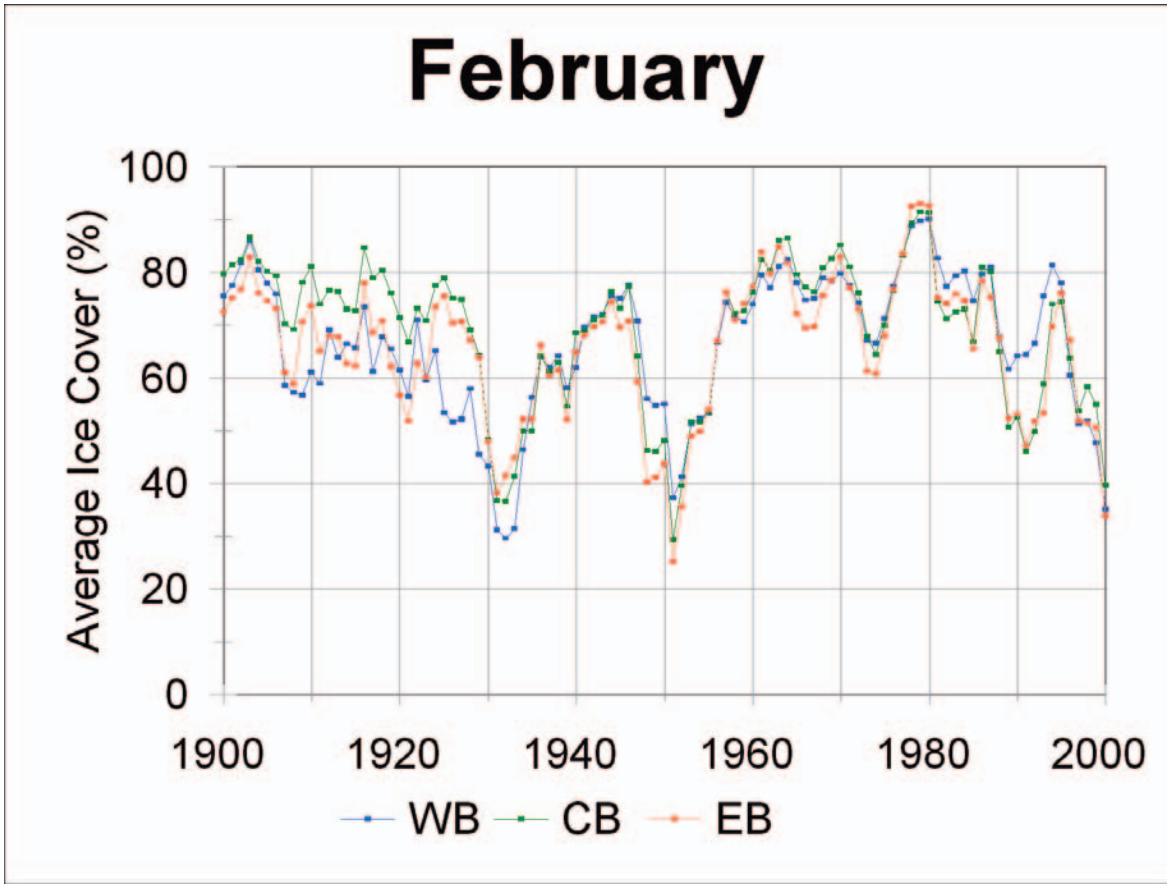

Figure 6c. Monthly averaged ice cover, 5-year centered running mean for February.

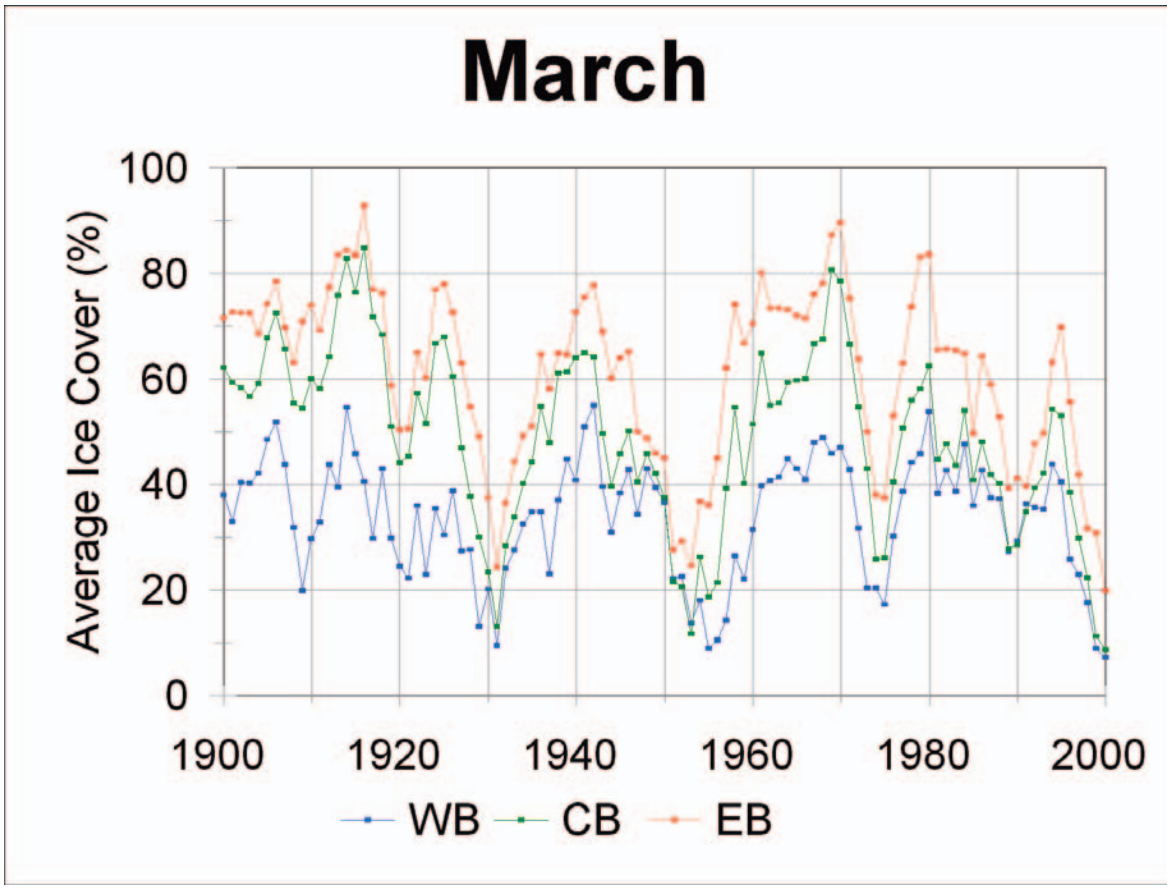

Figure 6c. Monthly averaged ice cover, 5-year centered running mean for March.

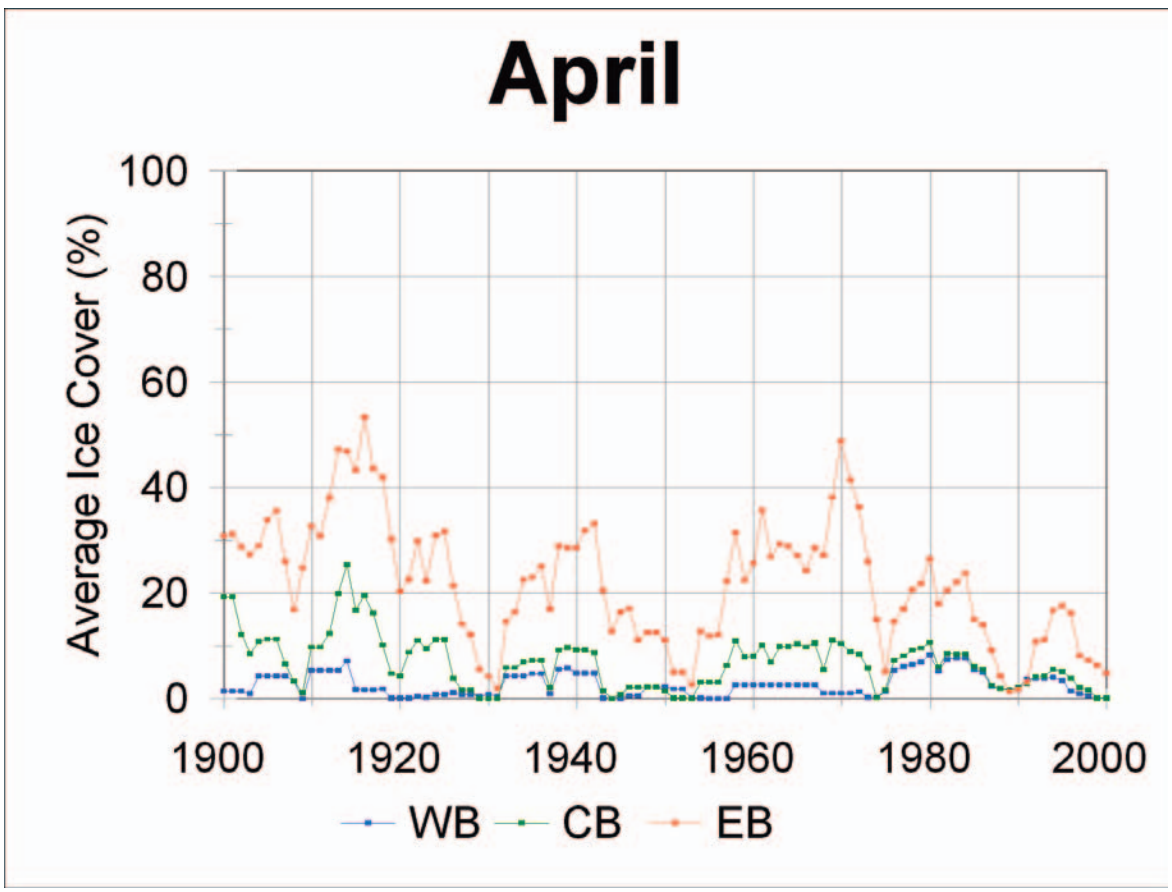

Figure 6e. Monthly averaged ice cover, 5-year centered running mean for April.

cover is greatest in the east basin, much less in the central basin, and almost nil in the west basin. April 30-winter contemporary averages are 3.5%, 4.3%, and 11.8% for west, center, and east basins, respectively. The standard deviation in monthly ice cover is generally lowest for the west basin over all months (Table 2).

3.6 Daily Ice Cover

Daily basin-averaged ice cover statistics were calculated only for the period of observed ice cover (1973-2002). Daily data are used to characterize the seasonal progression of the contemporary ice cover regime. The "normal" or "typical" daily progression over a season is defined by the median ice cover, i.e., the 50% point of the cumulative frequency distribution, Figure 7a. The typical ice cycle consists of an initial formation period, followed by a period of increasing ice cover, which culminates in the annual maximum areal extent, followed by a period of decreasing ice cover, which ends with the complete loss of all ice. The typical ice cycle has initial ice formation on all three basins of Lake Erie occurring the second half of December, but the period of increasing ice cover is much more rapid in the west basin relative to the center and east basins because of its shallower depth. The west basin approaches its seasonal maximum extent by mid-January and stays there until about mid-February, while the center and east basins do not reach maximum ice extent until about mid-February. The general progression of increasing ice cover is remarkably similar in the center and east basins between initial ice formation and maximum areal extent. The ice cover extent in the center and west basins begin to decrease during the second half of February. The decrease is quite similar in these two basins so that by the end of March, west and center basins have less than 10% ice cover. The east basin remains near maximum ice extent through about mid-March, when it too enters into the ice loss period, but by the end of March, it still has a 20% ice cover. The ice cover on all three basins is lost during April so by the end of that month the lake is virtually ice free.

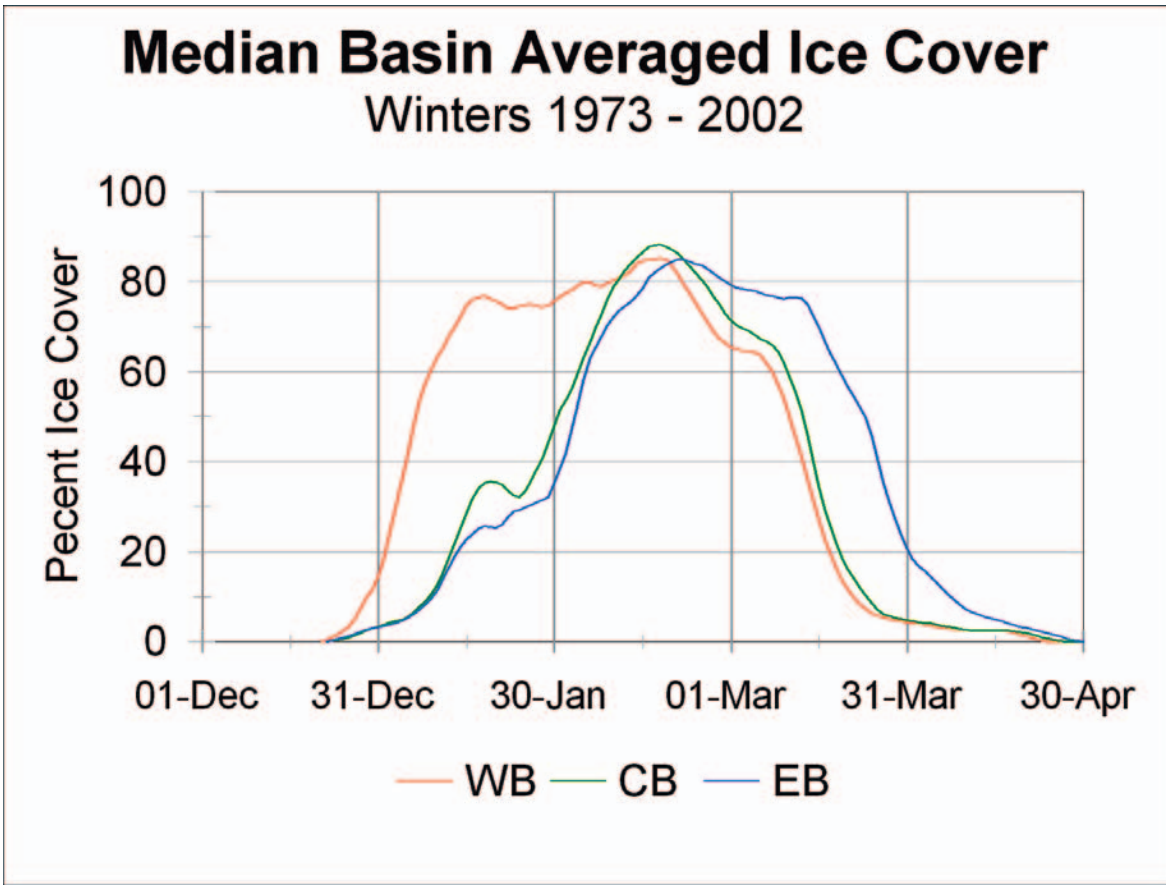

Figure 7a. Seven-day moving average of daily median ice cover for west (WB), center (CB), and east (EB) basins of Lake Erie.

The composite extremes, maximum observed ice cover on a given day and minimum observed ice cover on a given day over the 30-winter base period provide an estimate of the limits of ice cover under the climate regime of the past 30 years. Figure 7b shows that there can be large deviations from the "typical" ice cycle (Figure 7a). Extensive ice covers can form in the west basin the first half of December and in the center and east basins during the second half of December. All three basins can have in excess of 90% ice cover starting late December (west basin) or early to mid January (center and east basins) through the first half of March (west basin) or the second half of March (center and east basins). The winters of the late 1970s and 1994 and 1996 provide good examples of winters that helped to set the upper limits (severe winters). The composite daily maximums show that rapid loss of ice extent occurs in the first half of April but that the east basin can still have well over 50% ice cover in mid-April and over 20 percent ice cover by the end of April. In fact, the eastern end of the east lake basin can have ice cover well into May some years (International Niagara Working Committee, 2003). The composite daily minimum ice cover extent curves (Figure 7b) show that with the exception of the west basin during the last half of January, all three basins can be virtually ice free during any day in the winter season. The 1998 and 2002 winters provide good examples of winters that help set these lower limits.

The variation in the seasonal progression and extent for individual winter seasons is portrayed in line graphs at: http://www.glerl.noaa.gov/rsch/erie/data/Spatial/Ice/daily/. Spatial variations within each lake basin over a winter season are available at: http://www.glerl.noaa.gov/rsch/erie/data/Spatial/Ice/animation/.

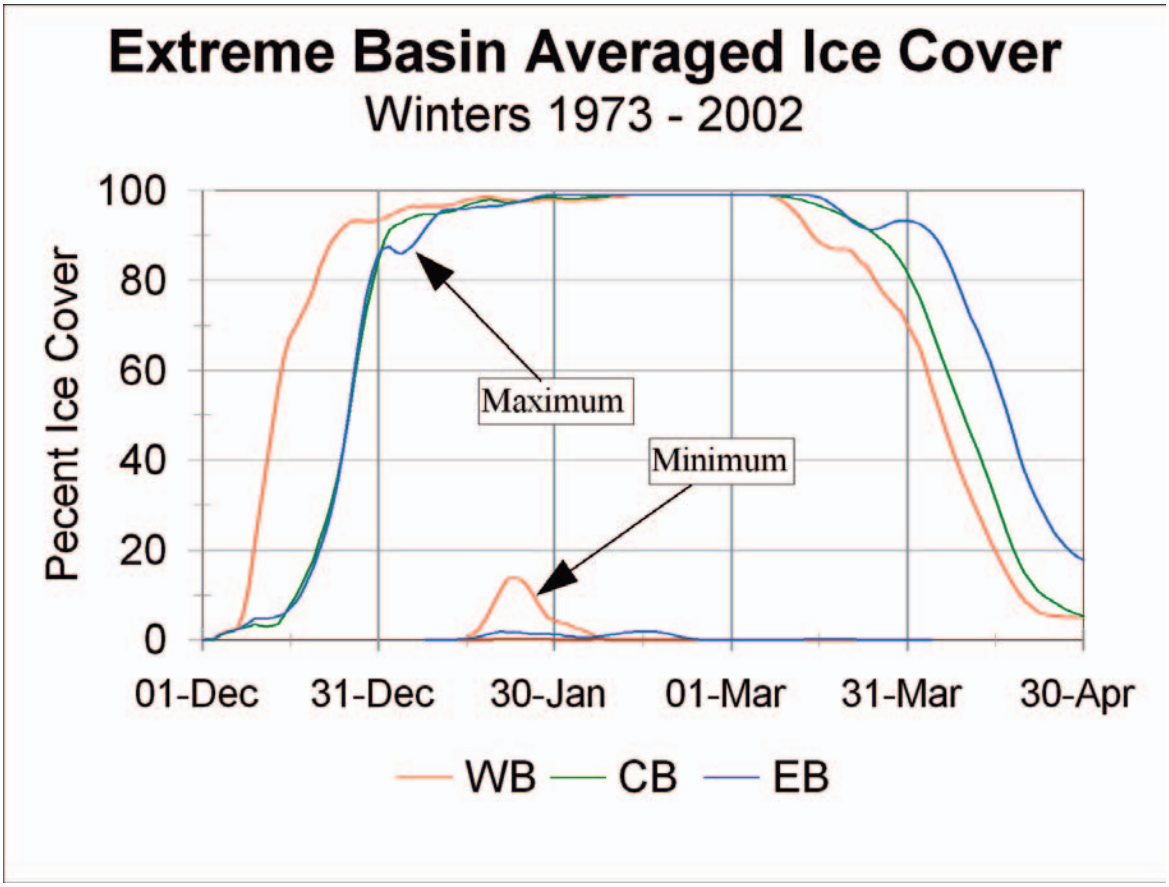

Figure 7b. Seven-day moving average of observed daily maximum and minimum ice cover for west (WB), center (CB), and east (EB) basins of Lake Erie.

4. Summary

Spatial averages of ice concentrations for the west, center, and eastern basins of Lake Erie are presented for a 105- winter base period (1898-2002) for daily, monthly, and annual time periods. Dates of first ice, last ice, and ice duration were also examined. The daily and monthly data for the contemporary 1973-2002 winter period were used to calculate statistics and to define and compare the seasonal progression of ice cover for each lake basin. Century trends included later first ice dates, earlier last ice dates, and shorter duration of the ice cover. These trends were also observed during the contemporary (1973-2002) period. Additional information on the seasonal progression of ice cover for each basin for each winter as well as ASCII files of these data, the monthly data, the annual data, and computer animations of the spatial progression of ice cover for the 30-winter period from 1973-2002 are available on the Internet and are considered an integral part of this report at: http://www.glerl.noaa.gov/rsch/erie/data/Spatial/Ice/Ice.html.

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