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AN ICE-COVER CLIMATOLOGY FOR LAKE ERIE AND LAKE SUPERIOR FOR THE WINTER SEASONS 1897–1898 to 1982–1983

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ABSTRACT

Observations of mid-lake Great Lakes ice cover are sparse prior to the decade of the 1960s. In an effort to provide an historical perspective of mid-lake ice cover back to the turn of the century, daily average ice cover for Lakes Erie and Superior over 86 winters (1897–1898 to 1982–1983) was reconstructed using empirical–statistical ice-cover models developed in an earlier study. Long term average maximal monthly ice cover occurs in February and is 68 per cent for Lake Erie and 40 per cent for Lake Superior. Mid-lake ice formation occurs about 1 month earlier on both lakes during severe winters. Average maximal monthly ice cover during severe and during mild winters is 95 per cent and 14 per cent for Lake Erie, 87 per cent and 17 per cent for Lake Superior. Severe winters are associated with lower 700-mbar heights over the eastern USA compared with mild ice-cover winters. Analysis of total winter ice cover indicates three ice cover regimes: (i) a high ice-cover regime from the late 1890s to early 1920s; (ii) a low ice-cover regime from the early 1920s to late 1950s; and (iii) a high ice-cover regime from the late 1950s to the early 1980s. Ice-cover climatologies developed during the 1960s and 1970s are not representative of ice covers in the low ice-cover regime of the 1920s to late 1950s. Spectral analysis of the reconstructed total winter ice cover suggests interannual variations in ice cycles that correspond with the 2–3-year interannual variation in atmospheric variables known as the quasi-biennial oscillation.

KEY WORDS Great Lakes ice Climatology Lake Erie Lake Superior

INTRODUCTION

Canadian and USA government agencies began regular aerial observations of the ice cover of the Laurentian Great Lakes of North America in the early 1960s. In prior decades, mid-lake ice conditions were not well documented (Snider, 1974) and, therefore, little is known about the climatology of the ice cover prior to the past three decades. In an effort to provide an historical perspective of mid-lake ice cover back to the turn of the century, statistical ice-cover models developed recently (Assel, 1989) are used in this study to reconstruct Lake Superior and Lake Erie ice covers over the 86 winters from 1897–1898 to 1982–1983. Contemporary ice cycles of Lakes Erie and Superior and the ice-cycle models are discussed. The severe and mild ice-cover seasons over the 86 winters are described in terms of mean monthly ice cover and average monthly 700-mbar circulation patterns. The climatology of monthly average ice cover is presented in terms of the long-term average and standard deviation. Total winter ice cover for continuous 5-year and 30-year periods portray annual trends in ice cover over the 86 winters. The 86-year total winter ice-cover time series is examined for cycles using spectral analysis techniques. The contemporary ice-cover climatology is discussed in the context of ice cover trends over the 86 winters.

THE ANNUAL ICE CYCLE OF LAKES ERIE AND SUPERIOR

The annual ice cycle consists of an autumn cooling period, a winter ice formation period, and a spring ice decay and loss period. In autumn and winter, surface water temperatures are higher than air temperatures, which promotes atmospheric instability and a decrease in lake heat storage, primarily by evaporation and sensible heat loss (Schertzer, 1978, 1987). On Lake Superior, with a volume of 12,100 km^3 and a mean depth of 148 m, only the upper 20 m of the water mass (about 12 per cent of the total lake volume) is heated in summer. The remainder of the water mass remains near 3·98°C after the spring warm-up. Thus, the annual maximal total heat storage of Lake Superior does not vary much from year to year. Annual variation in ice formation is due primarily to annual variations in cooling rate of the water mass in autumn and winter. In autumn, the entire water mass cools to the temperature of maximal density near 3·98°C; then in winter, the surface water cools to the freezing point that makes ice formation possible. Because of the large depth difference between the shore area (less than 60 m) and mid-lake area (between 100 m and 200 m) of Lake Superior, there are two distinct thermal and ice-cover regimes (Assel, 1986a). Ice formation occurs first along the shoreline in December and January and progresses to the deeper, more exposed lake areas in February and March. But the ice in mid-lake areas is more transitory than in-shore areas because, even when winter air temperatures are well below freezing, high winds can prevent or retard mid-lake ice formation (Richards, 1963). Thus, even in February and March portions of the deep mid-lake area can remain open water or undergo several ice-formation–ice-loss episodes.

Compared with Lake Superior, the date of initial ice formation on Lake Erie is more sensitive to autumn and winter heat fluxes, because of Lake Erie's smaller volume (484 km^3) and smaller mean depth (19 m). Thus, its annual maximal heat storage is much less and its autumn temperature decline is more rapid relative to Lake Superior's. Ice formation proceeds from Lake Erie's shallow west basin in December to the deeper central and eastern basins in January. The water column below the ice is nearly isothermal at a temperature below 1°C (Stewart, 1973).

Ice cover is lost in spring as a result of absorption of solar radiation by the ice and surface waters below the ice and by sensible heat flux to the ice from the overlying air. High wind speed events also cause loss of ice cover over large areas of a lake due to melting by upwelling of warmer waters. The length of the ice-loss period is a function of the amount of ice formed during the winter; to the rate of warming in spring; and to episodic wind events, related winter storms, and the air mass frontal movement across the lake.

THE ICE CYCLE MODELS

Statistical freezing degree-days (FDD) ice-cover models have been developed in the past to simulate ice formation (Snider, 1974; Baker and Baker-Blocker, 1976), ice extent (Richards, 1963; Rogers, 1976), and ice thickness (Hinkel, 1983) on the Great Lakes. Accumulations of FDD are a measure of the departure of the mean daily air temperature from 0°C and so they form an index of a winter's thermal severity relative to the freezing point of fresh water. If the mean daily air temperature was -3°C, then 3 FDD accumulate on that date, if the daily mean air temperature is $+3$°C, then -3 FDD accumulate on that date.

Assel (1989) developed FDD accumulation ice-cover models for the east, central, and west Lake Erie basins and for the east, west, and Whitefish Bay basins of Lake Superior (Figure 1). Each lake basin has a different mean depth and different heat storage capacity (Table I). Empirical threshold FDD accumulations are used to simulate the date the water temperature approaches maximal density in autumn on the Lake Superior basins (end-of-autumn overturn) and the dates of initial shore and mid-lake ice formation for both the Lake Erie and Lake Superior basins (Table I). Ice is not permitted to form prior to the accumulation of threshold FDD accumulations for shore areas. On Lake Erie, threshold FDD for shore and mid-lake areas are the same because of the shallow mean depth of that lake. On Lake Superior, shore ice is simulated to increase linearly to a maximal value of 15 per cent of the lake's surface between the threshold FDD for initial shore ice and threshold FDD for initial mid-lake ice.

A separate FDD regression equation was developed for each lake basin to estimate the daily progression of ice cover after initial ice formation; that is, the percentage of the lake basin covered by ice each day from the date of initial ice formation until the date of complete ice dissipation in spring. Equations of the form shown in equation (1) were developed for the deep east and west basins of Lake Superior; equations of the form shown in equation (2) were developed for the Lake Erie basins and for the Whitefish Bay basin of Lake Superior. The B term in equations (1) and (2) is the average FDD accumulation associated with the end-of-autumn overturn for Lake Superior basins and the threshold FDD accumulations for initial ice formation for the Lake Erie

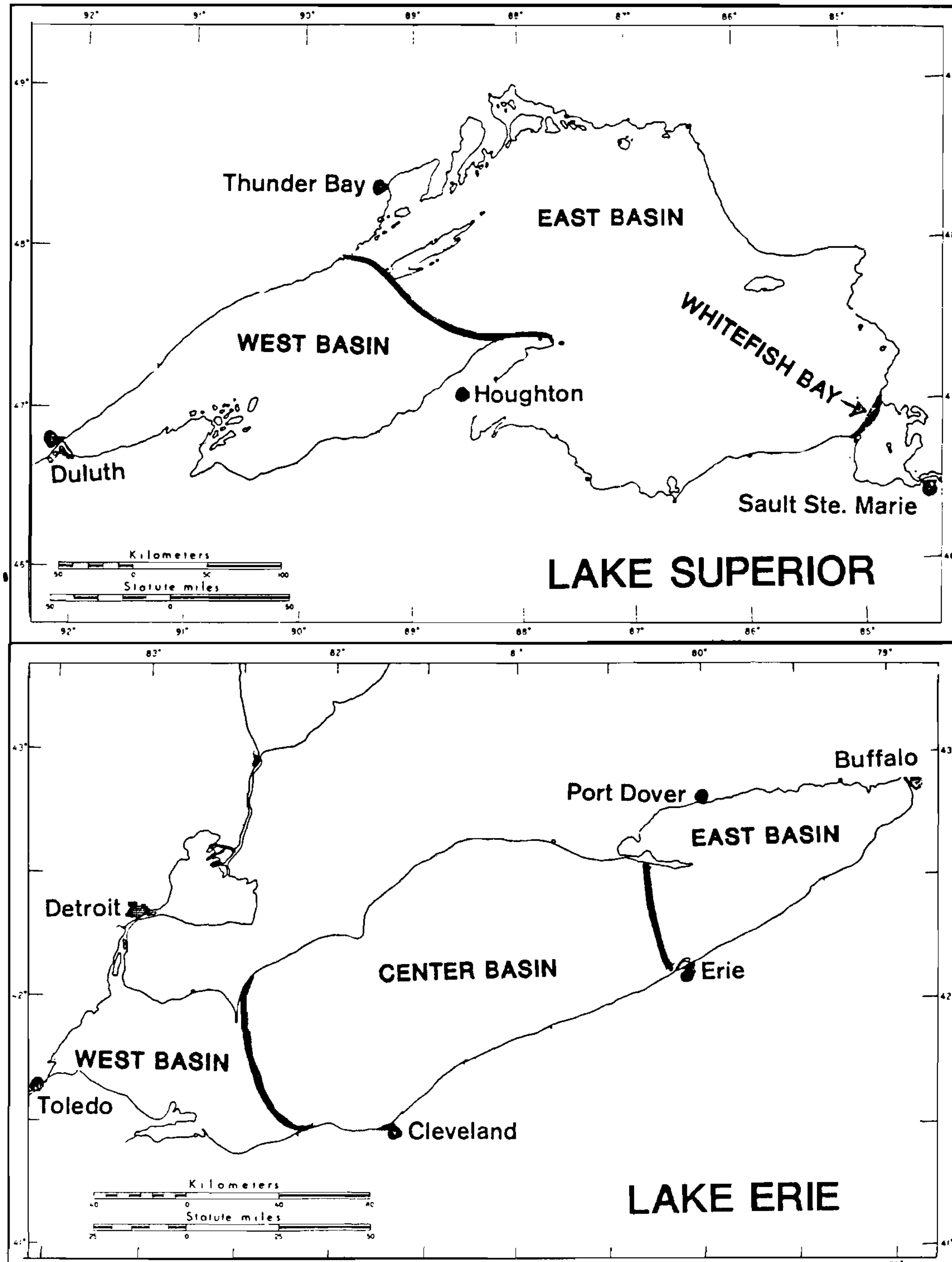

Figure 1. East, west, and Whitefish Bay basins of Lake Superior and east, central, and west basins of Lake Erie used in ice-cover models. Air temperature stations used for FDD analysis (see Tables I and III)

Table I. Lake basin parameters (approximate values)

	Lake Superior			Lake Erie		
	WB	EB	WFB	WB	CB	EB
Mean Depth (m)	135	152	41	9	19	27
Area (km^2)	21,971	58,947	1182	5135	14,635	5909
Volume (km^3)	2966	8960	48	46	278	159
Threshold FDD (°C)[a]						
Autumn Over-turn[b]	230	220	220	—	—	—
Shore ice	430	430	350	27	75	110
Mid-lake ice	730	730	450	27	75	110

[a] Based on air temperature data from meteorological stations on the perimeter of each lake basin (see table III).
[b] Average FDD accumulations observed on the date the water column was isothermal near the temperature of maximal density, 3·98°C.

basins. The regression equations are constrained to operate only after FDD accumulations increase beyond the threshold value for mid-lake areas. The ice cover is reset to 100 per cent in equation (1) if it exceeds that value. In equation (2), as FDD increases, the ice cover approaches 100 per cent as an asymptote. Coefficients of regression, C_1, C_2, and C_3, were determined during model calibration. The ice reduction term (TH) in equations (1) and (2) is set to zero until the date of maximal FDD accumulations; TH is a function of the date and amount of annual maximal FDD accumulations and the average daily ice-melt rate. The average daily ice-melt rate is a constant for each lake basin and its value was determined during the calibration of the model. Average basin ice thickness is estimated as the square root of the annual maximal FDD accumulation each winter. The length of the ice-loss period is a function of the average basin ice thickness and the average daily ice-melt rate.

$$\text{Ice} = \frac{100}{1 + C_1 \times \exp\{C_2 \times [(\text{FDD} - B)/J]\} + C_3 \times (\text{FDD} - B) + TH} \tag{1}$$

where J is set to 1 when FDD equals the threshold value B, and J increases by 1 every day after that date.

$$\text{Ice} = \frac{100}{1 + C_1 \times \exp[C_2 \times (\text{FDD} - B)] + TH} \tag{2}$$

In order to obtain an unbiased measure of model root-mean-square error (RMSE) the ice-cover models were calibrated on one half of the original calibration data and used to simulate ice cover for the second half of the original ice-cover calibration data. Assel (1989) found that RMSE over the six ice-cover models ranged from 15 per cent to 26 per cent on the first half of the data and from 18 per cent to 28 per cent when repeating this analysis on the second half of the data. When one considers that the accuracy of the ice-cover data used to calibrate and verify the ice-cover models is of the order of 10–15 per cent these RMSE values are not unreasonable.

ANALYTICAL METHODS

Model evaluation for climatic application

The ice-cover models do not include a term for wind effects. For storm wind speeds (88 km h^{-1}) occurring during the winters of the model calibration (the winters of the 1960s and 1970s), the ice-cover models overestimated ice cover by an average of 20 per cent, if basin ice concentration was low (40 per cent or less) at the onset of the storm. A good example of wind-related model error occurred during the 1970–1971 winter season. Winter temperature was below normal that winter, but the ice-cover model overestimated the seasonal maximal ice cover by 30 per cent, because there were five storms with wind speeds in excess of 88 km h^{-1} (Lewis, 1987) that retarded ice formation. Thus, for winters with a high frequency of storms, ice-cover models will overestimate ice cover.

The ice-cover models do not consider the effect of lake heat storage of the previous summer on the ice cover during winter. Thawing degree-days (TDD) are used as an index of summer lake heat storage (Richards, 1963) and FDD are used as an index for winter severity (Assel, 1980) for Lakes Erie and Superior. Lake-averaged values of TDD and FDD (Assel, 1986b) were used to classify these indices of summer heat storage and winter severity as above normal, normal, or below normal, based on the cumulative frequency distribution of maximal FDD and maximal TDD accumulations over the 86 winters under study (Table II). These data were then used to examine the relationship between errors in model estimates of maximal ice cover and summer heat storage–winter severity over 21 contemporary winters (1963–1983) with ice-cover observations. Lake-averaged annual maximal ice cover was calculated from the ice-cover models as the sum of the weighted mean basin ice cover (weights were the basin area expressed as a percentage of total lake area) for all basins on each lake. These data were compared with the observed seasonal maximal ice cover (DeWitt *et al.*, 1980; Assel, 1989).

Because Lake Erie is so shallow, the fact that the ice-cover models do not account for annual changes in summer heat storage apparently is not a critical factor affecting the simulation of maximal ice cover most winters. Largest errors (30 per cent) in estimated annual maximal ice cover occurred for Lake Erie only when summers with normal or below normal heat storage were followed by winters with below normal severity. For winters with normal or above normal severity, errors were small regardless of summer heat storage classification. On Lake Superior, it appears that for the majority of the winters with normal severity *preceded* by summers with below normal summer heat storage, the ice-cover models underestimate maximal ice cover by approximately 30 per cent. Thus, for cool summers followed by normal winters, the Lake Superior ice-cover models will tend to underestimate ice cover the following winter by a large amount.

Table II. Distribution of errors in estimates of maximal ice cover for summer heat storage class in combination with winter severity class over the 21-winter period, 1962–1963 to 1982–1983

Classification[a]		Errors in Maximal Ice Cover	
Summer	Winter	Lake Erie	Lake Superior
Above	Above	0	[b]
Above	Normal	15	5
Above	Below	[b]	[b]
Normal	Above	−2, 2, 3, 2	−5, 29, 10, −30, 9, −6, 0, −3
Normal	Normal	−1, −10, −1, 10, 4, 3	25, 6, 14, −1, −8, 19, 30
Normal	Below	−23	[b]
Below	Above	−3, 0	[b]
Below	Normal	−3, 7, 2	7, 32, 27, 38
Below	Below	30, 30	−2

	Lower Boundary of Class[a]			
	Summer Heat Storage (TDD °C)		Winter Severity (FDD °C)	
Lake	Above	Normal	Above	Normal
Superior	2730	2489	1282	928
Erie	3855	3576	429	216

[a] The 20th and 80th percentile of the cumulative frequency distributions of the annual maximal TDD accumulation and annual maximal FDD accumulations for the 86 winters under study defined the class limits for above and below normal summer heat storage index and winter severity index (see Assel, 1986b).
[b] This combination of summer heat storage class and winter severity class did not occur during the 21-winter period.

Table III. Air temperature stations used in FDD analysis

Basins	Temperature stations
Erie west	Detroit, MI, Toledo, OH, Cleveland, OH
Erie central	Cleveland, OH, Port Dover, Ontario
Erie east	Port Dover, Ontario, Erie PA, Buffalo, NY
Superior west	Duluth, MN, Houghton, MI, Thunder Bay, Ontario
Superior east	Sault St Marie, MI, Thunder Bay, Ontario
Superior Whitefish Bay	Sault St Marie, MI, Thunder Bay, Ontario

Table IV. Nine extreme winters between 1897–98 and 1982–1983

Lake Erie						Lake Superior					
Mild			Severe			Mild			Severe		
year	days[a]	ice[b]	year	days[c]	ice	year	days[d]	ice	year	days[c]	ice
1919	25	—	1904[e]	75	—	1906	28	—	1904[e]	47	—
1932[e]	4	—	1905	58	—	1919[e]	0	—	1912	74	—
1933	5	—	1912	72	—	1921[e]	0	—	1917	41	—
1937	20	—	1918[e]	71	—	1931[e]	0	—	1918[e]	27	—
1949[e]	0	—	1920[e]	62	—	1932[e]	0	—	1936	26	—
1950	33	—	1940	64	—	1942	25	—	1959	27	—
1953	0	<10	1959	68	—	1944[e]	0	—	1963[e]	38	95
1973	27	95	1970	68	95	1953[e]	21	—	1979[e]	37	100
1983	13	25	1978[e]	60	100	1983[e]	10	21	1982	52	97

[a] The number of days each season that the ice cover was greater than 30 per cent.
[b] the observed annual maximal ice cover from DeWitt *et al.* (1980), and Assel (1989); for 1953 Lake Erie ice estimated from US National Weather Service, (unpublished). The 95 per cent 1973 Lake Erie ice cover formed near the end of February was of short duration; an ice chart the first week in March shows much less ice cover (Assel, 1974).
[c] The number of days each season that the ice cover was greater than 80 per cent.
[d] The number of days each season that the ice cover was greater than 20 per cent.
[e] Identified (DeWitt *et al.*, 1980) as one of the 22 coldest winters over the past 200 years, or identified (Assel *et al.*, 1984) as one of the 20 mildest winters over the past 200 years.

Time averaged ice cover

Because of the potential for large errors due to high winds and to variations in annual summer heat storage, it is prudent to work with time averages of ice cover in the analysis of the ice-cover climatology. It seems plausible to make a climatic analysis of the monthly and seasonal total winter ice cover using the ice-cover models. In the case of the synoptic annual maximal ice cover, the error in the 21-winter *average* of annual maximal ice cover was 3 per cent for Lake Erie and 9 per cent for Lake Superior.

A daily running sum of FDD accumulation for the months of November through to May of the winters between 1897–1898 and 1982–1983 was calculated for each Lake Erie basin and each Lake Superior basin using the stations given in Table III. These FDD data were used to simulate daily basin ice cover for each of the 86 winter seasons. Daily average *basin* ice cover was used to calculate daily average *lake* ice cover, i.e. the weighted sum of the ice covers from all basins for a given lake and date. Monthly average lake ice covers were calculated for December through to May for each of the 86 winters. The integrated total winter season ice cover was calculated as the sum of the daily lake-averaged ice cover for the months of December through to May each winter.

Extreme winter seasons

The extreme winters between 1897–1898 and 1982–1983 were defined from the annual number of days that ice-cover concentrations departed from a threshold value. The mild winters were the nine winters (approximately 10 per cent) with the lowest number of days having 30 per cent or greater ice cover for Lake Erie and 20 per cent or greater ice cover for Lake Superior. The threshold ice-cover concentration for mild winters for Lake Superior was lower than for Lake Erie, because Lake Superior normally develops a less extensive ice cover. The severe winters were the nine winters (approximately 10 per cent of total winters) with the highest number of days with ice cover equal to or greater than 80 per cent. The extreme ice-cover winters (Table IV) are in general agreement with available historical Great Lakes ice-cover data given in US National Weather Service (unpublished), Rondy (1969, 1972), Assel (1974), Assel *et al.* (1979, 1984), and DeWitt *et al.* (1980).

SEASONAL PROGRESSION AND VARIATION IN ICE COVER

Average reconstructed monthly ice cover and its standard deviation for the 86 winters were used to examine the seasonal progression and variability of the ice cover. As shown in Figure 2 (a and b), ice cover develops later over the deep mid-lake areas of Lake Superior (February) than over Lake Erie (January). Lake Erie's January ice cover can vary greatly from year to year, because of the lake's small thermal inertia and its

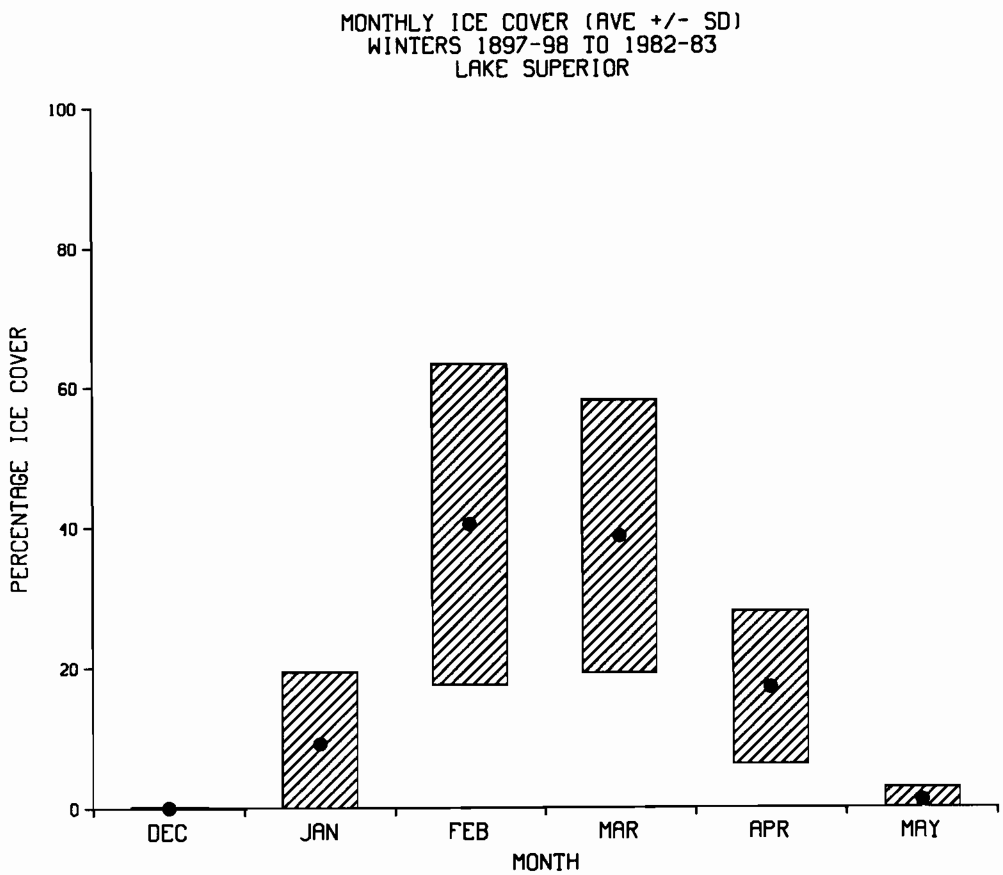

Figure 2. Reconstructed long-term (86-winter) average monthly ice cover (filled circle) plus and minus one standard deviation (hatched area): (a) for Lake Superior and (b) for Lake Erie

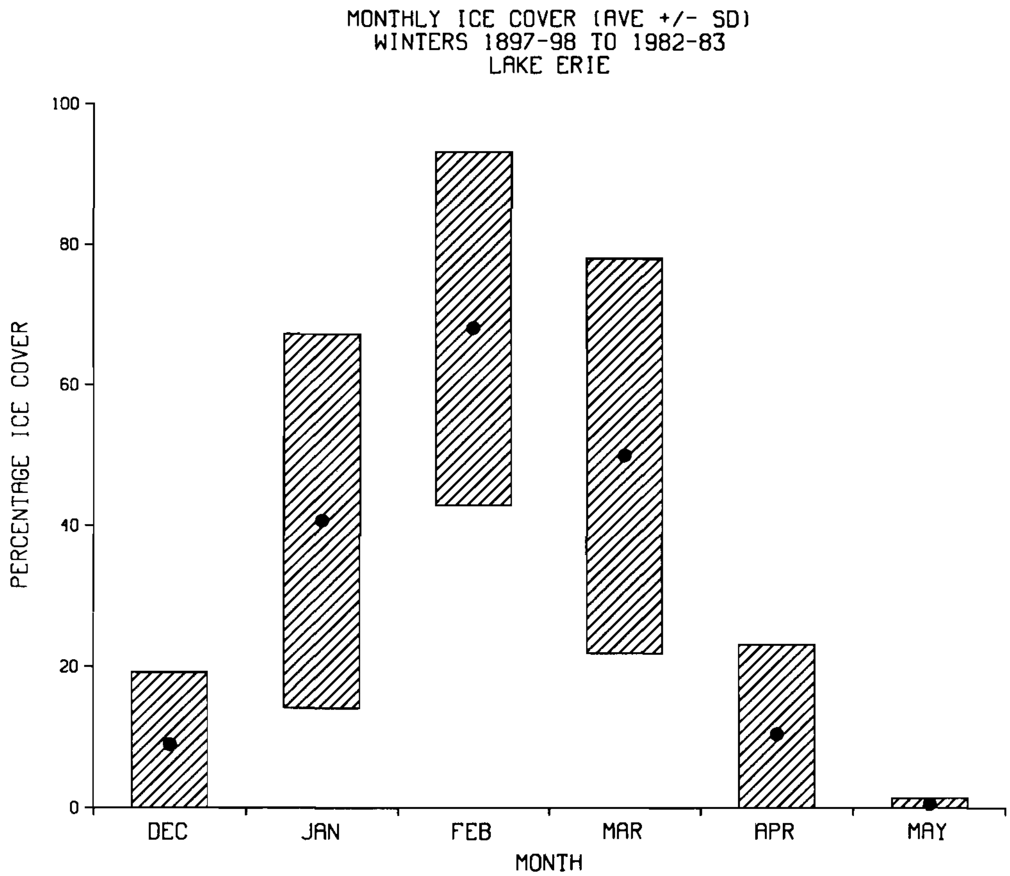

Figure 2. (*continued*)

correspondingly great sensitivity to air temperatures. The variability in February and March ice cover is large on both Lakes Erie and Superior and is at its seasonal maximum during these months. Lake Erie's long-term average February ice cover is 68 per cent; for Lake Superior, the long-term average February and March ice cover is near 40 per cent. Although Lake Erie usually has a greater percentage of its surface covered by ice at the time of maximal ice cover, average thickness of Lake Erie's ice cover would have to be over three times the average thickness of Lake Superior's ice cover for the total ice volume of both lakes to be equal, because of Lake Superior's much greater surface area. In late March and April, the areal extent of ice cover is normally greater for Lake Superior than for Lake Erie, because of Lake Superior's more northerly latitude and associated lower air temperatures. Lake Superior is about 47·5°N and Lake Erie is about 42·5°N; average March air temperature for Lake Superior is below freezing most years, while average March air temperature is usually above freezing most years for Lake Erie. By April, the spring melt is well under way, which results in reduced monthly ice-cover variation on both lakes. Average April ice cover is usually 17 per cent for Lake Superior and 10 per cent for Lake Erie. Ice covers on both lakes are usually lost by the end of April. During a few years, shore ice has been observed well into May on Lake Erie and into early June on Lake Superior.

Atmospheric circulation during severe and mild winters

Klein and Klein (1984) found that anomalies in monthly average air temperatures and in the 700-mbar height field are correlated, and that the 700-mbar height anomalies can be used to infer hemispheric flow patterns characteristic for above and below normal surface temperatures. For our study, monthly 700-mbar heights were averaged for the severe and mild winters after 1947 (data were not available before that year). The average 700-mbar height for mild winters minus the average for the severe winters was positive over the Great Lakes region (Figure 3 (a–c)). Cold arctic and polar air masses move toward the mid-section of North America in severe winters, which results in below normal 700-mbar heights. The development of a strong ridge aloft along the west coast of North America and a deep low over Hudson Bay favours this pattern of upper air flow

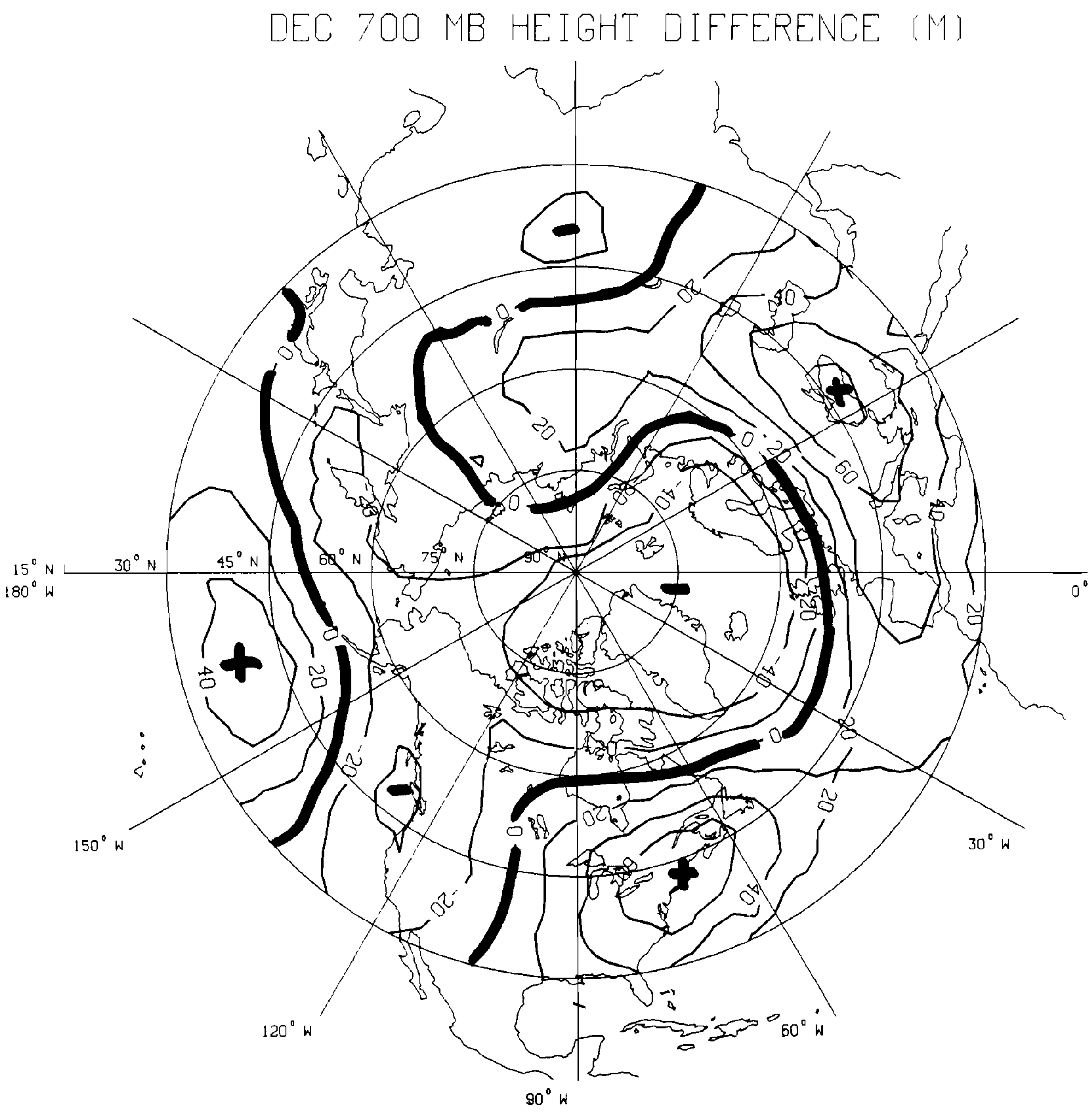

Figure 3. Contour analysis of: monthly 700-mbar heights averaged for the mild ice seasons (1948–1949, 1949–1950, 1952–1953, 1972–1973, and 1982–1983) *minus* monthly 700-mbar heights averaged for the severe ice seasons (1958–1959, 1962–1963, 1969–1970, 1977–1978, 1978–1979, and 1981–1982) for (a) December, (b) January, and (c) February. The contour interval is 10 m. Pluses and minuses show the centres of maximal positive and negative differences

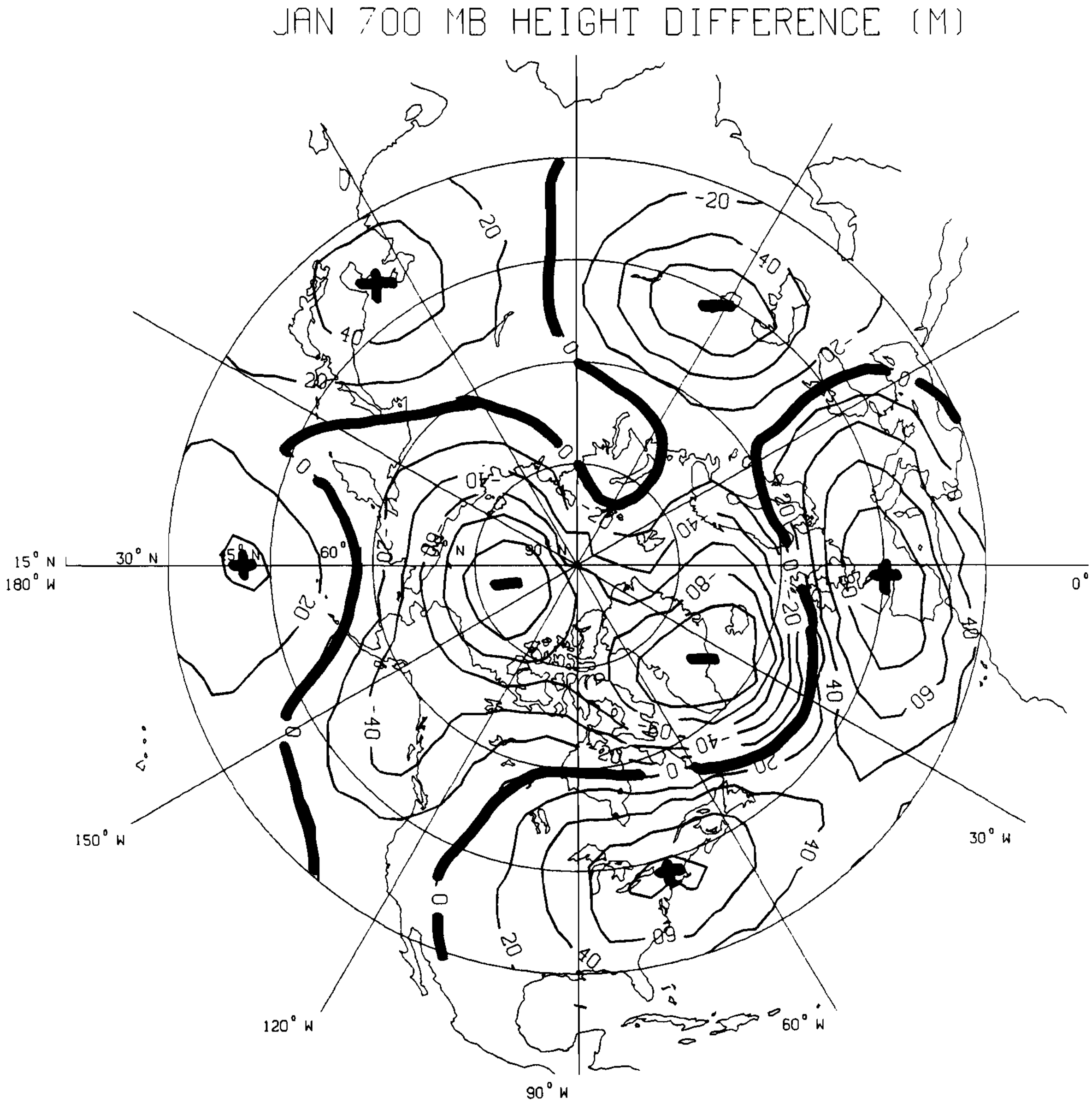

Figure 3(b). (*continued*)

for the Great Lakes. This upper air circulation pattern produces above normal ice cover (Quinn *et al.*, 1978; Assel *et al.*, 1979; DeWitt *et al.*, 1980).

During mild winters, the average mid-latitude monthly 700-mbar circulation for the Northern Hemisphere is typically weak and primarily zonal in nature (Erickson, 1984; Assel *et al.*, 1984). This circulation pattern permits frequent mid-continental intrusions of mild maritime air masses from the Pacific Ocean, which result in above normal air temperatures, above normal 700-mbar heights, and below normal ice cover over the Great Lakes.

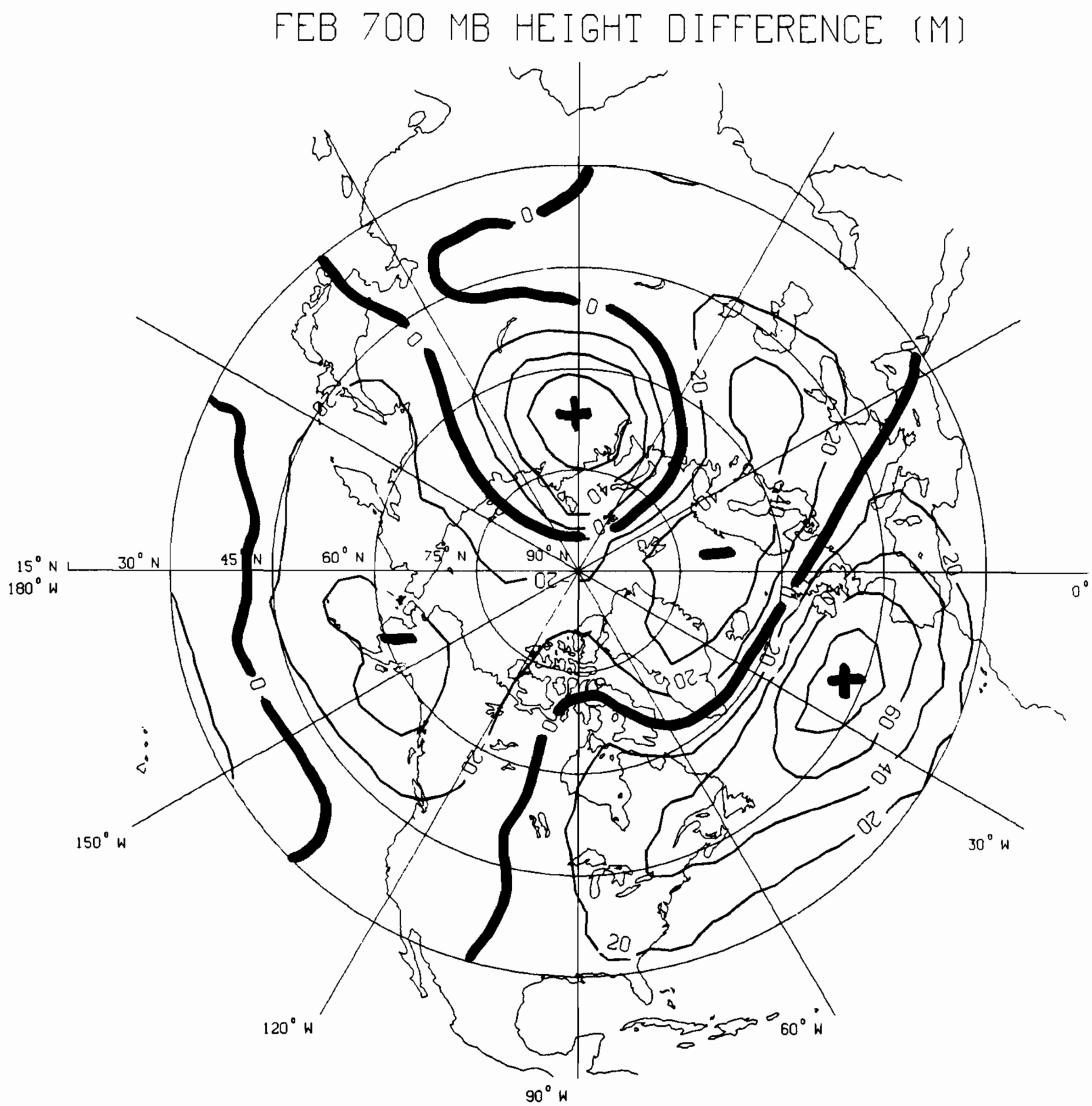

Figure 3(c). *(continued)*

Ice conditions during severe and mild winters

During severe winters, ice can form in mid-lake areas in December on Lake Erie and in January on Lake Superior (Figure 4 (a and b)). The large annual variation in mean monthly ice cover (which occurs during January for Lake Superior, and December and January for Lake Erie) reflects annual variation in the air temperature regime during these months. Variation in monthly ice cover for both lakes is low in February, because ice cover approaches 100 per cent. Average Lake Erie ice cover is over 95 per cent in February and over 84 per cent in March. Average Lake Superior ice cover is over 87 per cent in February and over 80 per cent in March. The standard deviation in monthly ice cover on both lakes was found to be less than 10 per cent for February and less than 12 per cent for March. Large losses in ice extent occurred in April, when monthly average ice cover dropped to near 30 per cent for both lakes; but this is still more than twice the long-term (86 winter) average April ice cover for Lake Erie and almost twice the long-term April average ice cover for Lake Superior. May ice cover averaged less than 3 per cent for both lakes (Figure 4 (a and b)).

Ice cover during mild winters is more sporadic and transient than during normal or severe winters because of wind action and above-freezing air temperatures. Except for short periods, the ice cover is, in general, restricted to the perimeters of Lakes Erie and Superior. Lake Superior's average monthly ice cover and ice-cover variation during mild winters are small due to the lake's large thermal inertia. During mild winters, most of the ice cover is restricted to harbours and shallow embayment areas that afford some protection from wind and wave action. The average monthly ice cover is at a maximum in March, when it is about 17 per cent (Figure 4(a)). Even in mild winters, however, shore ice can last into April and, some years, even into early May (Assel *et al.*, 1984).

Lake Erie ice cover variations during mild winters are larger than those for Lake Superior, because of Lake Erie's lower mean depth (Figure 4(b)). Extensive ice cover is restricted to the shallow west basin and to shore areas during most of the mild winter season; only during February or March is ice likely to form in the mid-lake areas of the central and east basins, and even then, only during some of the mild winters. Maximal monthly ice cover for Lake Erie occurs in March and is 14 per cent in mild winters.

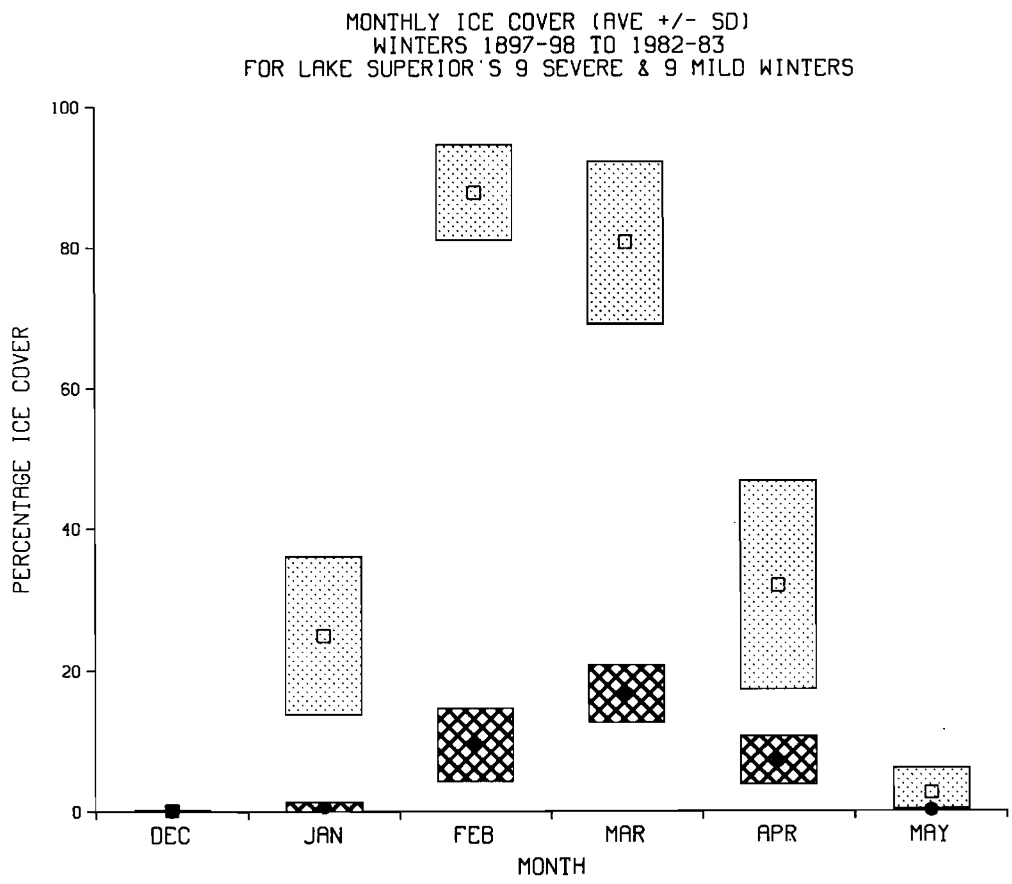

Figure 4. Reconstructed average monthly ice cover for mild winters (filled circles) and severe winters (open squares) for (a) Lake Superior and (b) Lake Erie. The hatched areas (mild winters) and stippled areas (severe winters) above and below the monthly average represent the variation over the nine winters (average plus and minus one standard deviation)

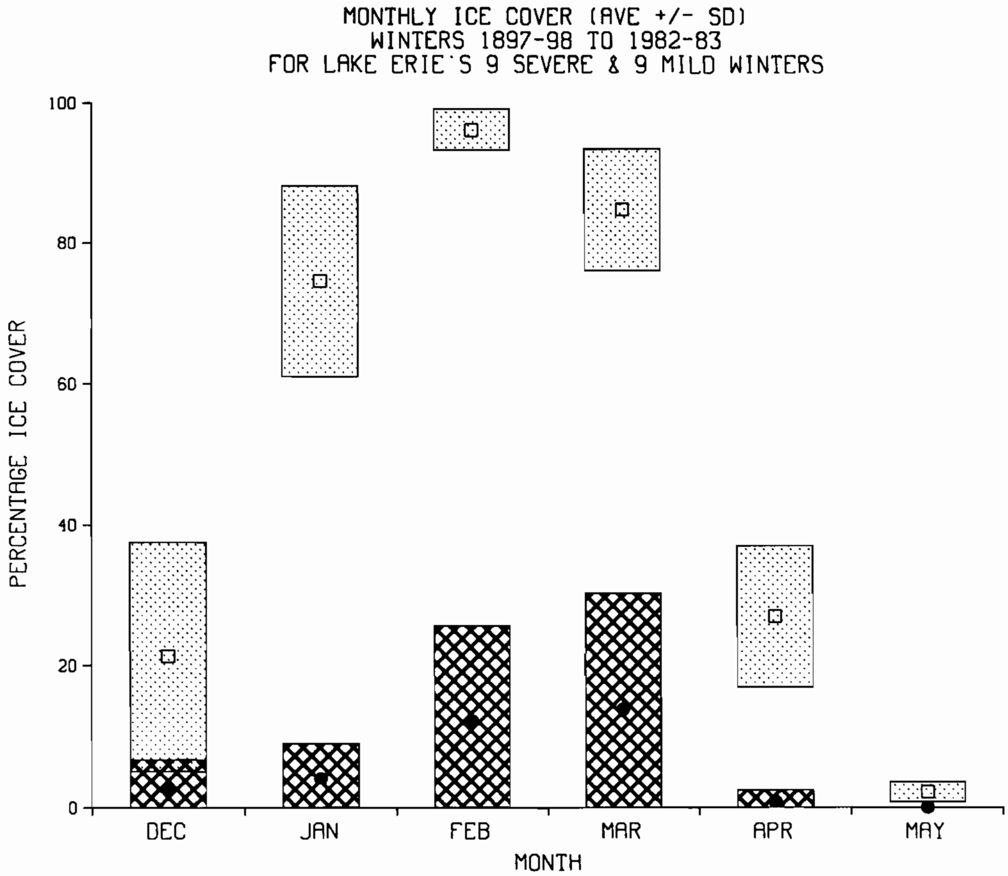

Figure 4(b). *(continued)*

ANNUAL TRENDS IN ICE COVER

The total winter ice cover

Continuous 5-year means (semi-decadal) and 30-year means were calculated to identify trends relative to the long-term mean in the reconstructed total winter ice cover over the 86 winters. On both Lakes Erie and Superior, the 30-year running mean of the total winter reconstructed ice covers decreased from the late 1920s to the late 1950s and increased from the late 1950s to the early 1980s (Figure 5(a and b)). The semi-decadal ice cover portrays two periods when the reconstructed total winter ice cover was frequently greater than the long-term average (86 winter average), (i) from the early 1900s to the early 1920s and (ii) from the late 1950s to the early 1980s and one period when the reconstructed total winter ice cover was generally less than the long-term average, from the early 1920s to the late 1950s. A non-parametric Wilcoxon rank sum test (Conover, 1980) was used to evaluate the hypotheses that total winter ice cover was greater during the winters 1898–1920 than it was for the winters 1921–1958, and that total winter ice cover was greater for the period 1959–1983 than it was for the period 1921–1958. Neither hypothesis was rejected at the 5 per cent significance level. Thus there appears to be three separate ice-cover regimes over the 86-winter period.

The temporal distribution of the winters with extreme ice cover (Table IV) is in good agreement with the three ice-cover regimes and with trends in winter temperatures for both the nation and the Great Lakes (Diaz and Quayle, 1980; Brinkmann, 1983; Assel, 1986b) over the past 86 winters. Two-thirds of the mild ice-cover winters for both Lakes Erie and Superior occurred between 1921 and 1958, a period of generally warmer winters compared with (i) the late 1890s to 1920 and (ii) the late 1950s to early 1980s. Almost all the severe ice-cover winters for both lakes (eight out of nine severe winters) occurred during these two periods.

A biannual periodicity in the annual ice cycle of European lakes has been known for almost a century (Voeikov, 1891). Rogers (1976) found evidence of a quasi-biennial pattern in the annual maximal ice covers of the 1960s and 1970s for Lake Superior, and he attributes the 2-year period to the quasi-biennial oscillation (QBO) phenomenon in the atmosphere (Landsberg, 1962; Angell and Korshover, 1968). A spectral analysis of the total winter ice cover of Lakes Erie and Superior over the 86 winters of this study was made using an IMSL (1987) computer algorithm (SSWD) for estimating the non-normalized spectral density of a stationary time series using a Daniell spectral window. Analysis was made with M, the spectral window smoothing parameter, varying from 10 to 60; results for $M=40$ are shown in Figure 6, but results for other values of M are similar. Peaks in the spectrum between 0·350 cycles year^{-1} and 0·400 cycles year^{-1} occur for both Lake Superior and Lake Erie. These peaks correspond to periods between 2·86 years and 2·50 years and are in agreement with the period of the QBO. Other peaks in both the Lake Erie and Lake Superior spectra may be aliases of harmonics of the QBO frequency; because of the length of this time series, it is not possible to accurately evaluate periodicities with frequencies below about 0·116 cycles year^{-1} (corresponding to about one-tenth of the 86-year period of record).

The synoptic maximal ice-cover climatology

The contemporary (1963–1983) observed averages of synoptic maximal ice cover is 90 per cent for Lake Erie and 70 per cent for Lake Superior. The reconstructed decadal averages of synoptic maximal ice cover for

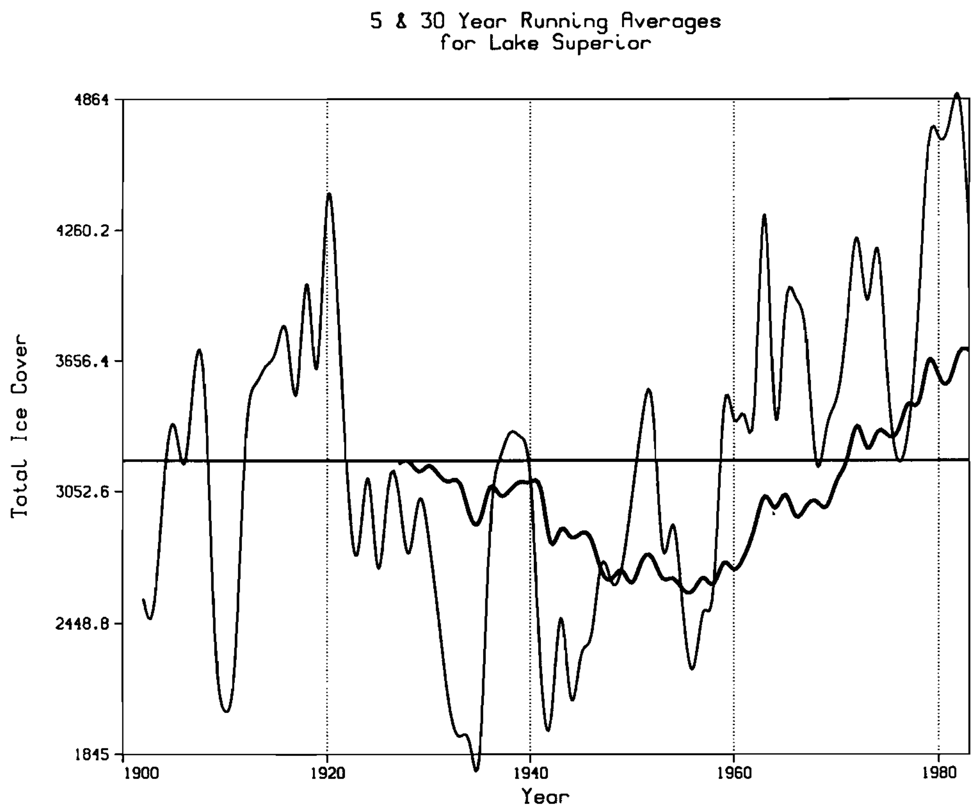

Figure 5. Equally weighted 30-year continuous (thick solid line) and 5-year continuous (thinner solid line) averages of the reconstructed total winter ice cover for (a) Lake Superior and (b) Lake Erie. The heavy horizontal line on each graph is the long-term (86 winter) average. The 30-year and 5-year continuous averages are plotted on the year they end; for example, the first 30-year continuous average is calculated for the years 1898–1927 and is plotted on the year 1927

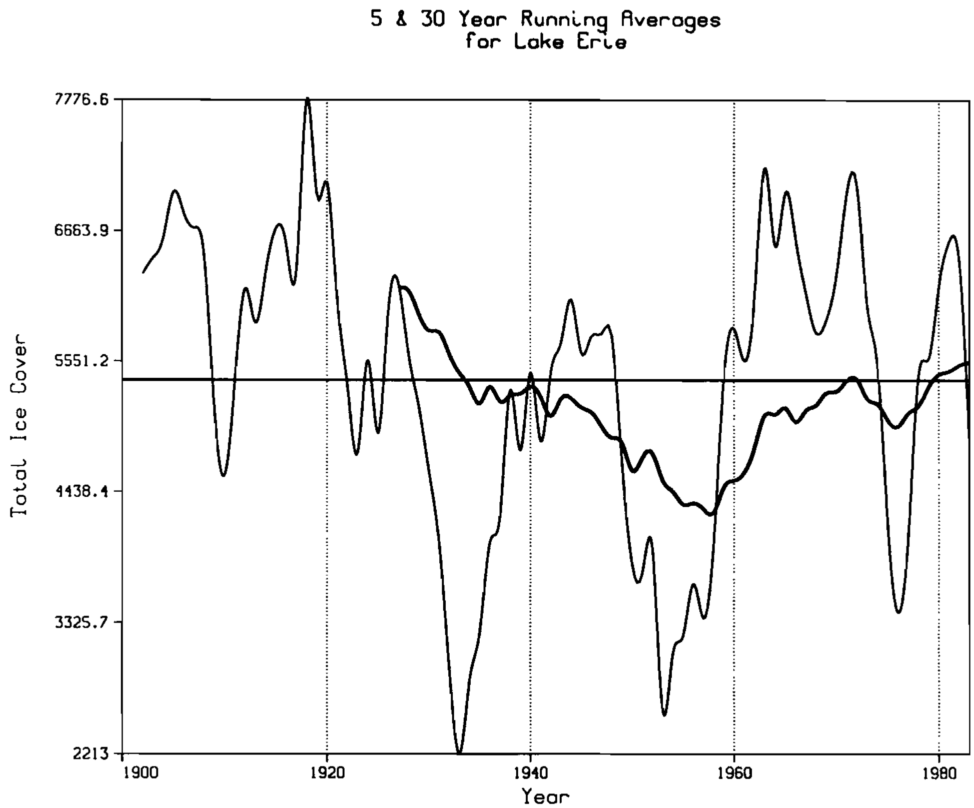

Figure 5(b). *(continued)*

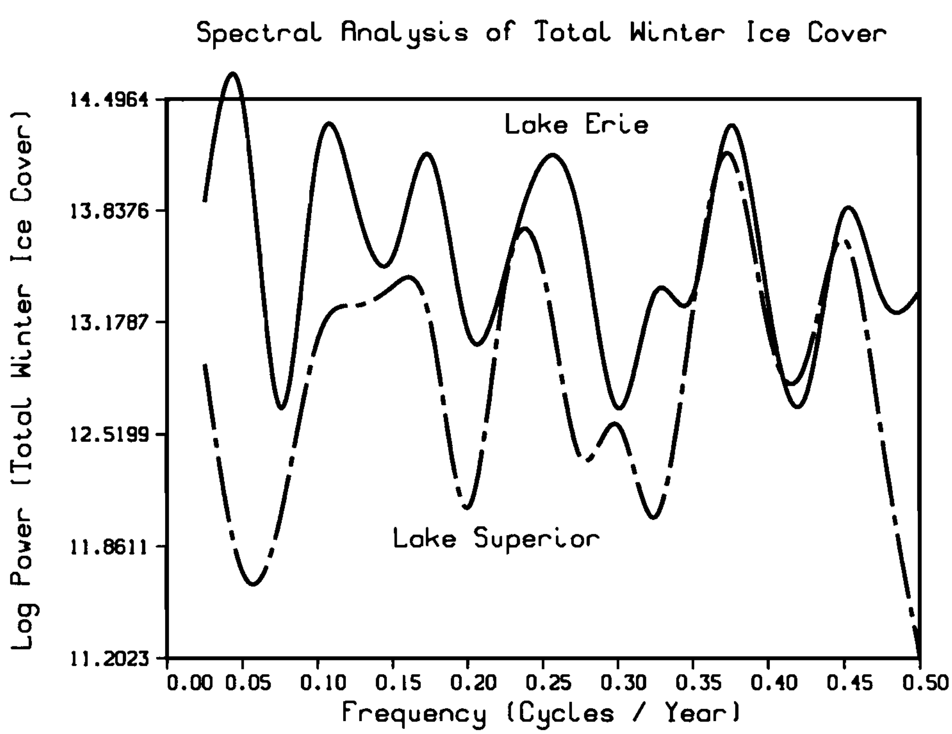

Figure 6. Spectral analysis of total winter ice cover for Lakes Superior and Erie, using the Daniell spectral window with the spectral window smooth parameter M set to 40

Table V. Average of synoptic annual maximal ice cover[a]

Period	Lake Erie	Lake Superior
1963–1983[b]	90	70
1963–1983[c]	87	60
1970–1979[c]	86	65
1960–1969	91	56
1950–1959	73	50
1940–1949	81	38
1930–1939	66	41
1920–1929	82	48
1910–1919	87	59
1900–1909	87	42
1898–1983[c]	82	50

[a] Percentage of lake surface area covered by ice.
[b] DeWitt *et al.* (1980) and Assel (1989)—actual observation.
[c] The ice-cover model used in this paper.

the 1920s through to the 1950s are 8–24 per cent less (Lake Erie) and 20–32 per cent less (Lake Superior) than the contemporary observed averages (Table V). In the case of Lake Superior, the average of the reconstructed synoptic maximal ice covers of the first decade of this century is also much less than the contemporary observed average. Thus, it is likely that Lake Erie and Lake Superior ice-cover climatologies developed after 1960, such as those of Rondy (1971), Assel *et al.* (1983), and Saulesleja (1986), are not, in general, representative of ice covers from the 1920s to the 1950s, when most of the mild ice seasons occurred.

SUMMARY AND CONCLUSIONS

Empirical–statistical ice-cover models (Assel, 1989) were used to reconstruct and analyse long-term average monthly and total winter ice cover, the seasonal progression and variation of monthly average ice cover, extreme ice-cover seasons, and temporal trends in total winter ice cover over 86 winter seasons for Lake Erie and Lake Superior. Results were in general agreement with available historical Great Lakes ice-cover data; it is difficult, however, to make a quantitative assessment of model errors prior to the decade of the 1960s, because of a lack of comprehensive over-lake ice-cover data. Error analysis over 21 winters from the early 1960s to the early 1980s indicates time-averaged ice cover is within 10 per cent of an observed 21-winter average.

The long-term mean (86-winter average) reconstructed monthly ice cover is greater and more variable on Lake Erie than it is on Lake Superior, because of Lake Erie's smaller thermal inertia. Ice cover begins to form on mid-lake areas of Lake Erie in January, which is about 1 month earlier than mid-lake ice formation on Lake Superior. Maximal ice cover occurs in February on Lake Erie and in February or March on Lake Superior. Long-term average reconstructed maximal ice cover is 25–30 per cent greater on Lake Erie than it is on Lake Superior. Mid-lake ice cover is lost earlier on Lake Erie, usually in March, because of milder air temperatures. Most years, shore ice is completely dissipated before the end of May. During severe winters, mid-lake ice covers can form a month earlier than normal; during mild winters, ice covers are confined primarily to shallow lake areas. A spectral analysis of the total winter ice cover for the 86 winters revealed periodicities of between 2 years and 3 years. This pattern is likely a reflection of the influences of the quasi-biennial oscillation on the interannual variation of Great Lakes ice cover. Three ice-cover regimes were identified during the 86-winter period (1897–1898 to 1982–1983): (i) a high ice-cover regime from the late 1890s to the early 1920s, when reconstructed total winter ice cover was generally greater than the long-term mean; (ii) a low ice-cover regime from the early 1920s to the late 1950s, when reconstructed total winter ice cover was generally less than the long-term mean; and (iii) a second high ice-cover regime from the late 1950s to the early 1980s, during which reconstructed ice cover once more was generally higher than the long-term mean. These results indicate that the current ice-cover climatologies, developed during the 1960s, 1970s, and early 1980s, are not generally representative of ice covers from the early 1920s to the mid-1950s, when it is quite likely that average ice cover extent and average ice season duration were smaller.

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