IMPACT OF GLOBAL WARMING ON GREAT LAKES ICE CYCLES

by

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Interagency Agreement Identification Number DW13932631-01-0

CONTENTS

FINDINGS[1]

Lake basin mean depth is an index of thermal inertia, and freezing degree-days (FDD) are an index for energy loss at the water surface. Daily basin mean FDD are correlated with daily basin mean ice concentration during winter. Annual ice cover duration and daily ice concentration are simulated with FDD regression equations for Lake Erie's West, Center, and East Basins and for Lake Superior's West, East, and Whitefish Bay Basins. Models are calibrated over a 20-year (1960-79) period. Models are applied to an independent four-winter period (1980-83) to evaluate simulation error. Standard errors on the independent winters ranged from 20 to 30 percent for annual maximum ice concentration, and standard errors were 2 to 4 weeks in magnitude for annual ice cover duration.

Average monthly air temperature for doubled CO_2 scenario winters is above-freezing for Lake Erie basins. Ice cover still forms during some doubled CO_2 winters because of a sufficient number of consecutive days with below-freezing air temperatures. Ice concentration and duration trends followed the air temperature trends of the three doubled CO_2 scenarios; that is, the coldest scenario (Oregon State University) had the greatest ice concentration with the longest ice cover duration, and the warmest scenario (Geophysical Fluid Dynamics Laboratory) had the smallest ice concentration with the shortest ice season duration. Daily average ice cover under all of the doubled CO_2 scenarios is limited to the shore area and shallows of each lake basin. Doubled CO_2 scenario winters without ice cover occur 37 to 83 percent of the time in the East and Central Basins of Lake Erie and up to 17 percent of the time for the West Basin of Lake Erie and the East Basin of Lake Superior. Average winter duration for the 1951-80 base period was 13 to 16 weeks. Under the doubled CO_2 scenarios, the average winter duration is 5 to 13 weeks shorter. The shorter duration and less extensive ice covers would affect lake ecology, and loss of some cold water fish species such as lake whitefish may occur. The shipping season, which traditionally stops during the winter months, would likely be extended, perhaps to a year-round season.

Under the 79-year transient CO_2 scenario (1981-2059), only Lake Erie basins have winters without ice cover. During the last three decades of the transient (2030-59) 30 to 80 percent of the winters for Lake Erie's Center and East Basins are without ice cover. Transient scenario daily ice concentration, averaged for the years 2010-39, is significantly less than the base period for all lake basins. However, extensive ice cover will occur under many transient CO_2 winters, particularly during the first 29 years (1981-2009). Average ice cover duration is 3 to 7 weeks shorter during the next 30 years of the transient 2010-39 relative to the 1951-80 base period. During the last decade of the transient scenario (2050-59), decadal-averaged ice concentration and ice cover duration is similar to the doubled CO_2 scenarios.

Ice cover simulation of an analog climatic warming period (1930-39) shows that average ice cover duration was 1/2 to 1 week shorter than the 1951-80 base period for Lake Superior and about 3 to 4 weeks shorter for the Center and East Lake Erie Basins. Annual maximum ice concentration was less than the base period but greater than the doubled CO_2 scenario.

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[1] Although the information in this report has been funded partly by the U.S. Environmental Protection Agency under contract DW13932631-01-0, it does not necessarily reflect the Agency's views, and no official endorsement should be inferred from it.

CHAPTER 1

INTRODUCTION

GREAT LAKES ICE COVER AND ICE CYCLES -- A BRIEF REVIEW

The Great Lakes ice cycle is divided into three periods: fall cooling, ice formation, and ice loss. During fall cooling, thermal stratification is lost as the entire water column cools to the temperature of maximum density near 4 degrees C. Subsequent cooling results in the formation of less dense surface water, winter restratification, and the start of the ice formation period. Ice loss occurs in spring owing to increasing solar radiation and above-freezing air temperature.

During the winter ice formation period, vertical ice accretion occurs as a result of heat transfer from the ice-water interface through the ice to the atmosphere. As the ice cover thickens its vertical extent reduces the rate of heat loss from the ice-water boundary and retards additional ice accretion. Under the current climate regime, the upper limit of thermodynamic ice growth appears to be about 50 to 100 cm for bay and harbor sites in the Great Lakes (Sleator, 1978). Local factors such as air temperature, water depth, winds, and snowfall are responsible for the variation of ice thickness. Winds can cause portions of an ice cover to compact and override or submerge under the remaining ice cover; the result is rafted, ridged, or jammed ice, depending upon the amount and vertical extent of ice rubble formed. The U.S. Coast Guard has reported wind-induced ice thickness of up to 8 m in the Great Lakes.

The Great Lakes' ice cover forms in the shallow bays and harbors in December and in deeper bays and along the perimeter of the Great Lakes during January. Lake Erie, with its shallow depth, forms midlake ice cover in January; midlake areas of the other Great Lakes usually form extensive ice cover in February. Annual maximum ice coverage occurs in February and early March, but even then, some areas tend to remain open water. Normal maximum ice cover expressed as a percentage of total surface area is 90% for Lake Erie, 75% for Lake Superior, 68% for Lake Huron, 45% for Lake Michigan, and only 24% for Lake Ontario (Assel et al., 1983). Lake Ontario's small annual maximum ice coverage results from the combination of (1) its large thermal inertia (mean depth of 86 m), (2) average water surface temperatures during winter near but above 0 degrees C, which make air-water temperature differences primarily a function of air temperatures, and (3) its relatively mild winter air temperatures (-4.4 degrees C, compared with -9.8 degrees C for Lake Superior). Air temperature is the single most important atmospheric climate variable affecting ice cover. The average winter temperature for all five Great Lakes in 1979 was -6.8 degrees C, and the annual maximum ice extent was nearly 100%. The average winter temperature for 1983 was -2.2 degrees C and the maximum ice extent was approximately 23% of the combined Great Lakes surface area (Assel et al., 1985).

In spring, ice loss results from melting caused by solar radiation and above-freezing air temperature. Solar radiation penetrates and is absorbed within the ice, reducing the structural strength of the ice due to preferential melting at ice crystal boundaries. The weakened ice cover can then be easily broken by winds and wave action, and melted or transported to windward (eastern) lake shores. In March, areas of open water and low ice concentration expand from the deeper, more exposed midlake areas toward the perimeter and eastern shores. By mid-April, any remaining ice is usually located in the shore zone; however, during some years, ice cover lasts into May.

ICE CYCLE MODELS

Ice cover models that lend themselves most easily to climate analysis are empirical and statistical in nature because of the availability of input data needed to calibrate and evaluate them. For this reason and because of a need to complete this analysis in a timely manner, only relatively simple empirical statistical models using cumulative air temperature in the form of degree-days are considered in this paper.

Freeze-up dates on shallow inland lakes in Canada were found to correlate with weighted mean daily air temperatures (Bilello, 1964) and accumulated freezing degree-days (FDD) (Williams, 1965). Later Williams (1971) also correlated breakup dates with previous dates of breakup and air temperatures. And Tramoni et al. (1985) and Barry (1986) found that freeze-up on shallow inland lakes in Canada and Finland are an index of fall air temperatures; an increase of 1 degree C in average fall air temperature corresponded with a 3- to 10-day delay in date of freeze-up. One of the earliest empirical ice cover studies on the Great Lakes was made by Oak and Myers (1953); they used February air temperature to forecast spring opening dates for navigation at various bays and harbors. Systematic aerial ice reconnaissance observations of Great Lakes ice cover began in the late 1950's; this established a data base for making empirical and statistical studies of large areas of the Great Lakes ice cover. Richards (1963) correlated antecedent heating degree-days for the previous summer (index of summer heating) and freezing degree-days for late fall and winter (index of water cooling and ice formation) with observations of lake-averaged Great Lakes ice cover. Snider (1971) developed threshold FDD accumulations for navigationally significant ice in specific areas of the Great Lakes, based on average heat storage in the water. Rogers (1976) used FDD and thawing degree-days to develop regression models of annual maximum lake-averaged ice concentration. More recently, Assel et al. (1985) developed a regression model of regional annual maximum ice cover of the combined area of the five Great Lakes, based on regional average winter temperature. Their model implies that a 4 to 5 degree C increase in regional average winter temperature from the 1951-80 base period average would result in regional annual maximum ice cover between 0 and 9% for the combined area of the Great Lakes. Howe et al. (1986) developed empirical models for each lake relating monthly average air temperature on the perimeter to annual maximum ice cover. They estimated the climatically "normal" annual maximum ice cover based on 1951-80 mean air temperatures and the expected annual maximum ice cover for a doubled CO_2 warming. Their results indicate that, except for Lake Erie, the expected annual maximum ice cover under a doubled CO_2 warming is nil.

The studies noted in the previous paragraphs developed models of different parts of the annual ice cycle. In this present study empirical models were developed that simulate daily mean basin ice concentration for the entire ice cycle, using some of the methods from the earlier studies. This initial analysis is limited to Lakes Erie and Superior -- the two lakes that represent the extremes in mean lake depth and air temperatures for the Great Lakes. A summary of development methodology and an assessment of model limitations are described. The range and expected values of ice concentration and ice cycle duration are presented and briefly interpreted relative to environmental and socio-economic implications.

CHAPTER 2

METHODOLOGY

MODEL DEVELOPMENT AND ADJUSTMENTS

Two important variables affecting ice formation are (1) heat stored in the water mass and (2) the energy budget at the air-water boundary. Mean lake basin depth (volume divided by surface area) is an index that reflects thermal inertia, and accumulated freezing degree-days (FDD) are an index of energy loss from the surface mixing layer. Lakes Superior and Erie are divided into basins using lake bathymetry: East, Center, and West Basins for Lake Erie, and East and West Basins for Lake Superior (Figure 1 and Table 1). In addition, Whitefish Bay is included as a separate basin of Lake Superior because of its importance to navigation.

Table 1. 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 (km2)	21971	58947	1182	5135	14635	5909
Volume (km3)	2966	8960	48	46	278	159
Max FDD (C)#	1299	1255	1255	318	342	368

Averaged annual maximum FDD for the 1951-80 base period.

Mean basin ice concentration is calculated for each lake basin from synoptic ice charts (Assel, 1983) for the years 1960-79. These data are used to develop regression equations between synoptic mean basin ice concentration and daily mean basin FDD accumulation through the date of the synoptic ice concentration observation (Table 2). Equation 1 was developed for Lake Superior's East and West Basins, and Equation 2 for Whitefish Bay and the three Lake Erie basin. Equations 3 and 4 differentiate between initial ice formation in shallow or mid-basin areas, and Equation 4 is used for initial ice formation in shallow areas of Lake Superior's East and West Basins. Equation 5 is an ice reduction factor that is part of Equation 1 and Equation 2.

The three periods of the annual ice cycle are simulated by the system of equations in Table 2. Initial ice formation is a function of threshold FDD accumulations given as part of the constraints in Equations 2, 3, and 4. Threshold FDD values are estimated from analysis of historic ice charts and corresponding FDD accumulations from November 1 to the date given on the ice chart. If these threshold FDD values are not accumulated, ice cover will not form. Threshold FDD values for Lake Erie's West, Center, and East Basins are 27, 75, and 110 FDD, respectively. Initial ice extent at these threshold values is 45%, 37%, and 30%, respectively. If less than 430 FDD accumulate for the East and West Basins of Lake Superior, ice cover will not form. The threshold FDD value needed for initial ice formation on Whitefish Bay is 350.

Ice growth is simulated by the expressions (FDD-BFDD) in Equations 1 and 2. These expressions are an index of heat loss at the air-water boundary and they also incorporate the hysteresis effect of antecedent FDD accumulations on increasing ice extent. The hysteresis effect in Equation 1 (exponential term) is a function of the number of days past the date of end-of-fall overturn because the maximum ice cover (which is usually below 100%) is related to the number of days past the date of end-of-fall overturn on Lake Superior's East and

FIGU.

LAKE BASINS AND TEMPERATURE STATIONS

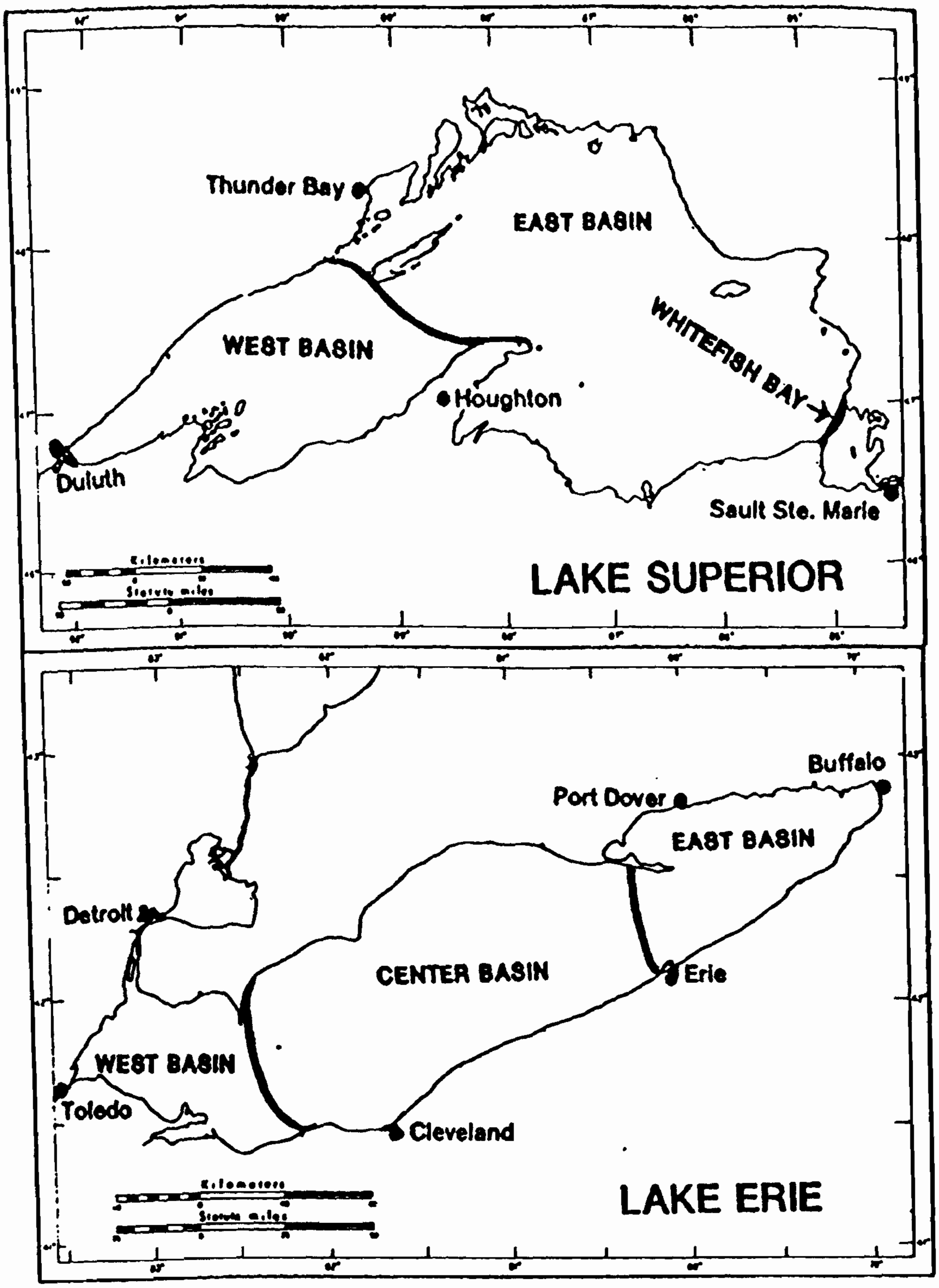


Table 2. Annual Ice Cycle Simulation Model Equations

EQ. 1

$$ICE = \frac{100}{1 + C1 * exp[C2 * ((FDD - BFDD)/JD)] + C3 * (FDD - BFDD) + THFAC}$$

EQ. 1 constraints:
1. $730 < FDD < FDDCRIT$
2. $JD = 1$ when $FDD = BFDD$ and JD increments by 1 every day after that date.
3. $ICE = 100$ if $FDD > FDDCRIT$

EQ. 2

$$ICE = \frac{100}{1 + FZFAC + C1 * exp[C2 * (FDD - BFDD)] + THFAC}$$

EQ. 2 constraints:
1. $450 < FDD$ (for Whitefish Bay only)
2. $FZFAC = 1000$ when $FDD < BFDD$, $FZFAC = 0$ when $FDD > BFDD$
3. $ICE = 0$ if $FDD < BFDD$

EQ. 3 $ICE = 5 * (FDD - 350)/100$

EQ. 3 constraints:
1. $350 < FDD < 450$
2. $ICE = 0$ if $FDD < 350$
3. $JD < DMFDD$

EQ. 4a $ICE = 5 + 10 * (FDD - 580)/150$

EQ. 4a constraints:
1. $580 < FDD < 730$
2. $JD < DMFDD$

EQ. 4b $ICE = 5 * (FDD - 430)/150$

EQ. 4b constraints:
1. $430 < FDD < 580$
2. $ICE = 0$ if $FDD < 430$
3. $JD < DMFDD$

EQ. 5

$$THFAC = \frac{1}{1 - [(JD - DMFDD)/\{Sqrt(MFDD - BFDD)/MELT\}]} - 1$$

EQ. 5 constraints:
1. $THFAC = 0$ if $JD < DMFDD$
2. $THFAC = 9999$ if $JD - DMFDD >$ a. or b. below:
   a. $Sqrt[(MFDD - BFDD)/MELT]$
   b. maximum historic observed value of days past annual maximum FDD to date of last observed ice.

See glossary for definition of terms.

West Basins. The hysteresis effect of antecedent FDD accumulation in Equation 2 is related to the FDD accumulation necessary for virtually 100% ice coverage because the ice cover on Lake Erie basins and Lake Superior's Whitefish Bay approaches 100% most winters. Basin ice concentration generally decreases by the date FDD accumulations reach their annual maximum value -- average air temperatures are usually above freezing after that date. Consequently, the date of annual maximum FDD accumulation defines the end of the ice growth period and the beginning of the ice decay period. A temporal ice concentration reduction factor, Equation 5, is activated in Equations 1 and 2 after the date of annual maximum FDD accumulation. Ice loss in Equation 5 is a function of average daily ice melt rate, average ice thickness on the date of maximum FDD accumulation, and number of days past the date of maximum FDD accumulation. The average ice melt rate (cm/day) during the ice loss period was optimized by trial and error during the regression analysis. The rate is 1.250 (cm/day) for Lake Superior's East and West Basins, and Whitefish Bay, and 0.889, 0.667, and 0.333, for Lake Erie's West, Center, and East Basins, respectively. Lake-averaged ice ablation rates for bays and harbors of Lakes Superior and Erie are 1.4 and 1.1 cm/day, respectively (Bolsenga, 1988). Lower ablation rates for Lake Erie's Center and East Basins apparently reflect the eastward advection of ice into these basins during the ice loss period, which in effect, prolongs the period of ice loss and reduces the average daily rate of ice ablation. A Stefan ice growth expression (the square root of the accumulated FDD) was used to estimate ice thickness. Complete ice loss occurs when the number of days past the date of annual maximum FDD exceeds the number of days needed to melt the ice at the average melt rate. The largest observed number of days between the date of annual maximum FDD accumulation and the date of ice cover loss was estimated for simulating ice loss in Lake Erie basins.

MODEL LIMITATIONS

Model prediction error for each basin was evaluated by the cross validation method; that is, the data were divided in half and model coefficients were generated for each subset of the original data. Coefficients for one subset were used to simulate ice concentration for the second subset. The model prediction error for each data subset ranged from 15 to 28% (Table 3).

Table 3. Model Cross Validation for Root Mean Square Error (RMSE)

	Lake Superior			Lake Erie		
RMSE	WB	EB	WFB	WB	CB	EB
First half of data	25.9	20.9	14.7	17.8	24.9	19.7
Second half of data	27.8	18.8	22.8	22.1	27.0	18.1

Model prediction error over the entire data base was evaluated by simulation of annual maximum lake-averaged ice concentration during four winters outside the model calibration period. Estimates of lake-averaged annual maximum ice cover and date of occurrence for the early 1980s have been provided by the U.S. Coast Guard (personal communication, United States Coast Guard, Ninth District Headquarters, Cleveland, Ohio). Basin mean ice concentrations from simulation models for Lakes Superior and Erie were areally weighted and summed to obtain the lake-averaged ice concentration for the dates of annual maximum ice concentration provided by the Coast Guard. The four "test winters" contained both extremely high and extremely low annual maximum ice concentrations (Table 4). Models did well for both winter extremes; standard errors are 30% for Lake Superior and 20% for Lake Erie. It is significant that the models did well during the mild 1982-83 winter, since that winter is ranked as the 10th warmest winter in the Great Lakes during the 200-year period 1783-1983 (Assel et al., 1985), and thus it likely approaches conditions of some of the CO_2 global warming scenarios.

Table 4. Simulation Error for Annual Maximum Ice Extent

Lake	Winter Season	Maximum Ice Concentration Observed	Maximum Ice Concentration Simulated	Error (Obs-Sim)
Superior	1979-80	75	34	41
	1980-81	92	62	31
	1981-82	97	96	1
	1982-83	21	13	8
Erie	1979-80	95	86	9
	1980-81	100	85	15
	1981-82	100	74	26
	1982-83	25	40	15

Errors in simulated ice cover duration were also analyzed. Ice cover duration is defined here as the difference in days between the dates of initial ice cover greater than 0.5% concentration and final and complete loss of ice cover. Dates of first- and last-ice were estimated from Canadian composite ice charts and from National Ocean Service water level gauge ice reports. Standard error in simulated ice cover duration ranged from 3 to 4 weeks for Lake Superior basins and from 2 to 3-1/2 weeks for Lake Erie basins (Table 5). Determining ice cover duration during mild winters can be difficult. The first and last dates of ice were used to determine season duration, but in mild winters this method may over-estimate the actual number of days with ice cover because of alternating periods of ice formation and ice cover loss. For example, an error of 40 days for West Basin of Lake Erie during the mild 1982-83 winter resulted from intermittent ice cover during two days in December. If those spurious data were omitted, the initial ice cover would have been on January 18th and the season duration would have been 45 days, producing an error of only 3 days.

It is difficult to quantify the magnitude of error in ice cover models caused by not considering wind effects because wind effects are highly nonlinear and depend upon physical processes that occur on time scales of a few hours to a few days. Analysis of data from Lewis (1987) indicates that for the 28-year period 1957-1985, the annual average number of storms with wind speeds of 88 km/hour or greater during the 3-month period January, February, and March is about one severe storm per winter. If winter storms of this magnitude were to increase in frequency during the climate warming scenarios, this would contribute to a reduction in both ice duration and ice concentration; a reduction in storm frequency from the present climate average of one per season would have the opposite effect. High winds during the early winter would tend to retard ice formation, particularly in the deeper lake basins; thus, models would predict initial ice formation too early and ice extent would be over-estimated. An extended period of calm conditions in early winter would have the opposite effect; initial ice covers would form earlier and be more extensive. High winds during the winter after an extensive ice cover exists could reduce ice covers temporarily, and models would over-estimate ice extent. High winds in spring could move the ice out of a basin or melt it by upwelling, resulting in an over-estimated ice coverage during part of the ice loss period and a tardy simulated date of last ice cover.

SCENARIOS USED

The 1951-80 climatological period used to define the current normal value for climate elements was used as a base period in this study. The decade of the 1930's had several years of much above normal temperatures and is used as a historic analog that approaches CO_2 global warming scenarios. Cumulative departures from long-term monthly mean temperature (1895-1977) for the contiguous United States show a increasing temperature trend from 1921 to 1954 and a decreasing trend after that (Diaz and Quayle, 1980). Mild winters

Table 5. Simulation Error for Ice Cycle Duration

	Ice Cycle Duration in Day								
Lake Superior	West Basin			East Basin			Whitefish Bay		
winter season	obs	sim	error	obs	sim	error	obs	sim	error
1979-80	105	87	18	108	88	20	108	101	7
1980-81	134	101	33	125	103	22	129	110	19
1981-82	123	119	4	139	118	21	150	121	29
1982-83	84	114	-30	91	92	-1	83	97	-14
Lake Erie	West Basin			Center Basin			East Basin		
winter season	obs	sim	error	obs	sim	error	obs	sim	error
1979-80	118	106	12	69	72	-3	76	86	10
1980-81	79	81	-3	94	80	14	121	103	18
1981-82	95	107	-12	92	89	3	113	111	2
1982-83	42	82	-40	37	16	21	28	17	11

obs = observation; sim = simulation

occurred in the Great Lakes during the early 1950's but not during the rest of the 1951-80 base period when severe winters were prevalent (Assel, 1986).

Monthly mean air temperatures ratios (doubled CO_2/1CO_2) for the GISS, GFDL, and OSU scenarios and for the GISS-A scenario were multiplied by daily mean air temperatures for stations on the perimeter of each basin for the 1951-80 base period data (Table 6). The closest grid point for a given global circulation model (GISS, GFDL, OSU) was determined for each meteorological station (Table 6), and the air temperature ratios at that grid were used for simulating the doubled CO_2 and transient CO_2 temperature time series. The daily observed station temperatures were converted to degrees Kelvin, multiplied by the appropriate ratio (year and month) for a given scenario, and then converted back to degrees C, following EPA instructions. Mean daily air temperatures for the 1930-39 historic analog scenario and the 1951-80 base period were abstracted from a Great Lakes Environmental Research Laboratory air temperature data base (Assel, 1986) for analysis. Mean basin daily air temperatures and FDD accumulations were calculated and the daily FDD data were used to drive the ice cycle simulation models. Winter seasons were started in November prior to the year shown as the first year of the scenario. For example, the 1951-80 base period includes air temperatures and FDD for November and December, 1950. The GISS-A scenario began November 1980; the average ice cover statistics for the first decade of these scenarios was only nine winters, 1981-89. Thirty-year monthly averaged temperatures for the 1951-80 base period, the doubled CO_2 scenarios, and decadal monthly averages for the 1930-39 analog and transient CO_2 scenario are given in Table 7 for East and West Basin of Lake Erie and East and West Basins of Lake Superior. Monthly air temperatures for the doubled CO_2 scenarios are above 0 degrees C for Lake Erie, but only during November and occasionally during March for Lake Superior. This is somewhat misleading since daily average temperatures are occasionally below 0 degrees C; consequently, global circulation model output statistics should concern a daily rather than a monthly time period. Daily values may produce significantly different results relative to ice cover simulation. The transient decadal average monthly temperatures for the first three decades are in general similar to the 1951-80 base period. November-through-March averaged temperatures for the last decade of the transient is similar to GISS doubled CO_2 scenario averaged temperatures. The 1930-39 analog temperatures are less then 2 degrees C warmer than the 1951-80 base period in most of the winter months.

CHAPTER 3

RESULTS

Daily mean basin ice concentration was simulated for the 30 winter seasons of the 1951-80 base period, the 30 winters of each doubled CO_2 scenario, the 79 winters of the transient CO_2 scenario, and for the winters of the 1930-39 analog scenario. These data and monthly statistics for all scenarios (average, median, maximum, minimum, and standard deviation) and decadal averages of monthly statistics for the transient CO_2 scenario are available at the Great Lakes Environmental Research Laboratory.

WINTERS WITHOUT ICE COVER

The winter of 1952-53 was extremely mild, and ice cover did not form in Lake Erie's East and Central Basins (International Niagara Working Committee, 1983). The ice cycle models for these basins accurately simulated the lack of ice cover that winter. This was the only winter during the base period that Lake Superior or Lake Erie lacked ice cover. Under the doubled CO_2 scenarios up to 7% of the winters for Lake Superior basins and up to 17% of the winters for the West Basin of Lake Erie lack ice. From 37 to 83% of the winters for Center and East Basins of Lake Erie also are without ice cover (Table 8). Under the transient scenario, only Lake Erie basins have winters without ice cover. During the first five decades, no more than 20% of the winters for Lake Erie basins are without ice cover. Because of the greater mean depth of the Center and East Basins of Lake Erie (compared to the West Basin), they have more winters without ice cover in the latter decades of the transient and for the doubled CO_2 scenarios. During the last three decades of the transient, 30 to 80% of the winters for Central and East Basins of Lake Erie (but no more than 10% of winters for West Basin) are without ice cover. During the 1930-39 analog decade, only the East Basin of Lake Erie had winters without ice cover, and then, for only 20% of the time.

DATES OF FIRST/LAST ICE COVER AND ICE COVER DURATION

The 1951-80 Base Period

Ice covers began forming in shore areas of Lake Superior during the first half of January and were lost near the end of April. The average annual duration of the ice cycle on Lake Superior basins was 15 to 16 weeks. Initial ice formation on Lake Erie occurred in the shallow West Basin the third week of December and was usually lost during the third week in March. On average, the West Basin of Lake Erie had ice cover for about 13 weeks. In Lake Erie's Central and East Basins, first-ice occurred early in January and it was completely lost by late March (Center Basin) or mid-April (East Basin). Average ice cover duration was about 12 weeks for the Center Basin and close to 14 weeks for the East Basin of Lake Erie.

Doubled CO_2 Scenarios

The average dates of first- and last-ice were based only on winters with ice cover, and all 30 winters were used in calculating the average annual duration of ice cover. Under the doubled CO_2 scenarios, Lake Superior ice formation starts 2-1/2 to 6-1/2 weeks later and ends 2-1/2 to 6 weeks earlier than it did in the 1951-80 base period; Lake Erie ice formation starts 3 to 4-1/2 weeks later and ends 4 to 6 weeks earlier than the 1951-80 base period (Table 9). The average duration of ice cover is 5 to 13 weeks shorter for Lake Superior and 8 to 13 weeks shorter for Lake Erie.

The Transient Scenario

GISS-A decade averages show a general trend of later first-ice and earlier last-ice dates. Because of the built-in bias of lower temperatures in the 1951-80 base temperature data used to construct the transient scenario

Table 8. Percentage of Winters Without Ice Cover

Scenarios		Lake Superior			Lake Erie		
		WB	EB	WFB	WB	CB	EB
$1CO_2$	1951-80	0	0	0	0	3	3
$2CO_2$	GISS	0	0	0	10	67	80
$2CO_2$	GFDL	0	7	7	17	73	83
$2CO_2$	OSU	0	0	0	7	37	60
GISS-A	1981-89	0	0	0	0	10	10
GISS-A	1990-99	0	0	0	0	0	0
GISS-A	2000-09	0	0	0	0	0	0
GISS-A	2010-19	0	0	0	10	10	20
GISS-A	2020-29	0	0	0	0	0	0
GISS-A	2030-39	0	0	0	0	30	30
GISS-A	2040-49	0	0	0	10	40	70
GISS-A	2050-59	0	0	0	10	70	80
Analog	1930-39	0	0	0	0	0	20

temperatures, dates of first-ice are earlier and dates of last-ice are later than the 1951-80 base period in some of the early decades of GISS-A. A 29-year (1981-2009) average and a 30-year (2010-39) average for dates of first- and last-ice and ice cover duration were calculated to filter out the effects of the bias of lower temperatures in the 1951-80 base period (Table 9). Average dates of first-ice, last-ice, and ice cover duration for 1981-2009 are virtually the same as the 1951-80 base period, with the exception of the Center and East Basins of Lake Erie. Average date of first-ice for 2010-39 is 1-1/2 to 2 weeks later and average date of last-ice is 2 to 4 weeks earlier than during the 1951-80 base period. Average ice cover duration for 2010-2039 is 3 to 4 weeks shorter for Lake Superior basins and 5-1/2 to 7-1/2 weeks shorter for Lake Erie basins. The decadal average ice cover duration for the last two decades of the transient are 6-1/2 to 9 weeks shorter for Lake Superior basins and 9 to 13 weeks shorter for Lake Erie basins, compared to the 1951-80 base period (Table 9). Average ice cover duration during the 2040-49 decade is similar to the doubled CO_2 OSU scenario, and average ice cover duration for 2050-59 is similar to the doubled CO_2 GISS scenario.

The 1930-39 Analog Scenario

The 1930-39 analog has a shift to both later first- and later last-ice dates for Lake Superior basins and the West Basin of Lake Erie, relative to the 1951-80 base period. Average ice cover duration was 1/2 to 1 week shorter than the base period for Lake Superior basins and for the West Basin of Lake Erie. Analog decadal average ice duration was 3 to 4 weeks shorter then the base period for the Center and East Basins of Lake Erie.

DAILY AVERAGED BASIN MEAN ICE CONCENTRATION

Daily averaged ice concentration was calculated for the 30-year base period, for each of the doubled CO_2 scenarios, and for consecutive 29-year and 30-year non-overlapping periods of the GISS-A transient scenario (that is, 1981-2009 and 2010-39). The standard deviation of the base period daily average ice concentration was also calculated as an estimate of ice cover variability under the current climate regime. Selected results are shown in Figures 2 through 10. The daily averaged ice concentration portrayed in these figures was set to zero before the average date of first-ice and after the average date of last-ice (Table 9). This modification was done to be consistent with the dates given in Table 9 and does not significantly alter any of the findings.

A t-test (Brownlee, 1967) at the 99% probability level was performed between the daily averaged ice concentration of the base period and each of the two non-overlapping periods of the transient, and for each of the doubled CO_2 scenarios. During the 1981-2009 period, average daily ice cover was significantly different than the base period during late March and early April for Lake Superior basins and during the last three weeks of February for the Center Basin of Lake Erie. The daily average ice cover for the period 2010-39 was significantly different than the base period daily average most of the winter for all lake basins. The t-test analysis for the doubled CO_2 scenarios showed significant differences between the daily average ice concentration of the 1951-80 base period and the doubled CO_2 scenarios. It is probable ice cover will be restricted to shoal areas and to the shore zone of each lake basin during an average doubled CO_2 winter (Figures 5-10). However, it will still be possible, although not very likely, to have extensive ice cover formation during some doubled CO_2 scenario winters. Extensive ice cover will form during many of the transient scenario winters, particularly during the 1981-2009 year period of the transient (Figures 2-4).

Table 9. Average First-Ice/Last-Ice Dates and Ice Duration

Average First Date of Ice Cover *

Lake Basin	1951-80 $1CO_2$	Doubled CO_2 GISS	 GFDL	 OSU	1981-2009 GISS-A	2010-39 GISS-A
Sup WB	Jan 6	Feb 14	Feb 20	Jan 25	Jan 5	Jan 16
Sup EB	Jan 9	Feb 18	Feb 22	Jan 30	Jan 10	Jan 21
Sup WFB	Jan 2	Feb 6	Feb 15	Jan 19	Jan 4	Jan 12
Eri WB	Dec 17	Jan 18	Jan 17	Jan 7	Dec 19	Dec 31
Eri CB	Jan 6	Feb 4	Feb 4	Jan 27	Jan 10	Jan 16
Eri EB	Jan 12	Feb 3	Feb 7	Feb 2	Jan 15	Jan 26

Average Last Date of Ice Cover *

Lake Basin	1951-80 $1CO_2$	Doubled CO_2 GISS	 GFDL	 OSU	1981-2009 GISS-A	2010-39 GISS-A
Sup WB	Apr 27	Mar 31	Mar 15	Apr 8	Apr 24	Apr 14
Sup EB	Apr 26	Apr 1	Mar 14	Apr 8	Apr 22	Apr 13
Sup WFB	Apr 26	Apr 1	Mar 14	Apr 8	Apr 22	Apr 13
Eri WB	Mar 19	Feb 17	Feb 13	Feb 14	Mar 13	Feb 25
Eri CB	Mar 29	Feb 28	Feb 28	Feb 28	Mar 24	Mar 4
Eri EB	Apr 18	Mar 2	Mar 7	Mar 7	Apr 9	Mar 18

Average Ice Duration (Days) **

Lake Basin	1951-80 $1CO_2$	Doubled CO_2 GISS	 GFDL	 OSU	1981-2009 GISS-A	2010-39 GISS-A
Sup WB	112	46	24	75	108	88
Sup EB	108	43	19	69	103	84
Sup WFB	115	55	26	80	109	92
Eri WB	93	26	23	35	84	54
Eri CB	83	8	6	19	71	41
Eri EB	97	6	5	13	82	43

Table 9. (continued)

Decadal average ice cover duration for transient and analog

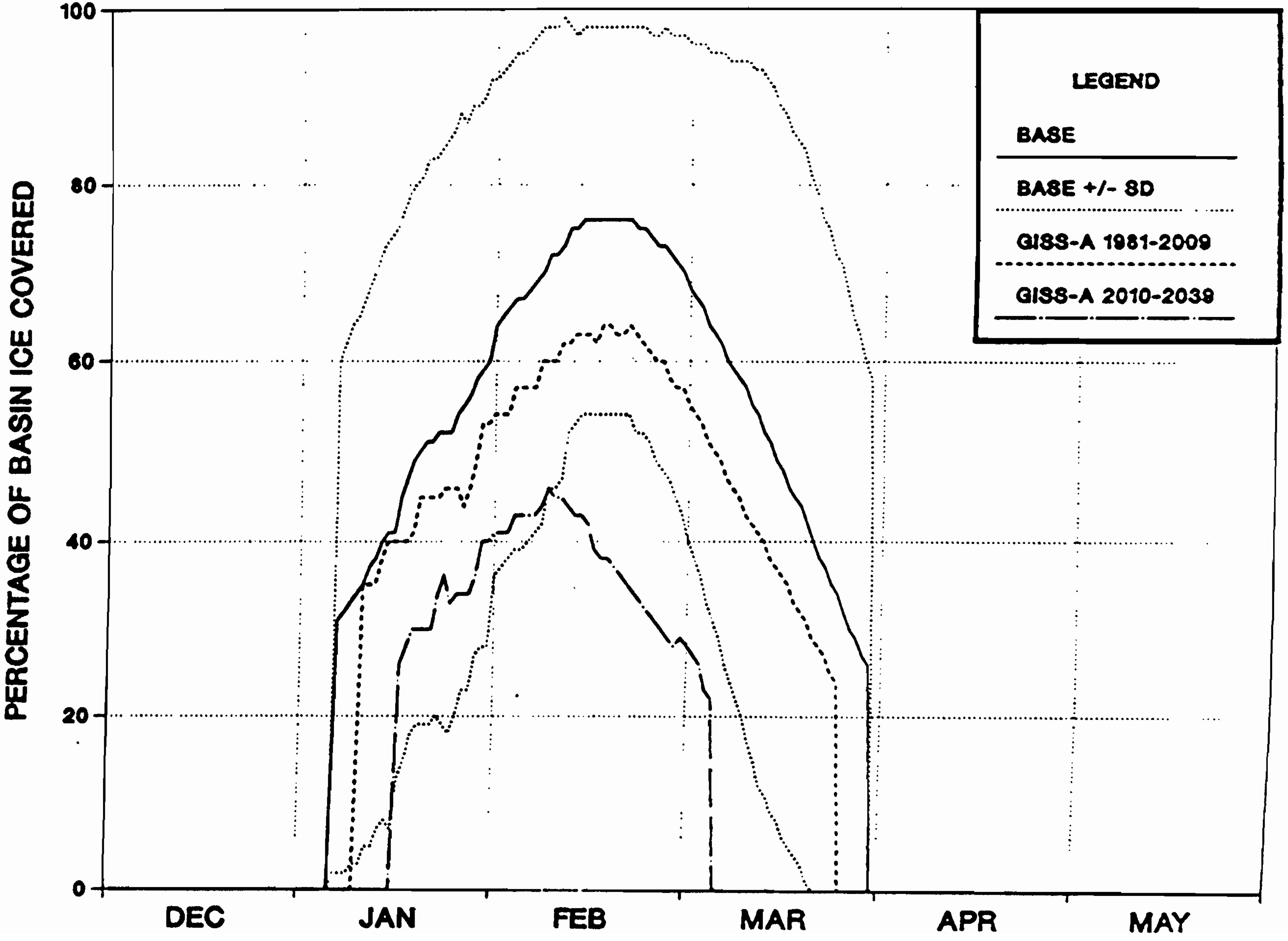
Lake	Decade Starting Year								
Basin	1930	1981	1990	2000	2010	2020	2030	2040	2050
Sup WB	106	110	107	109	93	86	86	66	46
Sup EB	103	103	100	105	86	82	83	61	44
Sup WFB	112	110	107	111	95	91	91	70	56
Eri WB	85	72	96	83	45	66	51	31	29
Eri CB	61	62	83	68	34	53	37	14	8
Eri EB	70	75	92	79	31	52	46	5	7

• Average dates of first- and last-ice for winters with ice cover.

•• Average season length for all winters in each scenario.

FIGURE 2

DAILY AVERAGED ICE COVER 1951-80 BASE & GISS-A SCENARIO
LAKE ERIE CENTER BASIN



DAILY AVERAGED ICE COVER 1951-80 BASE & GISS-A SCENARIO
LAKE SUPERIOR WEST BASIN

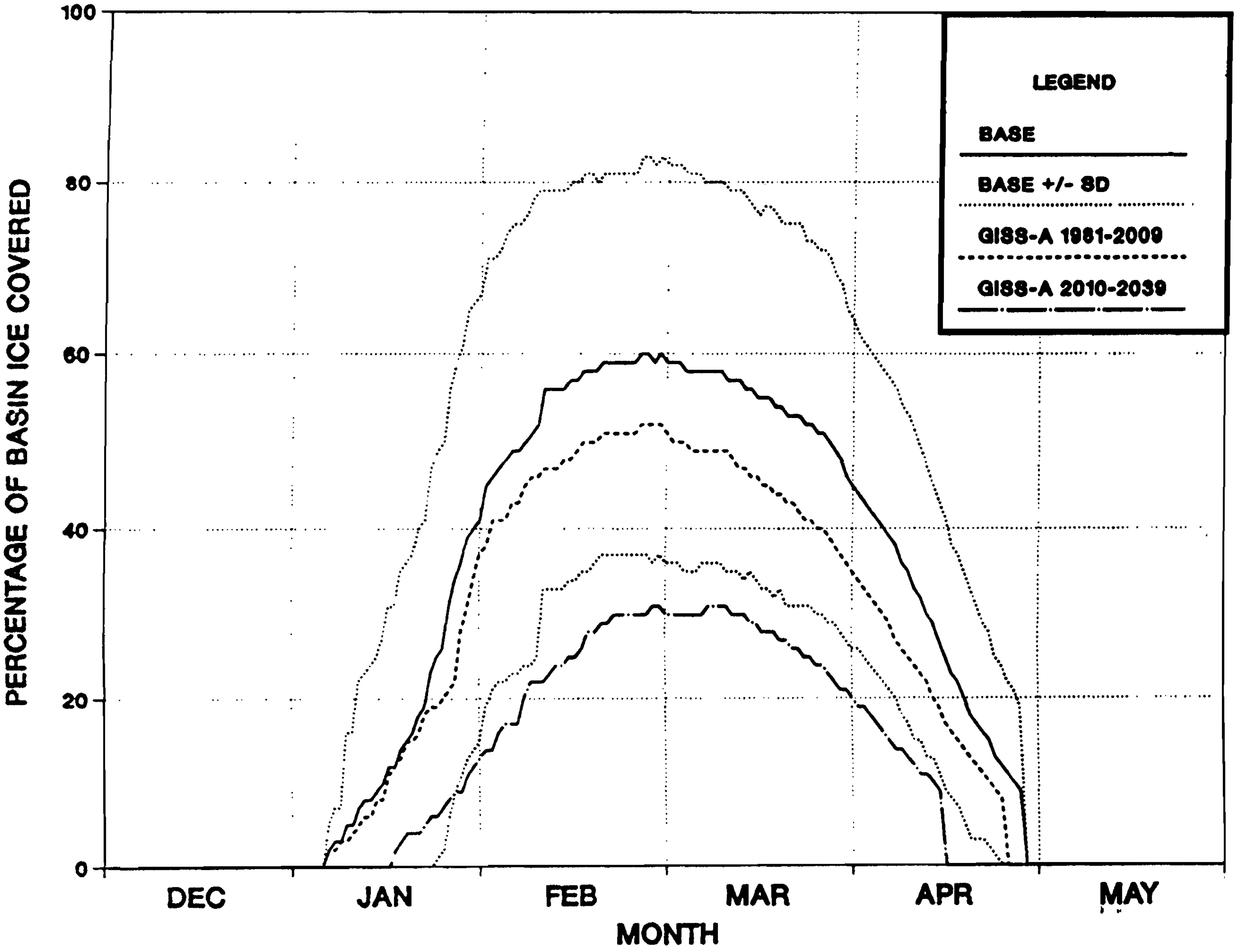
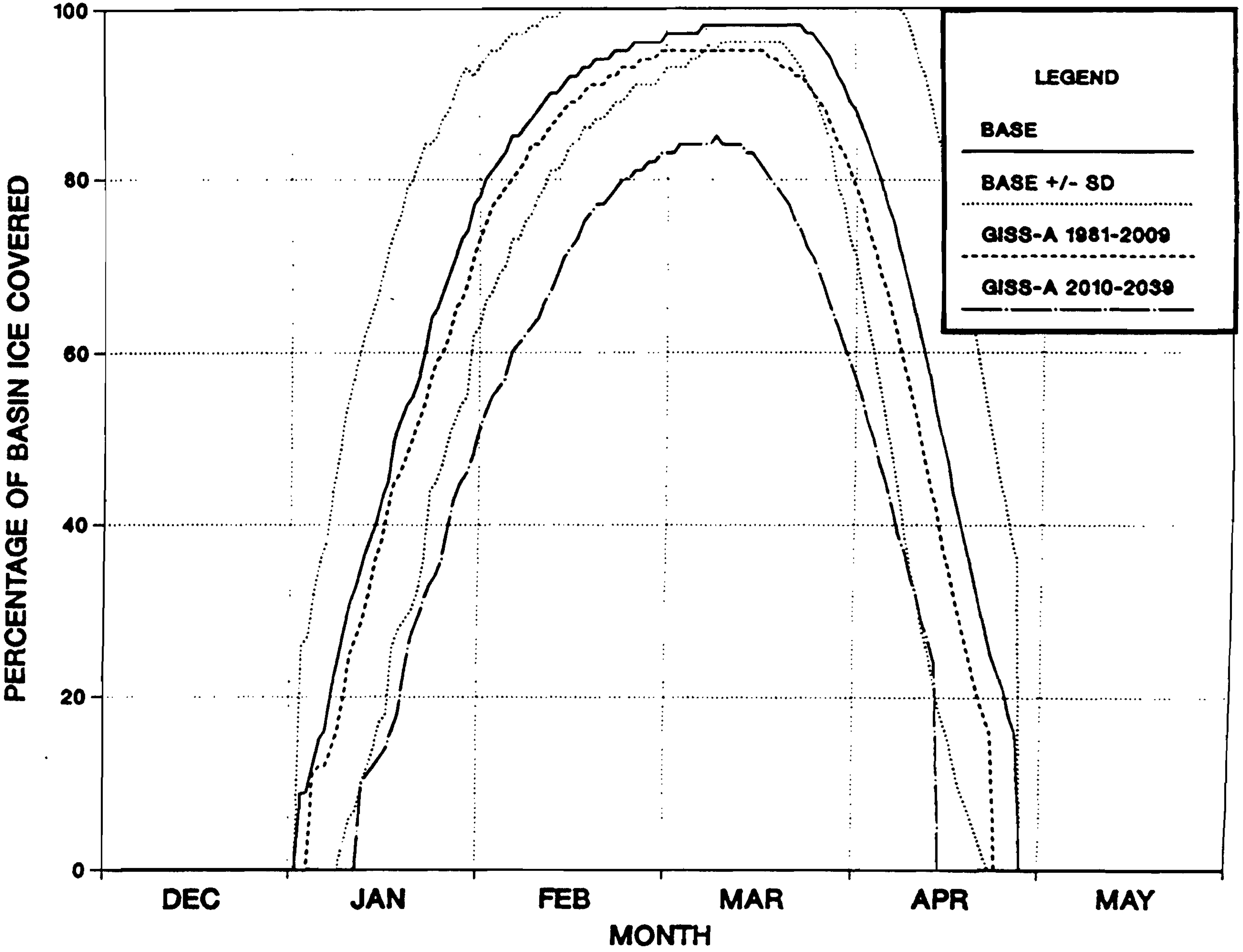
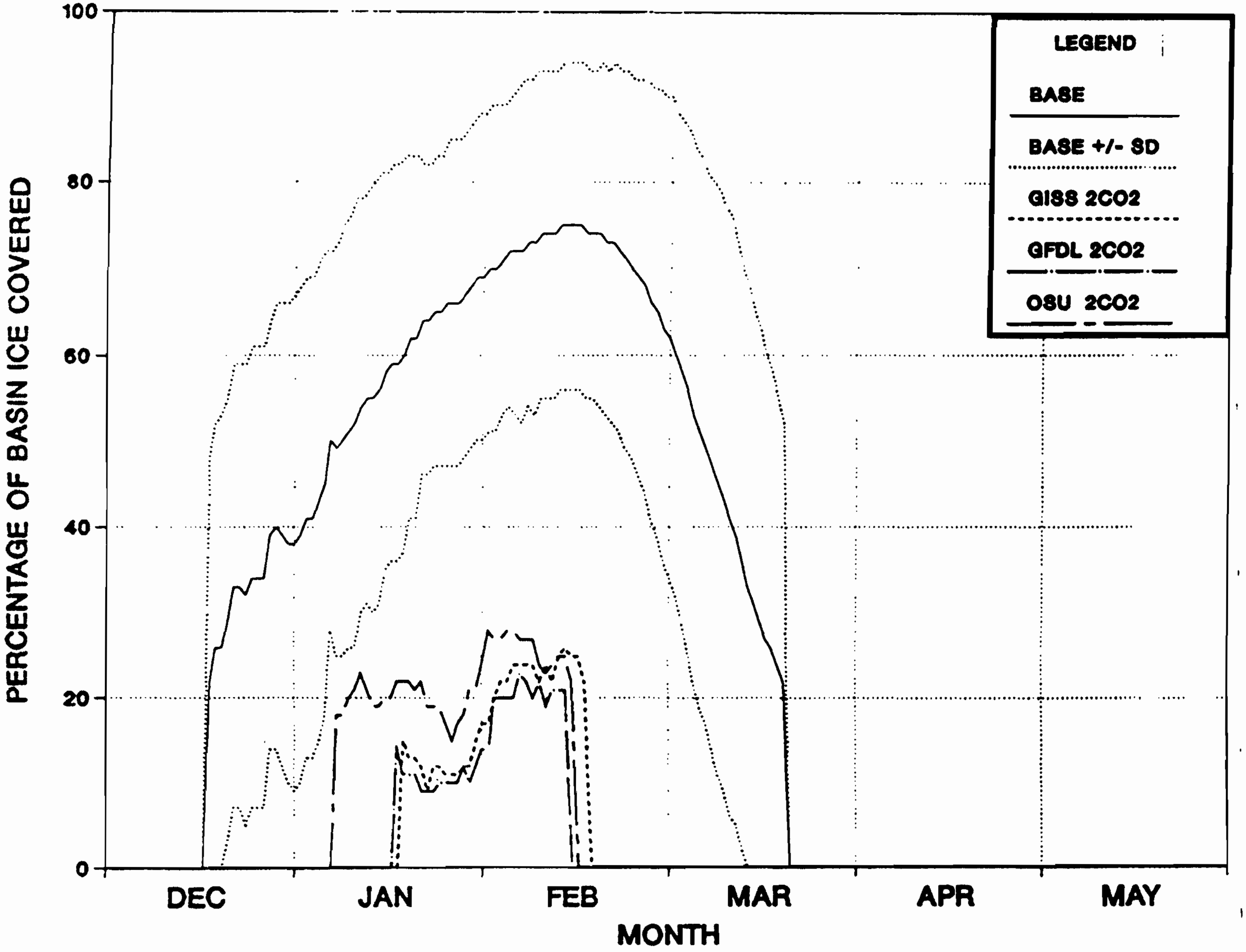


FIGURE 4

DAILY AVERAGED ICE COVER 1951-80 BASE & GISS-A SCENARIO
LAKE SUPERIOR AT WHITEFISH BAY

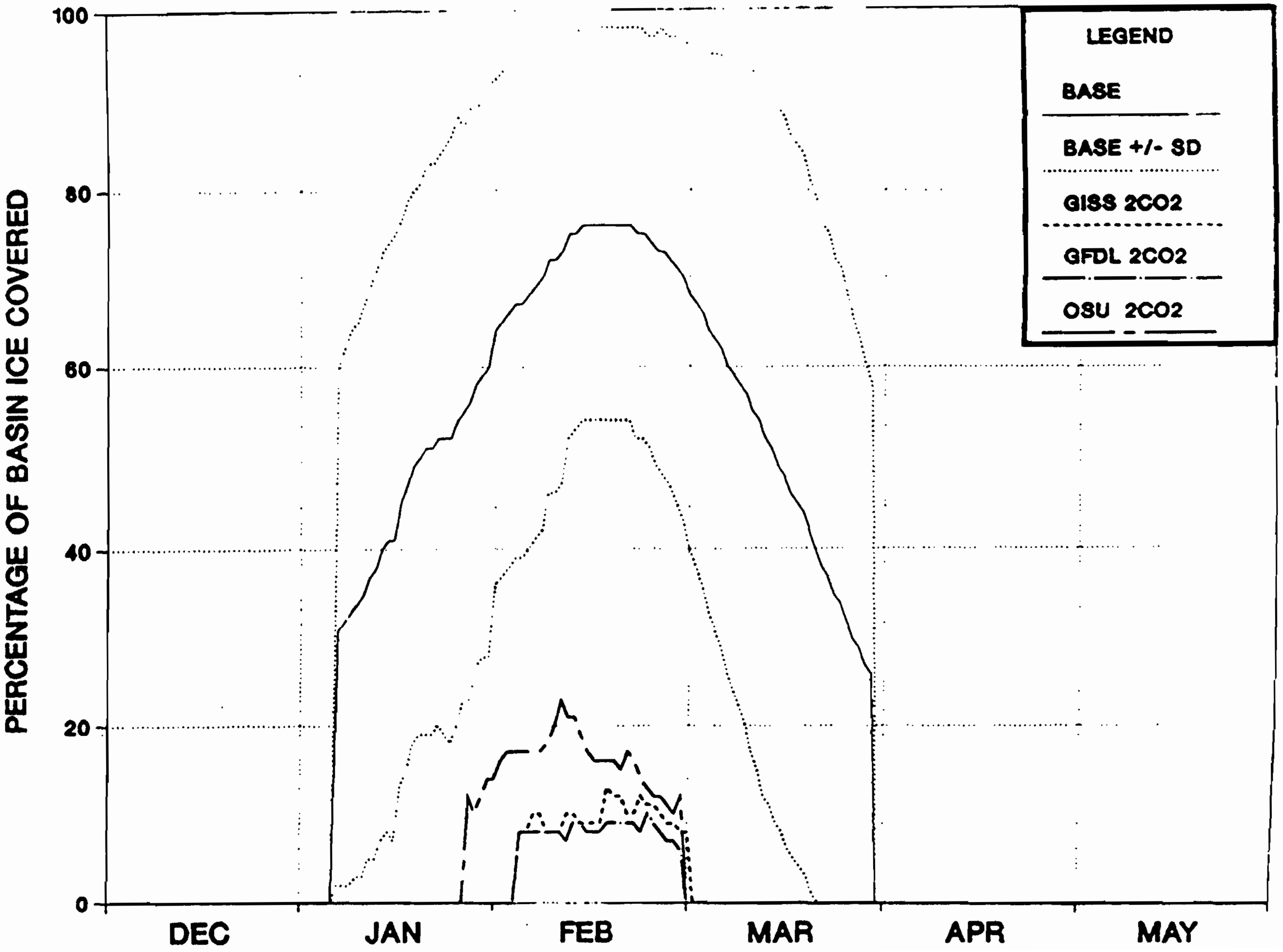


DAILY AVERAGED ICE COVER 1951-80 BASE & 2CO2 SCENARIOS
LAKE ERIE WEST BASIN



Assel

FIGURE 6
DAILY AVERAGED ICE COVER 1951-80 BASE & 2CO2 SCENARIOS LAKE ERIE CENTER BASIN



Assel

FIGURE 7

DAILY AVERAGED ICE COVER 1951-80 BASE & 2CO2 SCENARIOS
LAKE ERIE EAST BASIN

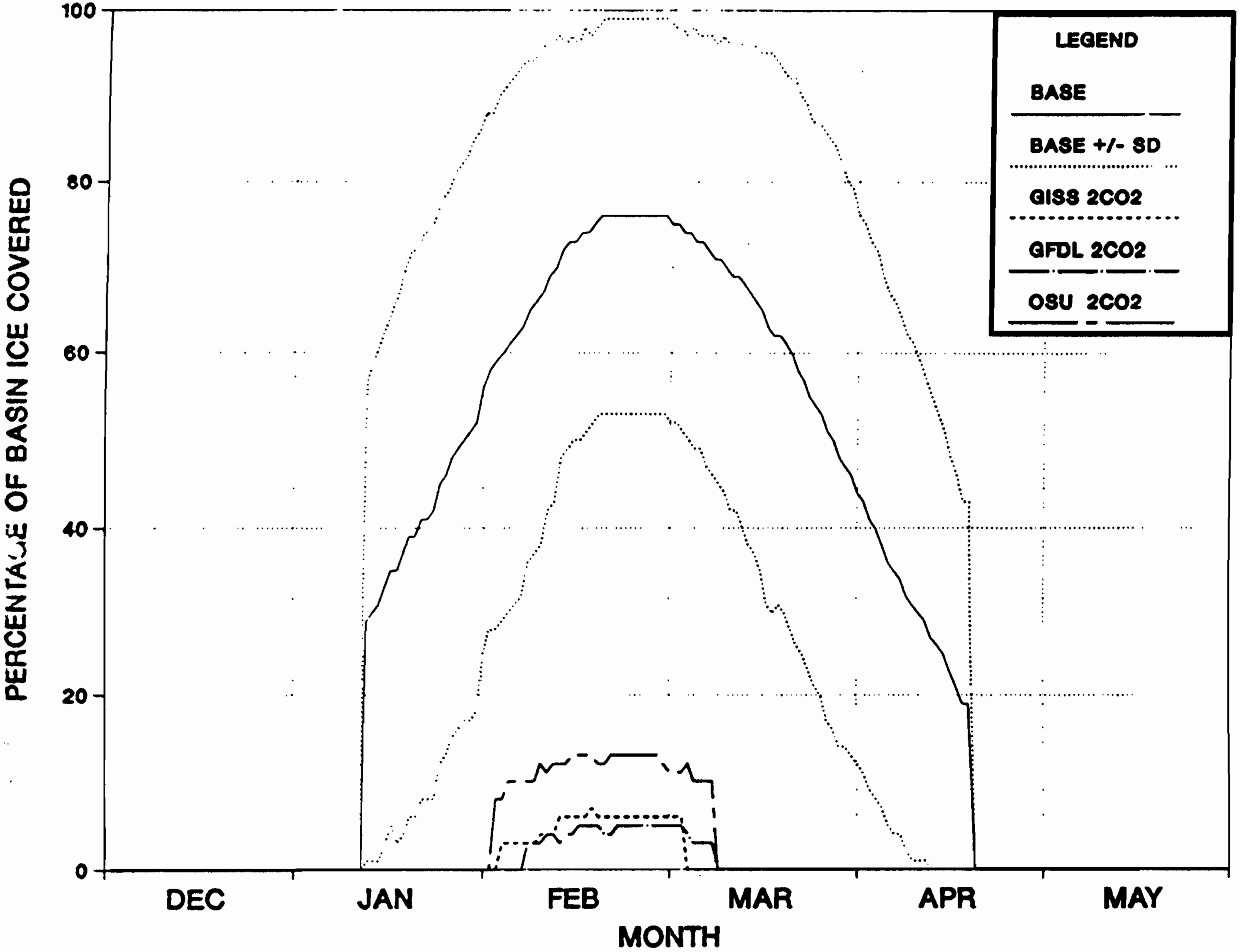
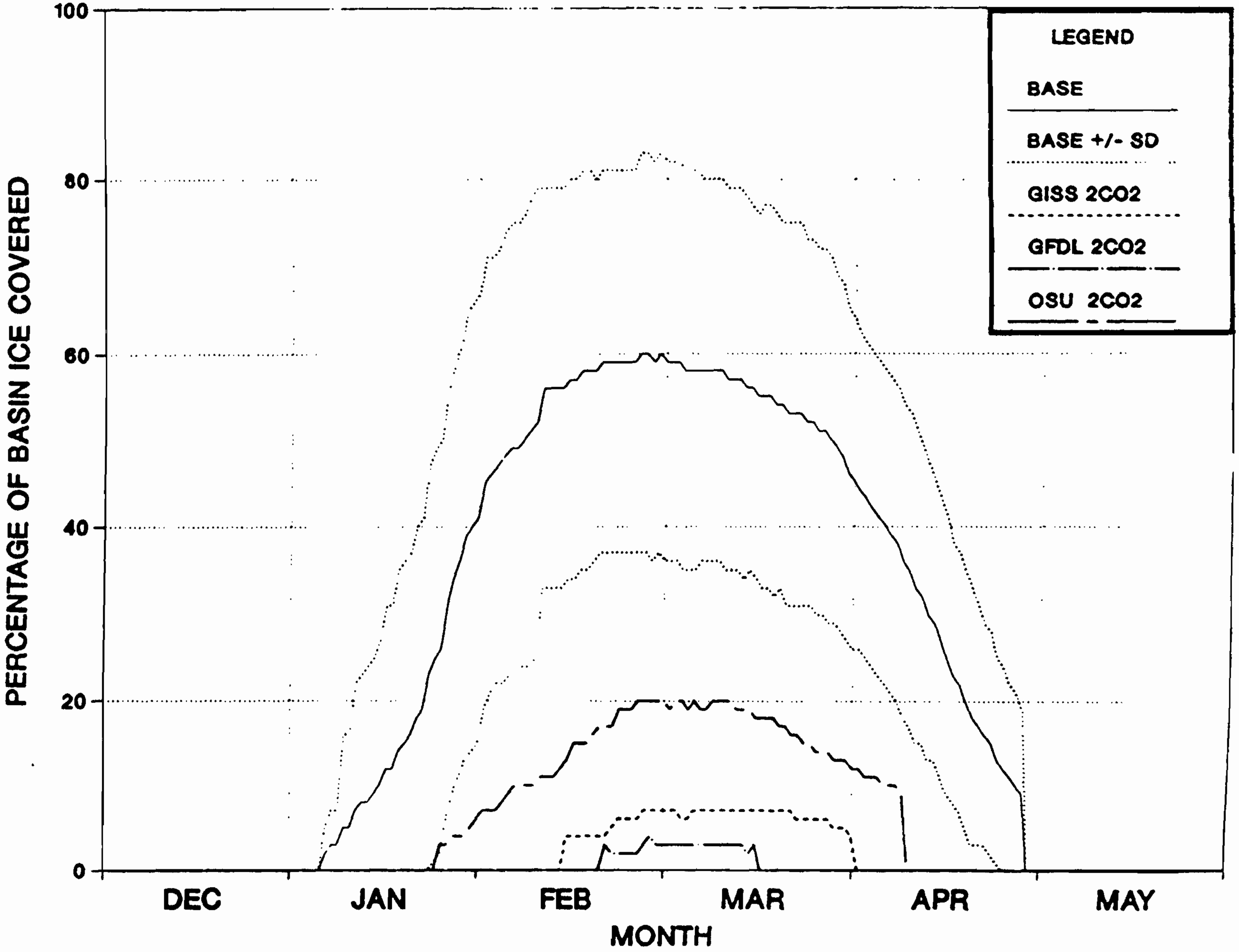


FIGURE 8
DAILY AVERAGED ICE COVER 1951-80 BASE & 2CO2 SCENARIOS
LAKE SUPERIOR WEST BASIN



DAILY AVERAGED ICE COVER 1951-80 BASE & 2CO2 SCENARIOS
LAKE SUPERIOR EAST BASIN

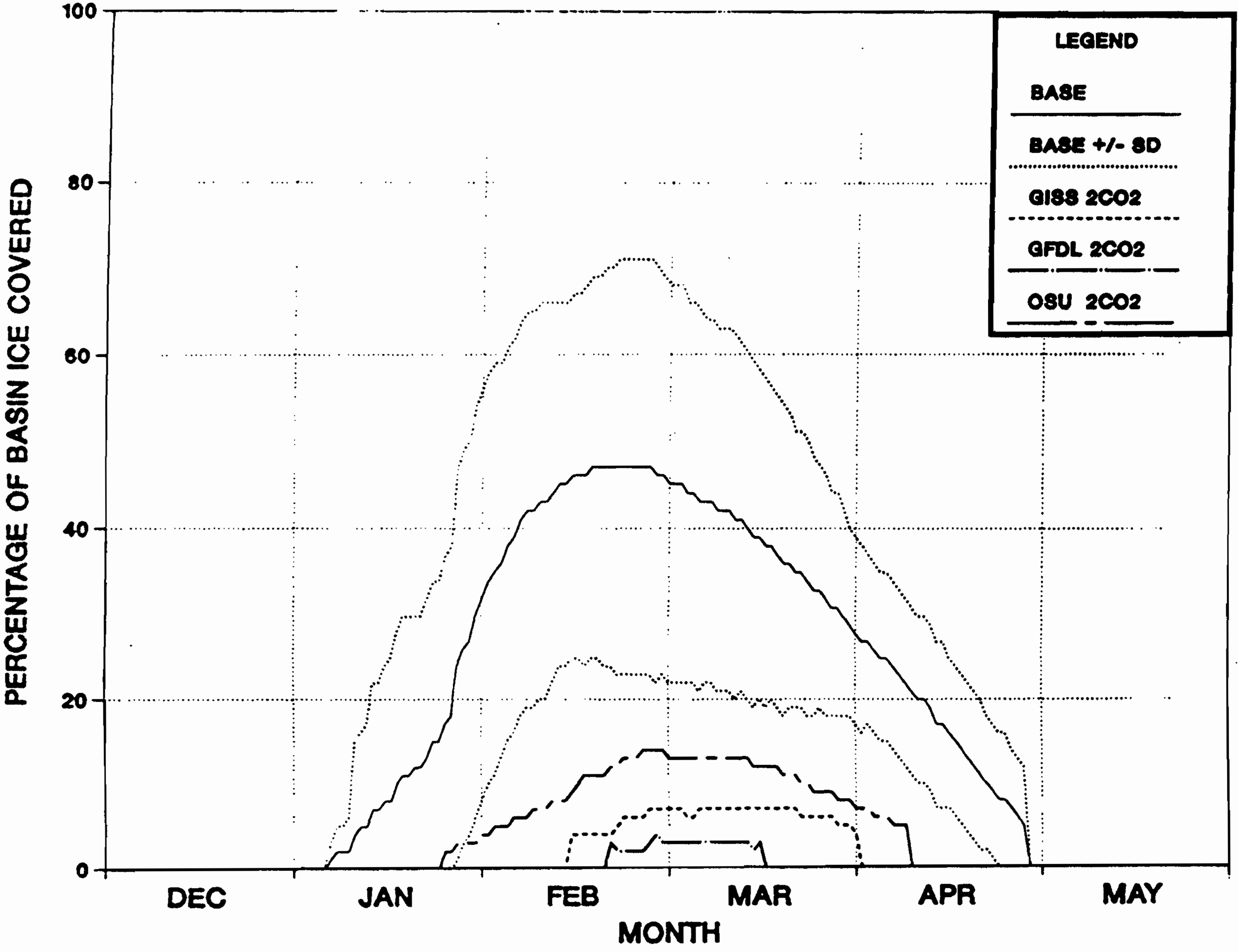
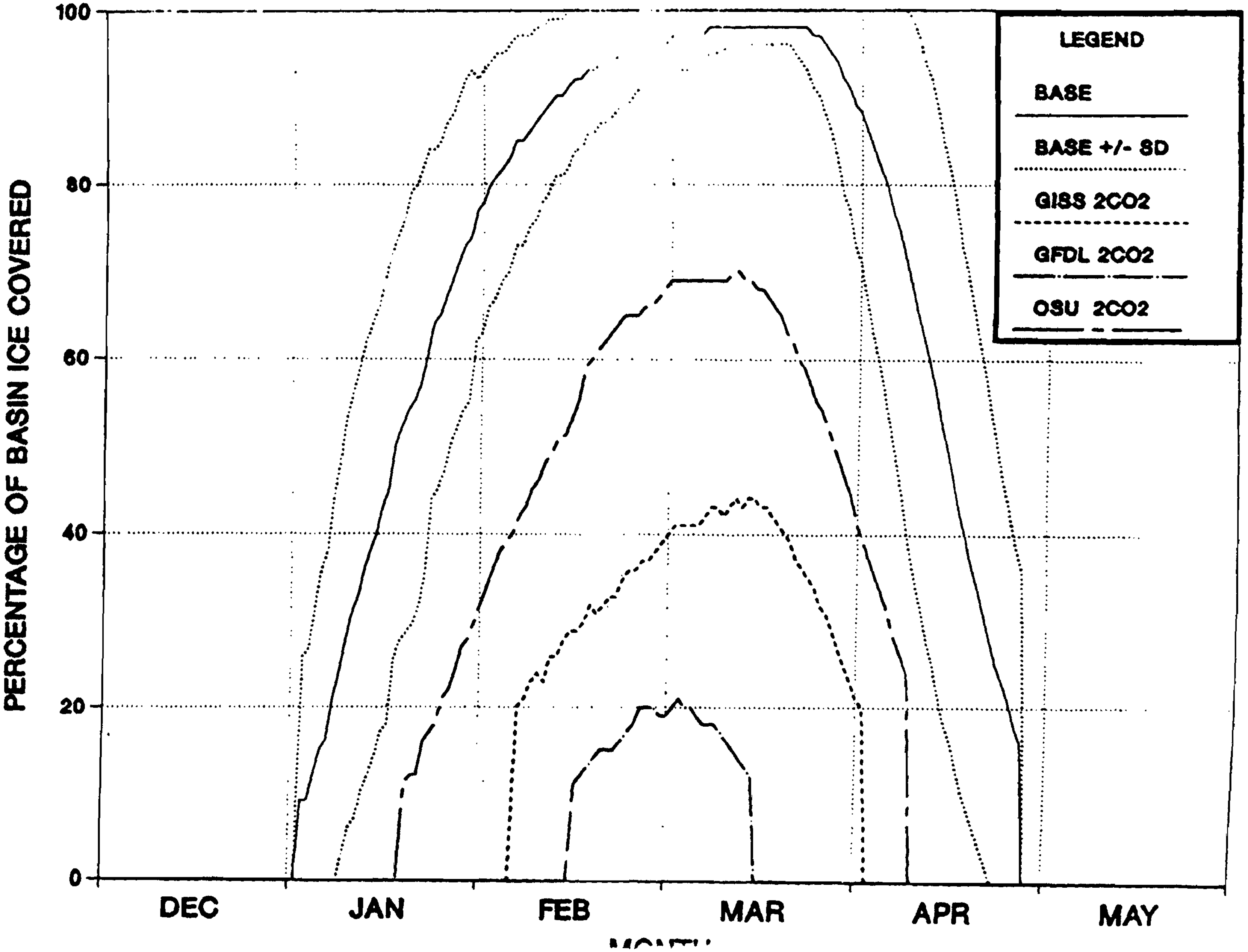


FIGURE 10
DAILY AVERAGED ICE COVER 1951-80 BASE & 2CO2 SCENARIOS
LAKE SUPERIOR AT WHITEFISH BAY



Assel

The uncertainty in simulated ice concentration and ice duration (standard error analysis) is estimated to range from 20 to 30% for ice concentration and from 2 to 4 weeks for ice cover duration. The models are sensitive to the magnitude and number of consecutive days with air temperature below freezing. If FDD accumulations fluctuate about the value needed for initial ice formation all winter, the models show intermittent periods of ice formation and loss. In such cases, ice cover and ice duration can be either over- or under-estimated.

Information on the spatial and temporal distribution of the ice cover is limited by the calculation of basin mean ice concentration. This is a significant limitation in studies where spatial details on ice concentration are needed, as in ecological studies where the date and extent of initial ice cover and duration of shore-fast ice is important.

CHAPTER 5

IMPLICATIONS OF RESULTS

ENVIRONMENTAL IMPLICATIONS

We are just beginning to understand the importance of ice cover to lake ecology. Freeberg and Taylor (in press) observed that year-class strength of lake whitefish is related to winter severity. Under the doubled CO_2 scenarios, the Great Lakes may not have ice cover some winters. If ice cover is missing, whitefish and perhaps other cold water fish species may vanish from the Great Lakes. Bolsenga (in press) has observed that some biological activity actually increases under the protection of the ice cover in the shore zones of the Great Lakes; the loss of the ice cover therefore may result in a reduction in the annual abundance of some micro-organisms and perhaps significantly affect larger life forms that prey on them. The ice cover also protects some shore areas against the impact of high-energy waves that might otherwise cause shore erosion (Zumburge and Wilson, 1953).

SOCIO-ECONOMIC IMPLICATIONS

The ice cover impedes and eventually stops most navigation in the Great Lakes during the winter months. Aids to navigation that would be damaged by ice are removed in late fall and reinstalled the following spring. Ice booms, which help prevent ice jams, are installed at the head of the St. Marys and Niagara Rivers to aid the formation of stable ice cover lakeward of the head of these rivers (International Niagara Working Committee, 1983). The U.S. and Canadian Coast Guard and hydropower authorities are involved in this activity; the Coast Guard also assists ships beset in the ice. The results shown here indicate the navigation season could be extended to 10 months or perhaps even 12 months under a doubled CO_2 climate warming. Thus a considerable cost savings may be associated with reduced Coast Guard and hydropower authority activity and increased shipping activity in the winter months. The greatly reduced extent and duration of ice cover will likely result in higher evaporation from Lake Superior and lower lake levels during the winter months (Croley and Hartmann, in press). The higher lake evaporation during winter implies an increase in snowfall in the Snow Belt regions of the Great Lakes. There is a considerable amount of winter recreational activity on ice-covered bays and harbors of the Great Lakes -- ice boating, ice fishing, snowmobile racing. Much if not all of this activity would be reduced or discontinued completely with reduced ice cover.

CHAPTER 6

POLICY IMPLICATIONS

The management of the Great Lakes fishery should be reviewed relative to commercial and sports fishing since there may be loss or reduction of some fish species and increases or introduction of other fish species. Port and harbor facilities may need to be upgraded to support increased ocean-going and local shipping activities that would become possible with year-round navigation. New regulation plans may need to be developed for controlling flows through the St. Marys, Niagara, and St. Lawrence Rivers.

GLOSSARY

LAKE & BASIN ABBREVIATIONS

Sup = Lake Superior
Eri = Lake Erie
WB = West Basin
CB = Center Basin
EB = East Basin
WFB = Whitefish Bay

UNITS ABBREVIATIONS

C = Celsius
cm = centimeters
m = meters
km = kilometers

SCENARIO AND AGENCY ABBREVIATIONS

EPA = United States Environmental Protection Agency
2CO2 = double carbon dioxide scenario
1CO2 = single carbon dioxide scenario
GCM = Global Circulation Model
GISS = Goddard Institute of Space Science
2CO2 GCM GISS-A = Goddard institute of Space Science transient
CO2 GCM GFDL = Geophysical Fluid Dynamics Laboratory
2CO2 GCM OSU = Oregon State University 2CO2 GCM

ADDITIONAL TABLE, FIGURE, AND TEXT ABBREVIATIONS

Eq. = equation
C1,C2,C3 = coefficients of regression in Table 2
FDD = the accumulated freezing degree-days (C) on a given date
FDDCRIT = a critical FDD accumulation for a given day in the annual Great Lakes ice cycle; if FDD exceeds this value ice cover remains at 100 percent.
BFDD = a threshold value of FDD representing (1) the date of the end of fall overturn in Eq. 1 and (2) the number of FDD needed to cool the near shore water to 0 degrees C for Lake Erie basins, Eq. 2.
FZFAC = a on/off switch for ice formation in Eq. 2, ice is not permitted to form until FDD equals BFDD. Before that time FZFAC=1000, after that time FZFAC=0.
JD = a day counter, the ice cycle starts (JD=1) the first day FDD is greater than BFDD
MFDD = the annual maximum FDD accumulation
DMFDD = the date of the annual maximum FDD accumulation
MELT = the average daily ice melt rate (cm/day)

ARITHMETIC OPERATORS

* = multiplication / = division
+ = addition - = subtraction
> = greater than < = less than
sqrt = square root
exp = exponential function (base e)

STATISTICAL ABBREVIATIONS

RMSE = Root Mean Square Error
SD = Standard Deviation

REFERENCES

Assel, R.A. "A Computerized Data Base of Ice Concentration for the Great Lakes." NOAA Data Report ERL GLERL-24, NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan, 1983. 26 pp.

Assel, R.A., "Great Lakes Degree-day and Winter Severity Index Update: 1897-1983." NOAA Data Report ERL GLERL-29, NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan, 1986. 54 pp.

Assel, R.A., F.H. Quinn, G.A. Leshkevich, and S.J. Bolsenga. "NOAA Great Lakes Ice Atlas." PB84160811, National Technical Information Service, Springfield, Virginia. 1983. 115 pp.

Assel, R.A., C. R. Sinder, and R. Lawrence. "Comparison of 1982-83 Winter Weather and Ice Conditions with Previous Years." Mon. Wea. Rev. 113(3):291-303, 1985.

Bilello, M.A., "Method for Predicting River and Lake Ice Formation." J. Applied Meteorology 3(1):38-44, 1964.

Bolsenga, S.J. "Nearshore Great Lakes Ice Cover." J. Cold Regions Sci. and Tech. 15:99-105, 1988.

Bolsenga, S.J. "An Under Ice Ecology Pilot Program, Operations and Preliminary Scientific Results." J. Great Lakes Res. (in press).

Brownlee, K.A. "Statistical Theory and Methodology in Science and Engineering", second edition. John Wiley & Sons, Inc. New York, New York, 1967. pp. 295-305.

Croley T.E.,II, and H.C. Hartmann. "Effects of Climatic Changes on the Laurentian Great Lakes Levels." NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan (in press).

Diaz H.F., and Quayle R.G. "The Climate of the United States Since 1895: Spatial and Temporal Changes." Mon. Wea. Rev. 108(3):249-266, 1980.

Freeberg M.H., and W. Taylor. "The Impact of Egg and Larval Mortality on Year Class Strength of Lake Whitefish." Department of Fisheries and Wildlife, Michigan State University, East Lansing, Michigan (in press).

Lewis, P.J. "Severe Storms Over the Great Lakes: A Catalogue summary for the Period 1957-1985." Canadian Climate Center Report No. 87-13, Atmospheric Environment Service, Downsview, Ontario, Canada.

Howe, D.A., D.S. Marchand, and C. Alpaugh. "Socio-economic Assessment of the Implications of Climatic Change for Commercial Navigation and Hydro-electric Power Generation in the Great Lakes St. Lawrence River System." Great Lakes Institute, University of Windsor, Windsor, Ontario, Canada. 1986. 118 pp.

International Niagara Working Committee. "1982-83 Operations of the Lake Erie-Niagara River Ice Boom." U.S. Army Corps of Engineers. Buffalo District, Buffalo, New York. 1983. 7 pp.

Oak, W.W., and H.V. Myers. "Ice Reporting on The Great Lakes." Weatherwise 6(1):7-10, 1953.

Palecki M.A., and Barry, R.G. "Freeze-up and Break-up of Lakes as an Index of Temperature Changes during the Transition Seasons: A Case Study for Finland." J. Climate and Applied Meteorology 25:893-902, 1986.

Richards, T.L. "Meteorological Factors Affecting Ice Cover on the Great Lakes." In: Proceedings of the Sixth Conf. on Great Lakes Research. International Association for Great Lakes Research, Ann Arbor, Michigan, 1963. pp. 204-215.

Rogers, J.C. "Long-range Forecasting of Maximum Ice Extent of the Great Lakes." NOAA Tech. Memo. ERL GLERL-7. National Technical Information Service, Springfield, Virginia. 1976. 15 pp.

Sleator, F.E. "Ice Thickness and Stratigraphy at Nearshore Locations on the Great Lakes." NOAA Data Report ERL GLERL-1-2. NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan, 1978. 434 pp.

Snider, R.C. "Great Lakes Ice Forecasting." NOAA Tech. Memo. NWS OSD 1. National Technical Information Service, Springfield, Virginia, 1971. 106 pp.

Tramoni F., R.G. Barry, and J. Key. "Lake Ice Cover As A Temperature Index for Monitoring Climate Perturbations." Zeit. Gletscherkunde 21:43-49, 1985.

Williams, G.P. "Correlating Freeze-up and Break-up with Weather Conditions." Canad. Geotech. J. 11(4):313-326, 1965.

Williams, G.P. "Predicting the Date of Lake Ice Breakup." Water Resour. Res. 7(2):323-333, 1971.

Zumburge, J.H., and J.T. Wilson. "The Effects of Ice on Shore Development." In: Proceeding of the Fourth Conf. Coastal Engineering, Chicago Ill., J. W. Johnson, ED. Council on Wave Research, The Engineering Foundation, University of California, Berkeley, California, 1953. pp. 201-205.

THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES:

APPENDIX A - WATER RESOURCES

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WASHINGTON, DC 20460

MAY 1989

Text Printed on Recycled Paper