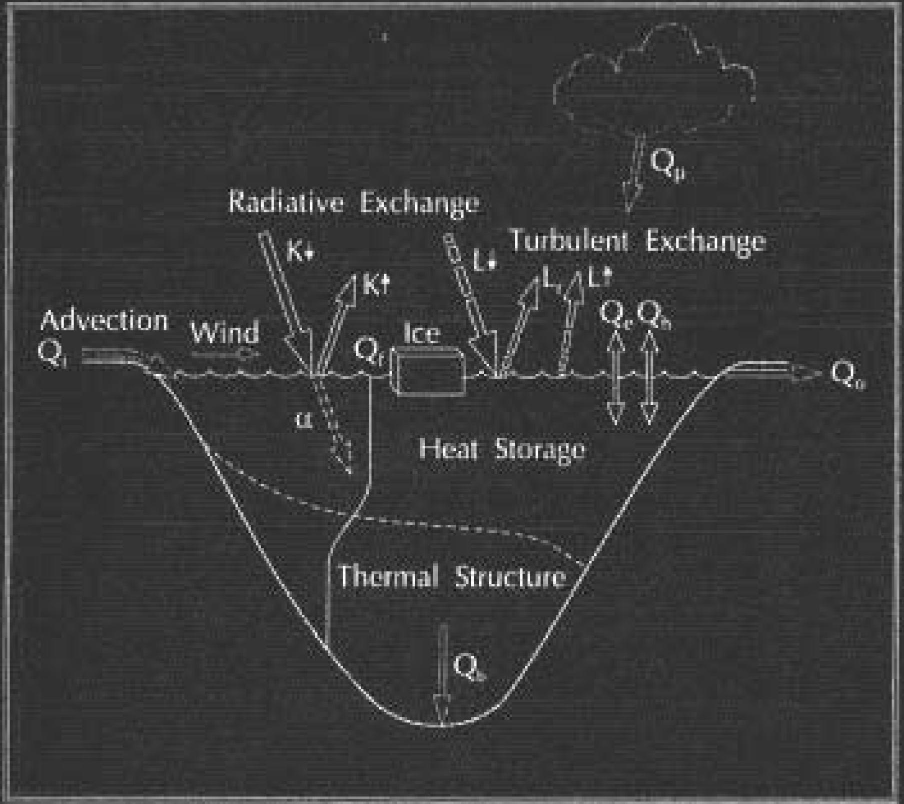
POTENTIAL CLIMATE CHANGE EFFECTS ON GREAT LAKES HYDRODYNAMICS AND WATER QUALITY



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Chapter 6
GREAT LAKES ICE COVER

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ABSTRACT : *The formation of ice on the Laurentian Great Lakes of North America affects the economies of the Unites States and Canada, the aquatic system of the Great Lakes and local weather and climate. The annual seasonal and spatial progression of ice formation and loss is described in general terms for all the Great Lakes and in more detail for each Great Lake (Section 6 2) including ice thickness, the different types of ice formed, and ice classification. Ice cover as a hazard for commercial navigation, hydroelectricity generation, and shore property are also discussed (Section 6.3). Evidence of the effects of the ice on the lake ecosystem is provided by several recent studies on whitefish and on under-ice ecology (Section 6.4). Climate trends in ice cover over the past century, (Section 6 5) and the potential implications of climate change on the Great Lakes ice cover regime are summarized briefly (Section 6.6). For example, preliminary results show that the average ice cover duration for the 1951-80 base period, ranging from 13 to 16 weeks for Lakes Erie and Superior, was reduced by 5 to 13 weeks under those 2 x CO_2 climate scenarios.*

6.1 INTRODUCTION

Lake ice was of great importance in prior centuries in Europe, Asia and North America providing a platform for transportation, fishing, and hunting during winter. An indication of the start of lake ice scientific studies is provided by Marshall (1977).

> *" The earliest historical records of scientific interest in lake ice date back to the early fifteenth century, in central Japan, southern Germany, and Switzerland."*

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During more contemporary times in the Laurentian Great Lakes of North America, the duration and extent of ice cover 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. Ice cover also impacts the water balance of a lake by affecting lake evaporation and other heat and momentum transfers. The biology and chemistry of the lakes are also affected by the duration and extent of ice cover; e.g., the period of ice cover significantly affects the over-winter survival of whitefish spawn and the amount of light penetrating the ice cover affects microorganism activity under the ice. Thus, changes in climate that affect ice cover will in turn affect other physical, chemical, and biological processes within the lake and adjacent atmosphere. The ice cover is also a sensitive indicator of climate change integrating fall, winter, and spring energy exchanges between the lake and the planetary boundary layer.

Although observations of shore ice thickness have been reported by the United States Weather Bureau since 1901 systematic observations of the large scale pattern of ice cover on the Great Lakes were not started until the late 1950's and early 1960, Canadian observations were begun in Ottawa, by the Meteorological Branch of the Department of Transport, in late 1950's. U. S. observations began in the early 1960's by the Army Corps of Engineers. Reports describing the annual ice cycles have been published by both Canadian and United States federal agencies. During the past four decades an illustrated glossary of Great Lakes ice cover (Marshall, 1966) and two atlases of normal seasonal progression of ice cover (Rondy, 1971--winters from 1963-69; Assel et al., 1983--winters of 1960-79) have been published. Starting in the late 1960's and into the 1970's satellite and side looking airborne radar observations have been used to augment visual areal ice reconnaissance flights over the Great Lakes. A Congressionally funded program, the Great Lakes and St. Lawrence Seaway Navigation Season Extension Demonstration Plan, was undertaken to demonstrate the practicability of extending the navigation season, which historically was closed from mid-December to early April because of the hazards of ice cover and winter weather (Great Lakes and St. Lawrence Seaway Winter Navigation Board 1979). Recently Wuebben (1995) provided a review of environmental studies related to the winter navigation program. A review of recent work on Great Lakes ice dynamics modeling is given in Croley and Assel (1994); Bolsenga (1992) provides a comprehensive review (250 papers) on Great Lakes ice research over the past century.

Here the limnological and atmospheric influences on Great Lakes ice cover, the characteristics of its annual cycle (i.e. its temporal and spatial pattern) and the physical attributes of the ice cover are reviewed briefly. Trends in the ice cover regime over the past century and the potential implications of climate change on the Great Lakes ice cover regime are also summarized.

6.2 ANNUAL ICE CYCLE

6.2.1 Atmospheric and limnological influence on Great Lakes ice cover

The Laurentian Great Lakes are inland seas located in the mid-latitude of North America, Figure 6-1. They rarely form a continuous ice cover over their entire surface area due to a relatively temperate continental winter climate. A study of Great Lakes teleconnections (Assel, 1992) indicates that when the northern hemisphere upper air flow pattern includes a weak ridge over the west coast of North America (NA) atmospheric flow is primarily zonal (east to west), winter air temperatures tend to be mild and ice cover below average. During winters dominated by a strong ridge over the west NA coast, flow tends to be meridional (north to south), air temperatures tend to be below normal, and ice cover tends to be average to above average.

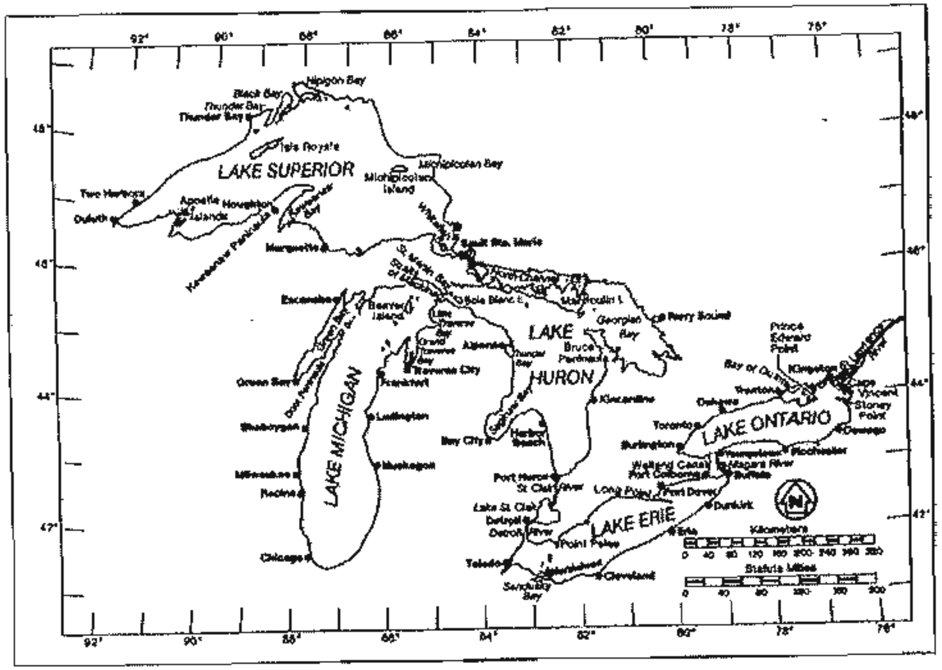
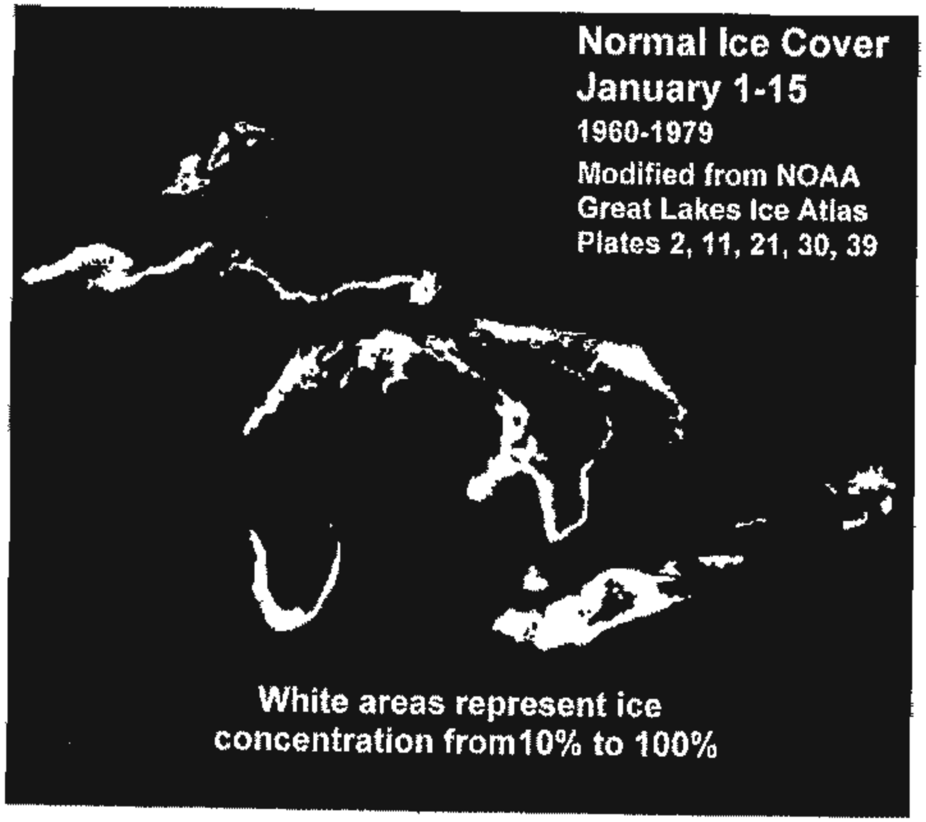


Figure 6-1. *Map of place names.*

The large heat storage capacity of the Great Lakes (Section 2.4, Chapter 2) in combination with high winds, which produce up-welling and horizontal currents, can prevent new ice formation and break up, melt, or compact existing ice covers any time during the winter. Air masses of Polar and Arctic origin alternate with warmer Pacific Ocean and Gulf of Mexico air masses over the lakes during winter. Cyclonic storms form and travel along the Polar Front in autumn and winter producing episodic high winds and precipitation (rain, snow, and sleet). Anticyclones bring below average temperatures, lower wind speeds, and lake-effect snowfall. Alternating cyclonic and anticyclonic passages over the Great Lakes produce periods of ice formation, ice loss, and changes in the configuration and thickness of the ice cover. The length of each of these periods is a function of the frequency, duration, orientation, and intensity of the cyclonic and anticyclonic passages and upon preexisting ice conditions. In the exposed mid lake areas, ice conditions can be highly transitory, changing by the hour (ice movement, ice compaction, ice formation, ice melt), or can be relatively stable, not changing significantly in extent for several days or for a week or more (formation of a extensive ice cover that is strong enough and extensive enough to withstand subsequent episodic high wind stress or mild temperatures). A more continuous and longer lasting ice cover forms in the shallower areas of the Great Lakes, in large bays, in the waters around island and shoal areas, and in the constricted areas of the shoreline such as the Straits of Mackinaw (north end of Lakes Michigan and Huron), Whitefish Bay and the Apostle Islands (at the east and west ends of Lake Superior), and the east end of Lake Erie from Long Point to Buffalo New York.



Normal Ice Cover
January 1-15
1960-1979
Modified from NOAA
Great Lakes Ice Atlas
Plates 2, 11, 21, 30, 39

White areas represent ice
concentration from10% to 100%

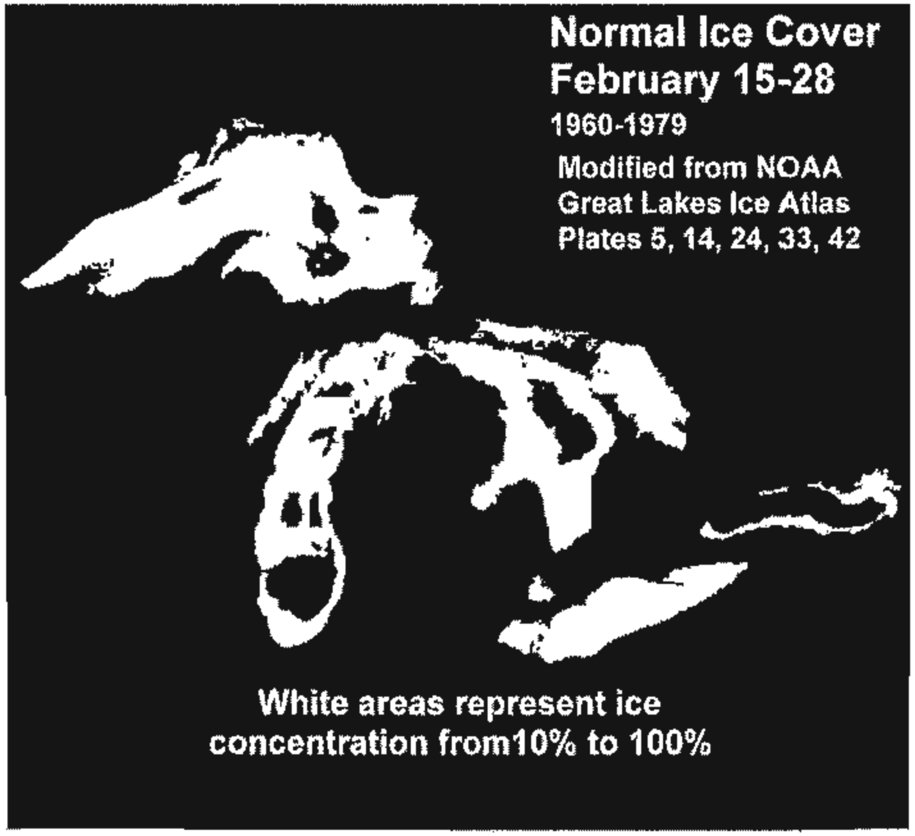
Figure 6-2. *Early winter ice cover (Assel et al. 1983).*

6.2.2 Seasonal progression of the ice cover

6.2.2.1 The general pattern.

The annual ice cycle consists of three periods: a water cooling period in autumn and early winter, an ice formation period starting in late autumn and ending in the maximum ice cover concentration for the entire winter, and an ice loss period starting in late winter or early spring and ending with the loss of the entire ice cover. Ice usually begins to form in the shallow nearshore waters of the Great Lakes in December and January (Figure 6-2) and in the deeper offshore waters in February.

Ice cover is usually at its maximum areal extent in late February or early March (Figure 6-3). Expected maximum ice covers are: Lake Erie 90%, Lake Superior 75%, Lake Huron 68%, Lake Michigan 45%, and Lake Ontario 24% (Assel et al. 1983). The deepest and longest wind fetch areas of the Great Lakes have the shortest duration of ice cover because winds frequently cause mixing of these waters so that any ice cover formed is melted or transported elsewhere. Lake Ontario develops the least extensive annual maximum ice cover of the Great Lakes because of the combination of its large heat storage (mean depth of 86 meters) and relatively mild winter air temperature (-4.4°C averaged for December, January, and February for Lake Ontario compared to -9.8°C for Lake Superior; calculated from data given in Derecki, 1976).



Normal Ice Cover
February 15-28
1960-1979
Modified from NOAA
Great Lakes Ice Atlas
Plates 5, 14, 24, 33, 42

White areas represent ice
concentration from10% to 100%

Figure 6-3. *Maximum ice cover (Assel et al. 1983).*

Ice deterioration and break up usually start in early March, first on the southern half of the Great Lakes and by mid month on the northern portion as well. Areas of open water and low ice concentration expand from the deeper, more exposed mid lake areas toward the perimeter and eastern shores of the Great Lakes in March. The movement of the ice toward eastern lake shores is in response to the prevailing westerly winds. By the middle of April (Figure 6-4) the bulk of the ice left in the Great Lakes is usually located in the shore zone. However, in winters with above average ice covers and below normal temperatures in spring, such as 1979, substantial mid-lake ice endures well into May (DeWitt et al., 1980). During an average winter heavily rafted and ridged ice in shore areas can also last well into May and can cause considerable problems for spring shipping activities.

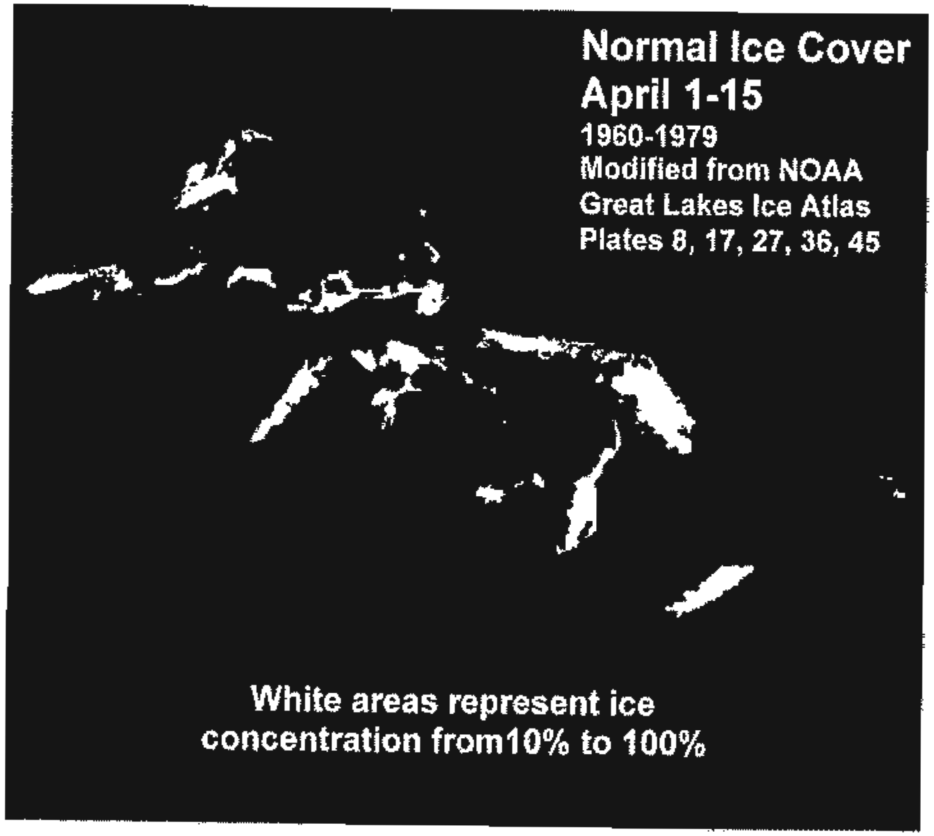


Figure 6-4. *Early spring ice cover (Assel et al., 1983).*

6.2.2.2 Autumn water cooling and the annual temperature cycle

The ice cover that forms on the Great Lakes each winter is a sub-cycle of the annual water temperature cycle (Section 3.1, Chapter 3). The water mass of the Great Lakes passes through the temperature of maximum density, near 4°C, twice each year, in the late spring or early summer and again in the late autumn or early winter. In summer a thermocline forms at approximately 10 meters and water in the epilimnion typically warms to 15°C to 25°C, waters in the hypolimnion remain near the temperature of maximum density. In autumn and winter the entire water mass cools to 4°C, and the surface waters cool below the temperature of maximum density, i.e. become less dense, and a weak reverse thermocline is formed. During winter, wind mixing and cooling take place to depths of 100 meters or more with temperatures between 1°C and 4°C typical of the entire water column; in shallow areas water temperatures are less than 0.5°C (Assel, 1985, 1986).

6.2.2.3 Ice formation and ice types

The timing of initial ice formation is dependent upon water and air temperatures and winds. Ice crystals can form when the surface waters cool to the freezing point and give up the heat of crystallization, if winds are calm. If air temperatures are sufficiently low, the surface waters can become super-cooled, i.e. cool below the freezing point of water, and individual ice crystals (frazil ice) form. In early winter, high winds can slow down ice formation even though surface water temperatures may be near the freezing point and air temperatures may be well below the freezing point.

Ice forms in calm or turbulent water. Ice formed in calm water is called plate or sheet ice, and ice formed in agitated water is called agglomeratic ice (Rondy, 1976). Ice formed in calm water directly from freezing of lake waters in the absence of snow is the strongest and purest form of lake ice. Agglomeratic ice forms from the freezing together of individual pieces of ice of various origins, such as snow falling into the lake (slush), frazil particles (individual ice crystals), or the wreckage of other ice that had formed previously. Frazil ice is composed of individual ice crystals that can be carried down in the water column by vertical currents. Frazil ice in rivers will adhere to any substrate such as rocks or water intake grates, forming anchor ice. Frazil ice can also accumulate vertically in rivers forming hanging dams that can reduce river flow rates and cause flooding upstream.

Another type of agglomeratic ice that forms in the shore zone is called an icefoot. This shore ice forms as a result of waves of freezing spray that build up mounds of ice and often contains sand and stone rubble from the surf zone (Fahnestock et al., 1973). Several ice ridges can form along lee lake shores, usually adjacent to deep waters that do not freeze until later in the (Evenson and Cohn, 1979; Marsch et al., 1973; O'Hara and Ayers, 1972). Once formed the icefoot complex can either act as a buffer against high energy waves that cause shore erosion or enhance shore erosion by transfer of wave energy from beach to shore and by moving sediment along shore and offshore (Barnes et al., 1994). Ice foot formation has been observed along the southeast shores of Lakes Superior, Michigan, and Erie. In the spring these ice formations, which contain sand and rocks, can transport this material many kilometers along the shore or offshore as the ice foot complex breaks-up (Barnes et al., 1993).

6.2.2.4 Interannual variation of annual maximum ice cover

The annual maximum ice cover can vary greatly from one winter to the next and vary from the normal (Table 6-1). Air temperature is perhaps the single most important climatic parameter affecting the interannual variation in seasonal maximum ice concentration. Figure 6-5, modified from Assel et al. (1996), shows a linear relationship between annual maximum ice cover (for the surface area of all five Great Lakes combined) and a regional index of average winter air temperature. During a winter when the regional air temperature index is -6°C or lower (as it was in 1994) maximum ice cover can occur two to four weeks earlier than average and it can exceed 90% on all the Great Lakes (Assel et al., 1996). During a mild winter, such as 1983, when the regional air temperature index was only about -2.2°C, ice cover was absent from the deeper mid lake waters, and seasonal maximum ice cover ranged from 17% (Lake Superior) to 36%(Lake Huron) and was less than 25% of the combined area of the five Great Lakes (Assel et al., 1985).

Winter	Superior	Michigan	Huron	Erie	Ontario
1979	99	99	99	99	95
1983	21	17	36	25	10
Normal[1]	75	45	68	90	24

Table 6-1. *Maximal percent of ice covered lake surface area (Assel et al., 1983)*

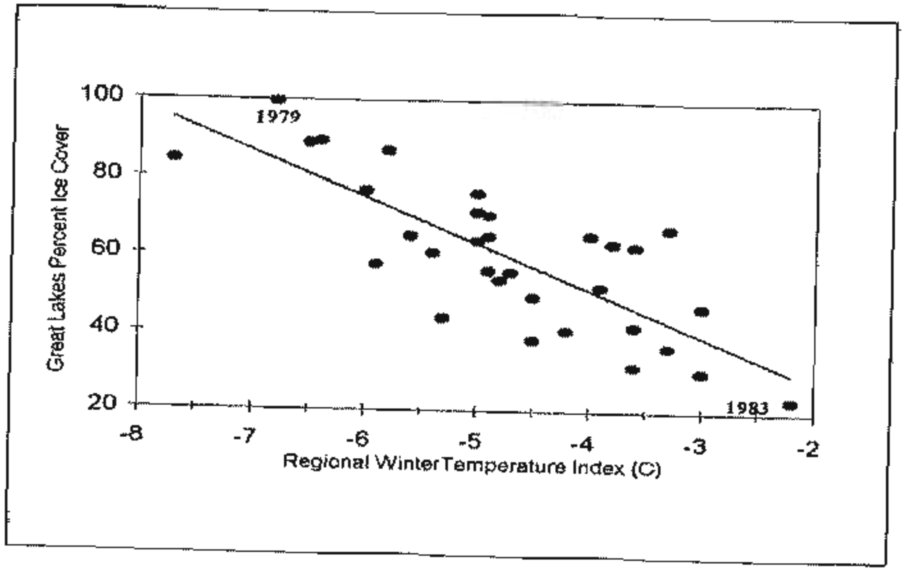


Figure 6-5. *Regional winter temperature index vs Great Lakes ice cover: winters 1963-1994 (modified from Assel et al., 1996).*

6.2.2.5 Factors affecting the loss of ice cover in spring

The main factors affecting ice loss in spring is the net energy gain in the ice. Above-freezing air temperature and solar radiation cause melting of the ice at the air-ice interface and produces water puddles on the ice. Once the ice loses its snow cover and melt puddles form, its albedo is reduced [snow-covered ice as a total albedo of 67%, slush ice 41%, and clear lake ice 10% (Bolsenga, 1969)] allowing more solar radiation absorption at the surface and within the ice. Solar radiation absorbed within the ice reduces its structural strength due to preferential melting at ice crystal boundaries. Lake ice has a pronounced columnar structure and as melting occurs between ice crystals the ice loses its structural integrity, making it vulnerable to dis-aggregation by winds and waves. Melting also occurs at the ice-water interface due to upwelling. Rising water level in spring, caused by increased runoff, results in melting of ice along shore and further fragmentation of the ice cover. The weakened ice cover is easily broken up and transported by winds and waves (Section 5.2.2, Chapter 5).

6.2.2.6 Lake Superior ice formation and loss pattern

Lake Superior has a surface area of 82,100 km^2, a volume of 12,230 km^3, a mean depth of 148 m, a length of 563 km, and a breadth of 257 km. Mean monthly air temperature is below freezing in November. Ice forms along the lake perimeter in December and January. Ice forms in the west basin building out from the shallow southern shore, the west part of the Keweenaw Peninsula, and along the northern lake shore from January 16-31 to February 1-14. Ice forms last in the deep, eastern lake basin in February and March. Monthly air temperatures are above freezing in April. Ice is lost over the entire lake from March 16-31 to April 1-15. Only shore ice remains in the second half of April.

6.2.2.7 Lake Michigan ice formation and loss pattern

Lake Michigan has a surface area of 57,750 km^2, a volume of 4,920 km^3, a mean depth of 85 m, a length of 494 km, and a breadth of 190 km. Because of the large north to south extent of this lake, mean monthly air temperature is below freezing in November at the northern end of this lake and at the southern end in December. Ice forms along the lake perimeter, in Green Bay, and the shallow, north portion of the lake to Beaver Island starting in December. Ice forms in the mid lake areas south of Beaver Island to Milwaukee, Wisconsin in the second half of February. The mid-lake area south of Milwaukee normally remains relatively ice free. Most of the mid-lake ice south of Beaver Island is lost during the first half of March. Ice north of Beaver Island and in Green Bay dissipates gradually over the next 6 weeks.

6.2.2.8 Lake Huron ice formation and loss pattern

Lake Huron has a surface area of 59,500 km^2, a volume of 3,537 km^3, a mean depth of 59 m, a length of 331 km, and a breadth of 294 km. Ice formation is restricted to the shallow embayments along the lake perimeter in December and January. Ice gradually builds out to the deeper lake areas in January and February so that only the mid lake area between Kincardine, Ontario and Alpena, Michigan remains free of ice by the end of February. This area of open water gradually increases in March. The only areas of extensive ice by mid-April are the large embayments along the northern shore, the Straits of Mackinaw, and the southeast shore. The ice in these areas gradually dissipates over the next 2 - 4 weeks.

6.2.2.9 Lake Erie ice formation and loss pattern

Lake Erie has a surface area of 25,675 km^2, a volume of 483 km^3, a mean depth of 19 m, a length of 388 km, and a breadth of 92 km. The progression of ice formation is from the shallow, west lake basin (mean depth 9 m) in mid December to the deep, east lake basin (mean depth 27 m) during the second half of January. By the end of January the lake is approaching its maximal ice cover. Lake Erie remains near its maximal ice cover during February. The ice loss pattern is from the west basin to the east basin, reflecting the orientation of the lake's axis approximately parallel to the prevailing westerly wind direction. The ice concentration in the first half of March decreases in the western lake basin. By the end of March the western third of the lake is ice free. By the end of April the only extensive ice left in the lake is located in the east end of the lake near Buffalo, New York.

6.2.2.10 Lake Ontario ice formation and loss pattern

Lake Ontario has a surface area of 19,000 km^2, a volume of 1,634 km^3, a mean depth of 86 m, a length of 311 km, and a breadth of 85 km. The combination of relatively mild winter air temperature and large mean lake depth, results in ice formation being restricted to the shallow areas along the lake shore throughout the winter. Extensive shore ice forms first along the shallow embayments along the northeast shore in January and along the entire lake perimeter in February. With the exception of the northeast embayments, ice dissipates from the lake perimeter during the first half of March. The ice in these embayments gradually dissipates over the next 4 - 6 weeks as well, leaving the lake ice-free by the end of April.

6.2.3 Ice classification

The two major classifications of Great Lakes ice cover are **fast ice** and **pack ice**. Fast ice is a continuous cover that is attached to shore and remains in place. Sheet ice is a common form of fast ice in shallow protected bays and harbors. Pack ice is a general term that includes all other forms of ice other than fast ice. It is classified by **size** (ice field: collection of ice floes at least 8 km, ice floe: single piece of pack ice, ice cake: ice fragments up to 11 meters across, brash ice: fragments up to 2 meters across), **age** (indicator of thickness, new: less than 5 cm, thin: 5-15 cm, medium: 15-30 cm, thick: 30-70 cm, and very thick: more than 70 cm), **arrangement**, and **concentration** (percent of a unit area of lake covered by ice). The majority of the ice in the Great Lakes is pack ice. The pack ice cover can be vary transitory during the winter, particularly in mid-lake areas where freeze up and break up events, snowfalls, and winds can move, compact, and cause upwelling of warmer water to melt the ice cover.

6.2.4 Ice thickness

When a solid ice cover forms, vertical ice accretion occurs as a result of heat transfer from the ice-water interface through the overlaying ice and snow layers to the atmosphere. As the ice sheet thickens, its own thickness retards further vertical growth by reducing the rate of heat transfer to the atmosphere. Snow cover on the ice retards ice growth more than the ice mass because snow is a much better insulator than ice. Thus, the thickness and duration of snow cover is an important factor influencing ice thickness. Average annual maximum bay and harbor ice thickness, (averaged by lake) and dates of maximum ice thickness are summarized in Table 6-2 (modified from Bolsenga 1988) based on ice reports collected over the late 1960's and 1970's. Under the present climate the upper limit of thermodynamic ice growth appears to be about 100 cm (Assel et al., 1983).

Lake	Maximum Thickness[1] (cm)	Average Date[2]
Superior	53	Feb. 8-15
Michigan	52	Feb. 24-28
Huron	51	Feb. 24-28
Ontario	42	Feb. 16-23
Erie	33	Feb. 1-7

Table 6-2. *Lake Averaged Bay and Harbor Maximum Ice Thickness (After Bolsenga, 1988). [[1] ice thickness is average of all stations for that lake, [2] date of maximum is average of all station values in quarter month increments]*

Ice thickness in excess of 1 meter occurs primarily as a result of wind-blown ice; thermal expansion of ice can also cause an ice cover to crack and form ridges of ice rubble in excess of 1 meter. High winds can cause portions of an ice cover to override or submerge under the remaining ice cover, especially if the ice is located in an area where the lake shore on opposite sides of the lake converge, such as the east end of Lake Erie, the north ends of Lakes Huron and Michigan at the Straits of Mackinaw, and the east or west ends of Lake Superior. The resulting ice is called rafted or windrowed ice, depending upon the amount and extent of ice rubble formed. Rafted ice in eastern Lake Erie has been observed to scour the bottom of the lake at water depths of 25 meters on the Canadian side of that lake (Grass, 1984), and bottom scour has also been reported on the United States side of Lake Erie (Alger, 1979). Rafted and windrowed ice thickness of 10 - 20 ft (approximately 1 to 7 meters) above the water or 30 - 35 ft (approximately 10 - 11 meters) below were reported by Oak (1955). The United States Coast Guard reported rafted and windrowed ice ranging from 1 to 3 meters at the east and west ends of Lake Superior, 2 to 9 meters in the Straits of Mackinaw, 8 meters in the St. Clair River, 1 to 2 meters in western Lake Erie, and 1 to 6 meters in eastern Lake Erie (U.S. Coast Guard, 1978).

6.3 ICE HAZARDS

Rafted and windrowed ice at harbor entrances and in the open lake impedes navigation and causes damage to ships. Ice jams cause flooding upstream of the jam. When the jam breaks, a large wave of ice and water travels downstream damaging shore property. In bays and harbors ice motion causes damage docks and piers.

6.3.1 Winter navigation

Areas of the Great Lakes where shifting ice fields and ridged and jammed ice cause navigation problems, particularly in winters with above average ice cover, include the west end of Lake Superior, Whitefish Bay, and the St. Marys River at the east end of that lake, the Straits of Mackinaw, Green Bay, harbor entrances along the southern and eastern shores of Lake Michigan, the southern end of Lake Huron and the St. Clair River, and the eastern end of Lake Erie (Assel et al., 1996). Great Lakes ships (e.g. bulk carriers of grain and iron ore) are in general not designed to travel through ice. Because of their blunt bow and relatively low power, many bulk carriers often require the assistance of a Coast Guard icebreaker or buoy tender to transit a heavily rafted or ridged ice cover. Higher powered Coast Guard vessels make tracks through thick or pressured ice fields and ore carriers follow the tracks. However, winds can close a track in a matter of hours and trap transiting vessels. Ice pressure can then damage ship hulls, or prevailing winds can transport the ice-field--entrapped ship to shoal areas where it can become grounded. During winter 1996 the U.S. Coast Guard recorded over 5700 hours to assist ships and to clear ice-clogged shipping channels (Assel et al. 1996), the highest in the previous 15 winters.

6.3.2 Ice jams and shore installations

The connecting channels of the Great Lakes include the St. Marys, the St. Clair, the Detroit, the Niagara, and St. Lawrence Rivers. The occurrence of an ice jam on these rivers results in a reduction of the water level below the jam and an increase in the water level and flooding above the jam. Ice jams also cause reduction of hydropower generating capacity for hydroelectric plants located on the St. Marys, Niagara, and St Lawrence Rivers. The formation of a stable ice arch across the head of these rivers in early winter helps to prevent large ice volume discharge and ice jam formation downstream (Daly, 1992). Ice jams are more likely to occur in spring because of the breakup of the ice cover, but they can occur anytime during the winter when a large volume of ice moves downstream. An ice control structure known as an ice boom is installed across the head of the Niagara and St. Marys Rivers and upstream of hydroelectric plants on the St. Lawrence River each winter to hasten and

lend stability to the formation of a natural ice arch across these rivers (Foltyn and Tuthill, 1996). The ice boom is a series of floating timbers connected with anchored steel cable that extends across the river.

Bolsenga (1992) reports ice jam flooding occurred in the area of the Niagara River in 1942, 1943, 1954, 1955, 1962, 1964, 1972, 1975, 1979, and 1985. One of the most severe ice jam events in recent times occurred in April 1984 on the St. Clair River (Derecki and Quinn, 1986). The ice arch at the head of the St. Clair River was apparently broken by early season ship passage. Large amounts of ice from southern Lake Huron were forced down the St. Clair River by northerly winds between March 30 and April 30. An ice jam formed on April 5th and lasted 24 days, establishing a record for both magnitude and lateness of occurrence. The cost to shipping companies due to delays in scheduled associated with vessels stranded above or below the jam was estimated to be over a $1 million per day.

Ice can also cause damage to shore installations (Wortly, 1985). Damage to docks can occur as a result of ice movement after freeze up. Rises in water levels causes posts frozen into the ice to be uplifted. Also shifting of one part of the ice cover due to thermal expansion of wind-induced ice movement can cause docks to be torn apart. Thermal expansion of a large ice field in a confined area or wind-induced shore movement of ice floes can cause large blocks of ice to move inland and literally bulldoze anything that is in their way (Boyd, 1981).

6.4 EFFECTS OF ICE ON THE LAKE ECOSYSTEM

Ice cover is an important climatic variable affecting the winter ecosystem of the Great Lakes because it acts as a filter for energy and mass (water vapor) transport between the atmosphere and the lake. Although there have not been many studies on the effect of the ice cover on the Great Lakes ecosystem to date several studies summarized below for Lake Michigan give an indication of the importance of the ice cover for Great Lakes biota (Section 7.3.2, Chapter 7).

6.4.1 Effects of changes in ice cover on the winter ecology of Lake Michigan

The amount of Photosynthetically Active Radiation (PAR) reaching the top of the water column beneath snow-free clear lake ice in Grand Traverse Bay was found to be about 45% of that at the air-ice interface (Bolsenga and Vanderploeg 1992). Vanderploeg et al. (1992) found that during the period of winter ice cover on Grand Traverse Bay (again with snow-free ice), that this amount of PAR (45%) was sufficient to produce a phytoplankton bloom that resulted in a 4-7 fold increase in feeding rate of adult *Diaptomus* spp. and enhanced reproductive output. Thus, the existence or absence of snow cover on the ice can have a significant affect on the activity of the micro-biota of the winter Great Lakes ecosystem.

Freeberg et al. (1990) showed that the overwinter egg mortality of whitefish in the spawning grounds of the east arm of Grand Traverse Bay was higher during the winter of 1983, a winter when the area did not freeze-up, than in 1984, a winter when the area did freeze-up. The ice protected the eggs against mortality induced by wind and wave action. Brown et al. (1993) found that extensive early-winter ice cover was an important parameter in models of whitefish recruitment in northern Green Bay and the north shore of Lake Michigan near Port Inland, Michigan. Taylor et al. (1987) compared historical trends of Lake Michigan whitefish yields during 1900-1982 with corresponding winter air temperatures near Lake Michigan. They found that around 1930, after several cold winters in the 1920's, Lake Michigan whitefish yields increased, whereas during the next 30 years (1931-1960), when winter temperatures were warmer (Assel, 1980), whitefish yields decreased, except in 1947. The high yield in 1947 was attributed to the cold winter of 1943, which produced a large year-class. Taylor et al. (1987) found that the cold winters of the late 1970's and early 1980's were associated with increases in whitefish yields in the early 1980's. Given this relation and assuming that other factors affecting the life cycle of whitefish in northern Lake Michigan have not changed, one would expect that the mild winters of the 1980's and early 1990's has increased the potential for a decline of whitefish yield. If so, projected decreases in ice cover (Assel, 1991) and projected increases in water temperature (McCormick, 1990) under GCM greenhouse warming scenarios lends credence to predictions of longer-term decreases in whitefish populations and possible changes in the fishery species composition (Meisner et al., 1987; Magnuson and Hill, 1990), both of which could have significant economic effects on the Great Lakes commercial and sports fishing industries.

6.4.2 Spring coastal plume in southern Lake Michigan

A preliminary study indicates that there appears to be a recurrent coastal plume (Sections 4.2 and 4.3.3, Chapter 4) that develops in southern Lake Michigan each spring (Eadie et al., 1996) which coincides with melting of the last snowpack and shore ice and with the occurrence of a major storm. The plume may play an important role in nearshore-offshore transport of sediment and may be important in the development of the spring diatom bloom and subsequent production. If the ice cover is more extensive than average or lasts longer than usual in spring this could delay the occurrence of both physical and biological activity associated with the plume and have consequences that are felt into the following summer.

6.5 CLIMATIC TRENDS

6.5.1 Nearshore ice cover regime

Analysis of long-term trends in lake-ice freeze-up and break-up dates (Assel and Robertson, 1995; Assel et al., 1995) and the results of a recent Intergovernmental Panel on Climate Change report (Fitzharris, 1996) indicate changes in mean date of freeze-up and break-up occurred at Grand Traverse Bay and Lake Mendota over the past 150 years. Average freeze-up dates were 8 to 12 days later and average ice-loss dates were 7 to 11 days earlier than from the 1850s to 1890. Average freeze-up date remained relatively steady after 1890 but average ice-loss dates again shift toward earlier dates, between 1940 and 1993 at Grand Traverse Bay (8 days earlier) and between 1980 and 1993 at Lake Mendota (7 days earlier). The timing of freeze-up and break-up at the two locations represents an integration of air temperatures over slightly different seasons (months). Thus, the second shift to earlier ice-loss dates at Grand Traverse Bay is associated with a trend toward warmer March temperatures starting in the 1940's and 1950's (Hanson et al., 1992; Skinner, 1993) and the second shift in Lake Mendota's average ice-loss dates is associated with a warming of average January through March temperature starting in the 1980's. Ten-year moving averages of ice event dates at Grand Traverse Bay and Lake Mendota show these trends (Figure 6-6), Assel et al. (1995).

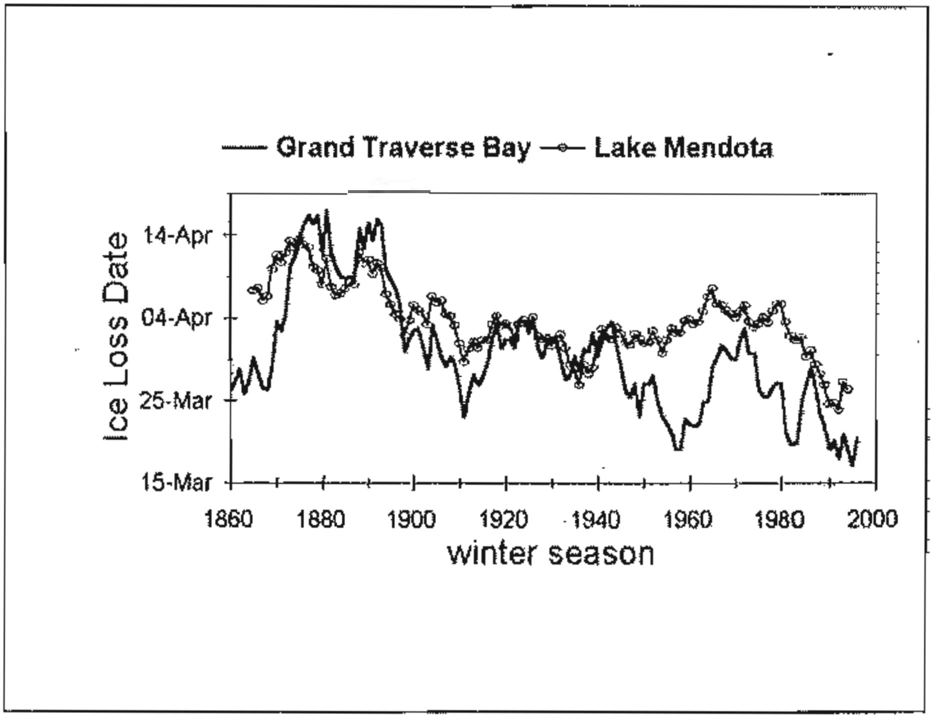


Figure 6-6. *Ten-year moving average of ice-loss dates at Grand Traverse Bay and Lake Mendota.*

6.5.2 Open lake ice cover regime

Three ice cover regimes were identified for Lakes Superior and Erie (Assel, 1990) using air temperature records from 1897 to model ice cover. These trends include a high ice cover regime (more extensive ice cover) from the early 1900's to the mid 1920's, a low ice cover regime from the mid-to-late 1920's to the mid-to-late 1950's, and a second high ice cover regime from the 1960s to early 1980's. The average February ice cover portrays these trends over the period of record (Figure 6-

7). A statistical analysis of observed ice conditions, using over 2800 historical ice charts from 1960 to 1979, defines the seasonal and spatial patterns of contemporary ice cover described earlier (Assel et al., 1983). A recent ice cover model (Croley and Assel, 1994) indicates that decadal average ice covers for the 1980's and for the 1950's was less extensive than the ice cover for the 20 year period of the ice cover climatology (1960-1979).

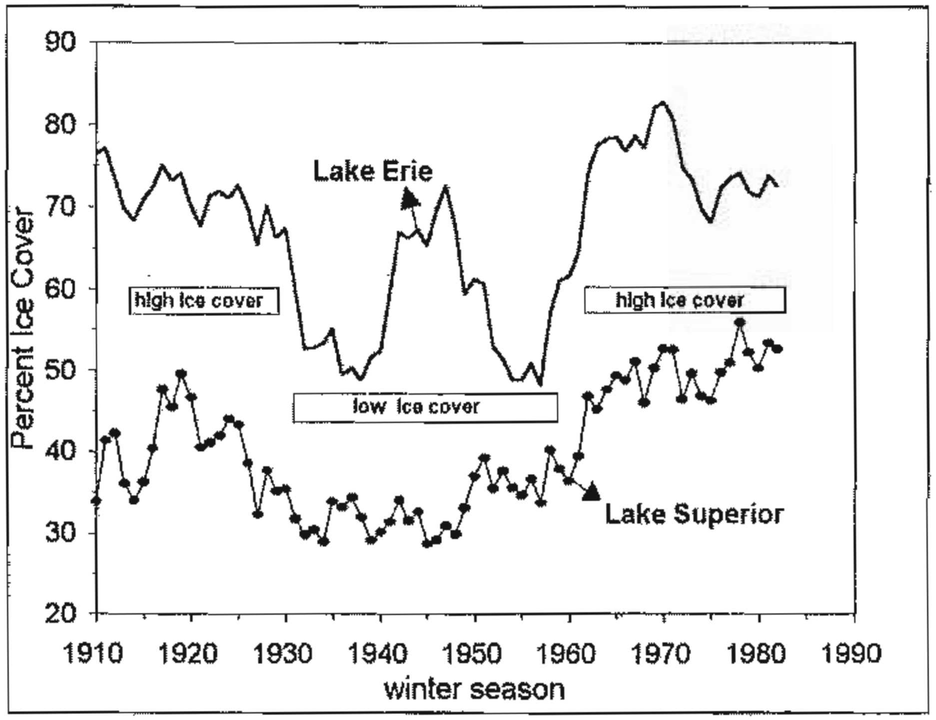


Figure 6-7. *Ten-year moving average of reconstructed February ice cover for Lakes Erie and Superior for winter seasons of 1900 to 1983.*

6.6 IMPACT OF CLIMATE CHANGE

6.6.1 Lake ice cover regime for double carbon dioxide scenarios

In a recent study (Assel, 1991) daily spatial average ice cover for Lakes Erie and Superior were modeled for a 1951-80 base period and for three 30-year 2xCO2 scenarios: the Geophysical Fluid Dynamics Laboratory (GFDL), the Goddard Institute of Space Studies (GISS), and the Oregon State University (OSU) general circulation models (Figure 6-8). The average ice cover duration for the 1951-80 base period ranged from 13 to 16 weeks; ice duration was reduced by 5 to 13 weeks under the three 2xCO2 scenarios. Winters with virtually no mid-lake ice cover became common, and average winter ice cover was limited to the shallow areas of both Lakes Erie and Superior under the 2xCO2 scenarios. Under this milder climate, the typical ice cover might be similar to that of the mild 1983 winter (Assel et al., 1985), complete freezing will become infrequent for the larger and deeper embayments in the Great Lakes, winters without freeze-up will occur at small inland lakes in the region, and the duration of the ice cover will decrease as freeze-up dates become later and break-up dates become earlier. Winter lake evaporation will increase due to the decreased ice cover (Chapter 2). Global warming effects on lake ecosystems in the Great Lakes may be similar to those described by Schindler et al. (1990) for inland lakes in northwestern Ontario, Canada. Potential effects of reduced ice cover for shore areas of the Great Lakes include greater over-winter mortality of whitefish eggs and thus potentially lower year class size, and lower diatom production, both due to loss of the stable environment afforded by formation of a continuous ice cover.

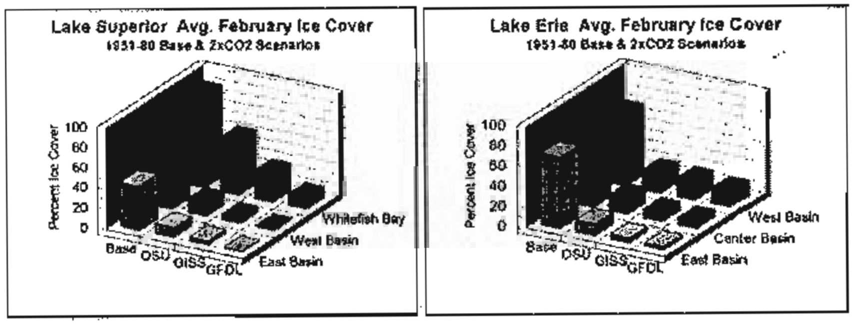


Figure 6-8. *Lakes Superior and Erie ice cover for 1951-980 base case and three 2xCO2 scenarios.*

6.6.2 Bay and harbor freeze-up and break-up dates

Freeze-up and ice-loss dates for bays of the Great Lakes and for inland lakes in that region correlate with autumn and winter air temperatures. Assel and Robertson (1995) show that a 1.5°C rise in late-autumn-to-mid-winter air temperature and about a 2.5°C rise in mid-winter-to-early spring temperatures between 1851 and 1993 are associated with approximately a 10 day retreat (later) in average freeze-up dates and about a 17-day advance (earlier) in average ice-loss date, respectively. Regression equations of air temperature with freeze-up date and regression equations with break up dates (Assel and Robertson, 1995) show that the sensitivity of both freeze-up and break-up for sites with long-term records in the Great Lakes average approximately 7 days per °C. Thus, if both the average winter and the average spring temperatures increase by 1°C, the average freeze-up date would be 7 days later, the average break up date would be 7 days earlier, and the average number of days between freeze up and break up, the ice duration period, would be reduced by 2 weeks. The impact on the Great Lakes ecosystem for these projected changes in ice cover phenology are given elsewhere (Magnuson et al., 1997).

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