

REPORT

A REVIEW OF GREAT LAKES ICE RESEARCH

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ABSTRACT. *A review of over 250 scientific and engineering articles on ice research in the Great Lakes covering the period 1906-91, with emphasis on the period 1960-91, shows a wide diversity of subject material. Studies on ice extent are the most prevalent. The engineering aspects of ice, primarily ice control structures, and ice forecasting have also received significant attention. Brief summaries of the articles are provided. The intention of this review is to provide an overview and a reference source of research conducted on Great Lakes ice.*

INDEX WORDS: *Great Lakes ice, freshwater ice.*

INTRODUCTION

The published literature on Great Lakes ice is extensive. Over 250 papers covering the period 1906-91 (with emphasis on the period 1960-91), which report research, engineering studies, or data on the ice cover of the Great Lakes and their connecting channels, were examined for this survey. (The St. Lawrence River has been excluded.) Although many of the reported studies were multi-dimensional, they have been categorized into the following groups: ice extent, thickness, characteristics, processes, effects, remote sensing, engineering, forecasting, and winter navigation. Usually a study is cited only under a single category, considered to be the primary content of the paper, even if the results apply to more than one category. The information can serve as a reference source for those desiring information specifically related to Great Lakes ice studies or for planning purposes. An attempt was made to be complete in the literature cited; however, even though the review was thorough, it is likely that a small number of articles have been overlooked.

The Cold Regions Research and Engineering Laboratory's annotated bibliography and the publication "Ice Engineering for Rivers and Lakes Bibliography" by Wortley (1990) include Great Lakes ice information. Many of those citations have per-

tinence to Great Lakes ice processes, but most of the studies were conducted on ice in other areas of the world. Other publications, such as Michel's (1971) "Winter Regime of Rivers and Lakes," include material applicable to the Great Lakes ice cover, but in this review, if the study has not specifically involved the Great Lakes, it is not covered.

Extent

Government agencies in both the United States and Canada have devoted considerable effort toward charting the extent of the ice cover by providing observers and observational platforms for this labor-intensive effort. The Navy/NOAA Joint Ice Center currently issues ice charts derived primarily from satellite data.

Great Lakes

Rondy (1971a) published the first Great Lakes Ice Atlas, which provided the first synoptic picture of the ice extent on each of the Great Lakes. Assel *et al.* (1983) updated Rondy's work to provide the most complete ice concentration climatology currently available. Over 2,800 historic ice charts from a 20-year period were combined to describe the maximum, minimum, and normal ice concentration from the last half of December through the last half of April. Detailed descriptions of the

development of the database for the Atlas are given in Assel (1983a, 1983b). During maximum ice extent in an average year, the median ice concentration is: Erie 90%, Superior 75%, Huron 68%, Michigan 45%, and Ontario 24%. The greatest ice extent declines occur during the first half of March on Lakes Michigan and Ontario, and during the last half of March on Lake Erie. The greatest declines in ice cover for Lakes Superior and Huron occur during the first half of April. Striegl (1952) provides a less complete description of ice extent and thickness.

In an early study of ice distribution on the Great Lakes, Heap (1963b) concluded that an analysis of known ice data at that time "would not substantially increase knowledge of ice distribution on the three upper lakes." Plans for an extensive field study were given in the report. Many of those programs were subsequently completed by various agencies. Detailed yearly ice extent charts from the 1962–63 to the 1978–79 winters and for the 1982–83 winter are described in Assel *et al.* 1984; DeWitt *et al.* 1980; Assel and Quinn 1979; Quinn *et al.* 1978; Leshkevich 1976, 1977; Assel 1972, 1974a, 1974b; Rondy 1966, 1967, 1968, 1969, 1971b, 1972; and Wilshaw and Rondy 1965. The early portion of the series, including the ice years 1962–63 to 1975–76, included charts of ice extent throughout the winter season and graphs of freezing degree days at selected locations. Tabulations of freezing degree days were included, beginning with the 1972–73 winter. Later reports, covering the 1976–77 through 1978–79 and 1982–83 winters, were expanded to include descriptions of the weather patterns, satellite imagery, and freezing degree-day accumulations for key cities.

Ice extent observations have also been reported by the Canadian Government (Canada, Department of Transport, 1960, 1962a, 1962b, 1963, 1966, 1968, 1969, 1971). Canadian ice advisory services, not including actual ice charts, are described in a series of reports (Canada, Environment Canada, Atmospheric Environment Service 1971–88).

Rondy (1976) described the varying severity and length of the winter season from the northern to the southern portions of the Great Lakes basin. Assel *et al.* (1985) categorized the 1983 winter as one of the mildest winters in the past 200 years. The attendant weather conditions established the lower limit of observed synoptic ice extent on portions of the Great Lakes. Wartha-Clark (1980) described ice extent on the Great Lakes for the 1978–79 period through satellite imagery. Ice con-

ditions throughout the Great Lakes during the 1969 season, which was one of the most severe ice years on record, are described in Linklater (1970) and Weather Bureau, ESSA (1969). The 1968 ice season is reviewed by Snider and Linklater (1969). Snider (1967) described the meteorological conditions and the resulting ice cover for the 1967 ice season. Oak (1955) provides a general description of nearshore and offshore ice conditions. Two of the earliest reports on ice conditions in the Great Lakes were by Conger (1906, 1908). Conger included nearshore ice information, such as opening and closing dates of harbors and duration of the ice cover over a 25- to 50-year period, in his second report. Observations of the "freezing across" of the lakes are given in Root (1944).

Lake Superior

Marshall (1967) identified three zones of ice formation, growth, and decay on Lake Superior: (1) nearshore lakes and ponds, (2) harbors and bays, and (3) the open lake.

Lake Michigan

Heap (1963a) described the ice conditions on Lake Michigan during the 1962–63 winter. More detailed information on Lake Michigan ice cover and winter temperatures is given in Heap and Noble (1966). Assel and Quinn (1979) analyzed the extensive ice cover that formed in the southern half of Lake Michigan during the 1976–77 winter when, in early February 1977, more than 90% of the lake was covered with ice.

Lake Erie

Assel (1983c) analyzed the typical ice cover on Lake Erie from December through April. Seasonal and regional trends as well as the average ice cover and percentage exceedance from the average ice cover are included. Ice conditions on Lake Erie from the 1976–77 through the 1986–87 seasons are reported by the Canadian St. Lawrence Seaway Authority (Canada, St. Lawrence Seaway Authority, Operations and Maintenance Branch, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984, 1985, 1986, 1987, 1988). Photographs and charts portray a rather complete picture during each winter season. Ice conditions—including ice extent, thickness, and ridging/rafting—on Lakes Erie and St. Clair and the Detroit and St. Clair Rivers from the 1970–71 through the 1975–76 winters—are reported by the Canadian Ministry of Transport

(Canada, Transport Canada, St. Lawrence Seaway Authority, 1971, 1973a, 1973b, 1975, 1976). Langlois and Langlois (1985) provide an illustrated account of ice formation, growth, and breakup on Lake Erie in the vicinity of South Bass Island. They compare ball ice to the large balls of ice on Lakes Michigan and Huron that were reported by Zumberge and Wilson (1954).

A thermal map of Lake Erie ice, using NOAA-2, VHRR-IR imagery with four cross sections to illustrate temperature variations across the ice-covered lake, shows the warming effect of the lake on ice temperatures (Wiesnet *et al.* 1974). The ice extent on Lake Erie during the 1974–75 season was tracked by McMillan and Forsyth (1976), using NOAA-4 visible and thermal imagery. Reporting on the 1975–76 Lake Erie ice cover, Wartha (1977) used imagery from three satellites, side-looking airborne radar, and aircraft.

Georgian Bay

Data from four winter seasons show a large year-to-year variation in ice cover (40 to 90% coverage) on Georgian Bay (Webb 1972).

Connecting Channels

Shen (1984) discussed ice extent in the connecting channels and offered suggestions for future work. An equation showing the relationship between air and water temperatures, by a simplified version of the convection-diffusion equation for thermal energy, is given to forecast water temperature decline and freeze-up. A natural, stable ice cover will not form in certain sections of the St. Clair and Niagara Rivers with fast flows or steep gradients, causing the formation of frazil ice. Bolsenga (1968) described the ice conditions on the connecting channels of the Great Lakes, emphasizing ice jamming. He cites conditions on the Niagara River, as reported by Foulds (1964, 1967), Strowger (1950), Pratley (1938), and Lyon (1912), and an article in the *Scottish Geographical Magazine* (1936) on freezing of Niagara Falls. A quotation from a 1921 report (U.S. Board of Engineers of Rivers and Harbors 1921) states: "St. Marys River ice effects—The retardation of flow in the St. Marys River is due to the ice cover on the river from Lake Superior to the head of the rapids, ice jams in the rapids occurring infrequently if at all. . . . St. Clair-Detroit River ice effects—. . . In addition to the normal ice cover, jams or blockades are of frequent occurrence and at times hold back

large quantities of water. Blockades usually form in the Detroit River in late December or early January followed in February and March by ice jams in the St. Clair River. These latter continue in April and occasionally into May. . . . After the breaking of the blockade in the St. Clair River each year there is frequently a blockade of short duration in the Detroit River."

St. Clair/Detroit Rivers

A rather complete description of the ice and winter flow conditions on the St. Clair and Detroit Rivers is given by Tsang (1975). An ice arch normally forms at the southern end of Lake Huron near the entrance to the St. Clair River. According to Calkins *et al.* (1982), the average annual surface ice discharge from the lake into the river is 907 km², ranging from 438 to 1814 km². The 1984 ice jam on the St. Clair River is discussed by Derecki and Quinn (1986). Water levels on Lake St. Clair and flow rates on the St. Clair and Detroit rivers were severely affected by this jam.

St. Marys River

Brazel (1971) reviewed the air mass patterns affecting the St. Marys River region, analyzed selected weather station records from the area, reviewed the freeze-up and breakup climatology, and discussed the importance of the micrometeorology to the ice cover. Vance (1980a) provides a detailed description of the physical characteristics of the river, along with estimates of ice growth, accumulation, and natural transport. Ice thickness measurements were reported by Voelker and Friel (1974). Extensive ice thicknesses are indicated, especially near the shipping channels. Cowley *et al.* (1977) described the natural ice regime of the St. Marys River and the effects of vessel movements. A series of reports describing the ice conditions on the St. Marys River and the performance of the ice boom at the Little Rapids Cut have been published by the U.S. Army Corps of Engineers (1979a, 1980, 1982, 1983).

Niagara River

In 1963–64, ice jams caused much destruction in the Niagara River area. An ice boom was installed at the head of the river the following year. The boom, which consisted of flotation buoys and timbers attached by chains, has proven effective in lessening ice runs—accelerating the formation of a stable upstream ice cover and providing additional

stability to the downstream edge of the natural ice arch that usually forms in the area. Russell (1972) described pre- and post-ice-boom conditions on the upper and lower Niagara Rivers. Foulds (1967) provides an account of ice conditions before and after the installation of the ice boom on the Niagara River. List and Barrie (1972) conducted a study on: (1) the relationship between frazil ice production on the Niagara River and synoptic meteorological patterns, and on (2) heat exchange between the river and the atmosphere. Wigle (1976) described frazil, bottom, and surface ice on the Niagara River. Arden and Wigle (1972) observed floating and anchor ice on the Niagara River. Instrumentation for this study is described in Arden (1970). Ferguson (1968) estimated the energy balance of the Niagara River by determining the approximate average and extreme daily values of climatological variables in the energy budget equation for the month of February. Cork and Chapil (1966) described frazil, anchor, and lake ice conditions on the river. A photographic account of ice conditions on the Niagara is given by Holden (1959).

Thickness

Much less information is available on Great Lakes ice thickness than on ice extent. Ice thickness data were collected over a period of about 10 years at several U.S. stations on the Great Lakes and on inland lakes near the Great Lakes shoreline (Sleator 1978). Ice thickness climatologies for a limited number of Canadian Great Lakes stations over a period of 12 years are given in Richardson and Burns (1975). An ice thickness climatology for the Great Lakes for the period 1963–1978, using data from Richardson and Burns (1975) and Sleator (1978), was published as an internal report by the Canadian Government (Canada, Environment Canada, Atmospheric Environment Service 1980).

Bolsenga (1988) analyzed Sleator's data for growth, dissipation, maximal thickness, and stratigraphy on a lake-by-lake basis. Average maximal ice thicknesses, and average dates of their occurrence were generally related to the water volume of each lake and to latitude-related climatological differences. Ice growth rates were nearly equal for all of the lakes, but dissipation rates were high for the upper lakes and low for the lower lakes. Bolsenga *et al.* (1988a) provide a station-by-station detailed

analysis of the data. Additional analysis of these data is presented in Bolsenga (1984a).

Characteristics

Strength

Relatively few studies have been conducted on the strength of ice in the Great Lakes environment. However, much work has been completed on freshwater ice strength in other environments and most of that information can be effectively and accurately used in solving Great Lakes ice problems (Wortley 1984, 1990). Studies directly involving Great Lakes ice include those of Frankenstein (1959) who conducted in-place cantilever and small beam tests on Lake Superior clear, snow, and combination clear/snow ice. Flexural strength of clear ice was high when the bottom was in tension and low with the surface in tension. Flexural strength of snow ice was unusually high. Followup, similar tests were conducted by Frankenstein (1961). He reported that on a clear day, with air and ice temperatures near 0°C, ice will decrease in strength by as much as six times from morning to mid-afternoon. In-place load tests, on Lake Superior ice, using a large tank filled with water as the load to determine the bearing capacity of ice are reported in Frankenstein (1963). Butkovich (1955) reported on tests to determine the crushing strength of lake ice from the same geographical area where Frankenstein conducted his tests. Large beams, cut from Lake Superior ice, were used in a laboratory study to determine the flexural properties of clear ice (Hitch 1959). The results showed: 1) lower temperatures gave higher values of the modulus of elasticity and strength, 2) ice with larger crystals will have a higher modulus of elasticity but little difference in strength, and 3) the rate of loading increases the modulus of elasticity but has little effect on the strength except at low temperatures. Horeth and Wilson (1948) reported on laboratory bending and shear tests for the U.S. Coast Guard on ice from northern Lake Michigan.

Models

Greene (1984) reviewed the status, strengths, and shortcomings of ice characteristics models, including models of ice growth and decay, dynamics in channels, deterioration, and transport.

Types

Marshall (1966) used aerial photographs to interpret some of the common basic ice features of the lakes. In his study of Duluth-Superior Harbor, Sydor (1978) stated that that location displays a range of physical and environmental conditions typical of many Great Lakes harbors. Case (1906) described ball ice formation that occurred on Lake Michigan near Milwaukee. A glossary of ice terms was compiled by the Lake Survey Center (1971).

Reflectances

A review of the optical characteristics of ice is provided by Bolsenga (1984b). Bolsenga (1969) measured the total albedo (300–3,000 nm) of various types of ice common to the Great Lakes. He later amplified on this study to show significant variations in albedo due to variations in solar altitude, ice decay, and changes in cloud cover (Bolsenga 1977, 1979). Albedo variations due to the interaction of solar altitude under clear skies and certain ice types, as well as albedo measurements in the near-infrared, are discussed in Bolsenga (1980). A dual spectroradiometer system was later developed (Bolsenga and Kistler 1982) to simultaneously measure incident and reflected spectral radiation, to obtain the spectral reflectance (340–1,100 nm) of freshwater ice types. Data were collected at small wavelength increments so that reflectances could be determined corresponding to the current or future sensitivity of remote-sensing detectors (Bolsenga 1983, Bolsenga and Greene 1984). Leshkevich (1985a, 1985b) and Leshkevich and Reid (1984) used an airborne radiometer for spectral reflectance measurements and an airborne calibration technique for atmospheric effects, but since the incident and reflected measurements were not made simultaneously, the ice types measured were often a combination of a number of discrete ice types because the surface measured was about 80 meters in diameter. Leshkevich (1988) found that the correction for the error in Lambertian response of a spray-painted barium sulphate reference panel used for calibration can make a significant difference in the resulting ice reflectance factors. Diurnal variations in the albedo of ice are discussed in Bolsenga (1987).

Transmittances

Transmittance of photosynthetically active radiation (400–700 nm) through ice was measured by Bolsenga (1978b, 1981) and a two-layer model was

developed to predict radiation transmittance through layered ice. Spectrally sliced data in the photosynthetically active range and a discussion of the relative usefulness of spectrally sliced and spectrally integrated data are given in Bolsenga (1989). Bolsenga *et al.* (1991) provide spectral transmittance signatures in the 400–850 nm range for a variety of freshwater ice types collected in Lake Erie. Dives with a remotely operated vehicle under freshwater ice showed crack and bubble structure as well as light transmitted along ice crystal boundaries (Bolsenga *et al.* 1989).

Chemistry

Adams and Smith (1973) examined the petrographic characteristics and ionic concentrations of Great Lakes ice at 11 sites during 2 consecutive years.

Processes

Icefoots

Zumberge and Wilson (1954) discussed formation of icefoots in the Great Lakes. O'Hara and Ayers (1972) observed the evolution of an icefoot on Lake Michigan during two winter periods. Marsh *et al.* (1973) studied the formation and structure of icefoots along the Lake Superior shoreline. The formations were composed of large masses of grounded ice in long continuous ridges parallel to the shoreline, separated by broad areas of low-relief ice. Dozier *et al.* (1976) presented observational evidence and an interpretation on the generation and evolution of icefoot cusps. Bryan and Marcus (1972) reported on the morphology of the same icefoots. A 3-m-deep trench was cut into the formation normal to the shoreline in order to map the structure. Marshall (1966) attributed the mode of formation and form of icefoots to the shoreline environment and weather.

Ice Cones or Ice "Volcanoes"

Fahnestock *et al.* (1973) observed "volcano-like" conical mounds up to 5 m high developing along portions of the southern shores of Lakes Erie and Ontario when the "lake is open and a shelf of ice is attached to the shore." Eruptions of slush, ice, and spray spouted up to 10 m in the air, rapidly adding ice to the cones so that some of the larger cones were formed in a few hours or days.

Ridging

Oak (1955) reported that when ice cover on the Great Lakes is reduced to 60 to 90%, surface winds can cause extensive ridging 10 to 20 ft above the lake level or 30 to 35 ft below, often becoming anchored to the lake bottom. Langlois and Langlois (1985) reviewed ridge formations in the Bass Island area of Lake Erie.

Wind-Driven Push

Wind-driven ice push is a phenomenon that occurs quickly and unpredictably. Gilbert and Glew (1987) described an ice push event (10 min duration) on Lake Ontario. Open water was necessary, in addition to winds, to create an ice push event. Boyd (1981) described a 20-minute ice push event on Lake St. Clair, which caused property damage. Conditions surrounding the event were: "1. . . . melting and shifting of the ice; 2. . . . open water for the ice to move and gain momentum; 3. . . . changing wind direction and gustiness helped loosen the floes although wind speeds were not particularly high; 4. . . . lake water level rise; 5. The floe grounded at a change in orientation of the shoreline; and 6. . . . temperature was below freezing before the event." Langlois and Langlois (1985) described an ice push event: "a large panel of ice, perhaps 100 yards wide, shoved up against the rocky cliff. . . ." Tsang (1974) analyzed ice piling on inland lake shores, reporting on two ice pilings that grew to a 9-m height in periods of a few minutes. Pilings occurred when the main body of ice rammed onto the shore ice, the floes telescoping and piling up by overriding, undersliding, or rafting.

Bottom Scouring

Grass (1984) described deep ice keels scouring the bottom of Lake Erie to water depths of 25 m and penetrating soft sediments to approximately 2 m. On the Canadian side, the scours in soft silty clay were preserved from year to year, due to the low energy environment; on the American side, the scours were obliterated. Alger (1977, 1978, 1979) found that, with an ice cover, river bottom sediment transport is greater during ship passages and that vessel-induced erosive forces can be large during spring breakup.

Dynamics

Rumer and Crissman (1977) reviewed the literature on ice transport in the Great Lakes, formulated the

ice transport problem mathematically, and conducted laboratory experiments. Additional information on the movements of ice, using remote-sensing techniques, was considered essential for advancement in this field. Most motion results from stresses at the air/ice and ice/water interfaces, which are, in turn, related to the wind or water movements and to the respective aerodynamic roughness of the surfaces. Two continuity equations, one that redistributes the ice mass and one that redistributes the ice area, are derived for a two-dimensional model of ice transport. Chieh *et al.* (1983) calibrated the model, using ice and meteorological data. For a freezing period, the model results agree fairly well with observed results. During melting, the simulation and observations agree when wind-driven surface water currents are included. Stubblefield and Bennett (1984) changed the finite difference scheme of Rumer *et al.* (1981) for enhanced efficiency and stability. In one test case, the modeled conditions did not agree with observed conditions primarily because the new version of the model did not include thermal changes. Some of the measurements desired by Rumer and Crissman (1977) were reported by Campbell *et al.* (1987). Four satellite-tracked drifting buoys were used to measure Lake Erie ice movement during one winter period. Chase (1972) discussed using satellite imagery for interpretation of Great Lakes ice extent and ice drifting.

Dingman and Bedford (1984) reported on the significant role of ice cover on Lake Erie during a storm surge caused by the most intense extratropical cyclone to ever cross the Ohio Valley and Great Lakes region. The wind force partially broke up the ice cover in the central basin, but ice in the western basin remained intact due to its thickness (> 30 cm). In the eastern basin, consolidated ice caused the water level to be 0.17 m lower than in nearby areas. An observed winter water level fluctuation maximum amplitude of 3.8 cm was reported by Hodek and Doud (1975) in a Lake Superior harbor. Roblee (1983) concluded that any Great Lakes harbor has enough seiche activity to cause problems with piles due to ice uplift and that high degrees of oscillation lead to more extensive uplift damage.

Jams

The U.S. Army Corps of Engineers (1985) reported on an ice jam that occurred in the Niagara River during January-February 1985. Flooding in

the river resulted from strong southwesterly winds, which caused ice from Lake Erie to override an ice boom placed at the Lake Erie end of the river. Floods occurred in the area during 1942, 1943, 1954, 1955, 1962, 1964, 1972, 1975, 1979, and 1985. Bryce (1968) described ice problems on the Niagara River that occurred both before and after installation of the ice boom on Lake Erie. Bolsenga (1968) reviewed ice jam literature on the Niagara, St. Marys, and St. Clair-Detroit rivers.

Bank Erosion

Ice in the connecting channels can disrupt sediment by pushing against and by retreating from the banks. Gatto (1978a, 1978b, 1978c, 1982a, 1982b) discussed the effects of ice-related erosion on river banks. He found that along reaches of the St. Marys River, ice seemed to protect rather than to damage the river banks. He stated "These results suggest that bank erosion processes during the winter may be more active on the St. Clair River than on the St. Marys River." The ice on the St. Clair River may be more mobile than on the St. Marys River, possibly due to ship traffic. In the Detroit River "The degree of erosion rarely changed between winter and summer." Wuebben (1978a, 1978b) and Wuebben *et al.* (1978) reported on the effects of winter navigation on bank erosion.

Ice Roughness

Hsiung Yu *et al.* (1968) recalculated the hydrodynamic roughness coefficient of the St. Clair River in the presence of an ice cover. An equation relating "stage" to "roughness" yields results that are comparable to other equations and that more reasonably satisfy boundary conditions.

Effects

Rondy (1976) reviewed some of the destructive effects of ice. Marshall (1968) presented a list of items that ice affects, including meteorological, hydrological, geological, geochemical, bacteriological, botanical, and biological processes. Assel *et al.* (1985) discussed some of the effects of a mild winter and the associated lack of ice cover on winter navigation, shore flooding, hydropower generation, and shore erosion. The effect of ice on the phytoplankton and zooplankton of the Great Lakes is an emerging issue and one on which little work has been attempted (Bolsenga *et al.* 1988b). Stewart (1973) found unusually cold water temper-

atures in Lake Erie and little-to-no vertical temperature stratification during winter.

Dingman and Bedford (1984) reported on water level fluctuations that occurred in Lake Erie during an intense tropical cyclone. The lake surface, significantly ice covered during the event, remained virtually intact in the western basin, but partially broke up in the central basin. The effects of ice on water movements in Lake Erie were measured by Palmer and Izatt (1972). Water movements shortly after ice cover had formed were nearly the same as those in an ice-free lake. Current magnitudes and persistence factors were similar to those during the ice-free months approximately one month after ice had formed. Wind-driven currents in partially ice-covered Lake Erie were modeled by Sheng and Lick (1972, 1973). Calculations were made corresponding to freeze-up in the western basin and to thawing in the eastern basin. Pickett (1980) speculated on the effect of ice on winter circulation in Lakes Ontario and Huron. The effects of ice cover on currents and movement of ice with respect to currents in Lake Huron are discussed by Saylor and Miller (1976). Both winter and summer circulation patterns in Lake Huron are reported in Saylor and Miller (1979).

Remote Sensing

Visible Imagery

The usefulness of NOAA-2 very high resolution radiometer (VHRR) data for monitoring the ice extent on Lake Erie was demonstrated by Strong (1973). Leshkevich (1981) found that different ice types could be differentiated and categorized using Landsat 1 digital imagery. He later used Landsat digital imagery to develop a method to classify Great Lakes ice types, assuming proper ground reflectance data were available (Leshkevich 1985c). Hagman (1976a) measured the density of satellite photographic transparencies and correlated calculated surface reflectance with ice-cover concentration. She encountered several difficulties, such as variable film densities and a lack of information on the reflectance, transmittance, and absorptance of ice and snow.

Infrared Imagery

Thermal infrared imagery can be useful as a supplemental tool to distinguish between ice and open water and, on a limited basis, to delineate the relative thicknesses of freshwater ice (Schertler *et al.*

1974). In that report, observations from Lakes St. Clair and Erie compare thermal, radar, and visual imagery.

Radar Imagery

Anderson *et al.* (1972) evaluated the usefulness of side-looking airborne radar (SLAR) imagery for remote sensing of freshwater ice. Bryan and Larson (1975a, 1975b) used a four-channel multispectral radar (SLAR) to obtain data on ice in Whitefish Bay and the Straits of Mackinac. Ice types identified included black ice, smooth brash, pressure ridges, and pancake ice. The ice had a very low dielectric constant and low loss tangent and was thus somewhat transparent to the SLAR energy. Additional observations, including ground data, from a small inland lake are reported in Bryan (1974). Bolsenga (1978a) commented on the usefulness of the same four-channel SLAR for ice characteristics research. Hagman (1976b) felt that microwave radar systems were advantageous for Great Lakes ice cover surveillance, but that lack of ground data greatly hampered interpretation of the imagery. Jirberg *et al.* (1974) made several flights over Lake Erie and Whitefish Bay with a SLAR, collected ground data in some of the areas, and interpreted the imagery. The strongest returns were with ice that had large vertical cross sections, such as brash and ice ridges, and ice with a rough bottom profile. Larowe *et al.* (1971a, 1971b) collected and analyzed radar imagery over the Whitefish Bay area of Lake Superior.

Early development of a short-pulse radar system for determining ice thickness is described by Vickers and Heighway (1974). They found that ice thickness could be measured with an accuracy of about 2 cm for a smooth (on both sides) ice cover thicker than 10 cm. Upper-surface geometrical roughness caused problems due to the reflected signals from off-axis bumps.

Engineering

Striegl (1952) grouped ice engineering problems into five categories: (1) maintenance of structures, (2) maintenance of open navigation channels, (3) operation and maintenance of water intakes, (4) flooding caused by high water levels due to jamming or other forms of ice, and (5) shore erosion. Design criteria for shore structures are included in his report.

Control Structures

General descriptions of a wide variety of ice sheet retention structures are provided by Perham (1983). Included are the ice booms on Lake Erie and the St. Marys River, light tower bases on Lakes Erie and St. Clair, and a rock-filled scow in the St. Marys River, associated with the ice booms at that location. Sodhi *et al.* (1982) described a model study of a proposed ice control structure at the head of the St. Clair River. Perham (1981) provided a 4-year summary of the performance of two ice booms installed on the St. Marys River in 1975. A 250-ft wide opening was included in the boom design to facilitate ship movement. Maximum forces, usually developed with ice moving over the boom, were measured in the ice boom anchor lines. The early design and operation of the ice booms are covered in Perham (1977, 1978a, 1978b). Another 4-year summary of the booms is contained in Perham (1984). A discussion of ice measurements and recommendations for improvements in the study are contained in Perham (1985).

The Niagara River ice boom has been the subject of controversy since it was first conceived. Perhaps the most definitive report on the effects of the boom was published by the National Research Council (1983). The panel reported that previous studies were inconclusive in demonstrating whether or not the boom caused a local climatic effect, but that those studies correctly concluded that if an effect does exist it does not extend as far as the Buffalo airport. The report states "The panel believes that the evidence is very clear that, while there has been a slight cooling of winters in Buffalo since the mid-1960s, the cooling did not start then and it was not limited to Buffalo. . . . An overall regional change in climate has occurred."

Quinn *et al.* (1980, 1982) found no significant cooling at Buffalo, New York, related to the ice boom when air temperatures at Buffalo and Lockport, New York, were compared or when water temperatures at Buffalo were compared to the pre- and post-ice-boom years. A general climatic trend toward more severe winters since 1958 was found. Rumer *et al.* (1975) concluded that the ice boom promotes ice retention in the lake. There was uncertainty on the degree of the effects of ice retention on water temperatures, based on the results of a mathematical model. An analysis of computed heat exchange at the air/ice interface was conducted in a later study (Rumer and Yu

1978). Rumer *et al* (1983) again used the model to assess the affect of the ice retention structure on the environment. Temperature data at Buffalo and Cleveland, Ohio, showed that at both sites, on the average, the post-boom winters were more severe and the pre-boom and post-boom springtime warming periods were similar. Rumer *et al.* (1983) were not, however, able to produce a conclusive judgement on the effects of the boom and felt that additional data were needed to reach a firmer conclusion. Hassan and Sweeney (1972) found a direct, positive correlation between the average daily air temperatures at three cities in the area, only one of which was adjacent to the ice boom. Webb (1973) concluded that the amount of ice retained by the boom would usually not be significant enough to seriously affect navigation. Two early reports on the operation of the Niagara ice boom were compiled by the International Niagara Working Committee (1978, 1979).

Natural ice arching—the bridging of a water gap by floating ice fragments—occurs in the Great Lakes at the outlets of Lakes Erie and Huron. In response to a proposal to construct an ice control structure at the head of the St. Clair River, Calkins and Ashton (1975a, 1975b) conducted a study that investigated force interactions of ice with the shore and the control structure. The distributions of stress components are presented in nondimensional form so that they may be applied to a region of any size, within the scope of the experiments. An estimate of the ice released by 100 round trips of vessels through a 122 m opening in the structure was 9 km².

Icebreaking

An extensive set of model and field tests has been conducted on the 140-ft icebreaker USCGC *Katmai Bay*. Vance (1980b) and Vance *et al.* (1981) reported that the vessel could penetrate up to 48 in. of brash ice in a continuous mode and 30 in. of plate ice by backing and ramming. An on-board bubbler system significantly reduced the amount of vessel power required for icebreaking. Tatinclaux (1984), in conducting model resistance tests, found that predicted resistance was significantly larger than values estimated from full-scale trials of the *Katmai Bay*. Propulsion tests compared reasonably well to those measured during full-scale trials (Tatinclaux 1985). Model and field tests were conducted on the U.S. Coast Guard Cutter *Mackinaw* in response to a research program to provide

design information for future icebreakers (Edwards *et al.* 1972).

Ship Vibration Levels

Haynes and Maatenen (1981) instrumented ice, ground, shoreline structures, and ships with accelerometers to measure vibrations caused by ships during ice conditions on the St. Marys River. Vibration levels were about one order of magnitude lower than levels that would damage building walls. Vibration levels with an ice cover were about four times greater than those without an ice cover.

Navigation Channel Maintenance

Clearing ice-clogged shipping channels on the St. Marys River by ice displacement, ejection, slurring, and rafting was investigated by Vance (1980a). Disposal by displacement under the remaining ice sheet was feasible in most portions of the river. Mellor *et al.* (1978) investigated the specific energy and/or power needed to remove ice in certain portions of the St. Marys river system. Calculations were made on the energy that would be expended per unit volume of ice material processed to melt, lift to a specific height, push or tow slabs, submerge flat slabs, chop or crush, transport in slurry pipelines, and ballistically eject the ice. Surprisingly, most of the final power estimates were in a relatively narrow band.

Ten operational concepts for moving Great Lakes freighters through ice-clogged channels by the aid of tows from warping or kedging systems are reviewed by Mellor (1979). He analyzed the crushing resistance of brash ice and the ship resistance in brash ice. Force and power requirements, design problems, operation, and procurement of the various systems are discussed.

Structure Maintenance

Collars of ice form along lock walls in the Great Lakes, reducing the effective width of the lock and restricting ship movements (Calkins and Mellor 1975). Lock-wall icing conditions are described in this report, along with operating assumptions and cost estimates.

Oil Spill Control

The containment and recovery of spilled oil in winter on the St. Clair and Detroit rivers is described in Tsang (1975). Perforated-type booms are recommended to separate the oil from the water, with removal by surface skimming using high-volume

pumps, with oblique booms located where the flow rate of the river is high.

Harbor and Structure Design

A rather complete manual covering a variety of aspects of small craft harbor and structure designs to mitigate Great Lakes ice conditions has been compiled by Wortley (1984). Design considerations as well as construction techniques—many of them tailored to specific areas of the Great Lakes—are covered.

Retardation

Quinn (1973) used a hydrologic-response mathematical model to determine the effects of ice retardation on Great Lakes water levels. Striegl (1952) cited a study completed in 1920 by the U.S. Lake Survey where, in Lake Ontario, the average excess elevation caused by ice in the outlet channel was 0.21 ft, with the maximum excess in 1908 amounting to 1.45 ft. In Lake Erie, the maximum depression of level due to reduced flow through the Detroit River was 2.37 ft, in 1918; in Lakes Huron and Michigan, the maximum excess elevation due to ice was 1.22 ft, in 1904.

Forecasting

The problems associated with forecasting ice formation, movement, growth, and decay were discussed by participants in a Great Lakes ice workshop (Assel 1984). In the connecting channels, present forecasts perform poorly when anomalous weather conditions exist, indicating a need for improved prediction of the parameters that drive the models. There is also a need to improve forecasting ability for ice-jam formation. In the near-shore zone, forecasts of freeze-up, ice strength, movement, thickness, and depletion need to be developed. Forecasts of the opening and closing of leads, areas of ridged and rafted ice, and movements of ice in bays and harbors are important to shippers, while forecasts of ice thickness and strength are important to recreational users. In mid-lake areas, improvements are needed in short-term forecasts. These could be best improved through the use of conceptual models that account for small time steps to describe mass and energy exchange processes. Long-range forecasts of mid-lake conditions could be improved by additional analysis of existing ice cover data sets, to define dominant space and time domains and to correlate

those with deviations in air temperature, winds, and ice reflectances.

Extent and Thickness

A National Weather Service ice forecasting manual published by Snider (1974, 1971) lists two input parameters required for freeze-up forecasts: the maximum amount of heat stored in the warm upper layer of water (epilimnion), and the rate at which this heat will be removed. The progress of freeze-up can be estimated by comparing the mean lake surface temperature to the long-term water temperature. The date of ice formation in shallow nearshore areas has a strong positive correlation with mean temperature anomalies during the last half of the warm season. The ice forecasting manual contains historical information on average freezing degree day accumulations, opening and closing dates at selected harbors, and other data pertinent to ice forecasting. More recent publications, such as Greene (1983), Assel (1976), and Rogers *et al.* (1975), have supplemented the forecast procedures for certain specific areas.

Jacobs *et al.* (1980) described the compilation of Great Lakes ice charts and surface water temperature charts by the U.S. National Weather Service. Oak and Myers (1953) described an ice forecasting procedure used by the Weather Bureau some years ago. Included are opening dates of navigation, ice thicknesses at various ports, and a description of the general ice conditions on the lakes.

Ashton (1984) discussed deterioration and thinning of ice covers. Thinning refers to changes in the overall dimensions of the ice cover. The process is conceptually straightforward, but the magnitude of the net heat flux from outside the ice cover to the boundary surface is difficult to calculate. Deterioration is defined as the loss of strength of the ice cover due to partial melting, by shortwave radiation, along grain boundaries. More *in situ* measurements of radiation extinction and analytical work on the complexities of absorption, scattering and reflection are needed before solutions to these problems can be found.

The thermodynamics of ice formation, growth, and dissipation on Lake Erie without the effects of ice dynamics models, are described by Wake and Rumer (1979). A two-dimensional convective dispersion equation for the conservation of heat energy in the water body, a two-dimensional depth-integrated equation of motion, and interfacial heat exchange equations are used.

Freezing and thawing degree-days have been used by a number of investigators as the basis for ice prediction techniques. Assel (1980) used an 80-year period of record of daily maximum and minimum air temperatures at 25 locations around the perimeter of the Great Lakes to generate long-term means of daily air temperatures and freezing and thawing degree-days. He later updated his analysis to include data from additional winters and lake-wide averages of freezing degree-days (Assel 1986). Richards (1963, 1964) used freezing and thawing degree-days ($^{\circ}\text{F}$), correlated with the percentage of ice cover, as a tool for ice forecasting. Lake Erie became 50% ice covered after 300 to 400 freezing degree-days and 90 to 100% covered after 700 freezing degree-days. Few thawing degree-days (100 to 150) were required to dissipate the bulk of the ice from Lake Erie. Lake Superior showed little ice cover until after an accumulation of 1,000 to 1,400 freezing degree-days, but Whitefish Bay and Thunder Bay froze after 900 freezing degree-days. Richards (1969) provided regression equations to predict ice extent on Lakes Erie and Superior, and discussed the importance of forecasting, for better prediction of the effects of ice cover on the weather and for winter navigation.

Assel (1976) used a weekly ice thickness database and freezing degree-day accumulations to develop regression equations to forecast ice thickness at 24 bay, harbor, and river sites in the Great Lakes. Standard errors were between 7 and 8 cm for the various equations. Hinkel (1983) correlated accumulated degree-days of frost with ice thickness data from 32 nearshore stations. Ice cover growth coefficients were computed that indicated the processes of ice growth and site-specific factors. The inhibiting influence of snow on ice growth as well as the degree of predictive accuracy of the relationships were shown.

Rogers (1976a) incorporated a technique, originally developed by Richards (1964) and based on pre-winter thawing and wintertime freezing degree-days, to predict the maximum ice extent on the Great Lakes. The quasi-biennial temperature cycle was used to predict the number of freezing degree-days that would accumulate by the average date of maximum ice extent. In a later report, Rogers (1976b) evaluated long-range air temperature forecasting techniques that could be used in ice forecasting. He found that an improved temperature-forecasting technique was possible by combining the use of quasi-biennial oscillation, extrapolation, and kinematic procedures. Chase *et al.* (1970) dis-

cussed ice data information available at the time and their use for ice prediction.

Greene (1983) used a 10-year data base to develop methods for predicting ice formation, growth, and decay at five sites on the St. Marys River. A site-specific heat transfer coefficient and observed water temperatures at Sault Ste. Marie were used to predict formation. The Stefan relationship was used to simulate growth, but was quite sensitive to accuracy of air temperature forecasts. The breakup forecast was strictly empirical and related to the data at which water temperatures rose above 0°C at Sault Ste. Marie. Rogers *et al.* (1975) developed an operational forecast for the Sugar Island ferry that operates on the St. Marys River. The vessel had experienced crossing problems due to ice breaking activities associated with extended winter navigation. Ferguson and Cork (1972a, 1972b) calculated regression equations, relating observed ice flow on the Niagara River to meteorological variables. A reduced form of the energy budget equation proved useful for establishing the regression equations. Clapper *et al.* (1975), using energy budget methods, investigated two methods of ice thickness prediction for Duluth-Superior harbor.

Currently, one of the most practical uses of ice information is as an input to weather forecasts. The affects of weather on ice and of ice on weather are described by Snider (1984), who comments on the processes wherein ice cuts off a portion of the energy, water mass, and momentum fluxes between the lake and atmosphere.

Movements

Ice dynamics have always caused severe problems in the Great Lakes. Unlike the ice cover of inland lakes, the Great Lakes ice cover moves throughout the winter. Predicting such movement is difficult. Rumer *et al.* (1979) found that ice transport in the Great Lakes is governed by wind action, water currents, lake surface tilt, Coriolis force, and internal ice stresses. Although governing equations for the transport of a multi-floe ice field can be written, they probably cannot be all-inclusive. Models employing the continuum approximation have been developed recently and can be solved by the use of numerical methods and high-speed computers. Inadequate field observations hamper the calibration and verification of models. The constitutive laws for Arctic pack ice need to be carefully investigated with respect to their transferability to

the Great Lakes ice cover. A model for ice movements on Lake Erie is described by Wake and Rumer (1983, 1979) and early development of the model is described in Rumer and Crissman (1977).

Rumer *et al.* (1980) found that internal ice resistance significantly affects the movement and deformation of a fragmented ice field. A viscous-type constitutive law was adapted to represent the internal resistance, but the degree to which actual conditions could be approximated by using this law was not demonstrated. A summary of ice transport modeling in the Great Lakes is contained in Rumer (1984).

Winter Navigation

Historically, winter hazards closed the waterborne link of the Great Lakes regional transportation system to major shipping from mid-December to early April. The Great Lakes and St. Lawrence Seaway Navigation Season Extension Demonstration Plan was undertaken to demonstrate the practicability of extending the season. The U.S. organizational units of the program consisted of (1) a Winter Navigation Board, composed of representatives of participating agencies and invited interests, which coordinated planning, budgeting, execution, and reporting of activities, and (2) the following seven working groups, which performed program activities directed by the Board:

- Ice Information
- Ice Navigation
- Ice Engineering
- Ice Control
- Ice Management in Channels, Locks, and Harbors
- Economic Evaluation
- Environmental Evaluation

A State Observers Group, Public Involvement Subcommittee, and Legal Committee were also included.

A separate Survey Study conducted by the U.S. Army Corps of Engineers was undertaken to identify costs, economic benefits, engineering feasibility, and the social and environmental acceptability of extending the navigation season. A synopsis of the U.S. projects conducted during the program is contained in the Demonstration Program Final Report (Great Lakes and St. Lawrence Seaway Winter Navigation Board 1979). Other reports resulting from the Winter Navigation Program include: four annual reports and a Demonstration Program Report prepared at the end of Fiscal Year 1976; "Legal Considerations Associated with an

Extension of the Navigation Season on the Great Lakes and St. Lawrence Seaway" (U.S. Army Corps of Engineers 1978); A three-volume Environmental Assessment—"FY 79 Winter Navigation Demonstration on the St. Lawrence River" (New York State Department of Environmental Conservation 1978); and "Impacts on levels and flows of Lake Ontario and the St. Lawrence River" (U.S. Army Corps of Engineers 1979b). Descriptions of Canadian programs involving the extension of the navigation season are contained in Anderson *et al.* (1973).

Conclusions listed in the Demonstration Program Final Report (U.S. Army Corps of Engineers 1979b) include: (1) the season was successfully extended, (2) movement of vessels through ice was demonstrated, (3) navigation aids were partially successful, (4) weather and ice information are required, (5) crew safety is aided by survival equipment, (6) ice control structures are useful, (7) year-round lock operations are possible, (8) the potential exists for increased shore erosion and damage to docks, (9) transportation for island residents can be maintained, and (10) sufficient data to assess the effects on the environment are not available.

A number of factors concerning the planning and implementation of the Navigation Season Extension Program were addressed by Argiroff (1975). Perrini (1979) discussed non-technical aspects of the Season Extension Study. Information on the extent and thickness of the Great Lakes ice cover was essential in the winter navigation demonstration program. Several agencies cooperated to provide such information to the shipping interests (Schertler *et al.* 1975, Gedney *et al.* 1975). During the 1971-72 winter, NASA attempted to correlate SLAR imagery with various types, features, and surface patterns of ice. NASA also tested a high resolution short-pulse radar for measuring ice thickness. The systems were used operationally, in all-weather conditions, in a near-real-time mode during the 1974-75 and 1975-76 seasons. The imagery was useful to the shippers in transiting ice congested areas, making dispatch decisions, and determining areas of refuge. Stewart (1973) observed visually, from the air, that the coastal regions seemed to offer the route of least resistance to winter navigation on Lake Erie. He noted one instance where two vessels proceeded into heavy ice and became ice-bound rather than take a longer, but ice-free, course. Quinn (1974)

described the various ice information systems in place for the extension of the navigation season.

Snider (1984) stated "Sooner or later there will again be large-scale winter navigation on the Great Lakes. . . . we should be better prepared the next time." He provides a number of suggestions or current research efforts, such as developing a practical manual of ice navigation, and working on the location and condition of leads and on-board meteorological observations to predict short-range changes in the ice cover.

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