PROCEEDINGS OF THE GREAT LAKES ICE RESEARCH WORKSHOP*

Held October 18-19, 1983
at the Ohio State University
Fawcett Center for Tomorrow
Columbus, OH

CO-SPONSORED BY OHIO SEA GRANT AND NOAA, ERL, GLERL

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Foreword

A workshop was held on October 18-19, 1983, at the Fawcett Center for Tomorrow, the Ohio State University, Columbus, OH. The primary purpose of the workshop was to assess where we have been, where we are, and where we should be going relative to ice cover research on the Great Lakes. The original papers, submitted by invited speakers and reports by subcommittee chairpersons, are reproduced in this proceedings without modifications in order to provide the user community with a working document in a timely manner. For this reason, the text appears in several different typescripts and report formats. It is hoped this publication will provide a useful tool for decision makers, as well as for those involved in basic and applied research in which Great Lakes ice is an important consideration.

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INTRODUCTION TO THE WORKSHOP

John G. Lyon
Department of Civil Engineering
The Ohio State University

I'm glad you could make it to our Great Lakes Ice Research Workshop. As you can see from the wide body of people here, there are different groups represented. It has been quite interesting working on and talking about the subject of ice, seeing where the research is now and where we're going in the future. About a year ago, several people came together and developed the idea for a Great Lakes Ice Research Workshop and we're lucky that it happened.

Originally, the concept was developed during a Sea Grant site visit. From an initial analysis, we determined it would be desirable to better understand the current work in ice research and prospects for the future. A workshop was determined to be the best vehicle for examining the questions involved, and a steering committee was appointed to organize the workshop. In brief, the members of the steering committee are Frank Quinn, Gordon Greene, Ray Assel, and myself, John Lyon, Civil Engineering at Ohio State, Keith Bedford from OSU, and Professor Herdendorf. This group organized the meeting and identified some people we hoped would be interested in speaking, and identified the many of you who were interested in attending the workshop.

As we hear the speakers, we will develop some idea of what they have accomplished in this research area, the things that are important to them, and it will give us some ideas and a common ground of information. Knowledge of different areas that are involved in ice research can be used as a touch stone for our conversations. We're going to try to look at the current state of research, some areas we want to develop research in the future, and get some ideas as to the importance of those kinds of things.

For a moment, lets take a look at the schedule. We now have had some lunch and we'll -be enjoying three speakers after introductory remarks from various people. At that point we'll have a break. From that we will go through another set of three speakers and try to end somewhere around 5:00. Then we'll go over to the Faculty Club. After we finish dinner, we'll go downstairs where we'll have a multimedia presentation of films that have to do with Great Lakes ice research. Tomorrow we will meet once again at 8:30. We'll split into three groups that deal with various general sorts of areas of Great Lakes ice research. At that point-we'll discuss where we've come in our research, what areas are important to use in terms of the future that we wish to explore. We'll break for lunch, and when we come back, we'll have reports from those subcommittee groups and try to further identify these needs. The point of doing all this is once again to identify research needs in Great Lakes ice areas and from this a group of us are going to put together a document from our work today and tomorrow, along with a questionnaire.

Our next speaker is Professor Herdendorf, who is the director of Ohio State Sea Grant and also the Center for Lake Erie Area Research here at Ohio State.

Professor Herdendorf:

John gave a few words about how this idea came about; maybe I can expand on that a little bit and tell you how we developed this notion of having an ice workshop and conference here. It goes back to 1982 at one of our site visits from the National Site Review Panel of the Office of Sea Grant. One of the projects that we proposed at that time and that the panel was reviewing dealt with flood and storm seiche forecasting during ice conditions on Lake Erie. That evoked a lot of discussion, and it really was revealed during the discussions that there was no comprehensive assessment of ice-related problems for the Great Lakes, that is no one had undertaken any long-term or comprehensive planning on ice research and ice research needs. One of the members of that review team was John Bennett, and John we know of from the laboratory in Ann Arbor. Shortly after that meeting, it was suggested we could all get together and have some kind of conference where we begin to look collectively at the Great Lakes in terms of ice research and needs and to share existing knowledge. Shortly after the site visit, Keith Bedford and John Lyon got together with John Bennett and other members of the staff in Ann Arbor and began developing a notion for this conference. The fruits of their labor will, I hope, be realized in the next 2 days.

From my perspective, I certainly know very little about ice research other than having spent a long time on. Lake Erie trapped in the ice a few times in boats. I've had some sort of experience, but not in a research way. Why is it important to have Sea Grant and a program like ours? I would like to mention some rather obvious things, such as we are all hearing more about winter navigation and it seems to be revitalizing. Closer to it is recreation. Our islands on Lake Erie happen to have as their sole source of winter income ice fishing, ice boating, and recreation dealing with the ice environment. Also, shore ice provides a certain degree of protection to the shoreline. The other side of the coin is the property damage that can be related to shore ice conditions. From some personal experiences, I've seen some cottages that have been totally crushed along Lake Erie where ice shelters have come in. I've seen huge blocks of ice hitting people's living rooms, coming in through their picture windows, and things like this. Keith Bedford has suggested that a brochure should come out on how to get rid of the ice on your porch every spring. It is a direct problem that we have with the Sea Grant entity. I didn't mention the environmental problems that can be concerned with navigation, both dealing with wetlands or park facilities, even things such as ferry service that might be interrupted by ice flows.

We need some kind of research effort that might come out of such a meeting of people concerned with this topic. Sea Grant programs are set up to deliver information to people using the Great Lakes, and we do this through a number of ways: through connecting direct research, through developing education programs in public school systems, through publications of a variety of types, and also through direct advisory service (one-on-one kind of information transfer). We have a mechanism for doing these kinds of information transfers. What we now need though are some good solid research plans and some research initiative. The next few days I wish you success in addressing this rather important topic.

Frank Quinn
NOAA, Great Lakes Environmental Research Laboratory

It's always interesting to come to these and find out 5 minutes before that you're going to introduce the speakers. Ice has been a problem on the Great Lakes for a long time, but really the main emphasis in performing research relative to ice came in the early 1970's with the advent of the Winter Navigation Program on the Great Lakes. It's a very controversial program--winter navigation has an effect on a number of environmental factors relating to breaking the ice, to ice growth, to forecasting the ice, and to ice management in the harbors. As you are all aware, the program has come to an end now. Those vast sources of funding which it provided have also trickled down a little bit. We are at the point where we can sit back and say--okay, where are we now? We've had a major program running roughly 10 years at the Great Lakes Environmental Research Lab in Ann Arbor and what used to be prior to that the Corps of Engineers. We've had an ice research program going back to 1962. Prior to that, there was very little done. The Canadians began systematic ice observations in the late 1950's, early 1960's, and this was basically the start of ice research on the Great Lakes. With the exception of a few people (usually those who lived around the shores who were interested), there was very little done. The emphasis today is on the economic aspect related to winter navigation and the environmental and scientific aspects--how is radiation transferred into ice, what happens to the flora and fauna under ice conditions, do we need better forecasting, what is likely to be the impact of climatic changes which will impact ice, which will impact our temperatures, such as greenhouse effect (the increase of CO_2 which is anticipated to cause a warming). There are various anthropogenic factors such as the Lake Erie ice boom which changed the climate of the ice and the climate in Buffalo, NY.

A Lot of these are factors/projects that will be looked at in the future and that require a scientific basis for decisions which will be made. One of the reasons we're all meeting here, and we have a very diverse group--we have people representing the Weather Service, the NY State Power Authority, Corps of Engineers--basically users who have definite needs for ice research. We have other people such as ourselves, Ohio Sea Grant, AES, who are providers, who are responsible for research programs to address some of the needs relating to Great Lakes ice. As you're all aware, last winter we had just about no Great Lakes ice. Lake Erie, which is normally covered with an ice concentration of 80% to 90%, had about 25% ice cover last year. These types of things may occur in the future. What we would like to do at this meeting is look at where we are now at this particular time in ice research. We have a number of speakers--all knowledgeable in their areas--who will address these points. More importantly, where are we going? What are the main research needs that should be addressed in the future? Coming out of this, we hope to determine the areas for future research and to prioritize the needs. We have a large group here representing various agencies from both the United States and Canada to look at areas for mutual cooperation and mutual studies. We hope to come out of this with proceedings which can be used as a basis for program development. For those of you who are representing the users, we would like to know where you feel the important needs are and the areas that should be addressed. I think as we listen to the speakers, see the films, and discuss programs in proposed areas of research, that we'll be able to look at ice in a broad prospective as to where we are and where we should be going.

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Chapter 1.3, Section 1.31

1. INVITED PAPERS--PERSPECTIVES OF GREAT LAKES ICE RESEARCH

1.1 REMOTE SENSING OF ICE

Rene Ramseier AES, Environment Canada Ottawa, ON, Canada

[Manuscripts not available.]

1.2 RESEARCH NEEDS FOR GREAT LAKES ICE FORECASTS

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It is difficult to make a statement of research needs that will prove useful over a long period of time. Very likely the most useful discovery will be made accidentally by a researcher who was looking for something quite different from that which he found. Past experience suggests that demands for ice information are likely to appear in those very areas where our knowledge is most woefully inadequate, and that answers will be required before we have had time to develop data we can present with confidence.

I would like to suggest that researchers just keep hacking away at the recognized gaps in knowledge, and follow any promising leads to wherever they may go. But I know that projects have to be funded, and that funding cannot be made available on such a basis.

Applied research must be directed toward the needs of a specific constituency. Right now a constituency for Great Lakes ice research is hard to find. Last winter the only customers for our ice forecasts were the Coast Guard and other NOAA agencies. And it is likely to continue that way until the most dormant segment of our national economy springs back to robust life or until another major interagency project is inaugurated.

The most practical use of ice data at the present time is for input into weather forecasts. The Great Lakes exert a major influence on the weather of downwind areas, and have some influence on circulation patterns of a large segment of the atmosphere. Those influences can vary with variations in ice cover. Therefore, weather forecasts could be improved if we had better observations of current ice distribution and better understanding of air-water-ice interactions.

ICE OBSERVATIONS.

Several methods of gathering ice observations were used during the Winter Navigation Demonstration Program. All provided useful information, and the totality of them enabled us to prepare the most detailed ice analyses yet attempted. But most of those methods were quite expensive. The only platform that can be efficiently and economically used for routine observations year after year is the satellite. We need, then, to glean more data from current satellite observations, and to develop new sensors for the Satellite which can get the data that is now most sorely lacking.

The problem is clouds. Extensi’>e winter cloud cover is a characteristic feature of the Great Lakes climate. The ice forecaster scans satellite photographs day after day searching for that brief clearing which will permit him to update a portion of his ice analysis. Surely there must be some radiation from the ice that can penetrate cloud cover. We need to find its wave length. If a passive receiver cannot get the information, then the satellite must bounce a cloud-penetrating signal off the ice. The design and

*Paper presented by Mr. Daron Boyce
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deployment of such an observing system, and the proper interpretation of the data it receives, should get high priority attention.

A well-designed satellite sensing system would measure the distribution and thickness of ice. An even better design might also get us roughness, density, and albedo. All of these would be useful parameters.

THE EFFECT OF WEATHER ON ICE.

We know that a storm rearranges the ice cover on the Great Lakes. But we never know what extent until the clouds clear away, often several days later. Until we achieve the ability to make direct observations through the clouds, we will have to continue our guesswork and extrapolation based on what we know about the physical characteristics of the ice and its reaction to the forces acting on it. That knowledge could be improved considerably.

It has been stated that more meteorological data than ice data is required in the art of ice forecasting. The truth of this statement depends on the high correlation between sequences of meteorological events and subsequent ice formations. Most of the correlation data we are now using were worked out about 1970, on the bases of fragmentary data then available. Though rough, and only partially tested, they have given useful results. If these same calculations were now repeated, using the vastly better data base we now have, it is likely that forecast precision could be improved.

The freezing degree day has been the most useful parameter. Indeed it is about the only parameter on which long range (30 to 90 day) forecasts can be based. Correlations between freezing degree day accumulations and ice cover need to be more sharply defined. And local geographical areas where those correlations are poor need to be scrutinized to determine what processes are interfering with orderly freezing and how those processes may be parameterized.

We know that long range forecasts for Lake Erie do not verify nearly as well as those for the other lakes. We assume that this is due to the more rid changes in ice cover that occur on Lake Erie. A study of the time scales api on which various changes normally take place, and a search for the causes of those temporal variations would be useful.

Wind is the second most important parameter in ice forecasting. The effect of wind on ice formations is still handled subjectively. We have reasonably good wind forecasts out to 48 hours, and can make useful estimates for another day or two. But we can only guess at how much wind it takes to rupture an ice sheet. And we have no idea what gives the ice its strength to resist breaking up. If we did know how to calculate the strength of the ice, how could we get the data in time to be useful?

We can calculate the wind-driven water currents in an ice-free lake. But what about a lake that is partially ice covered? Will such currents alter the wind drift of the ice? When floes drift together, how can we tell whether they will be rafted, windrowed, or sutured?

A strong wind sets up convection currents which bring warmer water to the surface and delay new freezing. How much wind does it take? How much heat is moved? And to what extent is the heat supply of the deeper water depleted?

Predictions of the initial freeze-up are based partly on the estimated supply of heat transferred from the atmosphere into the water during the summer months. Our methods of making this estimate are extremely indirect. A mass of bathythermal data is now available, from which it should be possible to develop improved methods of estimating a deep lake's thermal structure.

THE EFFECT OF ICE ON WEATHER.

The "lake effect" is an article of faith among Great Lakes Region weather forecasters. It manifests itself in many ways. There are many procedures, ranging from the most subjective rules of thumb to rigorously tested computer programs, for incorporating lake effect into the forecast. Each of these depends on one of two assumptions. Either the lake is assumed to be ice-free or it is assumed to have the "normal" amount of ice for that time of year. On most winter days neither of these assumptions is valid.

From the ice analyses we now have we could introduce an ice cover parameter into these procedures--if only we knew how.

There is a flux of energy, water mass, and momentum between the lake and the overlying atmosphere. Ice cuts off some of it. How much? Does the condition of the ice make a difference? And how about snow cover? What happens to that energy?

Ice floes blown onto shore by a storm can be very destructive. On the other hand a stable ice foot can provide protection against winter storms to an unstable shoreline. Can we make useful predictions of these phenomena?

Spring floods on tributary rivers change the levels, temperatures, and chemistry of lake water around the river mouths. How does this affect the ice? And how can we predict backwater conditions on a river when lake ice blocks its mouth?

What is the effect of waste heat from power plants on lake ice, and on the weather of the surrounding area? Could future lants be located so as to turn this waste into a useful by-product?

NAVIGATION THROUGH GREAT LAKES ICE

Sooner or later there will again be large-scale winter navigation on the Great Lakes. In view of the work we have already done, we should be better prepared the next time. Most of the results of our studies have appeared in scientific journals or technical memoranda. These are not likely to be used by a ship's officer on the bridge. A practical manual of ice navigation is needed.

Ice forecasts now available, and likely to be available in the future, are good for long range planning, such as dispatching decisions, and for warnings of imminent major changes. The mariner navigating an ice clogged channel needs much more detailed information He must develop most of it himself, but we can give him some useful hints.

We have not done a great deal of work on the opening, closing, and movement of leads. Such information is so highly detailed that we could not include it in transmitted forecasts. Yet that is precisely what is needed for on-the spot tactical decisions.

What is the best way to determine current ice conditions on the proposed track? How useful are macro-analyses received by radio? Can visual sightings or data received from preceding ships help? Is radar useful? If not, what other remote sensors can be developed? Is helicopter reconnaissance necessary, and how can it be most efficiently accomplished? Under what conditions is icebreaker escort necessary?

Once current conditions are known, how can meteorological observations made on.board be used to predict short-range changes? Are current observations enough, or do forecasts of wind and temperature have to be used? Can a set of easily applied rules be developed to enable the mariner to assess the probability of successfully traversing an ice field from information available to him?

ICE RESISTANT PLATFORMS

The deployment of buoys in the Great Lakes is a major seasonal activity. And, the removal of all those buoys before the beginning of each winter season leaves the lakes a virtual terra incognita.

Winter-time buoys would be a tremendous advantage for both navigation and science. Year-round observations of various physical parameters from mid-lake platforms would fill in serious gaps in present knowledge and would suggest many promising avenues for future research. Hardware is already in place to gather and disseminate such observations. But the problem of maintaining a platform in the ice environment has not been solved.

CONCLUDING REMARKS

Some of this may sound prosaic; much of it sounds like pie-in-the-sky. There is not much that is new. We have been talking about most of these ideas for a long time. All to often we have thrown up our hands and said, “Any sensible person knows that is impossible.” Maybe it is. But once in a while we have accomplished the impossible. Then, in retrospect, it looks easy. We can always dream, can’t we?

1.3 OPTICAL AND STRATIGRAPHIC PROPERTIES OF ICE

1.31 Shortwave Reflectance and Transmittance of Ice and Snow

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Introduction

A knowledge of the reflectances of ice and snow are critical to the accurate representation of wintertime energy budgets. Such budgets are widely used as models in ice prediction work, but it has been noted that errors in estimating the albedo term have caused large errors in prediction dates. In addition, identification of ice types and ice extent through remote sensing techniques is valuable when large geographic areas must be covered, as in the Great Lakes. A catalog of ground-based information on the reflectances of a variety of ice types in various spectral ranges according to the solar altitude, azimuth, and atmospheric conditions would fill a gap and would increase the ability to use ice imagery many-fold.

The amount of radiation penetrating an ice or a combined ice and snow cover is often critical to the survival of plants and animals in both large and small freshwater lakes. In spite of the importance of this problem, the nature and magnitude of shortwave radiation transmittances is only partially understood. Comprehensive understanding has been hampered by unrepresentative measurements due to instrumentation and measurement technique problems.

Significant new information on the spectral reflectances of ice and snow in the 340-1100 run range and on transmittance through ice and snow for the 400-700 nm range has been collected. This report is a brief summary of those studies.

Reflectance

A pilot study was conducted in early 1967. to obtain the total albedo (integrated shortwave) of ice common to the Great Lakes (Bolsenga, 1969). It was found that albedo values ranged from 10 percent for clear ice to 46 percent for snow ice (Table I). The program indicated that diurnal variations likely occurred in the albedo, that different ice types would probably exhibit different diurnal characteristics, and that the type and amount of cloud cover was a factor.

A new program was later initiated to develop a catalog of information indicating the spectral reflectances of ice according to a wide range of solar altitudes (10-45°), cloud types, and cloud amounts. A dual spectroradiometer system for field measurements over natural surfades was developed (Bolsenga and Kistler, 1982). Measurement sites were selected on the basis of Marshall's (1966, 1977a,b) ice classifications. Measurements were made on snow, clear ice, snow ice, refrozen slush ice, brash ice, pancake ice and slush curd ice (Bolsenga, 198lb and 1984).

Table 1.--Spectrally integrated reflectances of various ice types from an early pilot study (from Bolsenga, 1969).

ICE TYPE	ALBEDO λ		CLOUD CONDITIONS
	%	(DEGREES)	
Clear Lake Ice (snow free)	10	37	- Clear
Bubbly Lake Ice (snow free)	22	36	5/10 Cirrus & Cirrostratus
Ball (snow free)	24	40	1/10 cirrostratus
Refrozen Pancake (snow free)	31	32	4/10 Altocumulus
Slush Curd (snow free)	32	40	- Clear
Slush (snow free	41	38	- Cirrostratus
Brash (snow between blocks)	41	40	- Cirrus & Cirrostratus
Snow Ice (snow free)	46	32	5/10 Cirrus & Cirrostratus

Several scans were made over 3-4 cm of new snow overlying 15 cm of mostly clear lake ice. Figure 1 shows two runs characterized by a narrow range of values (81-89%) from 340-900 mu after which a pronounced dip to values of about 70% occurs near 1050 nm. One run was made over a snow surface that had reached an advanced stage of deterioration (Fig. 2). The mass was dark in appearance and nearly at the stage of complete melting.

Runs over approximately 30 cm of clear ice were made on the Straits of Mackinac (Fig. 3). The surface appeared very black, no doubt partly due to the 22 m water depth which precluded any influence of the bottom on scan values. The curves lack any abrupt changes in spectral reflectances with recorded reflectances remaining in a narrow 5-10% range. In another case, the spectral reflectances of 15 cm of clear ice on a small inland lake with a water depth of only 1 m were measured (Fig. 3). Although the surface was predominately clear ice, several fragments of white ice from a previously melted ice cover were frozen in the clear ice matrix and numerous cracks were noted. Higher spectral reflectances from 340-850 rim for this surface as compared to the Straits of Mackinac surface can be ascribed to cracks, the white ice inclusions, and the presence of some green plants visible on the bottom.

Refrozen slush ice is one of the most common ice surfaces on the Great Lakes and on smaller inland lakes. Figure 4 shows the spectral reflectances from a refrozen slush ice surface. The shape of the curve can be described as “typical,” however, the magnitude of values varies widely for this ice type.

Pancake ice is composed of fragments of a previously formed ice cover with characteristic raised rims caused by the grinding of one fragment against another appearing as a “whitish” rim enclosing an inner portion varying in appearance from white (snow ice, slush ice) to black (clear ice). Spectral reflectances of such ice could be expected to vary, depending on the makeup of the inner portion of the individual pancakes and the matrix in which the individual pancakes are frozen. Only one type of pancake ice was measured in which the individual pancakes were formed from white ice fragments frozen together in a mildly chaotic fashion. Figure 5 shows these spectral reflectances, but it should be recognized that the values are not necessarily characteristic of the spectral reflectances of all types of pancake ice.

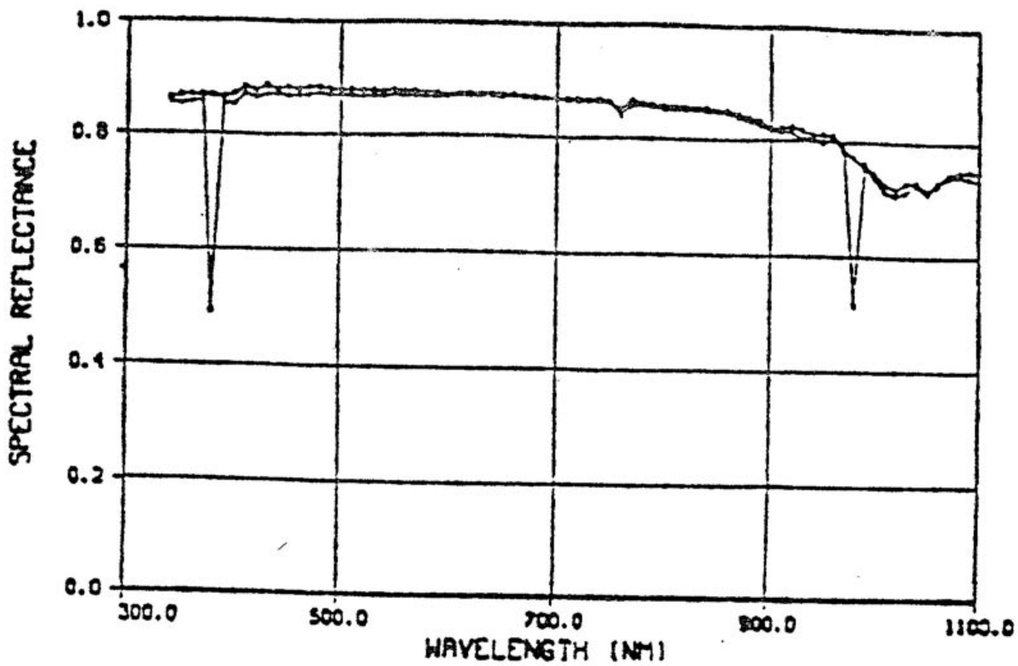

Figure 1. Spectral reflectance of new snow. Spikes in all traces are due to electronic noise (from Bolsenga, 1981b).

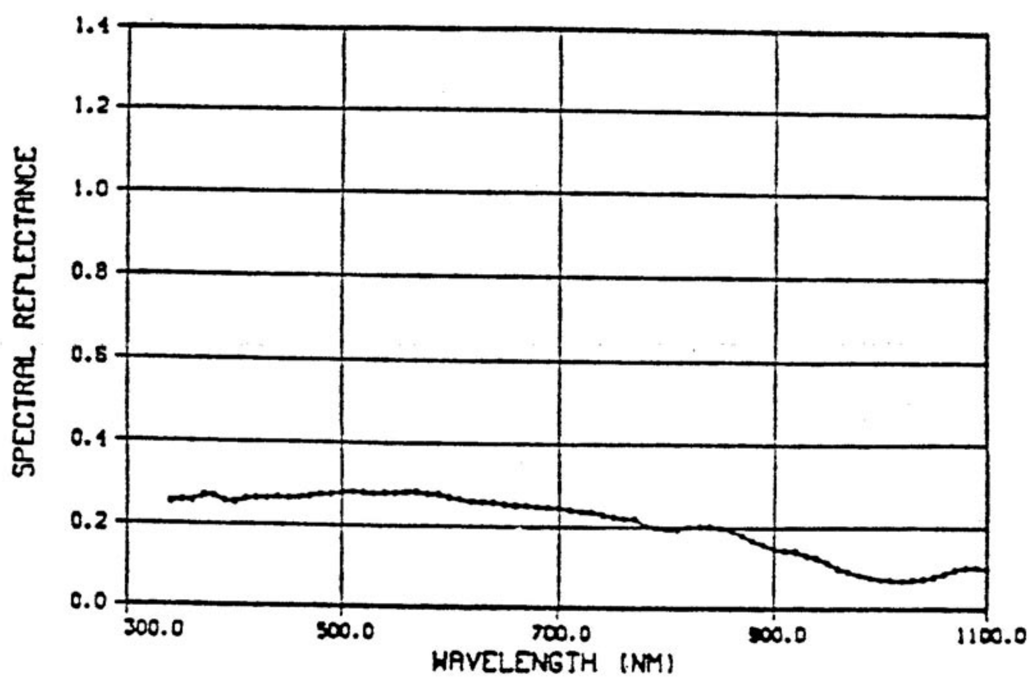

Figure 2. Spectral reflectance of a much deteriorated path of snow (from Bolsenga, 1981b).

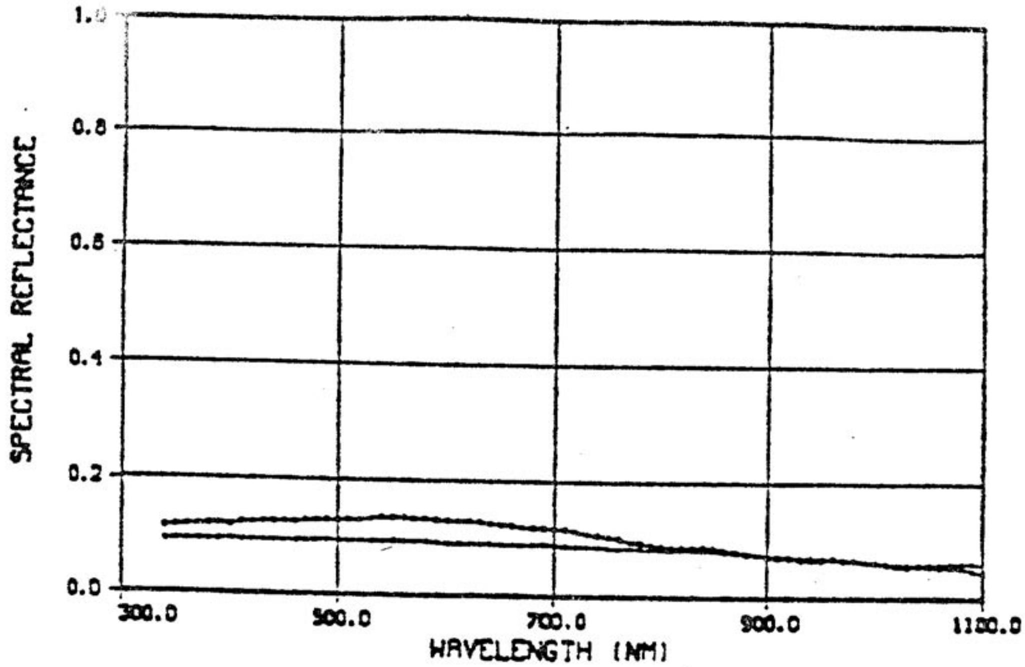

Figure 3. Spectral reflectance of clear ice on a small inland lake compared to Straits of Mackinac clear ice (from Bolsenga 1981b).

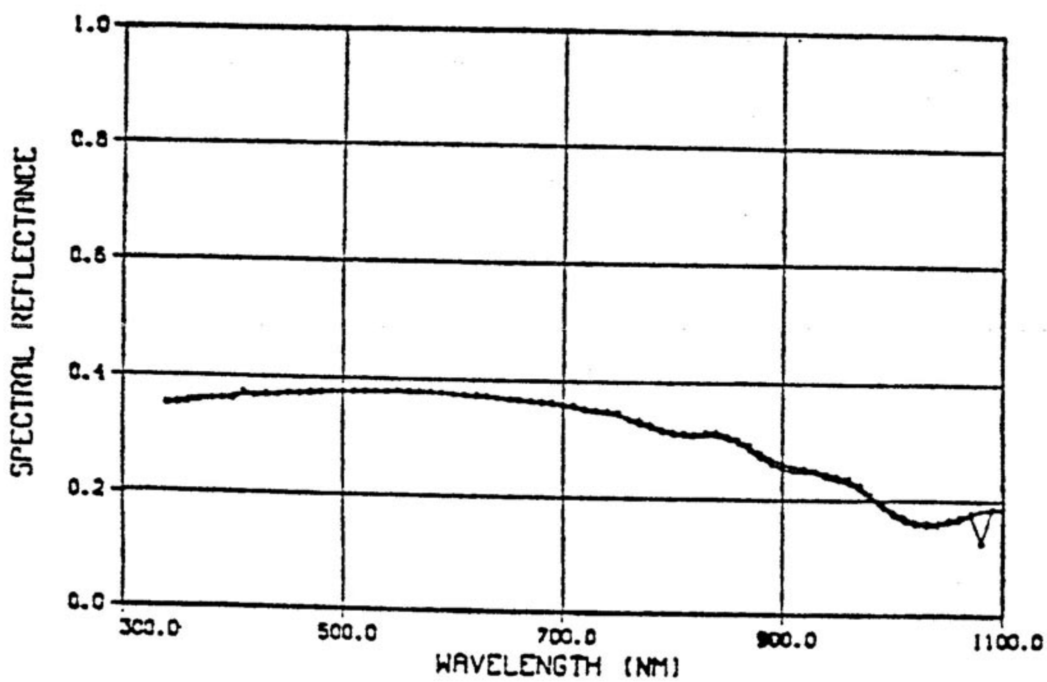

Figure 4. Spectral reflectance of refrozen slush (from Bolsenga, 1981b).

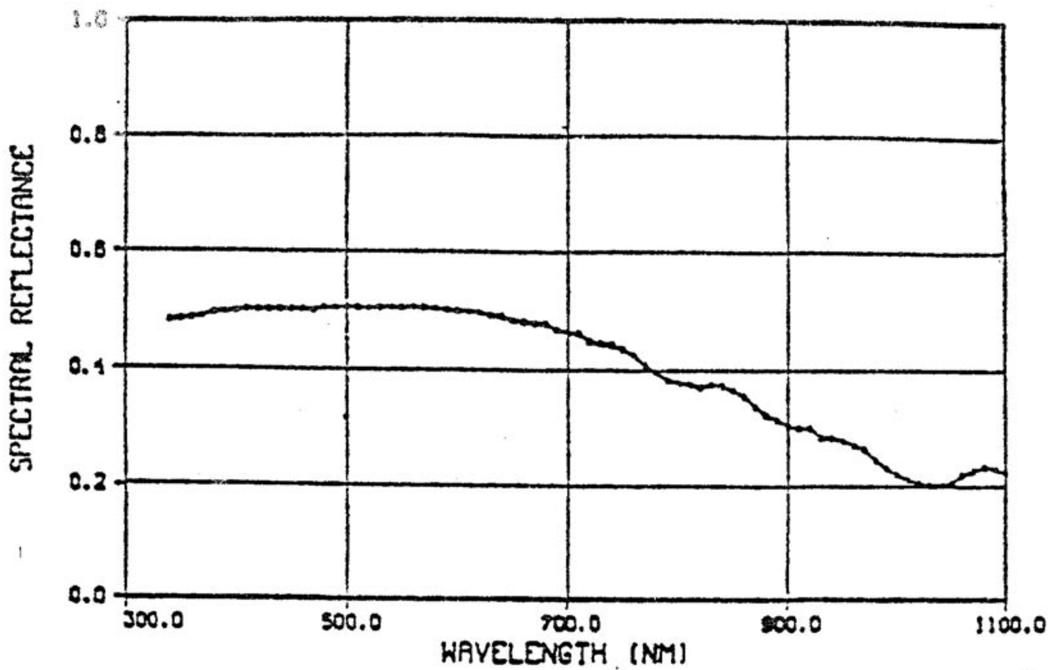

Figure 5. Spectral reflectance of pancakes ice (from Bolsenga, 1981b).

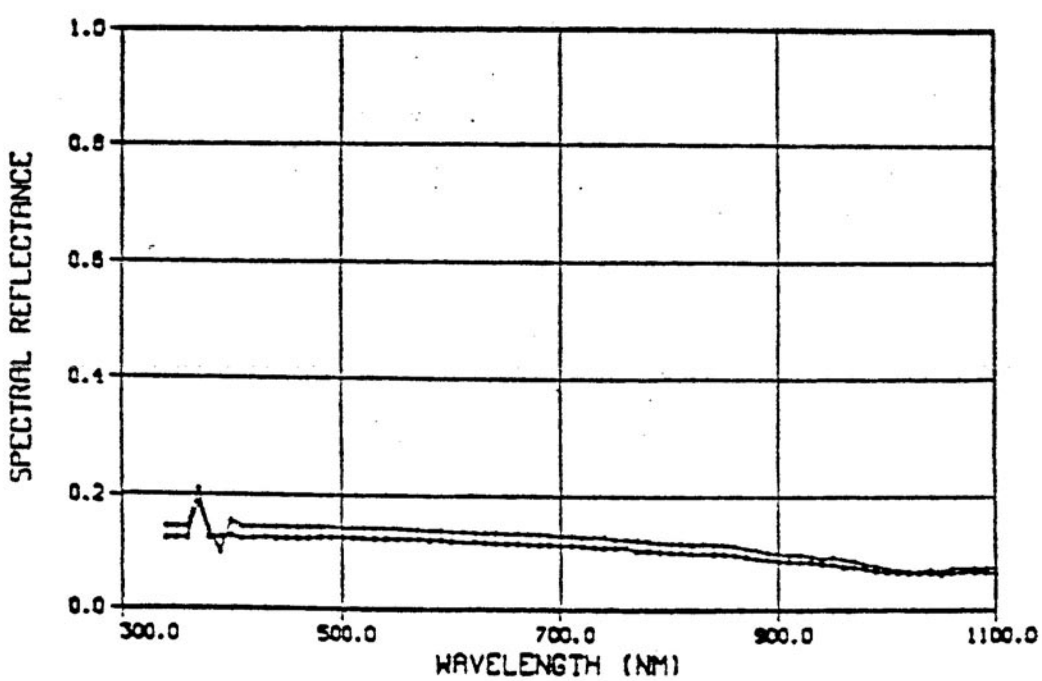

Figure 6. Spectral reflectance of slush curd ice. The upper trace is from a scan over a lighter portion of the ice while the lower trace is from data collected over a darker portion (from Bolsenga, 1981b).

The visual appearance of a slush curd ice surface observed in this study in which the curds were frozen in a matrix of clear ice was highly variable due to the variety in size and concentration of the individual curds. Multiple runs were made at two points to observe an anticipated difference in spectral reflectances over portions of the ice which appeared different. As shown in Figure 6 a small, but easily distinguishable, difference of 2-3% was measured between runs over the “darker” and “lighter” surfaces. It was surprising to the observers that the spectral reflectances did not exhibit a greater difference. Also, the similarity of the curves to clear ice curves is striking.

Brash ice could be described as one of the most visually distinguishable types of ice. It is perhaps a paradox that this ice type has little chance of being ascribed a “characteristic” set of spectral reflectance values. The individual blocks of ice might have been composed originally of clear ice or white ice with spectral reflectances varying accordingly. Final arrangement of the ice fragments after congelation can be either chaotic or preferred. A wide variation of spectral reflectances would thus occur for most brash ice sites on clear or partly cloudy days due to changing solar altitudes interacting with ice-block orientation. Brash ice spectral reflectances are thus not only site specific, but also diurnally dependent. Two brash ice surfaces were measured in this study each exhibiting quite different spectral signatures (Fig. 7).

Transmittance

Information was collected on the transmittance of shortwave radiation in the photosynthetically active range (spectrally integrated, 400-700 nm). Above and below ice radiation were measured using an under-ice boom and commercially available sensors. The measurements were obtained through a variety of natural ice types and under some anthropogenically influenced conditions. The results represent the first such measurements available for Great Lakes ice using quality sensors (Bolsenga, 198la).

As expected, snow cover caused the greatest diminution of radiation. A group of measurements were made from the same bore hole by swinging the support arm under the ice-water interface from a clear ice area to a continuously snow-covered area. The ice thickness was 28. cm and the wind-packed snow was about 3 cm thick. Readings taken under the snow-free ice at three locations showed ratios of transmitted to incident radiation of 0.77, 0.80, and 0.82. When the arm was moved under the snow, the ratios dropped to 0.08 and 0.10. Another example of the influence of snow cover on radiation transmittances is shown in Figure 8. Measurements were taken through 43 cm of ice with a small amount of snow noted on the surface in the morning. All of the snow had melted by 1400 TST accounting for the increase in transmitted radiation.

Some of the measurements in the studies described earlier indicated that the albedo was affected by the solar altitude under certain conditions. The same situation, with values opposite in magnitude, has been observed for the transmittance of white ice surfaces under clear skies (Figure 9), and is a subject for further study as described below.

Future Work

Much additional work is possible on the reflectances and transmittances of snow and ice surfaces. For example, significant diurnal variation of both the reflectances and transmittances of white ice surfaces, occurs under clear skies (Bolsenga, 1977, 1979, 1980). This is due to the fact that the beam radiation component of the shortwave flux decreases with decreasing solar altitude and the diffuse component

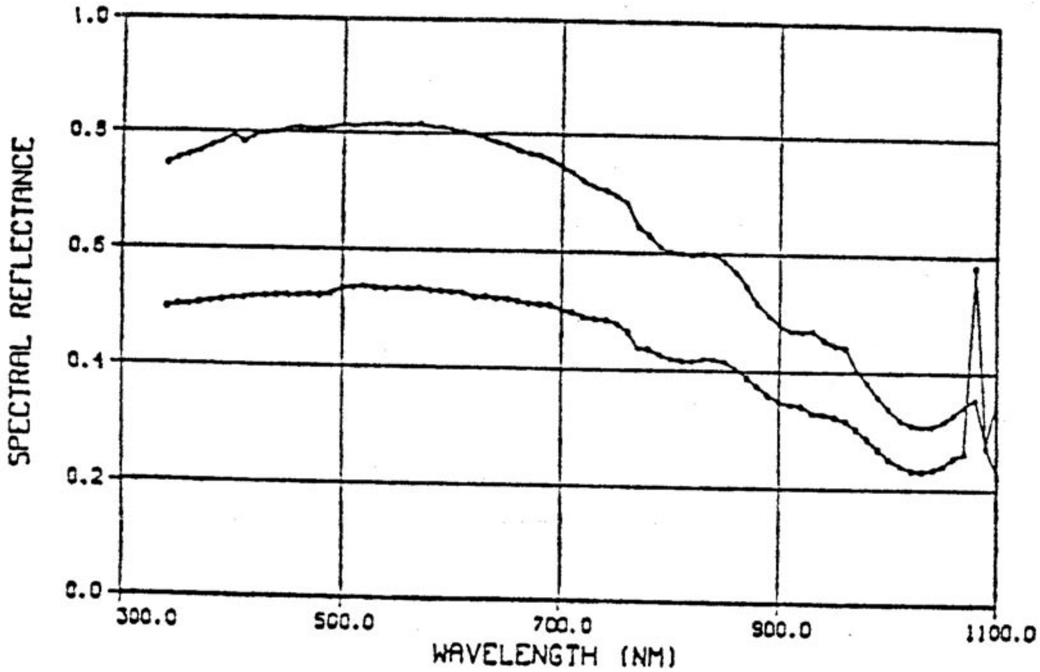

Figure 7. Spectral reflectance of two dissimilar brash ice t ypes (blocks up-thrusted-upper; blocks flat-lower) (from Bolsenga, 1981b).

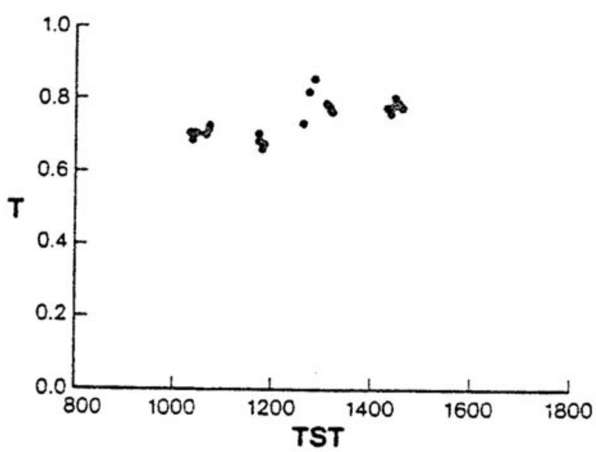

Figure 8. Transmittance (T) as a function of true solar time (TST) during a period of melting s now cover (after Bolsenga, 1981b).

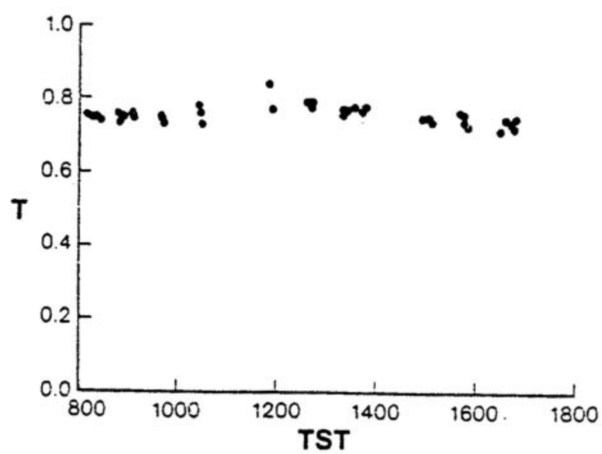

Figure 9. Diurnal dependence of the transmittance of white ice under clear skies (note slight domed-shape of the curve) (after Bolsenga, 1981b).

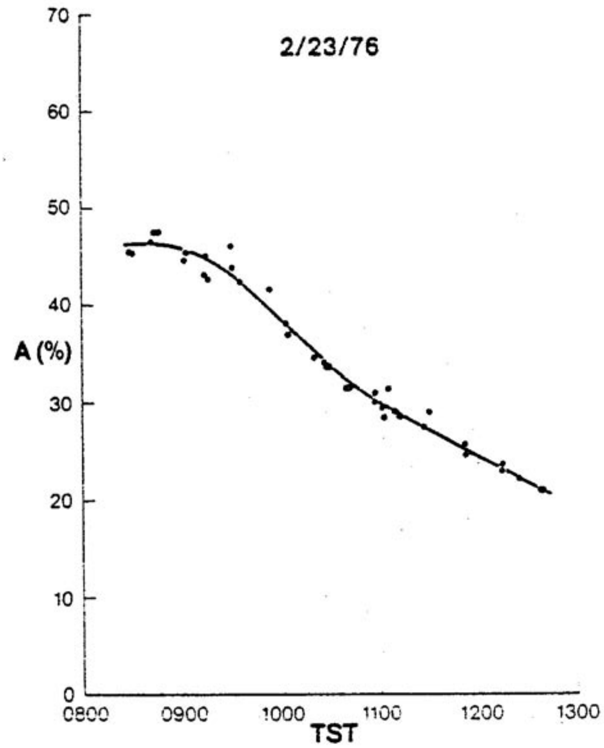

Figure 10. Significant decrease in ice albedo over the period of a day due to melting (after Bolsenga, 1977).

increases. Since the diffuse component is relatively rich in visible radiation and the reflectances of white ice are higher in the visible spectrum than clear ice, the reflectances and transmittances of white ice surfaces vary significantly with solar altitude under clear skies. A similar effect does not occur for white ice under cloudy skies or clear ice under clear or cloudy skies. Clouds can also have a significant effect on the magnitude of the albedo of certain ice and snow surfaces. Clouds convert direct to diffuse radiation altering the spectral distribution of the radiation which causes an increase in the spectrally integrated reflectivity of white ice surfaces. Information is also lacking on the progressive decrease of the albedo under decaying ice conditions (Figure 10).

Compensation intensity refers to the amount of photosynthetically active radiation that is necessary for a plant or animal to live. Models exist to accurately determine the amount of photosynthetically active radiation transmitted through ice and snow surfaces (Bolsenga, 1981a). However, little is known about compensation intensities for many organisms. Additional biological data is sorely needed to provide assessments of the well being of plants and animals in such bodies of water.

Other Work

Experimental work on the spectral reflectances of snow has been conducted by O'Brien (1977) and O'Brien and Munis (1975), Berger (1979), Grenfell et al. (1981), Grenfell and Maykut (1977) and Kasten and Mller (1960). Experimental work on the spectral reflectances of ice has been conducted by Grenfell and Maykut (1977) and Krinov (1947). Theoretical work on snow has been conducted by Warren and Wiscombe (1980), Wiscombe and Warren (1980), and Choudhury (1981).

Experimental work on the transmittance of photosynthetically active radiation through sea ice and snow has been conducted by Grenfell and Maykut (1977), and Maykut Sand Grenfell (1975). Experimental work on the transmittance of freshwater ice has been conducted by Maguire (1975a and b), and Croxton, Thurman and Shiffer (1937).

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1.32 Nearshore Great Lakes Ice Thicknesses and Stratigraphles

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Information on nearshore ice thickness and stratigraphy is necessary to solve a wide variety of engineering problems, such as siting nearshore structures, and in development of ice thickness forecasts. A program designed to collect such data was implemented during the winter of 1965-66 and terminated at the end of the 1978-79 season. The information included the dates of ice formation and breakup, and the type, thickness, and stratigraphic structure of the ice. Observers at about 30 sites on the Great Lakes collected the largest volume of information on nearshore ice thickness available to date.

Site locations normally had stable ice covers throughout the season, were at least 50 meters off-shore, and free from obstructions that might cause unusual snow drifts. Measurements were to be made on a weekly basis. The observer bored a hole in the ice and hooked a folding rule with foot attachment on the bottom of the ice. The total thickness of the ice and the thickness of each distinct layer were recorded by sighting visually through the bore hole. After quality control, the computer data base was archived at the World Data Center for Glaciology in Boulder Colorado. Subsequent analyses will yield a number of reports. To date, the work of Hinkel (1983), and Sleator (1978) are available. The following analysis contains selected information from Assel et al. (1984), Bolsenga et al. (1984), and Greene et al. (1984).

Some interesting statistics, determined by observations from all stations in a lake basin, are apparent. For example, the average date of occurrence of freezeup, was the last week in December for all five of the Great Lakes Lake Erie showed the earliest average date of occurrence of maximum of ice thickness (first week in February) while Lake Superior showed the latest date of occurrence of maximum ice thickness (second week in March). Average maximum ice amounts were 52 to 54 cm for Lakes Huron, Michigan and Superior. Lake Ontario showed an average maximum ice amount of 42 cm, while Lake Erie showed an average maximum ice amount of 33 cm. The second week in March marked the earliest average date of occurrence of breakup (Lake Erie), that date being a full month before the latest average dates of occurrence of breakup for Lakes Superior and Michigan (second week in April).

Ice growth rates were nearly equal for all the Great Lakes at 8-9 mm/day. Ice dissipation rates showed higher values for the upper lakes (14-17 mm/day) and lower values for the lower lakes (11-12 mm/day). Ice cover duration was higher for the upper lakes (105 days). On the lower lakes ice cover duration was over 3 weeks shorter (82 days).

White ice thickness as a percentage of total ice thickness was calculated. Those calculations yielded a fairly predictable pattern whereby Lake Superior showed the highest percentage of white ice to total ice at 23% while Lake Erie white ice was only 7% of the total ice thickness.

The data exhibited a number of crude geographical patterns of ice thickness and white-clear ice stratigraphy. Figure 1 shows a map of the stations used to illustrate these patterns with stations selected on the basis of period-of-record and reliability of data. Two west to east and one north to south transects of station data are shown. In the figures, the envelope curve shows the mean total ice thickness for the period of record and the inner curve shows the mean clear ice thickness for the period of record. Differences between the area under each of those curves indicates the amount of white ice

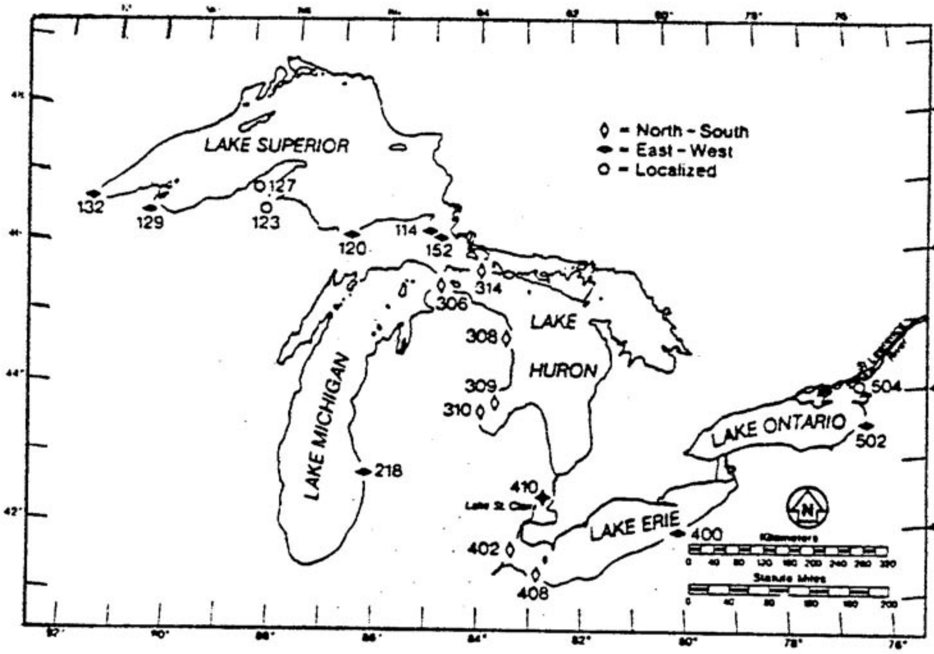

Figure 1. Stations selected from nearshore thickness network for north to south and west to east transects (from Assel et al., 1984).

present. Figure 2 shows a transect from DeTour, Michigan located on the St. Marys River southward to Marblehead, Ohio located on Lake Erie. Both total and white ice amounts decrease from north to south. Local variability is highly evident as indicated by the two Saginaw Bay stations which are located only a few miles from each other. It is important to note that this local variability often obscures even broad geographical patterns and presents a factor that makes it difficult to extrapolate conditions from one station to another. It is significant, however, that additional work on this data base shos promise towards ascribing some order to this often seemingly chaotic variation (Greene et al., 1984).

Figure 3 shows a west to east transect from Muskegon Lake near Lake Michigan to North Pond on Lake Ontario. Only small changes in total ice amounts can be detected between these stations. White ice amounts, however, vary from station to station. It is possible that locations with similar exposures such as Muskegon Lake and North Pond exhibit similar white ice characteristics.

Another west to east transect, across Lake Superior, from Duluth, Michigan to Point Iroquois is presented in Figure 4. Total ice decreases from west to east while white ice increases in the same direction. It is postulated that the high total ice amounts at Duluth and Ashland are due to relatively cool air temperatures caused by extensive land areas on the west and north. The increased white ice from west to east is possibly caused by air masses passing over the often ice-free central portion of Lake Superior which acquire moisture during their movement and later deposit snow on the eastern or southern shores of the lake.

Figures 2 to 4 emphasize the local variability between nearby stations It is felt that these conditions are caused by localized meteorological factors and physical conditions at a particular site. Local variability is further indicated in Figure 5 by differences in total and white amounts at L’Anse Bay and Portage Lake. L’Anse Bay is connected to the main body of Lake Superior. It is often subjected to high winds

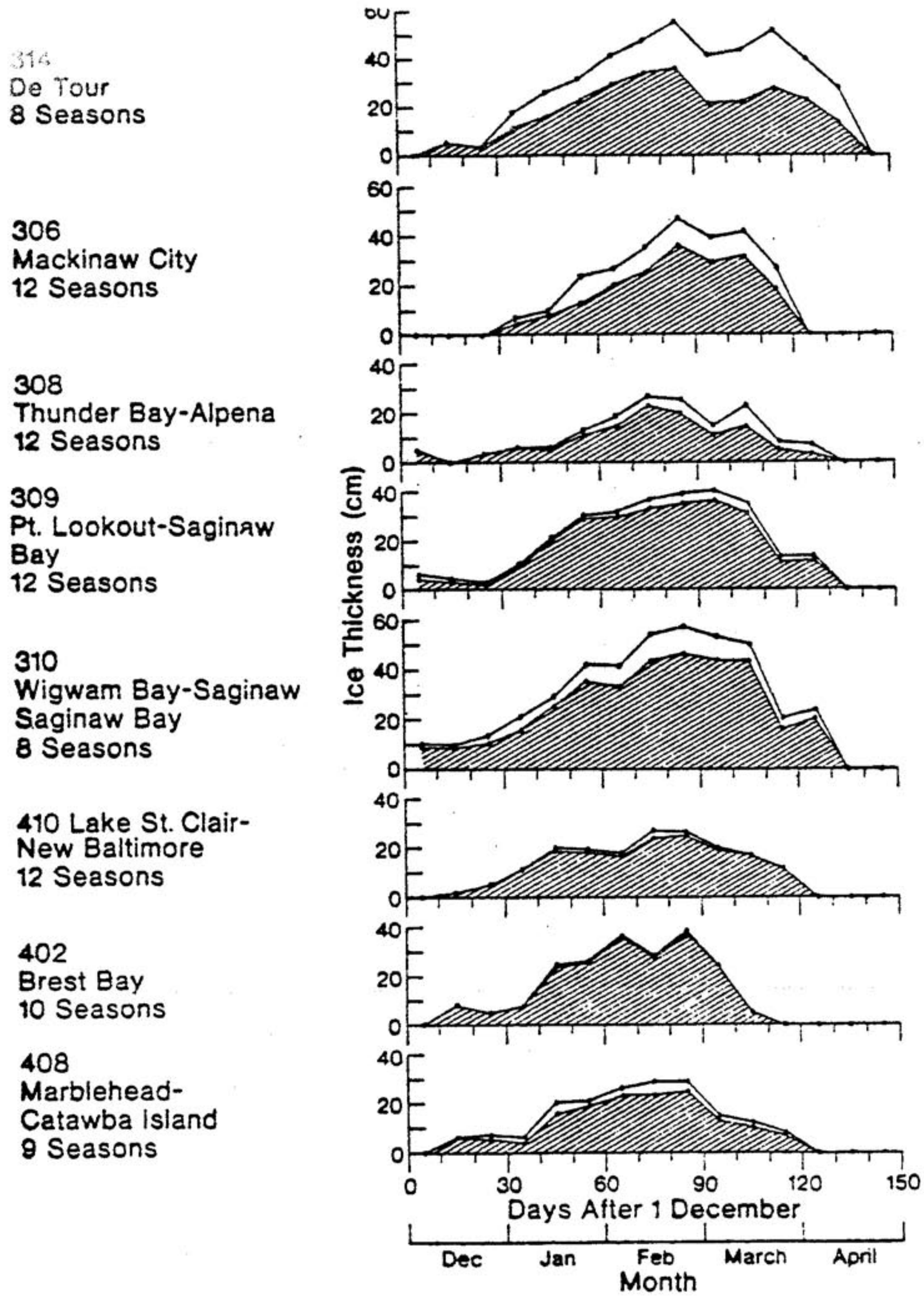

Figure 2. North to south transect of total and clear ice thicknesses for stations at DeTour, Mackinaw City, Thunder Bay-Alpena, Pt. Lookout-Saginaw, Wigwam Bay-Saginaw, Lake St. Clair-New Baltimore, Brest Bay, and Marblehead-Catawba Island (from Assel et al., 1984).

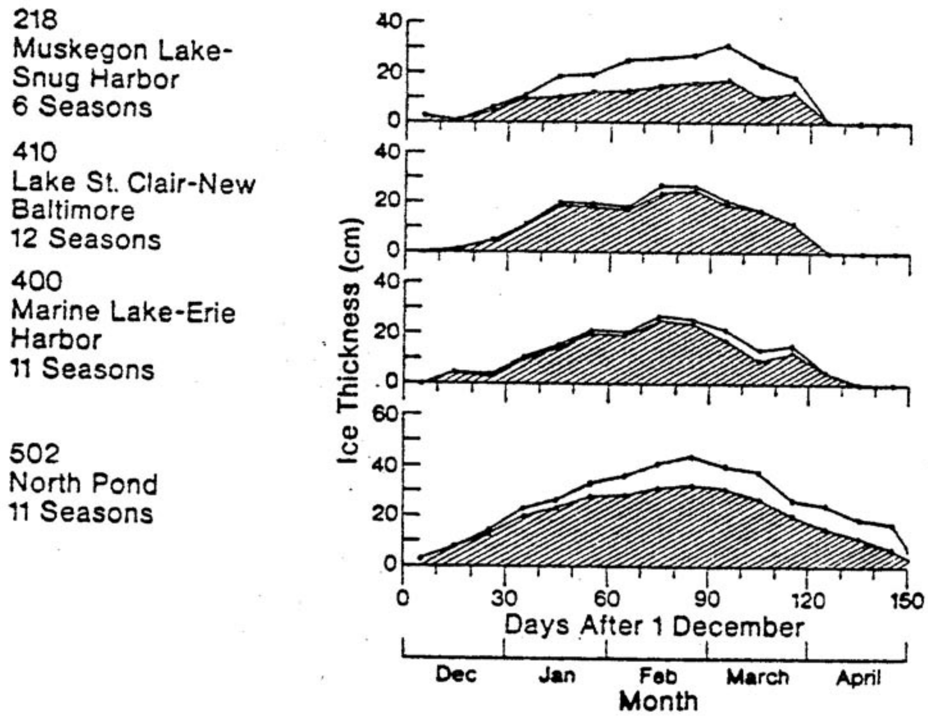

Figure 3. East to west transect of total and clear ice thicknesses for stations at Muskegon Lake-Snug Harbor, Lake St. Clair-New Baltimore, Marine Lake-Erir Harbor, and North Pond (from Assel et al., 1984).

which blow snowfall off the ice surfaces of the bay. Portage Lake is an inland lake surrounded by trees and not subjected to as high winds as L'Anse Bay causing snowfall to accumulate on the ice surface. Yearly total snowfall is 300 cm at L'Anse Bay and 430 cm at Portage Lake. Conditions at Portage Lake are thus conducive to producing large amounts of white ice with the opposite being true at L'Anse Bay. As indicated by the figure, white ice comprises nearly 60% of the ice at Portage Lake and only 16% of the ice at L'Anse Bay.

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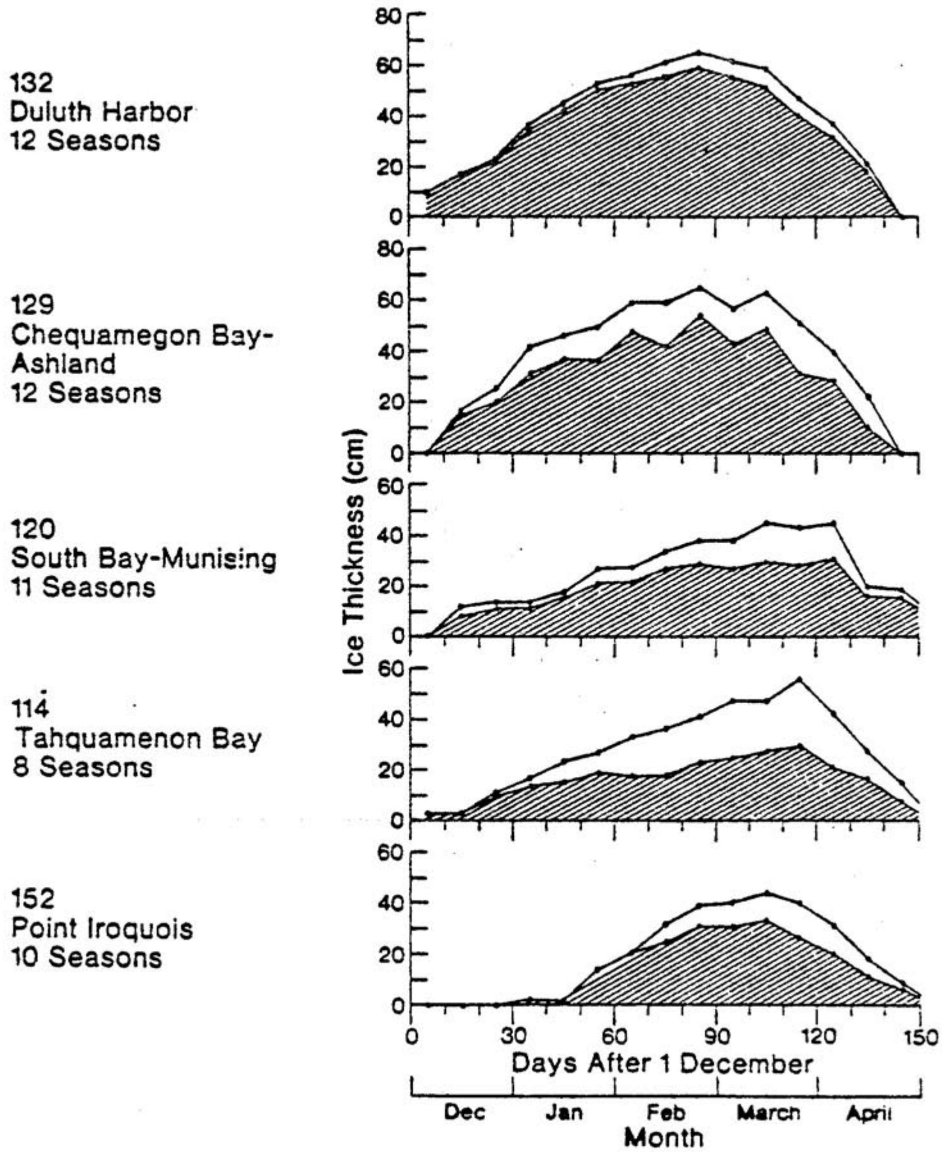

Figure 4. East to west transect of total and clear ice thicknesses for stations at Duluth Harbor, Chequamegon Bay-Ashland, South Bay-Munising, Tahquamenon Bay, and Point Iroquois (from Assel et al., 1984).

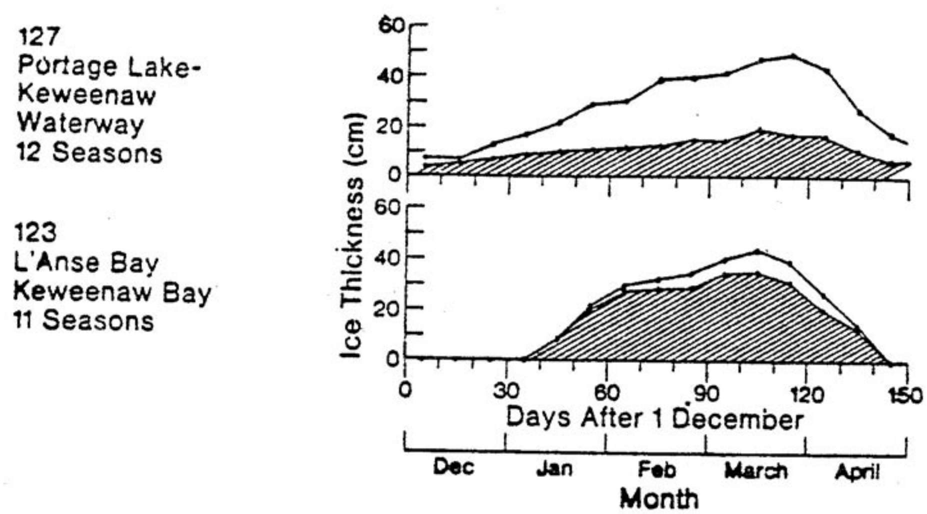

Figure 5. Ice thickness at nearby stations (Portage Lake-Keweenaw Waterway and L'Anse Bay-Keweenaw Bay) shown to illustrate local variability (from Assel et al., 1984).

1.4 ICE DETERIORATION

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Considerable attention has been devoted to the initial formation and thickening of ice covers, while relatively little attention has been devoted to the deterioration and thinning of ice covers. Here, current knowledge of the thinning processes and deterioration processes are reviewed and suggestions made of studies that will bring the understanding of these two processes to a more satisfactory level.

At the outset the thinning process is distinguished from the deterioration process. Thinning refers to the change in the overall dimension of the ice cover while deterioration refers to a breakdown of the internal structural integrity of the ice cover that results from partial internal melting. In the thinning process we are principally concerned with the rate of heat transfer to the boundaries both top and bottom, while in the deterioration process we are principally concerned with internal energy absorption.

THINNING OF ICE COVERS

The thinning process is conceptually straightforward and governed by the energy balance at the boundary where

$$q_e - q_i = p_i \lambda \, dh/dt \qquad (1)$$

where q_e is the net heat flux from outside the ice cover to the boundary surface, q_i is the heat flux into the ice cover, p_i is the ice density, λ is the heat of fusion, and dh/dt is the rate of retreat of the boundary surface.

The difficulty lies in calculating the magnitude of qe. At the top surface the value of q is the net flux associated with the energy budget components of sensible and latent heat fluxes and, long and short wave radiation all of which are highly variable in time, especially on a diurnal time scale. While there are good empirical means of estimating all of the components, the required input data is considerable and often unavailable. As a result, some effort has been made to simply use an air temperature index method to estimate the net flux (Ashton, 1983; Bilello, 1980; Williams, 1965). The increasing use of minicomputers should allow energy budget analyses to be easily made since even use of default values for the necessary parameters provides quite good estimates.

At the bottom surface the heat flux is more or less proportional to the product of the ambient water velocity and its temperature above 0°C. Again, empirical means exist to estimate this heat flux with the difficulty largely lying in the uncertainty of the magnitudes of velocity and water temperatures. One minor complication is that, associated with the turbulent heat flux, the boundary becomes corrugated with waveforms. As an approximation, these waveforms have a wavelength inversely proportional to the velocity and characterized by a wavelength-velocity product UL = 0.12 ms^{-1}.

In the above discussion, little has been said about estimating the internal conductive flux. In general, it is not important during periods of thinning. The exception occurs when warm water is artifically introduced to the water body during periods of cold weather and this warm water suppresses the thickening that would otherwise occur. In most practical cases for which thinning calculations are needed, the internal conductive flux may be adequately estimated by a quasi-steady analysis of the form

$$q_i = k_i \; T_s - T_m / h \tag{2}$$

In eq. (2), T5 is the cold surface temperature, Tm is the melting point, kj is the thermal conductivity and h is the thickness.

DETERIORATION OF ICE COVERS

The deterioration of ice covers refers to the loss of strength of the interior of the ice cover due to partial melting at the grain boundaries. This partial melting is due only to shortwave (solar) radiation absorption internal to the ice cover. Unless there is solar radiation present an ice cover will not deteriorate, and, indeed, an ice cover protected from solar radiation will not exhibit deterioration even when kept for days isothermally at 0°C. Accordingly, to estimate the deterioration we need first, an estimate of the incident solar radiation, then a value of the albedo to determine how much actually penetrates the top surface, then an extinction coefficient to estimate how much of the radiant energy is absorbed and where, and finally a model that relates loss of failure strength to the porosity that results from the melting that is due to the energy absorption. Such a model has been constructed by Bulatov (1970) that used daily calculations to estimate deterioration. Recently Ashton (1983, 1984) devised a similar model that included the interaction of heat conduction with radiation absorption and allows diurnal variation in deterioration to be estimated. Having just constructed such a model, the writer offers the following assessments of needed work to make such a model more reliable or the resulting estimates of deterioration more useful. Incoming Solar Radiation

There are reasonably good empirical means of estimating the incoming solar radiation if the latitude, time of year, time of day, and cloudiness are available. The effect of cloudiness is the greatest uncertainty and limited more by available estimates of the cloud type, height, etc., than by-the available theory. Albedo

The albedo is perhaps the most critical parameter in analysis of deterioration and we are here concerned mostly with the albedo associated with a completely melted snow cover. At this time the ice surface appears grey and splotchy, and puddling may be occurring on the surface. Bolseriga (1969) provides some good measurements of albedo under these conditions but more are needed as well as interpretation that will lead to estimates of albedo by those less experienced. Extinction Coefficients or Adsorption Rates

It is common to see estimates of radiation adsorption in ice presented within the context of the so-called "exponential decay law," that is, in the form

$$I(y) = I_o \, e^{-\beta y} \tag{3}$$

where I(y) is the radiation intensity at depth y, I_o is the radiation intensity just below the top surface, and ß is an adsorption coefficient. Following this approach, values of are commonly preseited and range from about 0.1 m^{-1} to 10^{-1} but implicitly presumed to be constant for any given type of ice. It is now abundantly clear that use of a constant value of is too simplistic. For any given wavelength of the spectrum of solar radiation, a constant value of seems to be the case for a given type of ice. However, since varies with wavelength, the bulk extinction coefficient (applied to the total wavelength content of the solar radiation) ends up having a depth dependence. The USSR experience, as reported by Bulatov (1970) suggests the radiation intensity at depth is of the form

$$I(y) = I_o e^{-2.62\, y0.6} \tag{4}$$

while one case of data reported by Grenfell and Maykut (1977) results in a form described by

$$I(y) = I_o e^{-1.36\, y0.3} \tag{5}$$

while quite similar in form, equations (4) and (5) yield absorption rates differing by as much as 100%. Clearly two efforts are needed; the first is more in situ measurements of actual radiation extinction and the second, more analytical work similar to that of Perovich and Grenfell (1981) in which all the complexities of absorption, scattering, and reflection are addressed. Porosity and Failure Strength

Once the absorption rate at any depth in the ice cover is determined, it is a simple matter to calculate the melt fraction or porosity of the ice cover. It is not so simple to relate this porosity to failure strength reduction both because the actual geometry of the melt inclusions is unclear and because there are few good measurements of the effect of porosity on strength.

There are various models of the melt inclusion geometry. Bulatov (1970) used a cubic-grained model and assumed the melt was uniformly distributed along the grain boundaries. Ashton (1984) used a hexagonal, columnar-grained, model and. similarly distributed the melt uniformly along the grain boundaries but also added the refinement of a finite dihedral angle at the edge of melt. Both models yield similar porosity-strength relationships except having quite different porosity values associated with zero strength. The basic assumption in these models is that the strength is proportional to the uninelted surface area of the faces of the grains. There is little work at a fundamental level to examine this assumption. The writer’s own attempts to examine the geometry of the melt inclusions showed them to be a series of apparently unconnected lens-shaped inclusions distributed over the faces of the grains.. Whatever the case, our understanding is meager.

Attempts to relate melt porosity to failure strength are sparse. Bulatov (1970) reports two studies, one in which small beams were tested after controlled absorption of radiation and one in which field measurements of strength were related to calculated absorption. The data shows large scatter and much more data is needed. The results of the melt geometry models described above seem to provide a bound on the strength reduction with increasing porosity and hence provide a useful conservative basis for practical calculations.

Porosity and Elastic Modulus

There is even more uncertainty regarding the relationship between porosity and reduction in the elastic modulus. For sea ice, Assur (1967) has proposed a linear relationship between reduction in modulus and increasing porosity based mainly on earlier work by Langleben arid Pounder (1963), Tabata (1958), and Abele and Frankenstein (1966). Again, there is little work on which to base firm conclusions.

Load Capacities

Once the profiles of failure stress and elastic modulus have been determined, it is necessary to use this information to calculate load carrying capacities. While not a particularly difficult task, since the applicable principles of mechanics are available, it nevertheless has not been done. A wide variety of loading configurations occur and deserve analysis of the effects of deterioration on the resulting ice cover behavior. Practical Guidelines

All of the above suggestions for research and additional work strike at the details of the process and causes of ice deterioration. While those details can be combined into a simulation that provides much knowledge of what to expect of an element of the ice cover that is subject to deterioration, there is also considerable need to develop simple, practical guidelines. As an example, at a given time of year and latitude, there is a threshold relationship, as yet not well defined, between air temperature, cloudiness, and albedo that bounds the occurrence or non-occurrence of deterioration. Such guidelines are very needed by those that must manage activities associated with the ice cover.

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1.5 ICE PROCESSES IN CONNECTING CHANNELS

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Much of the Great Lakes - St. Lawrence River systems becomes ice covered during the winter months. A better understanding of ice processes will lead to more efficient planning of various activities in connecting channels. In this paper, the present knowledge on ice processes in connecting channels will be discussed and future works will be suggested.

WATER TEMPERATURE DECLINE AND. FREEZE-UP

As a result of the natural cooling process, ice begins to form in a connecting channel when the water temperature reaches 0°C and continues to lose heat to the atmosphere. For the planning of the navigation season and the flow regulation, it is of interest to be able to forecast the freeze-up time. A few freeze-up prediction models have been developed by analyzing the energy budget of the water body (7,16,25). In these models, the air temperature and water temperature are correlated by a simplified form of the convection-diffusion equation for thermal energy. In the Lagrangian form this equation is,

$$\frac{DT_w}{Dt} = -\frac{h_{wa}(T_w - T_a)}{pC_pD} \tag{1}$$

in which, T_w = water temperature, T_a = air temperature; p = water denity; C_p = specific heat of water; D = depth of water body; and h_{wa}= a heat transfer coefficient, which is a function of air temperature, wind velocity, solar radiation, humidity, cloud cover, precipitation, and other factors. Using normal air temperature together with the air temperature forecast and the forecasted flow as inputs, a solution of Eq. 1 can be used to provide good predictions of water temperature decline at a river station until it reaches 0°C.

FRAZIL ICE PRODUCTION

In regions with very low velocity, frazil ice crystals form at the surface of the water. The crystals freeze together and rapidly grow into a thin cover which thickens during the winter. With the generally fast flowing velocity in connecting channels, the turbulent mixing will both supercool the water over the entire depth and entrain frazil crystals deep into the flow to prevent the formation of the thin static ice cover. The turbulent flow could lead to the formation of anchor ice and the flocculation of frazil ice into ice pans or floes. As ice floes grow in size, they will eventually float to the surface to form a moving surface layer of ice floes and slush ice mixture. This moving surface layer may develop into a continuous ice cover initiated by the formation of an ice bridge at a river section or from an artificial obstacle.

In rivers with very fast flow velocity or steep gradient, such as n sections of the St. Clair River and the Niagara River, a natural stable ice cover will not form. Without the existence of an ice cover, the production of frazil ice will continue in order to balance the surface heat loss. The continuous formation of frazil ice and anchor ice in open water reaches of a river could pose problems for wintertime power production (2,12,35).

The production of ice in a reach of a river with open water can be estimated by a heat budget analysis. The ice production rate I in a river reach of length XL can be calculated by the formula (27)

$$I = \frac{1}{p_i L_i}\left(-\Phi_u + \int_o^{X_L} \Phi * dx\right) \tag{2}$$

in which, I = volume rate of ice production in the river reach, ft^3/day; p_i = density of ice; L_i = latent heat of fusion of ice; $\Phi_u = Q_p C_p T_o$ = heat influx through the upstream boundary (x=o) of the reach; o = river discharge; p = density of water; C_p = specific heat of water; T_o = water temperature at the upstream boundary; and $\Phi*$ = net rate of heat loss which contributes to the change of water temperature or the formation and dissipation of frazil ice per unit length of the river. Eq. 2 can be used to calculate the total.rate of ice production in a river reach. To determine the initiation and the rate of progression of an ice cover, the distribution of ice discharge is required. In one-dimensional analysis, the ice discharge, Q_i, can be determined by the relationship $Q_o = C_i Q$. In which, Q = river discharge; C_i = volumetric ice concentration averaged over the river cross section. The longitudinal distribution of ice concentration can be determined by the solution of a convection-diffusion equation equivalent to Eq. 1 (28).

ICE COVER FORMATION

The phenomena of ice bridging is not well understood, even though ice bridges usually forms at the same location of a river each winter. The formation of an ice bridge at a river section is related to the ice transport capacity of the section and the rate of ice discharge coming from upstream. The maximum rate of ice discharge that can pass through a river not forming an ice bridge is dependent on the flow velocity, channel top width between banks or shore ice, surface slope, size and concentration of the ic layer, among other things (1). In the absence of a natural ice bridge, an ice cover can only be initiated at an artificial obstacle such as a dam or an ice boom.

Once an ice cover is initiated, it may progress very quickly upstream through the accumulation of incoming ice floes and slush. By conservation of mass, the rate of progression of an ice cover V_{cp} can be calculated as,

$$V_{cp} = \left(\frac{Q_i - Qu}{1-e}\right) / \left[h_o(1-e_p)B_c\right] \tag{3}$$

in which, Q_u = rate of ice entrained under the cover by flow; h_o = initial cover thickness; e = porosity of individual ice floes; e_p = porosity in the accumulation between ice floes; B_c = width of the newly accumulated cover.

In order for an ice cover to progress, a stability condition for incoming ice floes must be satisfied. The stability of an ice block can be determined by an equilibrium analysis of the arriving ice floe using a “no-spill” condition (3). A simple form of this stability condition is (20,22,23).

$$V_c = F\left(\frac{t_i}{l_i}\right)\sqrt{2g\left(\frac{p-p_1}{p}\right)(1-e)t_i} \tag{4}$$

where V_c critical velocity for underturnirig and submergence; t_i = thickness of the block; $F(t_i/\lambda_j)$ = a form factor which varies between 0.66 and 1.30; l = length of the ice floe. Under the criteria given by Eq. 4, an ice cover of one floe thickness will form by simple juxtaposition. At a higher velocity, ice floes will accumulate at an equilibrium thickness h0 determined by (22,23)

$$\frac{V_c}{\left[2gh_o(1-e_c)\left(1-\frac{p_i}{o}\right)\right]^{1/2}} = \left(1-\frac{h_o}{H}\right) \tag{5}$$

From Eq. 5 one can obtain a maximum critical Froude number for progression at $h_o/H = 0.33$. This critical Froude number is

$$F_{rc} = \frac{V_c}{\sqrt{gH}} = 0.158\sqrt{1-e_c} \tag{6}$$

in which, $e_c = e_p + (1-e_p)e$. Field observations (19) indicated Fre can vary from 0.5 to 09 for different floe and accumulation characteristics. Newly formed ice floes will have higher porosity and, therefore, smaller F_{rc} values.

When the leading edge of the ice cover reaches a section where Frc is exceeded, incoming ice floes will be carried under the ice cover. This process will be discussed later in relation to the formation of hanging dams.

MECHANICAL THICKENING OF ICE COVER

In a wide river the increase in streamwise force may exceed the increase in bank resistance. As the cover progresses upstream, the streamwise force acting on the ice will increase. If the stress in the ice accumulation exceeds its internal strength, the cover will collapse and thicken until an equilibrium thickness is reached (22,23,33). This process of mechanical thickening is commonly known as "shoving". The following equation for the equilibrium thickness h0 can be used to obtain the ice cover thickness h_o

$$\left[f_1 + \frac{p_i}{p}(f_b + f_1)\frac{h_o}{d_w}\right]\frac{V_u^2 B}{8g} = \frac{2\tau_c h_o}{pg} + \mu(1-e_p)\left(1-\frac{p_i}{p}\right)\frac{p_i h_o^2}{p} \tag{7}$$

in which, f_1 = Darcy-Weisback friction factors related to the ice covers and the channel bed, respectively; dw = depth of flow under the ice cover. Bank resistance per unit length of the ice cover is quantified as $\tau_c h_o$ + .uFs, where $\tau_c h_o$ is the cohesive contribution; μFs, is the ice-over-ice friction term; and F_s is the streamwise force per unit width of the cover. The coefficient μ has a value of about 1.28, and $\tau_c h_o$ varies between 75 lb/ft and 91 lb/ft (23).

THERMAL GROWTH AND DECAY OF ICE COVER

Once a stable ice cover is formed, the variation of its thickness is then governed by heat exchange processes between the atmosphere, the ice cover, and the river water. Assuming a linear temperature distribution in the cover, neglecting melting and thickening at the top surface of the ice cover, and the penetration of short-wave radiation. The.rate of change of the ice cover thickness can be obtained (6).

$$p_i L_i \frac{dh}{dt} = \left[(T_m - T_a) / \left(\frac{h}{k_i} + \frac{h_s}{k_s} + \frac{1}{h_{sa}} \right) \right] - h_{wi} (T_w - T_m) \tag{8}$$

in which, t = time variable; T_a = air temperature; T_w = water temperature; T_m = temperature at the ice-water interface (0 °C); k_1 thermal conductivity of the snow, typically 0.3 Wm^{-1} $°C^{-1}$; h = ice cover thickness; h_s = snow cover thickness; h^{sa} = heat transfer coefficient at the snow-air interface, approximately 20 Wm^{-2} $°C^{-1}$; and h_{wi} = heat transfer coefficient at the ice-water interface, 1622 Vw,°.8 ;u2 q2 oc_l Further simplification of Eq. 8 will lead to an empirical degree-day model (31).

$$h = \left(h_o^2 + \alpha s \right)^{1/2} - \beta D^{\theta} \tag{9}$$

in which, D = number of days since the formation of the ice cover, S = cumulative degree-days of freezing since the formation of the ice cover; a = an empirical coefficient which is a constant during the growth period and decreases linearly with the air temperature during the decay period; and O = empirical constants which account for the suppression effect of the turbulent heat flux from the river water. The value of 0 is approximately 1.0.

Detailed numerical models for thermal-ice conditions in connecting channels have been developed (15,28). Although these models provide acceptable simulation results, further studies are needed in order to better quantify heat exchanges at the air-ice or the air-snow interfaces.

UNDER COVER TRANSPORT AND HANGING ICE DAMS

Any ice floe or frazil ice that are swept under the cover will be transported or deposited on the underside of the ice cover. A large accumulation of such an ice mass is commonly known as a hanging dam. According to their formation processes, hanging dams may be classified into two categories. The first type of hanging dams, which will be referred to as fragment ice hanging dams, are accumulations of large ice plates or frazil ice pans. These dams are formed near the leading edge of an ice cover, usually during its upstream progression.

There are two basic mechanisms by which fragment ice hanging dams are formed. In the first mechanism, ice floes which are released from upstream, reach the leading edge of the downstream ice cover and are submerged, transported, and then arrested at some point beneath the cover. These floes can then accumulate until a dam is formed. In the second mechanism, the external forces acting on an ice cover exceed its strength, causing the ice cover to collapse upon itself and subsequently thicken. These mechanisms can occur either at the beginning of the winter during the formation of the new ice cover or during the spring break-up period when ice floes are generated. Little is known about the mechanism of the under cover transport and accumulation of ice floes. Using the laboratory data by Filippov (14). Ashton (4) obtained empirical relationships for under cover travel distance of ice floes. Tatinclaux and Gogus (32) studied the re-entrainment criteria of an ice floe resting under the ice cover behind an artificial obstacle of height d. They found that the critical Froude number for entrainment can be expressed in terms of the ratio ti/j and size of the obstacle 5

$$F_e \frac{V_e}{\sqrt{g\frac{\Delta p}{p}t_1}} = \left[C_1\left(\frac{t_1}{\ell_1}\right)^2 + C_2\left(\frac{t_1}{\ell_1}\right) + C_3\right]^{-1/2} \tag{10}$$

where Ve = velocity under the cover; and C1, C2, and C3 = coefficients which are dependent on the size of the obstacle. These theories are applicable to a flat ice cover. Further study on the under cover transport related to the hanging dam formation is needed.

The second type of hanging dams, which will be referred to as frazil ice hanging dams, are formed by the deposition of suspended frazil ice particles on the underside of a stable ice cover. A numerical model for simulating the transport and deposition of frazil ice suspensions has been developed by Halabi, et al. (17). The rate of deposition was found to be dependent upon the buoyant velocity and the activness of the frazil ice. Neither the buoyant characteristics no the adhesive properties of frazil ice particles are well understood however.

For a fragment ice dam, which is located near the leading edge of an ice cover, and is formed at the beginning of the ice covered season, a relatively soft outer layer of frazil slush could form on the surface of the fragment ice dam due to the accumulation of active frazil ice particles produced in the open water area during the winter. Such hanging dams have been found in the St. Lawrence River (29).

With the lack of understanding of the detail mechanics of undercover transport and hanging dam formation, a simple critical velocity criteria has been used to determine the location and size of hanging dams. Michel and Drouin (21) suggested that the critical velocity for ice deposition ranges between 0.6 and 1.3 rn/sec. Shen, et al. (29) found that this critical velocity is about 3 ft/sec in the upper St. Lawrence River.

A field study was made of a hanging dam near Sparrowhawk Point in the St. Lawrence River by Shen, et al. (29). Major conclusions found in this study are: a) the channel bottom topography may be used to provide a convenient guide for determining the location where a hanging darn will form beneath the ice cover in the study reach; b) the shape of a hanging dam is affected by the pattern of river currents;' c) the critical Froude number for the progression of the ice cover and the critical velocity of deposit of ice particles underneath the darn in the study reach are approximately 0.06 and 3 fps, respectively; d) the ice surface roughness at the upstream side of the hanging darn is smaller than that of the downstream side; e) the gross hydraulic resistance of the hanging dam remains relatively constant during the winter even though it is slightly affected by the air temperature; f) the size and shape of the hanging dam varies continuously with time.

BREAKUP PROCESS

The breakup of a river ice cover usually occurs as the result of the melting of the ice cover which reduces its thickness and strength. The mechanical destruction of the ice cover then often occurs due to such factors as the rise in river stage, increase inflow velocity, and in some cases wind action. With the arriving of warm lake water from upstream, ice covers in connecting channels often disintegrate in place when there is no significant rise in stage during the breakup period. This type of breakup will have little damaging effect. Existing numerical models for river thermal-ice conditions (5,28) can be used to simulate the ice cover recession under the effect of warm water. Semi-empirical models have been developed to predict the date of ice free in the St. Lawrence River (31) and the St. Mary's River (16).

Ice covers can breakup prematurely due to the rise in stage and increase in flow velocity. This type of breakup can cause major problems such as ice jams. It is generally known that the river stage has to rise above the maximum stable freeze-up stage, F'• in order to initiate the breakup. The principal forces that are responsible for the stresses that lead to the breakup are the streamwise component of the flow drag on the underside of the cover and the weight component of the cover. At the present time, no method exists for determining the mechanical breakup of a river ice cover. Beltaos (9) developed a conceptual model, and has show the existence of a dimensionless relationship for the flow depth '!B at which breakup will initiate.

The understanding of the breakup process has important implications in the flow regulation in connecting channels. Further studies on effects of various flow and channel parameters on the breakup process are needed.

HYDRAULICS OF RIVERS WITH ICE

The flow condition in a river not only influences but also interacts with all ice processes. Stage and discharge conditions in a river with a floating ice cover can be described by the continuity and the momentum equations (37). To solve those equations for the dischargeQ and the water level H, it is necessary to know the geometry of the cover and the additional resistance induced by the ice cover. The estimation of the ice cover geometry including its thickness and areal extent can be obtained from information discussed in previous sections. The resistance term in the momentum equation can be expressed in terms of the commonly used Manning's coefficients (37).

It is known that the roughness coefficient of the underside of the ice cover varies over a wide range throughout the winter. Shen and Yapa (30,36,37) developed a simulation model for the time-dependent .variation of in the St. Lawrence River. Using this model along with the degree-day model for ice cover thickness, Eq. 11, Yapa (37) has developed an unsteady flow model for the St. Lawrence River.

In the hydraulic resistance simulation model, Shen and Yapa (30,36,37) considered the Manning's coefficient of the ice cover n1, which includes the effect of large accumulations such as hanging dams, as a combination of three components, i.e., n = nd + + ±1. The first component, nd, is a simple function of time which increases monotonically during the freeze-up period and decreases monotonically during the rest of the stabled ice-covered period. The increase in flj during the decay period of the ice season is represented by the component nt in the simulation model. This component is assumed to be a linear function of time. The fluctuating component ñ is considered to be governed by the transport and deposition in frazil ice.

ICE CONTROL

For rivers developed for hydropower and navigation, various ice control measures can often alleviate difficult problems (10,34). In river reaches where a stable natural ice cover can not form, floating ice booms may be installed to minimize the open water area and to stabilize the ice cover. Massive ice movement and ensuing ice jams can then be prevented. For rivers with large velocities, there is no possibility of forming an ice cover. Other measures, such as diversion channels and dredging may be used to avoid the development of large ice discharges in the river. In connecting channels the massive runs of ice from lakes to the channel can lead to severe ice jams. Installation of booms at the lake outlet can effectively reduce the severity of the problem (11,26).

For channels used for winter navigation, ice booms with navigation openings have been installed to effectively minimize the downstream ice release during ship passages (13,24). Another problem encountered in winter navigation is the entrainment of brash ice into a navigational lock either by flow or by a vessel. The ice brought into the lock hinders gate operations, sticks to lock walls and freezes to gates. Some success has been reported by using an air screen placed across the lock entrance to minimize the amount of ice entering the lock (18).

SUMMARY

A review of the ice processes in Great Lakes connecting channels is provided. Considerable progress has been made in the understanding of this subject during the last decade. Much research remains to be done on problems such as the formation of share ice, the initial bridging, the undercover transport, hanging ice dams and its hydraulic effect, mechanics of ice cover breakup, and energy exchange processes through a river ice cover. A systematic well-coordinated program of field data collection is an important element for successful future progress. A mathematical model capable of simulating complete ice-hydraulic processes needs to be developed. This model will be a useful tool for the planning of river ice management. The development of such a model will also guide the design of effective field programs.

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1.6 ICE TRANSPORT MODELING*

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The rate of movement, deformation, and localized accumulation of ice in natural waterbodies depends on external factors, such as wind and water currents, and on the internal strength of the ice medium. The internal strength of the ice medium is, n turn, intimately related to its historical evolution and its present material state. The configuration of the shoreline and the bathymetry of the waterbody may also play an important role.

There are basically two methodological approaches that can be followed in an attempt to forecast ice conditions. One i'nvolves extrapolation forward in time based on the previously observed behavior of the ice medium in response to observed environmental factors, preferably over a period f many years. The other involves the mathematical representation of the processes that govern the behavior of the ice medium for use in the construction of a simulation model based on the conservation laws of physics. This brief paper will elaborate on th latter approach; however, it will become evident that model application will depend on previously observed behavior of the ice medium in considerably greater detail than is normally associated with the first approach.

The material state of an ice medium is time dependent. This is to say that the internal strength of an ice médiumdepends on its age, thickness, temperature, and its state of fragmentation and deformation. The analysis of the dynamic behavior of a discrete isolated ice fragment (floeYcan proceed without attention to most of these time-dependent factors. However, the analysis of the dynamic behavior of an ice field compoˆed of many fragments of varying sizes will involve the complexity of attempting to address the time-dependence of the internal strength of the ice medium. This complexity is a paramount consideration in the development of an ice dynamic simulation model.

A second, and almost equally important consideration, deals with the conceptualization of the ice medium as a continuum. This enables the ice system properties to be assumed -to vary continuously and smoothly over space and time. The employment of the continuum approximation imposes limits on the scale resolution of an ice dynamics model. It mathematically replaces the real discontinuous ice syste with a fictitious' continuum. However, the continuum approximation has been applied to many systems (solid and fluid) which are also discontinuous at small scales. The condition (or state) of the ice medium will largely dictate the scale resolution of the fictitious' or macroscopic continuum and, since the ice state is time dependent, the validity of the continuum approximation must always be questioned. The employment of the continuum approximation entails sacrifices which must be judged in view of the modeling objectives. The description of the ice dynamics simulation model that follows is based on the continuum approximation.

REPRESENTATIVE ELEMENTAL AREA

The elemental area for the continuum approximation is depicted in Figure 1. The appropriate size for this representative elemental area depends on the average size of the ice fragments that comprise the ice medium. Since the ice fragment size can vary over space and time and since the desired resolution may vary also, there is considerable latitude in the specification of the representative elemental area size. The

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solution to the ice dynamics problem will almost always involve the discretization of the formulated governing equations and selection of a numerical method for computing the approximate values of the system properties. The size of the grid or mesh used in this discretization is almost synonymous with the specificaton of the appropriate size of the representative elemental area (neglecting computer storage and processing time limitations).

A macroscopic point in the ‘fictitious’ ice continuum resolves to the dimensions of the representative elemental area. The continuously varying properties of this continuum are assumed to be given by the average values of the real discontinuous ice system contained within the representative elemental area. Thus, the ice area concentration or compactness, N, is given by N = Aj/AT where A is the area of ice contained within the representative elemental area and AT is the total area of the element. The continuum ice thickness, ti, is related to the real ice thickness distribution within the element according to, ti = tftj(real)dAj]/Ai. The continuum ice mass per unit surface area, Mj, is given by M1 = ..PitjN. The ice velocity, V1. is the average velocity of all the fragments contained within the representative elemental area. This conceptualization of the ice medium as a ‘macroscopic’ continuum permits the application of the calculus and the formulation of governing differential eqqations for the dynamic behavior of the ‘fictitious’ ice continuum.

MATHEMATICAL REPRESENTATION OF EXTERNAL FORCES

Wind Drag

The specification of wind speed and direction is generally based on the adjustment of over-land measurements to over-lake estimates and interpolation between shoreline observation points using some appropriate weighting scheme. In this manner, a continuously varying wind field can be obtained. There are uncertainties inherent in this approach that deserve continued study. One involves the adjustment of measurements, each of which are made at different altitudes at-widely different geographical locations, so that the obtained over-ice wind field pertains to a constant specified elevation above the ice surface.

The drag exerted by the wind at the air-ice interface depends not only on the wind speed but also on the roughness of the ice surface, the atmospheric stability, and the presence of loose snow n the ice surface. This drag is usually expressed as a tangential stress, ra, given by

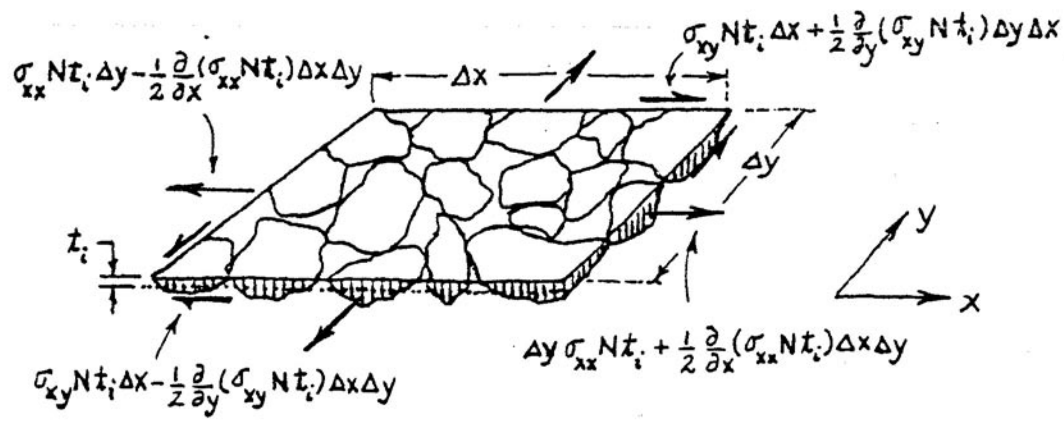

Figure 1. Schematic Sketch of Representative Elemental Area

$$\bar{\tau} = C_a(10)\rho_a \bar{V}_a|\bar{V}_a| \tag{1}$$

in which the resistance coefficient, CA(l0), is calculated on the basis of the wind speed, V, being measured 10 m above the ice surface. The air density is given by Pa. The presence of ice ridges can significantly increase the form drag of the ice surface. This additional form drag will depend on the ridge heights, ridge geometries,and ridge densities; i.e., number of ridges in the elemental area. A review of the available data (Wu and -Tang, 1979) indicated that, for a fully-developed boundary layer flow over ice, the value of Ca(10) varied by less than' a factor of two when comparing smooth ice without ridges to rough ice with ridge formation. A recommended value for Ca(10) was given as 0.0015.

When the ice area concentration is less than one and open water surface is present along with ice in the elemental area, the situation is modified. This situation has not been extensively studied and little information is available on the expected changes in the magnitude of Ca(lO).

Water Drag

Normally, measurements of the speed and direction of water currents are not available and the specification of the water velocity field may be subject to considerable error. The hydrodynamic behavior of an ice-covered waterbody is, in a sense, the inverse of the problem of describing the dynamic behavior of an ice field floating on a natural waterbody. In fact, these are coupled problems. In general, it is impractical to address this as a coupled system. Various simplifications can be made depending upon the specific circumstances and the information sought. If the emphasis is on the hydrodynamics, he ice cover may be treated as a rigid lid (Sheng and Lick, 1973). In the present case, the emphasis is on ice dynamics and the water velocity may be reasonably assumed to be zero for fully ice-covered waterbodies. For partially ice covered waterbodies, the wind-driven water currents may be important. An estimate of the wind-driven current may be obtained by equating the shear stress at the air-water interface, giving:

$$|\bar{V}_w| = 0.03[(1-N)]^{1/2}|\bar{V}_a| \tag{2}$$

In equation (2), the resistance coefficients for air and water have been assumed equal in the valuation of the respective shear stresses. Also, the quantity [?a/J) w]2 is given approximately as 0.03. The area of open water per unit surface area of the waterbody is given by (1-N). The direction of the water current in this case needs to be adjusted for the Conchs effect. Here again, a first approximation may be obtained by directingVIat 450 to the right of the interpolated wind direction.

The water drag on the ice underside is expressed similar to the wind drag as,

$$\bar{\tau}_w = C_w(1)\rho_w|\bar{V}_w - \bar{V}_i|(\bar{V}_w - \bar{V}_i) \tag{3}$$

in which the resistance C(1) is evaluated on the basis of the water velocity being specified 1 m below the ice surface. Here again, the roughness of the ice underside is important and the keels of ice ridges may have a pronounced effect on the total drag force exertd. The velocity of the water, V relative to the velocity of the ice, Vi, must be used in calculating t'e water drag. The magnitude of Cw(l) has been found to vary by almost one order of magnitude, in contrast to Ca(lO), which changed only by a factor of two (Wu and Tang, 1979). A recommended value of C(l) = 0.0093 is given as representative of average conditions. It is apparent that the estimate of the water drag has more uncertainty than the estimate of the wind drag.

Gravitational Force

The displacement of the water surface from mean water level and the resulting water surface tilt imposes a gravitational (or body) force on the floating ice medium. This force may be neglected in the analysis of ice dynamics in large lakes, especially when they are completely ice-covered. However, it may be important under certain circumstances; e.g., ice transport by water waves. This gravitational force may be expressed as a force per unit mass contained within the elemental area as,

$$\vec{G} = -M_i g \vec{\Delta} H \tag{4}$$

where H is the elevation of the water surface above some reference datum.

MATHEMATICAL REPRESENTATION OF INTERNAL ICE STRENGTH

The internal resistance of the ice continuum can be written in terms of the normal and tangential stresses acting at the boundaries of the representative elemental area (see Figure 1). The internal ice resistance force per unit surface area can be written as,

$$\vec{R} = \vec{i}\left[\partial/\partial x(\sigma_{xx} M_i) + \partial/\partial y(\sigma_{xy} M_i)\right] + \vec{j}\left[\partial/\partial x(\sigma_{yx} M_i) + \partial/\partial y(\sigma_{yy} M_i)\right] \tag{5}$$

Perhaps the most uncertainty in modeling the dynamic behavior of a fragmented ice field, in addition to the employment of the continuum approximation, deals with the Specification of the internal strength of the ice continuum. Two rheological models have been proposed as the basis for the constitutive law relating internal ice strength to the rates of deformation of the ice medium. Coon et al (1974) and Rothrock (1975) have elaborated on the elastic-plastic model while Hibler (1977) has contended that if time and/or length scales are chosen large enough, then stochastic variations in the deformation rates can cause the average stress-strain rate behavior at these scales to take on viscous characteristics, even though the nonaveraged behavior is plastic in character. He has shown that a two-dimensional plastic model with an elliptical yield curve, when stochastically averaged, takes the form of a viscous law for a compressible medium with a pressure term. A rule describing the plastic flow of the ice medium must be included in order to complete the formulation of the viscous-plastic constitutive law (Hibler, 1977). An extensive discussion of these proposed constitutive laws can be found in Rumer et al (1980).

GOVERNING EQUATIONS FOR THE ICE CONTINUUM

Equation of Motion

The equation of motion is obtained by considering the force balance on the representative elemental area shown in Figure 1. This equation can be expressed symbolically as

$$M_i d\vec{V}_i / dt = \vec{\tau}_a N + \vec{\tau}_w N + \vec{R} + \vec{G} + \vec{C} \tag{6}$$

in which C =-fM(k x Vi), the Coriolis force. The Coriolis parameter is given by f = 2d2isin , where d2 is the angular ‘velocity of the earths rotation and is the geographical latitude of the ice field. The other terms have been defined in the preceding discussion.

Conservation of Ice Mass Equation

This equation is derived by considering the net flux of ice mass transport into and out of the representative elemental area and the time rate of change of ice mass within the elemental area. It is given as,

$$\partial M_i / \partial t + M_i \vec{\Delta} \cdot \vec{V}_i = E_m \tag{7}$$

Em denotes the rate of ice mass change within the elemental area due to thermodynamic processes. Space does not permit elaboration on the specification of Em.
Conservation of Ice Area Equation

This equation is derived by considering the net flux of ice area transport into and out of the elemental area and the time rate of change of ice area within the elemental area. It can be written as,

$$\partial N / \partial t + N_i \vec{\Delta} \cdot \vec{V}_i = E_a - R_a \tag{8}$$

Ea represents the rate of ice area change due to thermodynamic processes and Ra denotes the rate of ice area change due to mechanical thickening processes (rafting and ridging).

Conservation of Ice Thickness Equation

This equation can be obtained by combining equations (7) and (8), giving,

$$\partial t_i / \partial t + \vec{V}_i \cdot \vec{\nabla} t_i = E_m / (\rho_i N) - (t_i E_a) / N + (t_i R_a) / N \tag{9}$$

This equation states that the ocal time rate of change of ice thickness within the elemental area results from (1) advection of thinner or thicker ice into and out of the elemental area, (2) the rate of change of the average ice thickness due to melting or freezi’ng, (3) the rate of change due to production of new ice in open water areas contained with the elemental area or melting away of thin ice, and (4) the rate of change of the average ice thickness due to mechanical ice thickening processes.

SOLUTION TO THE GOVERNING EQUATIONS

By defining appropriate initial and boundary conditions, discretizing the governing equations for numerical computation, and selection of an efficient numerical scheme, the governing equations can be solved for the dependent variables, V1, N, t1, and the internal ice pressure, p, assuming Hibler’s viscous-plastic constitutive law has been adopted to represent the internal ice strength. Suitable values for all model constants must be assigned and the model is generally calibrated by adjusting the magnitude of the ice viscosities contained in Hiblers constitutive law and the thermodynamic parameters, Em and Ea, so that the observed behavior of the real ice field agrees with the computed model behavior. Examples of model application can be found in Runier et al (1981), Wake and Rumer (1981), and Chieh et al (1983).

SUMMARY

If the ice medium is viewed conceptually as a continuum and the governing equations formulated accordingly, the principal avenue for calibration of a numerical model is through adjustment of the model coefficients employed in the consttutive law relating internal ice strength to ice movement. The thermodynamic constants must also be adjusted if freezing or melting is important over the simulation period. Perplexing aspects of this modeling approach include the obvious limitations of the continuum approximation cornbined with problems in scale resolution, and the specification of an equation of state for the ice medium relating ice pressure to the ice condition when the viscous-plastic constitutive law is adopted to represent the internal strength of the ice medium.

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2. WORKSHOP SUBCOMMITTEE MEETING REPORTS

SUB-COMMITTEE REPORT

Summary of the Discussion on

2.1 Ice Characteristics

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This subcommittee met to discuss both current research on fresh water ice characteristics and the direction of future research. The group was composed of both researchers and users of ice research, making it important to see how each group defined an ice characteristic. To a researcher, an ice characteristic is that properties (e.g. speëtral reflectance or thermal conductivity) that help quantify the degree to which a physical process affects an ice sheet. To civil engineer or weather forecaster, however, an ice characteristic may be an abstraction of a whole suite of processes which a primary researcher might hesitate to lump together. An example would be the factor which determines to what extent ice growth for a given site is approximated by the abstract Stefan relation between ice thickness and air temperatures.

For both researchers and users our way of looking for significant characteristics was to answer the question - at what points in your simulation models, equations or procedures did you have to assume some value, wishing that you had better information? Our discussion is summarized by looking at four general classes of existing models.

Models of Ice Growth and Decay

Existing models of thermal growth and decay perform reasonably, not so much because of their sophistication as because there seem to be many compensating factors. For example, empirically, we can estimate the thermal conductivity of ice as a function of ice density. This variation is less significant in determining growth rates, however, than is the thickness and density of the snow cover. When there is no snow cover, the ice surface temperature is most influence by variation in the albedo and in the aerodynamic roughness coefficient. These characteristics have less influence on overall growth then they do ice deterioration and movement, respectively.

Model of Ice Dynamics in Channels

With these models, the transfer of heat and momentum at the lower surface are the critical processes. The critical characteristic is the roughness coefficient. Shen’s paper describes various method of assigning a value, but all are dependent on either flow stage models or profiles of water temperature and velocity. A further difficulty is that the value does not remain constant over a given winter season.

A second problem area is the properties of frazil ice, critical both during the ice cover formation and in the formation of hanging dams. There is little data on either the buoyant velocity of frazil particles or the factors influencing frazil “activeness” (stickiness).

Models of Ice Deterioration

In these models there are a number of unknowns that are only roughly approximated. Both surface reflectance and the extinction coefficient for incident solar radiation are constant for a given wavelength and ice type. For modeling purposes, however, it is simpler to work with bulk values. Unfortunately, these bulk values are not constants. Surface albedo changes with the sun angle and atmospheric conditions. The extinction coefficient changes with depth in the ice layer.

The second problem comes in simulating the mechanical weakening of the ice layer as the bonds between ice crystals weaken. In order to develop simple models of strength, we need to have values for both the elastic modulus and failure strength as functions of ice porosity.

Models of Ice Transport

In understanding lake-wide ice sheet dynamics, the overwhelming need is to be able to describe the time dependence of the internal strength. Unlike ice deterioration, concern is less with the properties of a small area of rigid ice than with the bulk properties of an area than contains both ice and open water. Thus, strain rates of ice layers covering a range of areas are needed.

Most work on air-ice drag coefficients have been done in the Arctic and vary by orders of magnitude. We need values applicable to the Great Lakes, not so much because of different ice types but because the pattern and magnitude of ice ridging is not comparable to the Arctic. Likewise, estimates of under ice drag coefficients can vary by a factor of ten, presumably because of the influence of keels beneath the ice.

Users of ice information ask awkward questions that the above models cannot always answer. For example: is this particular stretch

of ice likely to develop a lead within the next twenty four hours? In general, they need to know if ice is present, how thick it is, and what is likely to happen over the next 1-7 days. Remotely sensed data (either visual or radar) can detect presence but provides little information on ice condition, making forecasting difficult.

Even when the condition of the ice sheet is known, stating what may happen is difficult because ice strength as a function of ice conditions is not well understood.. Users such as design engineers would settle for estimates of maximum and minimum values but these are rarely available for the complex conditions found in mid-lake or shore line areas.

SUB-COMMITTEE REPORT

Summary of the Discussion on

2.2 Ice Transport Modeling and the Modeling of Ice Characteristics

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Summary

We examined several topics related to the modeling of ice transport processes and measurements of ice characteristics. In particular we discussed: a) the current state of research, b) areas for future research and priorities for tasks, and C) the information needs of user groups. Examination of these topics involved discussion of several ice models including examples used for the Great Lakes. We also discussed the need for a comprehensive data set to be collected for a Great Lakes Ice system, and how the data could be supplied by an intensive "field' season. Finally, we developed ideas for.-future cooperation between researchers and users of ice information in U.S. and Canadian agencies, universities, and industry.

Modeling

With regard to ice transport modeling, we examined models that currently supply detail on Great Lake ice processes. An example would be Ralph Rumor's model of deterioration or decay of ice at the end of the season. Another interesting example is Shen's model of hanging ice dams. We feel comfortable with these models and some other examples. Hence, the current need is for further testing of these models.

A basic interest is a comprehensive verification of the ice dynamics model that Ralph Rumor developed. Researchers at GLERL have been running the model for the last year and developed an understanding 0-f it. They've come to the conclusion that it works well mathematically. However, there needs, to be a detailed verification of the model which has not been possible due to data limitations.

We examined several other ice transport models that are available and of value to us. In particular, marine programs of research can potentially provide answers to problems in gathering and analyzing data from Great Lake systems. An example is the winter navigation program conducted by the Swedes in the Baltic Sea. The Swedes have experienced various problems, solved many of them, and have developed an operational program. Information from similar research and navigation programs would assist us in problem-solving tasks, and in selection o4 parameters to be measured in future research projects.

We also concluded that it's important to examine not only the dynamic characteristics of the ice but also the thermodynamics. This is particularly true for ice modeling problems, as demonstrated by Ashton in his talk. Thermodynamics can greatly affect other processes, and failure to adequately account for thermodynamics can greatly influence predictions of other ice phenomenon.

Field Season

The subcommittee determined that the ice scientific community was currently data bounds. There is a general lack of data for further testing of the ice transport models •and models of ice characteristics. Ice research has been conducted in a piecemeal fashion due to limitations of funding and human resources. Hence, “Field” data sets of ice parameters are seldom available, and are often limited in scope or many years old. We concluded there is a vital need to proceed with a comprehensive program of field experiments.

In preparing for a field program, we felt it was important to evaluate parameters for measurement and insure that a variety of parameters are included. This will assist in the comparison of several models which are composed of different parameters. With such a data set we can evaluate other varieties of parameters in a model of interest, using the data for hindcasting and forecasting analyses. This would allow researchers to generate now ideas, test them, and operate with a good data set for calibration of models and for verification of results.

Measurements

Further discussion of a field program involved parameters for measurement and measurement technologies. Ice measurements are required for several variables to better characterize ice phenomenon. Additional data sets are needed on ice density, ice albedo, snow cover distribution on ice, ice roughness at both the air-ice and ice-water boundary, and flow rates and water temperatures under the ice. This information is required to develop and improve existing thermodynamic and hydrodynamic models of lake ice.

Many of yesterday’s presentations dealt with remote sensing technologies using visible, infrared and microwave radiation. The talks demonstrated that many instruments are adequate for the job, but their capabilities and applications need to be expanded in the future (see papers by Bolsenga, Ramsier and Ashton). In particular, we heard about the problem of measuring ice thickness, which is necessary for understanding and modeling ice dynamics and thermodynamics. Thickness is a very difficult thing to measure, and current techniques range from helicopter crews and manual coring to remote sensing with radar sensors. In his talk, Rene Ramsier described the capabilities of impulse or short-pulse radar for measurement of ice thickness. Researchers at NASA in the U.S. and Atmospheric Environment Service have or are working with short-pulse radar for ice thickness determinations. In addition, a commercial system is available which operates at 388mHz. This commercial system has been successful in measuring ice thickness or water depth for several ice applications. Researchers at CRREL are further evaluating the capability of this instrument for thickness measurements.

Ice Movement

There is a large information requirement for measuring the dynamics and movement of ice. Several approaches were suggested. A LaGrangian approach can be implemented by use of shore-based radar and corner reflectors as position indicators on the ice. Range and azimuth measurements of the reflector will allow one to plot their locations, and frequent sampling allows calculation of ice movement. This approach would be valuable for studying ice in connecting waterways or nearshore.

A more interesting approach is the use of buoys frozen in the ice and satellite telemetry to track the movement of buoys. Current types of satellite tracking buoys are $5,888 instruments that are about five feet long, and a foot and a half in diameter. Scientists have employed these units in the Arctic and other oceans for a number of years. In the last year or so, GLERL has used them to track summer currents in Lake Michigan, and to a certain extent on Lakes Ontario and Huron. According to John Bennett, the capabilities of the buoys have been investigated and they can be used for ice applications. During the winter of 1993-84 GLERL will launch some of them in Lake Erie to monitor ice movements.

A proven and practical approach is a program of monitoring ice movements and ice type with airor spaceborne radar. An experimental program similar to past NASA, Coast Guard, and AES activities would be very desirable. While the Canadians presently have airborne programs, the cost of flights necessitates their use in special research problems. There is a great need for radar remote sensing measurements of ice characteristic for research purposes. These research needs and needs of ice information users should justify further research and development, which could lead to an operational and low-cost approach to supplying ice data. The advent of the Canadian C-band, synthetic aperture radar satellite or RADARSAT will potentially allow the collection of Great Lakes ice coverage data after 1988. Other low cost approaches to acquiring data should be developed to provide synoptic data of ice characteristics.

Users

We need to develop support among users of ice information to help organize a program of research. Previously, there was no urgent requirement to conduct research due to the economy and the suspension of winter navigation. Currently, several groups maybe interested in -further research on the breakup or the freezeup portion of the season. There is an ice in-formation need, because early or late navigation continues and ice problems are encountered. For example, broken ice choked the St. Clair River in late April, 1984 halting navigation and creating a very expensive. Estimates of monetary losses of 1.5 million a day were offered. The delay has created a heighten interest in ice phenomenon and the impact of ice damage to coastal and navigation interests.

This ice phenomena and the resulting damage occurred during the early part of the normal navigation season. A program of research directed at understanding similar problems can potentially obtain support, due to the interest in early or late season navigation. As the traditional ice in-formation user (Coast Guard, Weather Service, AES) are still active, there are sufficient parties to provide support for research on segments of the ice season.

Our discussions also draw attention to the noticeable lack of information on economic losses sustained by non-navigation interests. Coastal users are concerned as ice often creates shore and property damage. Ice also can damage hydroelectric generating systems. We have judged the economic impact of ice damage to non-navigation users to be very large. It is important to conduct a study to quantify this loss, as the results may help to justify -further programs of research.

Conclusions

Several areas of research need to be developed in the future. We concluded that:

a) Scientists are concerned with the availability of -field season data. The major need is for an experiment to provide a comprehensive set of ice data to help calibrate and verify ice transport models we now have. We also discussed potential cooperation of ice scientists and data users to -facilitate such a -field season.

b) There are many concerns, about the adequacy of current measurement technologies. We want to investigate remote sensing technologies for tracking ice movement, and for measuring ice thickness and ice characteristics. These technologies need to be further developed and made relatively low cost, to help provide data on a systematic basis.

c) We must interest a variety of ice in-formation users to provide -further opportunities for research. Many users have a need for information during the onset of ice -formation and breakup of the ice, and their support can provide the stimulus for -further research.

Prioritized Goals for Research

A Field season is required to supply data to help calibrate and verify models of ice transport and ice characteristics.

Improved radar remote sensing techniques for detection o4 ice thickness and ice concentration need to be adopted and utilized.

Estimates of the economic impact of ice damage on non-navigation users, coastal property owners and natural resources need to be developed.

SUB-COMMITTEE REPORT

Summary of the Discussion on

2.3 Ice Information and Forecasting

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The ice information and ice forecasting subcommittee addressed the questions of: -

1) What is the state of the art.

2) What are future research needs.

3) What are priorities of research needs.

relative to three geographic regions in the Great Lakes:

1) Connecting channels (rivers).

2) The shore zone of the Great Lakes, and

3) The mid lake areas of the Great Lakes.

The following is a summary of the subcommittee's findings.

I.- Connecting Channels of the Great Lakes

a) State of Art ice information Currently ice cover distribution and extent is documented by aerial photography and visual reconnaissance. An extensive data set of aerial photographs exist for the St. Lawrence River for the.past 10 years. Ice thickness data in the past has been measured manually. However, work with pulse radar indicates that ice thickness data can be collected by this remote sensing technique. To date extensive point source records of ice thickness have been collected for the St. Lawrence and St. Marys Rivers. However, there is little if any information on the synoptic variation of ice thickness over a continuous reach of a river. Both ice thickness and ice extent data are collected on a non-real-time basis, the lag between measurement or observation and operational use of the data can vary from a few days to a few weeks. There are currently no observations to assess ice strength. Water levels are monitored to assess the possible formation of ice jams.

b) Future Research Needs ice information For operational users of ice information there in clearly a need for ice thickness and ice extent and ice strength information in near real-time (on the order of 1-2 hours to 1-2 days). This information is needed to make decisions about (1) when to reduce flow rates to encourage a stable ice sheet to form, (2) when to increase flow rates in an effort to minimize the formation of "hanging dams" under the ice cover, (3) when to install and remove ice control structures such as ice booms. For researchers there is clearly a need to have detailed information on the above parameters, in both sp.ace and time domains as well as information on ice density, ice albedo and snow cover distribution on ice and ice roughness at both air-ice and ice-water boundary and flow rates and water temperatures under the ice. This information is needed to develop and improve existing thermodynamic and hydronamic models of river ice, winter river flows, and winter thermal characteristics of rivers. There is a need to develop and improve remote sensing techniques to get ice information to the user in near real-time.

c) State of the Art ice forecasting Currently there are operational forecast models for freezeup and breakup on the St. Lawrence River and recently for freezeup, ice growth, and breakup on the St. Marys River. These forecasts are primarily emperical and statistical in nature because of (1) lack of detailed ice and hydrological and meteorological data sets to verify conceptual models and (2) the lack of accurate mid to long range forecasts of the needed input parameters to

.drive the conceptual models. There has also recently been developed hydrodynamic models to simulate the formation of hanging dams and water flow rates under an ice cover.

d) Future Research Needs ice forecasting There is ,a need for more accurate long and short range forecasts of ice formation, ice extent, and ice breakup and loss. Present forecasts, because they are emperical and statistical in nature often perform poorly when anamolous weather conditions exist. Therefore there is a reed for improved ice forecast models and improved prediction of the parameters that drive the models. There is a need to develop a model to predict ice strength. Improved freezeup forecasts are needed on time scales of 1-2-days (for determining appropriate flow rates to control ice cover formation) up to 3 months in advance (for planning ship schedules for winter navigation). Improved breakup forecasts of 1-2 days to 2 months in advance are also needed for hydropower generation operations and planning the opening of navigation. Finally there is a need for improved forecast of ice dam formation and ice jams for better hydropower generation management and to minimize the possible damage to shore structures and shore property.

Shore Zone of the Great Lakes For the purpose of this discussion the shore zone will be defined as bays and harbors of the Great Lakes as well as more exposed shoreline and shoal and island areas of the Great Lakes.

a) State of Art ice information Information on ice conditions in the shore zone of the Great Lakes is sporatic in frequency, quality, and quantity. Most of the data sets in existence have not been quality controlled, these include daily water level gage visual ice observations of ice conditions in the immediate area of the gage, U.S. Coast Guard ice thickness and weather observations at specific shore locations, and National Weather Service ice thickness measurements at specific bays and harbors. There is also an ice thickness data set established by the Great Lakes Environmental Research Laboratory that has been quality controlled, it consists of weekly ice thickness measurements at specific bays and harbors. Period of record varies from 6 to 12 years at most of the 32 shore sites. There is also long term ice thickness measurement records at 4 to 6 sites along the Canadian shore of the Great Lakes, primarily at locations critical for navigation or hydropower generation. Much of the existing data sets are archived and documented at the National Snow and Ice Data Center, Boulder, Colorado, and. at Ice Climatology Branch, AES, Ottawa, Canada. A limited amount of work has been done on describing various ice formations such as ice foots that develop in the shore zone.

b) Future Research Needs ice information Future research needs can be divided into data needed in real time and long term data record needs, i.e., the history of ice conditions. Real time ice information is needed to support winter navigation. (the time of freezeup in bays and harbors, ice thickness and areas of rafting and ridging, ice transport into and out of bays and harbors, especially in spring when ice can block harbor entrances); real time ice infôrffiation is also needed to support recreational use of the Great Lakes ice cover (ice strength thickness information is needed for ice fisherman, etc. who regularly go out on the ice in winter and early spring); there is a need for added information on water flow patterns under the ice for environmental considerations, for example, possible location and movement of oil spills and toxic substances). In the long term the type thickness, and duration of ice cover that typically forms in specific shore areas needs to be improved or developed partly by further analysis of existing data sets and partly by the development of remote sensing techniques to collect the data and develop automated methods to edit and archive the data. These data have application for the design and construction of shore installations water intakes and areas of likely shore erosion and ice damage.

c) State of Art ice forecasting Currently there are various studies that predict ice cover thickness based primarily on correlations with freezing degree-days. In a few isolated locations conceptual models to predict freezeup, ice growth, and-ice decay have been developed.

d) Future Research Needs ice forecasting Forecasts of ice freezeup, ice strength, ice movement, ice thickness, and ice loss on time scales of 1-2 days to 3 months in shore areas such as Whitefish Bay on Lake Superior and the Straits of Mackinaw (Lakes Michigan-Huron) need to be developed to support winter navigation and recreational use of the ice cover in the near shore zone. Forecasts of the opening and closing of leads, areas of rafted and ridged ice, and the movement of ice into and out of bays arid harbors is important to shippers while forecasts of ice thickness and ice strength are important for recreational use of ice cover. Forecasts of ice movement on shore due to winds or thermal expansion is also important to owners of shore property as considerable damage can result from ice shove on shore. On the other hand the absence of ice may result in flooding of some shore areas.

III. Mid-Lake Areas of the Great Lakes.

a) State of Art ice information The bulk of the existing information on mid-lake ice conditions is contained in ice charts. These charts depict ice concentration, ice age, ice distribution, and various other characteristics that can be observed or estimated. Most of the

.historic ice charts were produced making aerial overflights with visual observations recorded on base map work sheets. In the late 60's and in the 70's Side Looking Airborn Radar (SLAR) and to a lesser degree satellite imagery was used to produce ice charts. The remotely sensed data is visually interpreted. The satellite data in particular has been of limited use because of (1) the lack of machine automated objective analysis procedures for interpretation of ice cover, (2) the resolution of most satellites, on the order of 1 - 5 km, and (3) the sensors making observations in only the visible and IR portion of the spectrum; during much of the winter the Great Lakes area is frequently cloud covered. At 20 year (1960-79) computerized digital ice concentration data set has been abstracted from the historical ice charts at GLERL and these data were used to identify the extreme and normal ice cover distribution characteristics for 9 half month periods during the winter and spring. With the decline of winter navigation in the 1980's funding for the SLAR ice observations declined so that currently ice charts are based on visual aerial ice reconnaissance and satellite imagery. Mid-lake ice information is used operationally for winter navigation, to aid in decisions on when to deploy and remove ice control structures, aids to navigation, and as input to weather forecasts.

(b) Future Research Needs ice information The primary need is for more frequent and more detailed observations of all types of mid-lake ice information, including information such as ice thickness, ice albedo, ice strength, and ice surface temperature for which we currently have virtually no historic records. The frequency requirement is-on the order of hours to days. This temporal scale of observations is needed in order to assess what the dominate time scale is for processes effecting the ice cover and operationally it is needed in the early and late part of the ice cycle, i.e., during initial formation and final ice loss because ice conditions can change rapidly during these times so that frequent observations are needed for decision making processes associated with recreational use of ice cover, hydropower generation, and winter navigation. The second most important need is to get this information to operational users in near real-time so that they can factor it into their decision making processes. However to accomplish both of these needs we must develop the capability to remotely sense ice cover in mid-lake as this seems to be the only practical way of obtaining the data in the time and space scale that are required. Other important mid-lake ice parameters needed, but not noted above are: (1) amount and locations of areas of ice ridging and rafting, (2) distribution of ice of various concentrations, and movement of ice into and out of specific lake areas.

c) State of Art ice forecasting Because of the lack of detailed hydrometeorological and ice observations on time and space scales of sufficient resolution to develop conceptual modes of ice processes in mid-lake the main techniques currently used in making ice forecasts for mid-lake areas are primarily statistical in nature. Oak (1957) was perhaps the earliest to develop a forecast related to ice cover. He used mean February air temperature to forecast opening dates of navigation at various Great Lakes ports. Richards (1963) correlated FDD's and TDD's with ice cover extent on the Great Lakes. Snider (1971) formalized and summarized much of the early statistical emperical ice forecasting techniques in his "Manual of Great Lakes Ice Forecasting" that is still used for guidence by the National Weather Service in making operational ice forecasts today. However some work has been done on conceptual models of ice cover that perhaps point the way for improved ice forecasting techniques in the future. Dilley (1976) developed a simple 2-dimensional model of heat conduction to simulate ice cover for Lake Ontario during the International Field Year on the Great Lakes. And Rumer, et. al. (1978) developed a semi-emperical model of ice dissipation for eastern Lake Erie. Rumer, et al. (1981) also developed a Great Lakes ice dynamics model for Lake Erie - that model is currently being evaluated at the Great Lakes Environmental Research Laboratory. Currently mid-lake ice forecasts made by the NWS include forecasts of initial ice, forecasts of ice formation and extent during the winter, and forecasts of ice decay in the spring. The length of the forecast varys from 30 to 90 days (ice outlooks which are based on deviations of normal air temperatures from monthly and seasonal values to adjust normal ice distribution patterns) to less than 24 hours to 5 days forecasts (based primarily on air temperatures and wind speed and wind direction forecasts).

d) Future Research Needs ice forecasting Improvements need to be made in the accuracy of short term detailed ice forecasts (less than one day out of 5 days) and for medium to long range more general ice forecasts (on the order of 2 weeks to 3 months). The forecasts are needed to support winter navigation, hydropower generation, and ecological studies related to lake physics, lake chemistry, and lake biology. Short range forecasts would best be developed and improved through the use of conceptual models that take into account small time steps to describe the physical processes of mass and energy exchange that affect ice conditions. However because of the present lack of accurate long range forecasts of daily or hourly variation in the input parameters that drive conceptual models long range and more general ice forecasts could best be improved upon by additional analysis of existing historic ice cover data sets in order to define dominate space and time domains of ice cover variation and to correlate those variations with deviations of 2 week to 90 day mean values of air temperature, wind direction and speed, and ice albedo. The conceptual models will require synoptic observations of ice and meteorological parameters over the period of 1 to 2 winter seasons on each Great Lake. At present a combination of an extensive field program and use of remote sensing techniques offers the best hope of obtaining such data sets. There is also a need to continue to collect data for long range ice forecast models, including data on lake thermal structure, and ice albedo.

IV. Priorities of Research Needs Three items have been identified as the areas where future research is most important if significant advances are to be made in ice information and ice forecasting.

1) There is critical need to have more detailed ice and hydrometeorological observations to be used in real time and to be archived for later use in improving ice forecasting techniques. The data observations should be synopic in nature so that the entire "system" can be analyzed. At the present time we do not have the technical capability to obtain the detailed synoptic observations. Because remote sensing techniques offers the best hope of obtaining this capability we should develop and improve remote sensing instruments capable of meeting our data observation and collection needs.

(2) There is a large mass of existing historical ice cover data much of it has not been computerized and much of it has been collected to meet operational needs. These data sets should be analyzed for use in both development of improved historic ice cover information and to develop improved ice forecasting techniques (primarily emperical in nature).

3) One of the main problems with existing data sets is the lack of continuity in methods of observations, methods of recording measurements, and the type and frequency of measurements recorded. Universal systematic methods should be developed to collect, reduce, and archive ice observations.

Appendix A.--WORKSHOP PROGRAM AND ATTENDEES

GREAT LAKES ICE RESEARCH WORKSHOP

Program

11:00 - 1:00	Registration
1:00 - 1:20	Introduction, John Lyon Civil Engineering Ohio State University
	Welcome, Charles E. Herdendorf, Director Ohio Sea Grant Program
	Objectives of the Workshop, Frank Quinn GLERL
1:20 1:55	"Remote Sensing of Ice" Rene Rarnseier Atmospheric Environment Service Environment Canada Ontario, Canada
1:55 - 2:30	"Research Needs for Forecasts" Daron Boyce National Weather Service Forecast Office Cleveland, Ohio
2: 30 - 3: 05	Optical and Stratigraphic Properties of Ice" Stanley Bolsenga Great Lakes Environmental Research Laboratory Ann Arbor, Michigan
3:05 - 3:25	BREAK (coffee and soft drinks)
3:25 - 4:00	"Ice Deterioration" George Ashton Cold Regions Research Engineering Laboratory Hanover, New Hampshire
4: 00 - 4: 35	"Ice Processes in Connecting Channels" Hung Shen Cold Regions Research Engineering Laboratory Hanover, New Hampshire
4: 35 - 5:10	"Ice Transport Modeling" Ralph Rumer Department of Civil Engineering State University of New York
5:10 - 5:20	Activities for the Next Day Frank Quinn, GLERL
6: 00 - 6: 45	Mixer at the OSU Faculty Club (see map)
6:45 - 7:40	Banquet at the Faculty Club
7: 40 - 9: 30	Movies on Great Lakes Ice, "Lake Erie Storm Surge Under Ice Cover", K. Bedford, OSU, "Lake Superior Ice Cycle", G. Leshkevich, GLERL "Lake Erie Ice Scouring, J. Grass, Ontario Hydra

October 19, 1983

8:10 a.m.	Refreshments
8:30 - 12:00	Sub-Committee Meetings on Needs inResearch
	The objectives are to: a) discuss the status of research; b) determine areas for future research c) prioritize the research needs; and d) suggest areas for future cooperation.
Topics and Groups	“Ice Characteristics” “Ice Transport Modeling” “Ice Information and Forecasting”
11: 30 - 1:00	LUNCH (at the Fawcett Center)
1: 00 - 2: 15	Sub-Committee Reports to the Attendees
2:15 - 3:00	Group Discussion

GREAT LAKES ICE RESEARCH WORKSHOP

Attendees

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Appendix B.--GREAT LAKES ICE RESEARCH AND INFORMATION SURVEY

A survey was conducted to identify and evaluate current and future needs related to Great Lakes ice information. The survey was conducted by mail prior to the ice research workshop and the results were presented at the workshop. We received 29 responses to the 120 survey forms distributed. A summary of the responses to each questions is given on the following pages.

The most frequent answer to the four major questions:

1. What is the primary area of interest? Scientific research (22%).

2. Is the information you now receive adequate to meet your needs? Not adequate (557.).

3. What is the desired time and space resolution of the ice data that you need? Time resolution, daily (32%) Space resolution, shore sites (37%).

4. What additional information r.equiremen.tsand desires do you have? Ice cover thickness (12%).

GREAT LAKES ICE INFORMATION USERS' SURVEY - OCTOBER 1983

We received 29 responses to the 120 survey forms distributed. A summary of the responses is outlined below (multiple answers were allowed):

Primary Area of Interest

13 - scientific research
8 - hydropower plant operation
11 - construction
7 - small harbor design or operation
9 - winter navigation
1 - data archiving

9 - meteorological and
1 - recreation planning ice forecasting Adequacy of Ice Information Available

6 - adequate
16 - not adequate
7 - no comment

Desired Resolution of Ice Cover Information

Time Space

4 - hourly
15 - shoreline sites
13 - daily
11 - major lake divisions
11 - weekly
8 - lake-wide averages
4 - monthly
3 - segment of connecting channels
4 - whole season
3 - higher resolution throughout
5 - long term average the lakes
1 - navigationally significant areas

Additional Information Requirements and Desires

16 - ice cover thickness
6 - ice cover effects on lake
15 - ice cover distribution biology and chemistry
14 - ice cover strength
4 - effects of ice on structures
14 - ice cover duration
4 -ice processes near shore

12 - properties relevant to
3 - frazil concentration in remote sensing connecting channels
11 - ice cover transport
3 - rafting, ridging, and bottom
7 - near real time reports of scouring ice cover distribution
3 - forecasts of thickness and strength
7 - ice and snow cover surface
2 - historical data, newspaper accounts, temperature aerial photographs
7 - effects of snow on ice
1 - effect of ice cover on waves cover properties
1 -frequency analysis of ice thickness
6 - synoptic values for ice and properties cover properties (thickness, reflectance, etc.)