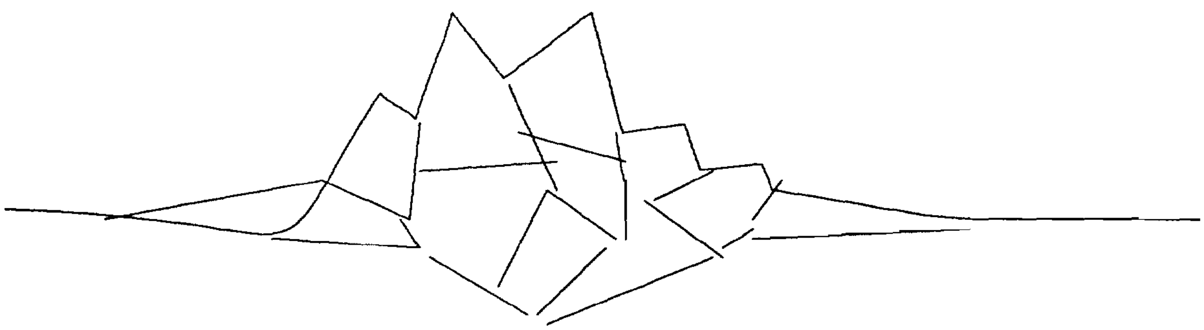
Proceedings of the

Sea Ice Mechanics and Arctic Modeling Workshop

April 25-28, 1995, Hilton Hotel, Anchorage, Alaska

Volume 2



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U.S. Navy Office of Naval Research,
U.S. Minerals Management Service,
Canadian National Energy Board,
Amoco, Arco, Chevron, Exxon, and Mobil

Organized by: NorthWest Research Associates, Inc.
Bellevue, WA

Preface

The U. S. Navy, the U.S. Department of Interior Minerals Management Service (MMS), and the off-shore industry continue to need field data, laboratory data, and ice modeling results to address a variety of Arctic modeling, engineering, and operations problems, including:

- Ice loads on fixed and floating structures;
- Ice gouging of the sea floor above buried well completions and pipelines;
- Arctic atmosphere, ocean, and ice models;
- Oil spills and oil transport by sea ice;
- Forecasting ice conditions for routing ships and fixed structure operations;
- Environmental issues.

To support these requirements, a significant quantity of new Arctic field data, laboratory data, and modeling results are now available as a result of the Office of Naval Research's Sea Ice Mechanics Initiative (SIMI) and Minerals Management Service (MMS) programs. The data include measurements of sea ice stress, ice motion, ice thickness distribution, keel depths, ice and keel strength, ice friction coefficients and fracture properties, meteorological parameters, and ocean currents. The modeling results include studies on scales ranging from ice crystals to the whole Arctic Ocean of ice dynamics and thermodynamics, ice constitutive laws, ice failure mechanisms, and ice fracture.

In order to make the new information readily available for use by the Navy, MMS, and industry, a mechanism to transfer the information was necessary. The SIMI program had been planning a meeting of its principal investigators to provide a forum for information exchange. It became apparent that these two functions could best be accomplished during a single workshop, attended by SIMI researchers, MMS researchers and oil industry representatives and researchers.

"The Sea Ice Mechanics and Arctic Modeling Workshop" was held in Anchorage, Alaska, April 25 - 28, 1995. The Proceedings, Volume 2, describe the results of that workshop. Volume 1 of the Proceedings, distributed before the workshop, contains the preliminary results of the work done by the SIMI researchers. Our objective here was to disseminate information about the SIMI research so that little time would be necessary for data presentation and more time could be spent at the workshop on discussions of current practices and data, defining data gaps and important areas for future research.

SUMMARY OF SIMI

The Sea Ice Mechanics Initiative (SIMI) is an Office of Naval Research Accelerated Research Initiative (ARI), spanning the years 1991 to 1996. Its goals are to:

- Understand sea ice constitutive laws and fracture mechanics over the full range of geophysical scales, and

- Determine the scaled responses to applied external forces and develop physically based constitutive and fracture models.

The goals of SIMI were established at a planning meeting held at Airlie, Virginia, in November 1990. Oil industry representatives participated in this planning process. The report from that meeting is included as Appendix A in Volume 1 of these Proceedings. The main field experiments were defined at a second SIMI planning meeting held at Sidney, British Columbia, in August 1993 and are described in the Summary Plan included as Appendix B in Volume 1. The main field experiments were conducted in the Beaufort Sea during 1993 and 1994.

STEERING COMMITTEE

A steering committee was established to provide planning guidance for the workshop. The committee included representatives from both industry and government to help assure the results of the conference would be useful to both communities. We give a hearty thanks to the committee members for their efforts.

Mr. Walter T. Bugno
Chevron USA

Dr. Max D. Coon, Workshop Chairman
NorthWest Research Associates, Inc.

Dr. Gordon F. N. Cox
Amoco Eurasia

Dr. Thomas B. Curtin
Office of Naval Research

Mr. John Eldred
Arco Alaska

Ms. Judith Gottlieb
Minerals Management Service

Dr. Walter Johnson
Minerals Management Service

Dr. Ibrahim Konuk
National Energy Board

Dr. Ronald Lai
Minerals Management Service

Dr. Brad Lauback
Office of International Activities and Marine Materials
Minerals Management Service

Dr. Yapa Rajapakse
Office of Naval Research

Dr. Charles Smith
Minerals Management Service

Dr. Robert E. Smith
Arco Exploration and Production Technology

Dr. Walter Spring
Mobil R&D Corporation

Dr. Thomas Swean
Office of Naval Research

Dr. Albert T. Wang
Exxon Ventures (CIS) Inc.

SPONSORSHIP

The workshop received financial support from a number of government agencies and oil companies, including:

U.S. Navy Office of Naval Research,
U.S. Minerals Management Service,
Canadian National Energy Board,
Amoco, Arco, Chevron, Exxon, and Mobil

Our thanks go to these organizations for making this workshop possible.

ORGANIZING COMMITTEE

Those who served on the NWRA in-house workshop organizing committee with Max Coon were: Ed Fremouw, President of NWRA; Karen Hewett, Workshop Coordinator; Stu Knoke, and Skip Echert. The many positive comments we received about the workshop were due to their efforts.

RUSSIAN SCIENTISTS

The workshop sponsored travel and expenses for five Russian scientists and provided partial support for a sixth Russian scientist to attend the workshop. Funding for these individuals was provided by Minerals Management Service, Arco and Mobil. These scientists were:

Prof. Robert. V. Goldstein of the Institute for Problems in Mechanics, Moscow, Russia,
Dr. Anatoly M. Polomoshnov of the Sakhalin Oil and Gas Institute, Sakhalin Island, Russia,
Dr. Vladimir E. Ryabinin of the Hydrometcentre of Russia, Moscow, Russia,
Dr. Victor N. Smirnov of the Arctic and Antarctic Research Institute, St. Petersburg, Russia,
Dr. Pavel A. Truskov of the Sakhalin Oil and Gas Institute, Sakhalin Island, Russia, and
Dr. Alexander Bekker of the Far-Eastern State Technical University, Vladivostok, Russia.

We thank them for sharing their knowledge and for their important contributions during the workshop panel discussions.

Tom Curtin, ONR
Charles Smith, MMS
Max Coon, NWRA

June 1995

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INTRODUCTION

The "Sea Ice Mechanics and Arctic Modeling Workshop" focused on defining current state of the practice and future research needs related to the interaction of sea ice with structures used by the oil and gas industry and the U.S. Navy and to the natural behavior of sea ice over a range of scales and forcing conditions. The workshop was motivated by the need to summarize and assess results from research over the past several years sponsored by the U.S. Department of Commerce Minerals Management Service and the U.S. Navy's Office of Naval Research (ONR) Sea Ice Mechanics Initiative (SIMI).

MEETING FORMAT

The Workshop began with a day of providing information to, and among, the attendees. On Tuesday morning a series of speakers provided background information to all participants. That afternoon was a poster session in which 43 posters were presented and discussed. The remainder of the week was spent in working panel sessions and in presenting results to, and discussing them with, the other attendees. On Wednesday morning (April 26) five panel sessions were held, each focusing on processes at different physical scales. On Thursday morning four panels were held on topics of current importance. The afternoons of Wednesday and Thursday were spent in presenting and discussing the results of the morning sessions to the other attendees. Friday morning was a plenary wrap-up and summary session of the workshop results.

PANEL MEMBERS

The workshop panel members were as follows:

Panel on 100 km scale (pack ice)
Max Coon (NWRA)
Andrey Proshutinsky (U AK)
Ruth Preller, NRL

Panel on 10 km scale (floe cluster)
Jim Overland (NOAA)
Bryan Kerman (AES Canada)
Jackie Richter-Menge (CRREL)
Gordon Cox (Amoco Eurasia)

Panel on 1 km scale (floe, ridge, crack)
Mark Hopkins (CRREL)
Henrik Schmidt (MIT)
Robert Goldstein (Inst. for Prob. in Mech.)
Peter Wadhams (Scott Polar)

Panel on 10 m scale (macro-crack)
John Dempsey (Clarkson Univ.)
Walt Bugno (Chevron)
Peter Stein (Sci. Solutions, Inc.)
Zdenek Bazant (Northwestern)

Panel on 1 cm - 1 m scale (materials)
Erland Schulson (Dartmouth College)
Graham Thomas (BP)
Victor N. Smirnov (Arctic and Antarctic Res. Inst.)
Dave Cole (CRREL)

Panel on ice loads on fixed and floating structures, including vessels
Ken Croasdale (Croasdale and Assoc.)
Alexander Bekker (Far-Eastern State Technical University
Tom Murrell (MMS)
Pavel Truskov (Sakhalin Oil and Gas Inst.)

Panel on ice forecasting for ship routing and operations
Robert Pritchard (ICI)
Anatoli Polomoshnov (Sakhalin Oil and Gas Inst.)
Kyle Monkelien (MMS)
Ben Danielewiscz (CANMAR, Ltd)

Panel on ice gouging of the sea floor
Willy Weeks (Univ. of Alaska at Fairbanks)
Albert Wang (Exxon)
Vladimir Ryabinin (Hydrometcentre of Russia)
Chris Woodworth-Lynas (C-CORE)

Panel on oil spills and oil transport by the ice
Walter Johnson (MMS)
Stu Knoke (NWRA)
Katherine Hedstrom (IMSC)

FINAL PROGRAM

The final program from the workshop is given below:

Monday, April 24, 1995

6:00 pm - 8:00 pm Ice Breaker and Registration

Tuesday, April 25, 1995

7:00 am	Breakfast meeting for Tuesday's speakers
8:00 am	Registration
8:30 am	Opening and Welcoming Remarks Ed Fremouw (NWRA) Tom Curtin (ONR) Judith Gottlieb (MMS) Max Coon (NWRA)
9:15 am	Workshop Introduction Albert Wang (Exxon): "Industry-Government Cooperation in Ice Mechanics and Modeling"
9:45 am	Break
10:15 am	MMS Programs: Jeff Walker (MMS)
10:35 am	NEB Canada Programs: Ibrahim Konuk: "Programs of the National Energy Board of Canada"
10:55 am	Finnish Programs: Jukka Tuhkuri (Arctic Offshore Research Centre, Helsinki Univ. of Tech.): "Mast III"
11:15 am	CANMAR Program: Ben Danielewicz (CANMAR)
11:25 am	BP Programs: Graham Thomas (BP)
11:35 am	Introduction to Poster Sessions: Max D. Coon (NWRA)
12:00 pm	Lunch
1:30 pm	Poster Sessions
5:00 pm	End

Wednesday, April 26, 1995

7:00 am	Breakfast meeting for Wednesday's panels and co-chairmen
8:00 am	Form five concurrent working sessions (in separate rooms) divided by physical scale of sea ice: **100 km Scale (Pack Ice)** **10 km Scale (Floe Cluster)** **1 km Scale (Floe, Ridge, Crack)** **10 m Scale (Macro-crack)** **10 cm to 1 m Scale (Micro-crack, Crystal)**
9:45 am	Break
10:15 am	Resume working sessions
11:30 am	Lunch
1:00 pm	Joint session for working session reports: Co-chairmen Tom Swean (ONR) and John Elder (Arco)
1:00 pm	Report on 100 km scale (pack)
1:15 pm	Discussion on 100 km report
1:35 pm	Report on 10 km scale (floe cluster)
1:50 pm	Discussion on 10 km report
2:10 pm	Report on 1 km scale (floe, ridge, lead)
2:25 pm	Discussion on 1 km report
2:45 pm	Break
3:15 pm	Report on 10 m scale (macro crack)
3:30 pm	Discussion on 10 m report
3:50 pm	Report on 10 cm - 1m scale (micro-crack-crystal)
4:05 pm	Discussion on 10 cm - 1m report
4:25 pm	Joint kick-off for Thursday's working sessions. The sessions are structured the same as Wednesday's sessions.
5:00 pm	End

Thursday, April 27, 1995

7:00 am	Breakfast meeting for Thursday's panels, and co-chairmen
8:00 am	Form four concurrent working sessions divided by topic: **Ice Loads on Fixed and Floating Structures, Including Vessels** **Ice forecasting for Ship Routing and Operations** **Ice Gouging of the Seafloor** **Oil Spills and Oil Transport by the Ice**
9:45 am	Break
10:15 am	Resume working sessions
11:30 am	Lunch
1:00 pm	Joint session for working session reports: chairmen Bob Smith (Arco) The chairman of each panel presents their report.
1:00 pm	Report on ice loads on fixed and floating structures, including vessels
1:15 pm	Discussion on ice loads report
1:35 pm	Report on ice forecasting for ship routing and operations
1:50 pm	Discussion on ice forecasting report
2:10 pm	Report on ice gouging of the sea floor
2:25 pm	Discussion on ice gouging report

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2:45 pm	Break
3:15 pm	Report on oil spills and oil transport by the ice
3:30 pm	Discussion on oil spills report
3:50 pm	End
7:30 pm-10:00 pm	Workshop Banquet, Speaker: Jim Hansen, Manager of oil leasing program for the State of Alaska Banquet program includes speakers and presentation of awards to winners of photo contest and others.

Friday, April 28, 1995

7:00 am	Breakfast meeting for panel, speakers, chairman, and co-chairman.
8:00 am	On-stage panel discussion. Panel consists of chairmen from the Wednesday and Thursday panels. Panel reports the research needed to provide the following products and services for the future. Chairman: Ron Lai (MMS)
10:15 am	Break
10:45 am	Closing remarks: Charles Smith (MMS), Tom Curtin (ONR)
11:30 am	Adjourn workshop

CONTENTS OF VOLUME 2

Volume 2 of the Workshop Proceedings has two major parts. Part I includes a summary of the workshop results and contains the results of the nine panel discussions held at the workshop. Part II includes summaries of the speakers' presentations made on Tuesday (April 25) and on Thursday evening (April 27). Also included in Part II are abstracts or summaries of the posters presented at the workshop. Between the two parts are photographs taken at the conference.

Errata to Volume 1 are contained in Appendix A. An index of authors, speakers and panel members is given in Appendix B. Appendix C contains a list of the workshop attendees.

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1. PART I - RESULTS OF WORKSHOP SESSIONS

On the mornings of Wednesday, April 26, and Thursday, April 27, panel meetings were held. Workshop attendees could attend any panel session. In the afternoon of each day, the entire group was reconvened to hear the results of the morning panel work and to have open discussion on the topics. On Wednesday afternoon, ice mechanics on various scales was discussed, and on Thursday afternoon, ice mechanics applications were discussed.

Friday morning was left to a discussion of all panel results including the ice mechanics on scales and the applications. During the discussion, there was vigorous interaction between the researchers of ice mechanics at different scales and the users and practitioners of ice mechanics used in engineering and operations.

1.1 Summary of Workshop Results -

Recent Accomplishments and Research Needed

This section is a summary of the Friday (April 28) morning session. The objective of this session was to describe the research needed in each workshop topic area:

- 100 km Scale (pack ice)
- 10 km Scale (floe cluster)
- 1 km Scale (floe, ridge, crack)
- 10 meter Scale (macro-crack)
- 1 cm to 1 m scale (micro-crack, crystal)
- Ice Loads on Fixed and Floating Structures, Including Vessels
- Ice Forecasting for Ship Routing and Operations
- Ice Gouging of the Sea Floor
- Oil Spills and Oil Transport by the Ice

For most of the topic areas the most important accomplishment by SIMI and most important area for future research, as judged by the panels, are contained on the table below. The topics on ice forecasting, ice gouging of the seafloor, and oil spills were not specifically addressed by SIMI. The main text for the ice forecasting topic includes a description of the current state of the practice. For the ice gouging topics we include a summary of what currently is known. The needs and findings on any topic are best determined by reading the panel report on that topic.

1.2 Results of Panel Discussions

The results of the discussions are summarized in Table 1.

Table 1 - Summary of Recent Accomplishments and Research Needed

Panel Name	Most Important Accomplishment	Most Important Future Research
100 km Scale (pack ice)	From GPS buoys, stress buoys, and SAR, the importance of lead formation and direction on the large scale behavior of pack ice has been verified. New leads have been shown to be created from states of compression and shear stress as measured on the scale of a floe but representing stress on tens of km. Also, when leads are open, the measured stress state is compression parallel to the lead and zero perpendicular to the lead.	Need formulation and verification of model against deformation (strain rates), leads (direction and deformation), and ice concentration using buoy and satellite data.
10 km Scale (floe cluster)	SIMI acquired the first major data set of stress and strain rate of a pack ice cover on scales of 1-100 km. Results confirm the hypothesis that ice behaves as a hardening plastic, with the basic unit for continuum behavior being a cluster of floes on the scale of 10 km.	Understand what mechanical properties control the spacing of discontinuities (slip lines, leads, etc.). By mechanical properties we imply what determines the minimum strength of sea ice as a composite material on a 1 km scale, i.e. existence of cracks and floe distribution, orientation, and thickness.
1 km Scale (floe, ridge, crack)	The ratio of work to potential energy in pressure ridging is 10:1 to 17:1, depending on ice thickness.	Determine the effects of consolidation (formation of a frozen layer growing down from the water level and contact freezing between ice blocks) on the strength of first-year ridges and rubble fields.
10 meter Scale (macro-crack)	The significant scale effect on the failure strength of first year sea ice is given by the relationship: $$\sigma_n = \frac{0.68}{(1+L/0.26)^{1/2}}$$ where L is the characteristic dimension of the structure.	Complete the ongoing development of a nonlinear fracture model and sea ice constitutive model to make full use of the large scale fracture and constitutive measurements made to date; this, in turn, must then be used to assess and refine the scale effect predictions for the 100 - 1000m scale.

1 cm to 1 m scale (micro-crack, crystal)	Established failure mechanisms: both dislocation relaxation and grain boundary relaxation account for the anelasticity of first-year sea on both the small and the large scale; grain boundary sliding accounts for high-rate crack nucleation in pore-free ice under compression; frictional crack sliding and crack interaction account for brittle compressive failure; competition between crack propagation and crack-tip creep accounts for the brittle-to-ductile transition under compression; and brine-filled pores inhibit crack propagation.	Using meter-sized blocks of pre-cracked columnar sea ice loaded under controlled conditions, test predictions that the ductile-to-brittle transition strain rate scales inversely with crack size, as (crack size)$^{-1.5}$, and that the brittle compressive strength scales inversely with crack size, as (crack size)$^{-0.5}$.
	Developed compressive failure envelopes and surfaces and found that Hill's criterion and a truncated Coulomb criterion describe the ductile and brittle failure stress, respectively.	Determine compressive failure envelopes/surfaces and failure criteria for first-year columnar sea ice where the loading axes are inclined to the growth direction.
	Found that large-scale anelasticity can be predicted from laboratory experiments, that c-axis alignment affects ice sheet compliance, and predicted that the ductile-to-brittle transition strain rate scales inversely with lead size, as (lead size)$^{-1.5}$, and that the brittle compressive failure stress also scales inversely with lead size, as (lead size)$^{-0.5}$.	Establish and model the relationship between sea ice growth and loading history with the in-situ anelastic and viscous creep behavior.

Ice Loads on Fixed and Floating Structures, Including Vessels	**Applications of SIMI Results:**	
	Ice Crushing - Use the newly measured failure envelopes for columnar saline ice obtained from multi-axial testing by Schulson's group to predict ice crushing pressures. The envelopes plot the failure stress versus degree of confinement, the strain rate and the temperature. They are significant because when combined with stress analysis of the contact zone, the envelopes allow failure pressures to be calculated. However, the results may be applicable only to local ice pressure design criteria because lab scale tests cannot account for size effects on ice crushing.	Use the learnings from the recent SIMI lab tests and theoretical analyses to improve the interpretations of full scale load measurements, and enable their extrapolation to other situations. Test the ductile to brittle transition size effect theory on larger samples, but before doing this, it is recommended that a scheme for incorporating the results into an ice crushing pressure size effect be demonstrated.
	Better understanding of scale on the ductile to brittle transition has been obtained. Specifically, laboratory experiments suggest that the transition strain rate decreases with increasing flaw size (l), scaling as $l^{-3/2}$. Again, however, there is a potential problem in extrapolating lab scale results to larger scales.	
	Sloping Structures - The discrete element modelling by Hopkins to simulate ridge formation could be applied to the problem of ridge disintegration when interacting with a structure.	Field measurements to better define the physical and mechanical properties of ridge keels (strength - cohesion - friction angle - constitutive properties; porosity; density etc.).
	Pack Ice Driving Forces - A pack ice stress envelope was developed by Coon and others. This envelope is the largest 2-D stress state that the pack ice can withstand. Such a stress envelope can be used to: a) Define the effect of confining stress on the driving forces on a blocking floe. b) Help define the effect of ice conditions on these forces and enable probabilistic load calculations to be performed (by combining the stress envelope as a yield surface with wind and current distributions).	Complete the interpretation of the in-situ pack ice stress measurements from an ice loading perspective: (i.e. to assess whether there is spatial averaging of ridge building forces across the width of influence and use existing data to establish pack ice stresses as a function of floe width).

	Floe Splitting - The fracture research in the SIMI program will determine the scale dependence on the tensile failure strength as well as provide a fracture model that is applicable to sea ice in the range of 0.1 to 1 km.	Complete the interpretation of the SIMI experimental work to develop a size effect law for fracture and splitting. Develop a new theory for flow splitting from the above (with and without surrounding pack ice).
Ice Forecasting for Ship Routing and Operations	The SIMI anisotropic plasticity ice dynamics model can describe and forecast ice behavior on smaller scales (~ 3 km) than previous models.	Develop failure laws for a complete suite of full-scale processes (*e.g.*, opening, rafting, and ridging), develop a numerical scheme, and test model performance.
Ice Gouging of the Sea Floor	What we now know: The form of the gouge depth distribution at a given instant of time is a negative exponential. The coefficients of the gouge depth distribution function vary systematically with water depth. To obtain meaningful statistics concerning the number of gouges per km or per km^2 per year, a sampling period of several years duration is required. Gouges generally run parallel to the isobaths. The deepest, as well as the most frequent, gouges occur at water depths of between 25 and 40 m.	There is a critical need to develop procedures for determining gouge depth distributions for regions where sediment transport is so large that gouges are so quickly destroyed as to leave no record on the sea floor.
Oil Spills and Oil Transport by the Ice	What we now know: Improved coupled ice-ocean models for central Arctic have been constructed. Nested ocean and ice model techniques have been applied to Arctic problems. Improvements in the convection parameterization in ocean models has been shown to accelerate the melting rate of ice. Improved wind fields from atmospheric models has been applied for input to ice-ocean models.	Small-scale (2 to 10 km) ice-ocean model development and validation, including the anisotropic parameterizations of ice mechanics, to properly characterize the nearshore ice motion since oil transport is primarily by ice motion.

PANEL REPORT ON 100 KM SCALE (PACK ICE)

Chairman: Max D. Coon
NorthWest Research Associates, Inc.

Ruth Preller, Recorder
Naval Research Laboratory

Andre Proshutinsky, Recorder
Institute Marine Science, U of AK, Fairbanks

This panel met Wednesday, April 26, 1995, in the morning. The discussion of the 100 km scale (pack ice) centered around the anisotropic behavior of the pack ice as indicated and driven by the formation, deformation, and closure of leads.

GOALS

The SIMI goals are reported in Appendix B, Vol. 1, of these Proceedings.

- Understand sea ice constitutive laws and fracture mechanics over the full range of geophysical scales and determine the scaled responses to applied external forces
- Develop physically based constitutive and fracture models

One of the aims of the Sea Ice Mechanics Initiative (SIMI) was to bridge scales in sea ice mechanics. This can and has been done by considering pack ice on a scale from 3-100 km as made up of two types of ice as shown in Figure 1. The two types of ice are not necessarily represented by presently used nomenclature. The scene in Figure 1 is intended to represent a sea ice element system with an active lead in it. A lead system is made of parallel leads that are shown as one lead in the element of Figure 1.

So, what is the Type-1 material in Figure 1? The ice in material Type-1 includes multiyear ice, first-year ice, ridged-ice, rafted-ice, and inactive refrozen leads. The material has a wide distribution of sea ice thickness and is made up of closely-fitting, angular particles, grains, or cells, often diamond shaped in the winter. Type-1 material is deformable, controlled by a 2-D Coulomb behavior with no significant thickness redistribution due to deformation. The particles, grains, or cells that make up Type-1 material are of order 100 meters, and they have been formed by out-of-plane loadings such as thermal loading or isostatic imbalance. These loadings have led to cracks which have produced the grains or cells, and the cracks have only partially healed. This cracking and rehealing are the small-scale mechanisms which cause the Type-1 material to have its properties. When this material deforms, it produces new areas for Type-2 material (leads).

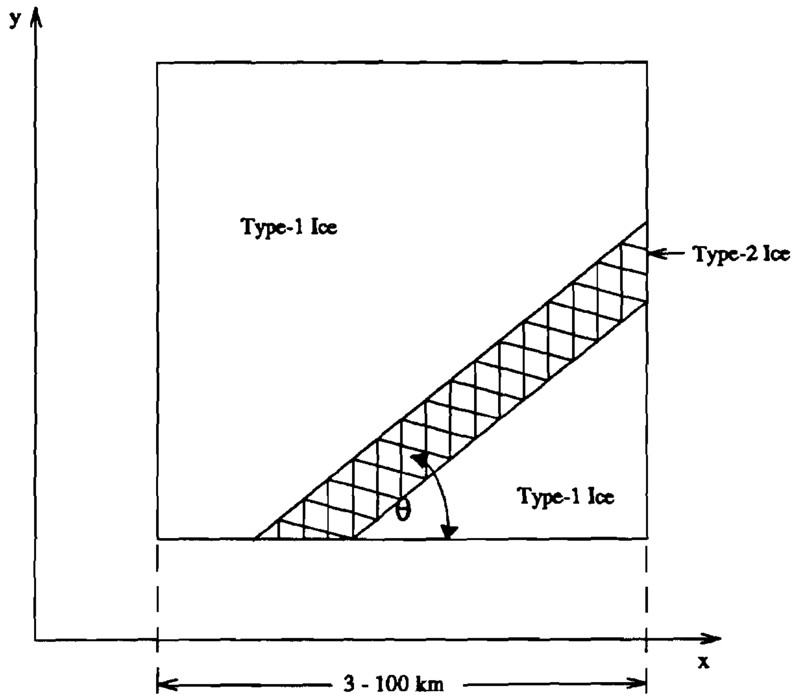

Fig. 1. Element of pack ice with a refrozen lead.

Type-2 material is what we typically think of as lead ice or rafted-lead ice or ridged ice. It is the ice that was formed in the openings made in Type-1 material and then deformed. Therefore, the constituents of Type-2 ice are open water, thin new ice, thick new ice, rafted ice, ridged ice, and floating broken pieces of the lead ice. This material has a thickness distribution which is associated with a direction, θ in Figure 1, and the redistribution is caused by deformation. This material has two discrete kinds of behavior, both of which are the small-scale mechanisms. One is the failure or initialization of dynamics of the Type-2 ice. This initialization is controlled by small-scale mechanisms such as the strength of an intact new ice sheet in tension, compression, or shear. This type of behavior is affected by ice thickness, temperatures, salinity, grain size, and strain rates. Another type of failure of this material is controlled by buckling instabilities which might be elastic under short-term loadings or visco-elastic under longer duration loadings. A third intermediate type of initialization of failure for this material is the buckling of individual (ridged) blocks that might be floating in the lead. The second kind of behavior here is that of the mechanical redistribution of the ice, and this is then controlled by either the rafting process which depends on ice thickness and friction or the ridging process which is controlled by thickness, friction, and change in energy state.

Type-1 ice is isotropic and has a failure surface which can be expressed in terms of stress resultant invariants which change very slowly and may be approximated as constant in time.

The Type-2 ice is oriented, and its failure surface cannot be expressed in terms of invariants and its failure surface varies over shorter time scales (hours) driven by the ridging and rafting pressures. Pack ice is a combination of Type 1 and Type 2 and has an anisotropic behavior whose properties can change over time periods of hours.

Coon et al. [1992] introduced a method for incorporating the behavior of individual leading, rafting, and ridging events into the large-scale constitutive behavior of pack ice. This was not expressed in terms of Type 1 and Type 2 materials, but that is what it represents. The concept is that the large-scale stress state must lie within all of the yield surfaces that describe failure of individually resolved ice features. Ice conditions are described in terms of an oriented thickness distribution including the thickness of ice in leads. In resolving behavior on scales from one to hundreds of kilometers, processes of leading, rafting, and ridging that describe and control the behavior of sea ice are explicitly considered. Previous models [e.g., Coon et al., 1974] are applicable only over scales large enough that the multiplicity of ice features give rise to an isotropic response.

SIMI included nested arrays of drifting buoys to measure deformation on different scales. The large, pack scale Arctic buoy array, with resolution of order tens of kilometers, is not useful for locating individual events. The floe cluster array of GPS and the stress buoys was deployed at roughly 3 km intervals over a uniform grid 15 to 20 km on a side, allowing the deformation of individual events to be tracked. Vol. 1 of these Proceedings discusses the data taken.

The SIMI data collection plan for this scale is given in Appendix B of Vol. 1 which said: "An anisotropic model enables measurements of stress, deformation, and ice conditions associated with individual leading, rafting, and ridging events to be used as components of a large-scale model. During SIMI, these variables will be measured during specific events. At times, isolated events with length scales of order 100 m will likely occur within the floe cluster array while the remainder of the array will be nearly rigid. Such events will be described by observations on the scale of 3 to 15 km by the deformation of the array and by direct ground observations. Airborne imagery of the region near the end of October will help identify earlier events and provide a baseline for comparison in spring. Ice motion vectors will be derived from SAR and AVHRR imagery." A test of this model and data is given by Coon et al. [1995] in this Volume. For the first time, simultaneous measurements of sea ice stress on both sides of a lead, ice motion from sequential SAR imagery, and ice motion from drifting GPS/Argos buoys are compared. The lead, which appeared early in Day 35 (Feb. 4), 1994, was observed, relative motions were calculated across and along the lead direction, and stresses were transformed to this same coordinate system. The lead orientation and approximate location were determined from SAR images of the pack ice surrounding the SIMI camp, as well as net ice motion at 3-day intervals. The ice motion around the lead was provided in greater detail by an array of drifting GPS/Argos buoys producing hourly positions. Sea ice stress was measured on each side of the lead using flapjack sensors. The ice motion normal to the lead and the ice stress normal to the lead are compared as well as the ice shear motion and the ice shear stress.

Shortly before the lead opening motion is apparent in the ice motion data, the ice stress state abruptly changed from biaxial compression to uniaxial compression with traction on the lead near zero. We thus measured the stress conditions at lead creation as sheared compression; there was no tension at the time. The Type-1 ice, made up of closely fitting angular particles, begins to fail and create a lead under shear and compressive stress just as sand can expand under shear and compressive stress by going from a closely packed configuration to a loosely packed configuration. As the lead continues to open the stress normal to the lead is zero, the stress parallel to the lead is compression, and there are no tensile stresses. Excellent correlation was observed between ice motions measured with SAR products and drifting buoys. The SAR products provide a more precise definition of the orientation of the lead. It was also concluded that a properly installed 20-cm stress gauge in a single floe can provide a reasonable measurement of the large-scale (50-km) pack ice stress resultant.

The needs of two user groups were expressed during the meeting. Ruth Preller expressed needs from the National Ice Center for methods of predicting leads (interpreted to mean direction and area) and a need for smaller scale, i.e., a few kilometer resolution. Ruth went on to describe the plans for the Navy in its Polar Ice Prediction System (PIPS) to have a model which would cover all areas in the northern hemisphere covered by sea ice with a resolution down to 20 kilometers. There was discussion and concern about one model being acceptable for the multi-year pack ice in the central Beaufort Sea and the marginal sea ice zones. One model can be made to work if the ice properties in the model vary sufficiently such that the multi-year and marginal regions can be described.

The needs of the oil industry were articulated by Albert Wang. Albert explained that for the oil industry real-time information was important. Forecasting of the pressure in the ice was a key as well as the ice conditions including leads and thickness distribution. There is a desire to use large-scale ice models to get large-scale forces that would be valuable for loads on structures. There is a need for ground truthing of the models such that confidence can be developed. For the oil industry and offshore operations, a three-to-four-day forecast of extreme events would be desirable but a one-day forecast could lead to a form of orderly shutdown.

Kate Hedstrom discussed ice modeling work at Rutgers University where they are coupling an ocean model to an ice-atmosphere climate model (ARCSyM, from U. of AK, Fairbanks). They also have done ice-ocean modeling for use in oil spill risk assessment studies for MMS. A third project involves the development of a spectral finite element ocean model to be used on a global, variable-resolution grid. Several of these projects require an ice model with better small-scale ice physics. For additional information, see Hedstrom (1995) in this Volume.

Igor Appel of Fairweather Forecasting discussed a model they use. The approach used is described in Appel (1990) and results of the model are presented in Appel and Samuels (1995). In this model the anisotropic behavior (interpreted as leads) is described by a viscous model. The viscosity depends on the value of principal strain rate. In this model the leads would open across the direction of the principal extension strain rate direction. This is a difference between this model and that of Coon et al. (1992) when there would be an angle between the direction of the lead and principal strain rate direction. In the work of Cunningham et al (1994), there is evidence of such an angle.

There is also a model by Moritz (1995) that accounts for leads in a statistical manner. In this model and the viscous model discussed by Appel there is no direct way to bring in the small scale ice mechanics as there is with the Coon et al. model.

The need to be able to account for leads and their behavior is a theme that comes up in many of the other panel discussions on ice behavior and applications in this Volume. Accounting for this behavior and using small scale mechanics to do so will meet the goals of SIMI as stated above.

The discussion of the panel is summarized by the two lists below. The first item in each list is that of most importance.

LIST OF THINGS WE HAVE LEARNED:

1) From GPS buoys, stress buoys, and SAR, the importance of lead formation and direction, on the large scale behavior of pack ice, has been verified. New leads have been shown to be created from states of compression and shear stress as measured on the scale of a floe but representing stress on tens of km. Also when leads are open the measured stress state is compression parallel to the lead and zero perpendicular to the lead. These findings are new and very important to the large (100 km) behavior of the ice.

2) We have developed a formulation for an anisotropic behavior (constitutive law) for pack ice which can account for creation and direction of leads

3) Examples of improved ice-ocean models are northern hemisphere PIPS, ARCSyM (U. of AK, Fairbanks and Rutgers University), etc. Desirable features are:
   - Higher resolution coverage,
   - Ability to assimilate satellite data, and
   - Coupling to the atmosphere.

WHAT NEEDS TO BE DONE NEXT:

1) Need formulation and verification of model against deformation (strain rates), leads (direction and deformation), and ice concentration using buoy and satellite data.

2) Need to put new rheology into improved models.

3) Need to use SIMI data to quantify the terms in the new constitutive law.

4) Need to incorporate results of smaller-scale models in large-scale model.

5) More aware of user needs.

LIST OF ATTENDEES

- Ruth Preller, Naval Research Laboratory
- Kate Hedstrom, Rutgers University
- Mike Vanwort, Office of Naval Research
- Igor Appel, Fairweather Forecasting
- Andre Proshutinsky, Institute Marine Science
- Max Coon, NorthWest Research Associates, Inc.
- Ed Fremouw, NorthWest Research Associates, Inc.
- Albert Wang, Exxon Production Research Company

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PANEL REPORT ON THE 10 KM SCALE - FLOE CLUSTER

Jim Overland, Chairman
NOAA- PMEL

Bryan Kerman, Co-Chairman
AES Canada

Jackie Richter-Menge, Recorder
CRREL

Gordon Cox, Recorder
Amoco Eurasia

The 10 km scale is critical to understanding and modeling spatial and temporal variability of sea-ice dynamics (Figure 1). Applications are ice forecasting, ice loads on structures, and pollution transport. At this scale there are two important transitions as the scale increases: from understanding ice as discrete floes to a continuum medium and from a stochastic view of ice processes to deterministic parameterizations. In the early 1970s, during AIDJEX, researchers developed the concept of sea ice on the regional scale as a strain-hardening plastic material. This remains the prevailing approach. In a plastic response, as the external forcing increases, the stress in the ice pack will increase up to a certain failure limit, at which point the ice will deform. As the pack ice converges, its strength/compactness/thickness increases and thus its failure limit increases and the pack "hardens". This process results in the development of regional stresses in the ice cover, which probably relates to sea-ice features such as the long, linear leads seen on AVHRR images. The question exists as to whether these sea-ice dynamics assumptions are valid based on measurements at the 10 km scale, where we consider a cluster of floes.

The essential processes that control ice-dynamics behavior are leading, rafting, and ridging. The present generation of isotropic sea-ice models were originally developed to describe ice dynamics on scales averaged over 100 km and larger. Researchers hypothesized that this scale was large enough to include the effects of many leads and/or ridges at random orientation within the sampling scale. There are times, however, when an individual large feature can dominate behavior even on these scales; for example, if one huge lead opens or narrow, linear discontinuities propagate in from boundaries. The isotropic model may adequately represent behavior averaged over 10 km, such as during conditions just after freeze-up when the floes are small (<1 km) with randomly oriented thin ice between them. As the scale is reduced from 100 km, however, the likelihood of encountering strongly oriented features increases, particularly for winter pack ice conditions. Thus, to resolve regional sea-ice dynamics behavior it appears necessary to account for anisotropy. Deriving more accurate solutions by reducing grid size in existing models is beneficial, but these solutions must still be interpreted as averages over the larger scale. A major conclusion of SIMI research is that it is important to understand and model anisotropic sea-ice processes on the 10 km scale to correctly interpret processes on the 100 km scale. The final summary discussion of the meeting noted a need to merge the 10 and 100 km scales in terms of understanding ice mechanics.

The findings of LEADEX and SIMI Experiments indicate a mismatch in scales between the forcing on the ice field, primarily wind and coastal orientation, and pack ice itself. Atmospheric storms have large spatial scales (order of 800 km), and small temporal scales (order of days). Regional sea-ice motion has a temporal scale of a week or longer and a spatial scale of kilometers. Therefore, the cluster scale response of the sea ice is not directly forced by a similar cluster scale variability in the wind. The cluster scale response of the ice is determined by the aggregate mechanical properties of the ice field in response to nearly uniform wind fields, acting over 3-5 days, before or after passages of a storm front. Figure 2 shows a SAR motion vector plot for a shear/opening event near day 35 in early February 1994. The vectors are 5 km apart. There are large regions (plates?) which behave with apparent solid body motion separated by long (100 km), narrow (<5 km) shear lines. The sea-ice problem on the 10 km scale is the aggregate problem: describe a material which under uniform winds, subject to boundary forcing, will respond by the formation of plates, which are large compared to the floe size and separated by discontinuities. Also, what pack-ice mechanical processes result in this material description when aggregated? A goal of SIMI and post SIMI research is to describe and model this internal sea-ice mechanics.

During the SIMI field program, researchers examined sea ice dynamics concepts at a variety of spatial and temporal scales. The 10 km studies concentrated on identifying and studying cluster-scale events during an extended period with both Synthetic Aperture Radar (SAR) data and Global Positioning System (GPS) buoy data (Days 23 to 75). Three technical advances facilitated this work at the 10 km scale. The first was the availability of ice motion vectors derived from SAR data processed at the Alaska SAR Facility. This product uses sequential SAR images to track ice motion at a 5 km resolution over an area of 80 X 80 km per product. Taken together, these products can define regional (80 x 400 km) deformation fields at a three day sampling interval. The second technical advance was that the accuracy of the GPS allowed researchers to resolve relative motions between adjacent floes in the vicinity of the SIMI ice camps. These GPS measurements provided a comparison between the differential GPS ice motion with the SAR-derived ice motion fields. The third advance was the deployment of arrays of stress sensors that had been developed and tested on earlier experiments. Two major events were studied during the SIMI period. One significant event occurred in early February 1994 (days 38 to 41) with uniform northerly winds in which a convergence/shear event propagated northward away from the coast, reaching the location of the SIMI ice camp 400 km north of Alaska in 3 days. A major opening/shear event occurred between days 63 to 74.

Preliminary results from a 20 km stress and deformation array, centered about the west camp floe, suggest a correspondence between stress and deformation at the 10 km scale, but not at the 5 km scale. Further, a comparison of in situ stresses on the central ice floe show a strong linear correlation in time, indicating that the floe responds to regional (10 km), rather than local (1 km) deformation events. Together these results imply that there is a lower bound, between 10 and 5 km, for considering the ice floes in a region as a continuum. There is a higher frequency of major stress and regional deformation events as compared to large-scale (50 to 100 km) deformation events, defined by the formation of shear line patterns observed in SAR images. This may indicate several levels of continuum behavior, with the basic unit being a cluster of floes on the scale of 10 km. Once the floes within these clusters have moved into a close-packing, the clusters themselves can lock together in response to a forcing system. This structure can then form regional plates separated by discontinuities.

There are several promising approaches to describe the ice interaction and the spatial evolution of stress at the 10 km scale. One approach is to model the pack ice as a classical granular material with an effective stiffness and strength. Results of such models suggest that variation in size, shape, and orientation of the granular elements, or ice floes, are important to producing fracture-like features. Application of this technique could lead to the development of an effective (i.e., large-scale parameterization) constitutive response (i.e., stress/strain rate relationship). A very promising approach is to directly observe the aggregation properties of pack ice through the analyses of SAR imagery. Two state parameters, texture and structure, can be derived from measures of nearest neighbor pixel intensity differences on the SAR data. Sharp changes in the slopes of observational points on a texture/structure axis plot have an analog to phase transitions and may correspond to boundaries between different ice types. There is a relationship of "information content" between these analyses and similar 1-D analysis of ice thickness estimates from sonar. There are subsets of SAR pixels which possess a similarity property which are multi-fractal. These sets display a critical connectivity tentatively associated with ice fracture nucleation, i.e., similar to avalanche phenomena. A value exists of the nearest neighbor probability measure where pixels are mobilized into a space-spanning path called the percolation cluster. For large-scale compression of a mixture of stiff, brittle inclusions (i.e., multi-year ice floes?), and the percolation cluster (i.e., the rubble field?), the least unconsolidated part absorbs the strain. In materials other than ice, observations show that stress is transmitted along such poorly bonded paths. If the analog of sea ice to other stochastically described materials is consistent, then the percolation cluster hypothesis associated with FY rubble/ridges, may relate to the load-bearing capacity of the ice field.

A third approach to model pack ice at the 10 km scale is the oriented pack ice constitutive law. This law includes the creation of new leads in thick ice and the effects of leads and their orientations on the strength of the ice cover. The behavior requires an oriented ice thickness distribution to account for the growth and deformation of ice in refrozen leads. The shear and compressive strength of each lead are functions of the lead's ice thickness distribution. This approach predicts the orientation of lead systems and accounts for the highly anisotropic strength of the pack ice resulting from lead systems.

In summary, wind and coastal boundaries have large spatial scales (order of 500 km) while ice response is at all scales, with a tendency to form long, linear discontinuities at the 10-100 km scale. There are distinct patterns apparent in currently active leads and ridges which depend on boundary conditions and the type of forcing. Historical ridges and leads may appear more random. There appears to be a scale discontinuity in understanding between the regional and smaller scales. At the 0.1-100 m modelers can provide scaling laws for strength. However, at the 1 km scale much of the work on ridging is focused on linear compression, where evidence from

SAR analyses suggests that shear is a major yield mechanism and that failures follow lightening bolt, fault-like structures. Studies of strengths and failures of 1 km structures need to be coordinated with the horizontal 2-D percolation ideas discussed above. It is important to understand how stress propagates through the pack based on coastal orientation, wind forcing and ice property distribution on a 10 km scale.

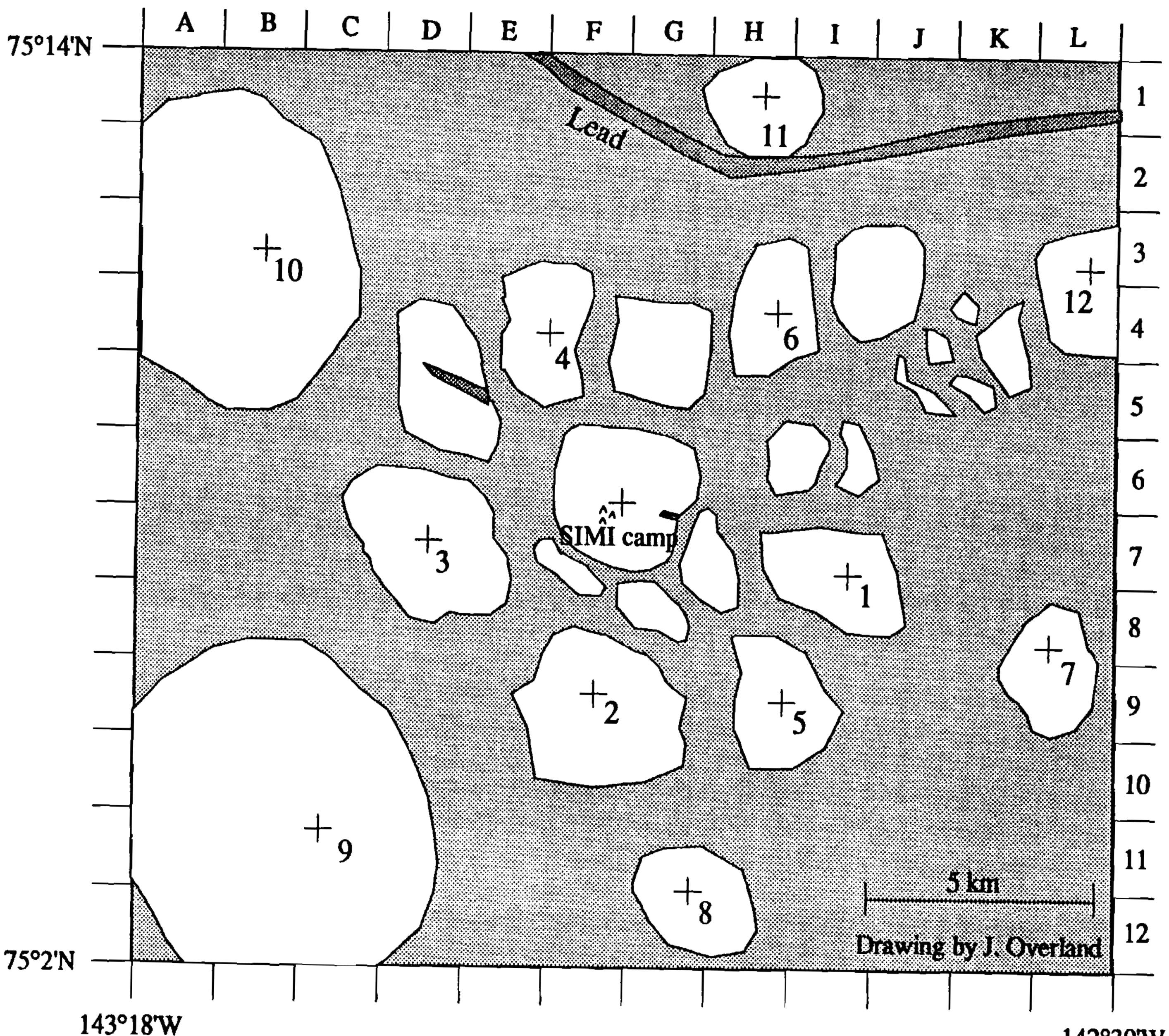
The group stated that the most important SIMI accomplishment was to acquire the first major data set of stress and strain rate of a pack ice cover on the 10 km scale, and to correlate this with results from both smaller and larger scale observations. There was good correlation between stress and strain rate at the 10 km scale, but not at small scales, even though the stress and strain measurements existed down to a 1 km scale. We believe that ice can be treated as a continuum at 10 km as long as the medium allows plate/discontinuity type structures.

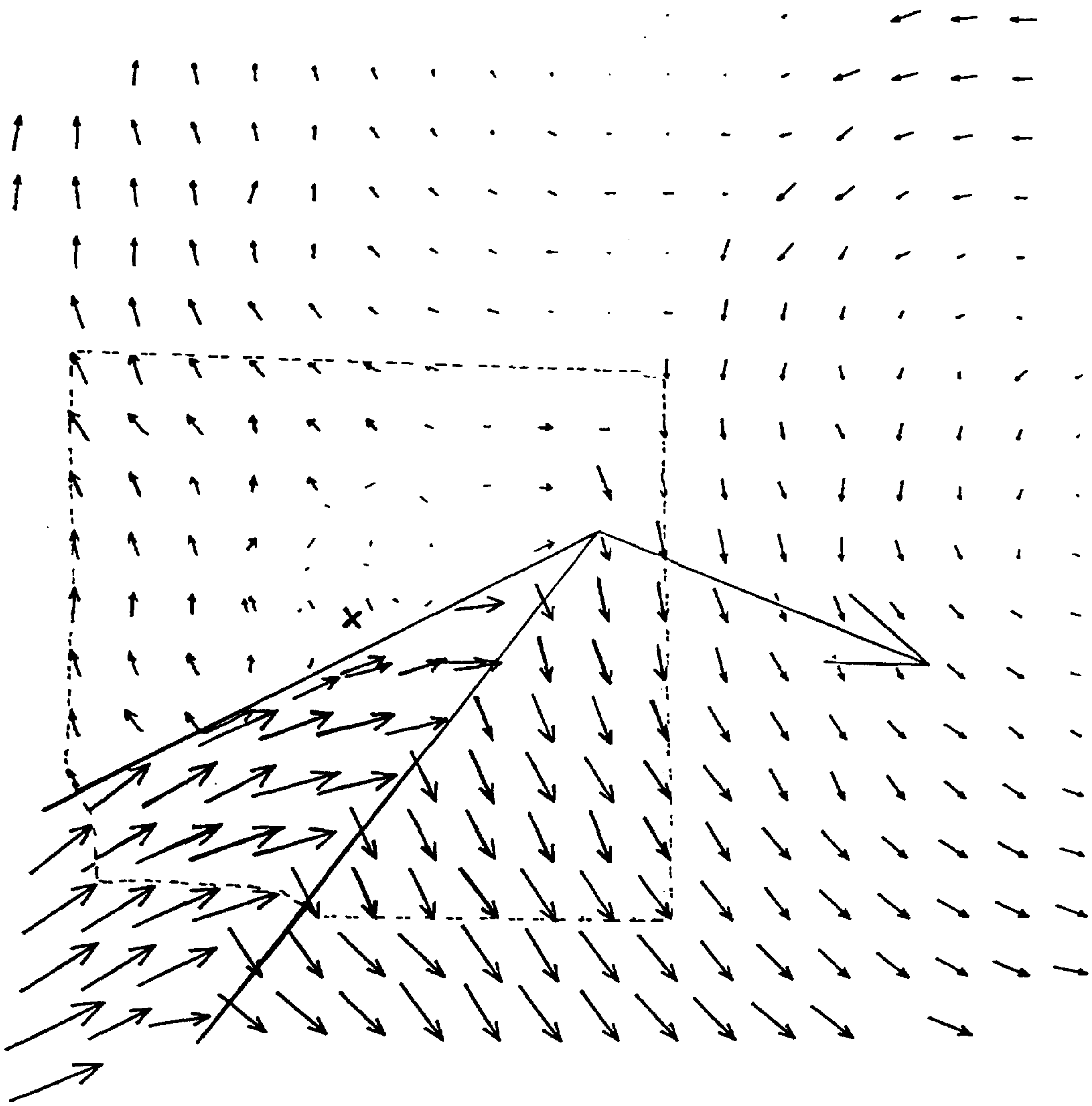
The group recommended that the main goal for future research is to understand what mechanical processes control the spacing of discontinuities (slip lines, leads, etc.). On AVHRR imagery there seems to be a preference for a 15 km and a 35-40 km separation scale. There is a need for more case studies of the stress-strain relationship for ice deformation events and modeling of buckling, rafting, and ridging in a 3-D context to characterize the anisotropic strength parameters of pack ice in terms of an oriented thickness distribution.

Figure 1. Distribution of large floes in the vicinity of the SIMI camp. Space between the larger floes was filled with rubble and small floes.

Figure 2. Relative motion of an ice field in the vicinity of the Ice Camp on day 35-38, 1994 from 5 km spacing SAR motion data. The large arrow is north. (Figure courtesy of H. Stern).

Map 1. Vicinity of SIMI West Camp, September 1993.





REPORT OF THE 1-KM-SCALE PANEL

By

Mark Hopkins
US Army Cold Regions Research and Engineering Laboratory

and

Henrik Schmidt
Massachusetts Institute of Technology

The large-scale composition of the ice pack is the aggregate of the basic 1-km-scale building blocks, discrete parcels of multiyear and first-year ice, and leads. Similarly, large-scale deformation is the aggregate of the basic 1-km-scale processes of pressure ridging, rafting, in-plane sliding, and opening, which redistribute energy from larger scales to smaller scales. By determining stress levels in the surrounding pack, 1-km-scale processes help define design loads on offshore structures. The 1-km-scale work in the SIMI program should be assessed on the basis of the following criteria:

- Contribution to understanding of the processes of ridging, rafting, floe splitting, and in-plane sliding between ice parcels;
- Contribution to determination of realistic estimates of forces on offshore structures;
- Contribution to large-scale modeling efforts.

1-KM-SCALE PROCESSES

Pressure Ridging

A realistic computer model of the pressure ridging process [Hopkins] was developed in SIMI. This two-dimensional ridging model is based on a concept of ridge growth in which an intact sheet of thin ice is driven against a thick ice floe. The key assumption is that the ice sheet breaks in flexure. The important features of the ridging model are: a dynamic linear viscous-elastic model of a floating ice sheet, flexural failure (including buckling) of the ice sheets, blocks broken from the parent sheet at points where tensile stress exceeds strength, secondary flexural breakage of rubble blocks, inelastic contacts between rubble blocks, frictional sliding contacts between blocks, separate friction coefficients for submerged and above water contacts, buoyancy of the ice sheets and rubble, and water drag. Simulations were performed with the model to determine the energetics and dynamics of the ridging process. Major unknowns in modeling the ridging process are the various friction coefficients.

In-situ friction measurements between blocks of sea ice were made during SIMI by Coon et al. and Pritchard. Preliminary analysis [Pritchard] of data from dry override tests points to a coefficient of sliding friction of approximately 0.8+-0.2 and a static friction coefficient of approximately 1.2+-0.2. Corresponding values in wet rafting tests were approximately 0.2 and 0.4. In pressure ridge simulations [Hopkins], the various friction coefficients were found to control the relative volumes of the ridge sail and keel. The coefficients which gave the most realistic balance between sail and keel volume were in the range 0.8 to 1.0 – very similar to the values found by Coon and Pritchard. The ridge simulations were less sensitive to the underwater (wet) friction coefficient, but again values of 0.3 to 0.6 used in the simulations were similar to the values reported by Coon and Pritchard. Because sliding friction is the dominant energy sink in the processes of ridging, rafting, and the compression of floating rubble, this data set should be studied carefully.

Based on the results of long-term ridging simulations [Hopkins], the pressure ridging process can be divided into three phases. The first phase begins with an intact sheet of relatively thin ice impacting a floe and ends when the maximum sail volume is reached. In the second phase, the ridge keel maintains a triangular shape, deepening and growing in the leadward direction, eventually creating a rubble field of more or less uniform thickness. The second phase continues as long as there is a sufficient driving force and a supply of thin ice. The third phase is the compression of the rubble field between floes. In this scenario, the formation of rubble fields naturally follows the formation of ridges.

The effect of consolidation on the strength of first-year pressure ridges and rubble fields was the subject of numerous discussions during the workshop. In coastal areas, consolidated rubble fields and pressure ridges are an important consideration in the design of offshore structures. Consolidated pressure ridges are a major impediment to ship passage and may increase the severity and depth of scour events in near-shore areas. Future pressure ridge modeling efforts should focus on the effects of consolidation on the strength of ridges and rubble fields. The study of the consolidation of a first-year ridge by Shapiro et al. will be useful in such an effort.

Opening

Macro-cracks in first-year and multiyear ice precede lead formation. Deformation and fracture processes at the scale of 1 km are characterized by formation of ordered systems of cracks as well as coupled systems of cracks and ridges. Tensile crack formation perpendicular to a ridge was detected acoustically during the SIMI field program [MIT]. Systems of cracks perpendicular to ridge lines have been theoretically predicted by Goldstein and Osipenko (1995).

Acoustics provide the only viable remote sensing capability for detecting, characterizing, and identifying failure mechanisms in natural sea ice on the 1-m to 10-km scale. A major SIMI accomplishment is the development of a layered approach to seismo-acoustic mapping of sea ice fracture processes. The concept uses a 32-element horizontal hydrophone surveillance array with a 500 aperture. Focus beamforming is performed using parallel processing, producing a real-time map of ice seismicity over a floe cluster, permitting early detection of active floe boundaries. When an active region is identified, a mobile array of five 3-component geophones and a single hydrophone is rapidly deployed to provide near-field measurements of the acoustic emission from the ice fractures. An important component of this concept is the development of a novel digital telemetry system, providing a wireless extension to a local-area network in the camp. This permits wireless data transfer from geophone clusters.

During the Fall and Spring SIMI experiment the layered concept successfully detected, located, and monitored several ice-mechanical events [MIT]. A particularly interesting event was a large, 1-km-scale fracture, mentioned above, which propagated transversely from a new ridge located N of East Camp. Another event was the formation of a major lead 2 km NE of East Camp in the latter part of the experiment. The dynamics and refreezing of this lead was monitored by two geophone clusters for several days, providing near-field measurements of acoustic emissions from rafting and early ridge building processes. At the same time, strong signals corresponding to what are believed to be "edge waves" were recorded. A preliminary analysis of this data suggests that the signals were associated with a 20 s stick/slip behavior along a lead which was part of a large, 30 – 40-km long, lead structure. Similar waves were recorded by tilt-meters and accelerometers at a ridge on the perimeter of the West Camp floe [Wadhams].

Another accomplishment on the floe scale was the execution and monitoring of plate wave experiments performed at Resolute as part of SIMI using automated hammer blows and geophone arrays. The analysis of the data collected [MIT] suggests strongly frequency dependent, transverse anisotropy of the sea ice. The precise nature of the frequency dependence is unresolved.

The analysis of SIMI seismographic data will address the following issues:

- Spatial and temporal statistics of ice events in the vicinity of the West Camp. The spatial distribution of fractures in relation to old and new ridges is of particular interest;
- Analysis of data from geophone arrays for fracture type, size, and speed. The analysis is expected to reveal the dominant fracture mechanisms associated with rafting and ridging. The results should be compared with recent theoretical predictions of compression induced ice fractures [Goldstein];
- High-resolution analysis of plate wave data has revealed frequency dependent anisotropy of sea ice. This behavior may be associated with unknown phenomena having a length-scale of 20 – 40 m;
- Edge waves were observed in SIMI along leads [MIT/WHOI] and along ridges on the floe perimeter [Wadhams]. The floe recordings of Wadhams indicate narrow-line spectrum, whereas the lead recordings by MIT/WHOI are of a more wide band nature which suggest a 20 s period, stick/slip dynamic behavior of motion parallel to leads. This observation may shed light on the dynamics of in-plane sliding between ice sheets.

THERMAL STRESSES AND CRACKING

The splitting processes which dictate the size of floes are poorly understood, particularly the role of thermal cracking in furnishing the precursors for large-scale crack growth. Although the research [Stein and Lewis] into thermal stresses is fully addressed in the report on the 10 – 100-m scale, it is important at the 1-km scale and some of the results are also mentioned here. The seismoacoustics work has shown that extensive thermal cracking occurs on the successive cold nights which follow frontal passages.

Thus, thermal cracking occurs 1–3 nights in a row on roughly a weekly basis from early fall through spring. The modeling predicts both the stresses and the occurrence of fracturing accurately. Cracks have been observed which are 10's of meters long and 10's of cm deep. Modeling shows that these cracks first extend and connect across the floe and then can extend downward through the floe. Stein and Lewis hypothesize that thermal fracturing is a means by which the ice maintains its weakness in tension. Effectively, at the floe scale, the ice is infinitely weak in tension. This is supported by the stress data, which shows that tensile stresses only develop as a result of thermal effects and not as a result of wind and current induced forces. Future work should focus on a detailed spatial and temporal mapping of thermal cracks at the floe scale.

FORCES ON STRUCTURES

Design loads on offshore structures are based on three competing criteria [Croasdale]: "limit stress" due to local failure of the ice in contact with the structure, "limit momentum" due to collisional transfer of momentum, and "limit force" due to pressure ridging and other failure processes in the surrounding ice pack. The first, "limit stress", depends on local crushing and splitting, a topic discussed in the 10-m-scale report. The second, "limit momentum", was not considered in SIMI. Pressure ridge modeling and stress measurements in SIMI contribute to our understanding of "limit forces".

The multiyear floe is the basic unit of the ice pack and a natural platform for in-situ stress measurements. Measurements were made at a number of sites on the floe that served as a base for the SIMI West Camp. Preliminary analysis [Richter-Menge] of this data shows peak stresses measured at the floe edge during winter were typically from 100 – 250 kPa with a maximum of 400 kPa. This finding is in good agreement with earlier studies on pack ice stress and may provide a lower bound for design loads for offshore structures. Stresses measured at the center of the floe were a combination of a dominant thermal component and a dynamic component due to edge loading. The dynamic component of the center stress was typically attenuated by an order of magnitude compared to the stresses measured at the floe edge. Data from stress sensors located on radial lines between the floe center and the edge sites have not yet been processed. Analysis of this data will focus on the attenuation process. Future work should address the magnitude and distribution of stresses around a floe boundary.

Coon et al. have developed a simple and elegant approach to defining limiting values of pack ice failure stresses. They plot a large number of hourly stress measurements in a Cartesian frame in which the axes are the pressure and shear stress invariants. The data points define a failure envelope with a magnitude in the 100 – 200 kPa range. This approach, which may obviate the necessity for a detailed knowledge of failure processes, should be applied to stress data collected by other investigators.

The forces exerted by the pack ice on offshore structures are limited by the strength of the surrounding ice pack. The strength of the pack depends, in turn, on the strength of individual pressure ridges and rubble fields distributed throughout the surrounding pack. Long-term simulations using the pressure ridge model have determined maximum sail heights, keel depths, and ridge building forces. Average ridging forces obtained from the simulations range from 20 kN/m for 30-cm-thick ice to 90 kN/m for 100-cm-thick ice. Peak forces are typically 3 times larger. The convergence between ridging forces calculated in simulations and in-situ stress measurements point to pack stress levels in the 100 – 200 kPa range.

CONTRIBUTION TO LARGE-SCALE MODELING EFFORTS

A large fraction of the energy imparted to the pack ice by driving forces is ultimately dissipated in the formation of pressure ridges. The potential energy of the ridged ice in an area of the pack can be calculated from knowledge of the ice thickness distribution. However, the potential energy represents but a small fraction of the energy dissipated in ridging. The ratio of the total energy expended in ridging to the increase in potential energy of ridged ice is an important parameter used in large-scale ice/ocean models to calculate the strength of the ice pack [Hibler, Flato]. Determination of the ratio of ridging work to potential energy was a major goal of the pressure ridge modeling efforts in SIMI. In pressure ridging simulations, with the discrete element model of the ridging process described above, the ratio of work to potential energy varied from 10:1 to 17:1 depending on ice thickness. Since the ratio had typically been assumed to be 2, this is equivalent to a large increase in the assumed strength of the ice pack.

The correct form of the plastic yield surface used to define failure stresses in large-scale sea ice models has never been empirically determined. The stress envelope determined by Coon et al., that is described above, may be useful in this regard.

SUMMARY OF MOST IMPORTANT ACCOMPLISHMENTS IN SIMI

1) Determination of the ratio of work to potential energy in pressure ridging;
2) Identification of three stages of pressure ridging beginning with ridging of intact thin ice and ending with creation of a rubble field;
3) Convergence between in-situ stress measurements and pressure-ridge modeling results which point to peak pack ice stresses in the 100 – 200 kPa range;

4) Compiled the longest existing time series on spatial and temporal variability of pack ice stresses at the floe scale;

5) Development of ability to acoustically locate and map failure processes such as ridge building and crack formation;

6) Identification of strongly frequency dependent transverse anisotropy in sea ice;

7) In-situ ice friction measurements.

SUMMARY OF MOST IMPORTANT WORK REMAINING

1) Determine the effects of consolidation (formation of a frozen layer growing down from the water level and contact freezing between ice blocks) on the strength of first-year ridges and rubble fields;

2) Determine the stress distribution in a floe from local events such as ridge building, which take place on the perimeter;

3) Identify phenomena responsible for frequency dependent transverse anisotropy of sea ice;

4) Understand how thermal pre-cracking facilitates the floe-splitting process.

10 METER SCALE (MACRO-CRACK)

Scale Effects On The Fracturing Of Sea Ice

John Dempsey, Chairman
Clarkson University

Walter Bugno, Co-Chairman
Chevron Petroleum Tech. Co.

Peter Stein, Recorder
Scientific Solutions, Inc.

Zdenek Bazant, Recorder
Northwestern University

The broad goals of the Sea Ice Mechanics Initiative (SIMI)[1] are to develop physically-based constitutive laws and fracture models to describe the deformation of sea ice over the full range of geophysical scales. This chapter summarizes information gained to date over the range 1 - 100 m. Guidance for future research directions is also provided.

At the outset of the SIMI program it was realized that significant research efforts needed to be focused on the 1 - 100 m scale, in order to bridge knowledge at the 10 cm - 1 m scale with knowledge at the scale of 1 km and above. Several research issues have since been identified that lie at the core of efforts to bridge these scales, *viz.*,

- Do the fracture properties at the large scale differ significantly from those at small scale?
- Can laboratory-scale testing be used to predict fracture and strength properties at large scale?
- What particular problems are faced with large-scale testing?
- What is the status of existing size effect laws? What is their predictive capability?
- Are there important differences between different scale effects - be they in-plane (floe-floe interaction, floe splitting) or bending (penetration, submarine surfacing)?
- What progress has been made in relating the mechanical and physical properties of sea ice?
- What are the important forcing mechanisms at large scale, be they due to thermal or kinematic (as in ice-structure interaction) conditions?

[1]Volume 1 of the Proceedings of the Sea Ice Mechanics and Arctic Modeling Workshop (abbreviated from hereon as *SIMIW*) held in Anchorage, Alaska, April 25-28, 1995 has research summaries of most of the investigators involved in the SIMI project. Reports of particular relevance to this chapter are those by Bazant et al (fracture), Cole (properties), Dempsey and Adamson (large scale controlled fracture and cyclic & creep recovery testing), Farmer and Xie (acoustics), Shapiro et al (properties), Lewis and Stein (thermal fracturing), Petrenko and Gluschenkov (electrical/electromagnetic signals), and Rodin et al (constitutive/fracture) (listed in full in the references).

An up-to-date collection of technical papers by these investigators (and others) is found in the bound volume edited by Dempsey and Rajapakse (1995) entitled *ICE MECHANICS - 1995, ASME AMD-Vol. 207*, proceedings of an ice symposium held at the ASME Joint Applied Mechanics and Materials Meeting, Los Angeles, June 28-30, 1995.

- Do we need detailed small scale information at the large scale (in the context of ice-structure interactions)?
- What is the path from current status to the prediction of forces on structures?

ACCOMPLISHMENTS

Large-Scale Fractures Generated By Controlled Load Tests: Many of the issues identified above have been discussed (Adamson et al, 1995; Dempsey and Adamson, 1995; Mulmule et al, 1995). It remains here to single out the most important findings.

- Dempsey and co-workers at Clarkson University have determined from preliminary analyses of the data obtained from the second field trip (Phase II: 0.5 - 80 m) that there is a significant scale effect on the strength of first year sea ice. There is a separate section devoted to this finding.
- Dempsey and co-workers have determined from analyses of the data obtained from the first field trip (Phase I: 0.34 - 28.64 m) that there is a scale effect on the strength of large-scale macrocrystalline freshwater ice. Though there is a scale effect, efforts to fit any type of size effect law proved fruitless. Unfortunately, the specimen sizes tested do not seem to have been large enough to rule out specimen inhomogeneity effects. That is, specimen size versus grain size (which were up to 0.3 m in size) and grain orientation versus crack plane orientation effects dominated over too large a fraction of the size range studied (even though sizes up to 29 m in length were tested). Rodin has made some interesting analyses and observations regarding this issue that seem to agree with the experimental observations. Much larger specimen sizes need to be tested on this ice type.
- Since the transitional test size for first year sea ice is of the order of 3 m for the rate studied, the use of linear elastic fracture mechanics at lab scale is correct for suitably high loading rates only. Lower loading rates require a nonlinear fracture mechanics treatment or the testing of much larger specimens. Significantly, the nonlinear fracture mechanics framework is still under intense development. Almost all available present fracture lab data is jeopardized by this sub-size issue.
- A very large amount of constitutive information in the field has been obtained—see the *SIMIW* reports by Dempsey and Adamson, Cole, and Shapiro et al. Combined with the large-scale fracture test information, field applicable physically-based constitutive and fracture models can now be quantitatively developed.
- Acoustic (Farmer and Xie, 1995) and electromagnetic (Petrenko, 1995) signals from controlled fracture tests allow the key parameters to be deduced: fracture scales, cracking speed, jump-arresting time scales. The data analysis has uncovered new revelations on the behavior of 10-100 m scale fractures. Crack signatures demonstrate that fractures propagate with a start-stop behavior. Individual small segments of a large crack propagate at roughly 400 m/s, while the overall crack propagates at

roughly 20 m/s, much slower than previously thought. Studies were also conducted to measure the signature of various failure mechanisms including stick/slip and ice block impacts. These studies will enhance the ability to invert the acoustic signatures to infer the cracking mechanisms.

- Distinct technical advantages reside with cooperation between the sea ice mechanics specialists and the acoustic/electromagnetic specialists. The generation of acoustic, electrical, and electromagnetic signals from controlled load tests has advantages for both groups.

Thermal Fracturing: The modeling and measurement effort related to thermally induced fracturing has obvious relevance at a scale lying between 10 - 100 m and above. Thermal fracturing is the most pervasive of Arctic ambient noise mechanisms at frequencies between 500 and 1500 Hz. Generally, it is understood that extensive thermal stressing occurs from early fall through spring in both first year and multiyear ice. However, thermally-induced fracturing is apparently more extensive in multiyear ice. Episodes of high thermal fracturing activity occur generally on successive cold nights and following frontal passages (every 3 to 7 days). Thermal fracturing impacts the entire ice pack on almost a daily basis. It has been speculated that thermal forcing extends existing cracks laterally and vertically with the ability to weaken and, eventually, split a floe. As cracks are extended by thermally-induced fracturing, a floe's capability to withstand additional tensile stressing is further weakened. Tensile thermal forcing will tend to eventually split a floe along existing cracks and form leads. Moreover, thermal cracks may well have an orientation as a result of the ubiquitous c-axis alignment.

The most important findings in the area of thermal fracturing are:

- Thermal fracturing occurs at very low stress levels, on the order of 50 kPa in tension.
- Only tensile stresses which are induced by thermal forcing occur in the Arctic pack ice. This is supported by stress measurements which clearly show that a floe never undergoes a tensile stress induced by winds and currents.

Seismoacoustic Findings: Recent measurements of the elastic wave propagation through a floe are also revealing important aspects of the mechanical nature of the Arctic pack ice on the 10-100 m scale. These measurements can be used to give the bending rigidity of the ice on scales associated with the wavelengths of propagating waves. Data were collected on both very clean first year ice and highly irregular multiyear ice.

- The data from first year ice shows a distinct jump in the bending rigidity of the ice as the spatial scale increases above 30 m (Schmidt et al, 1995). It is hypothesized that this is a result of existing cracks distributed over the floe.
- The wave propagation shows an anisotropic behavior of the ice with clearly different vertical and horizontal shear modulii, and a vertical shear modulus much slower than previously thought.

Further work needs to be performed to understand these phenomenon and how to best use the information to determine the ice mechanical properties. The wave propagation data collected from multiyear ice is very complex, and further studies are required to determine how to glean information about the ice mechanical properties from these signatures.

Progress in Relating the Mechanical and Physical Properties of Sea Ice: A primary goal of the joint experiments at Barrow (Cole et al, 1995; Dempsey and Adamson, 1995) is to link the physical and mechanical properties of first-year sea ice with the microstructure of the material. The detailed examination of the microstructure and fabric during the Barrow experiments (Cole et al, 1995), provided new information on brine drainage networks, uncovered unusual brine inclusion geometries and gave useful insight regarding the loss of c-axis alignment deep within the sheet. Specifically, the micrography revealed bands near the bottom of the sheet with horizontal brine pockets extending either partially or completely across the platelets. The fabric analysis indicated that the strong c-axis alignment that developed within the upper part of the sheet did not persist throughout the entire sheet. At approximately the same depth for two consecutive years, an in-flux of fine-grained material occurred. These grains were randomly oriented and grew at the expense of the aligned ice, significantly reducing the intensity of the alignment within approximately 200 mm.

A small scale testing program in parallel with the large scale tests at Barrow revealed that the flexural strength is very sensitive to the c-axis alignment (Shapiro et al, 1995). During the early stages of sheet growth, the in-plane strength is relatively isotropic, even at depths where alignment has begun to develop. However, once the intensity of alignment reaches a certain level, the strength becomes anisotropic within the horizontal plane. Correspondingly, the flexural strength reaches a minimum when the in-plane tensile loading is along the direction of the c-axes alignment and a maximum, when perpendicular to the direction of alignment. The reason for the anisotropy appears to be related in part to the platelet-like array of brine pockets.The platelet-like arrays constitute preferential fracture paths. The effect of the brine drainage channels appears to be similar to that of the platelet-like array of pores, but only stronger. Thus, depending upon the size of the test specimen and the size and number density of the drainage networks, the channels can limit the flexural strength.

The fundamental cyclic loading/anelasticity work at Barrow (Cole and Dempsey) and the related topic of failure under cyclic loading supports the analysis of ice sheet failure in the following ways. The wave-induced deformation and break-up of ice sheets and large ice floes may be analyzed as a cyclic loading phenomenon. Interpretation and analysis of in-situ stress measurements from either applied or thermally induced cycles requires a working model of the relaxation processes operating in the ice. The anelasticity work has quantified the kinetics and magnitude of the grain boundary sliding process, which is of great interest in the modelling of crack nucleation. The anelastic strain model will improve the analysis of bulk material behavior (as distinct from the process zone behavior). Thermal fracture models have, to date, been correlated with observations but apparently not with fundamental constitutive behavior.

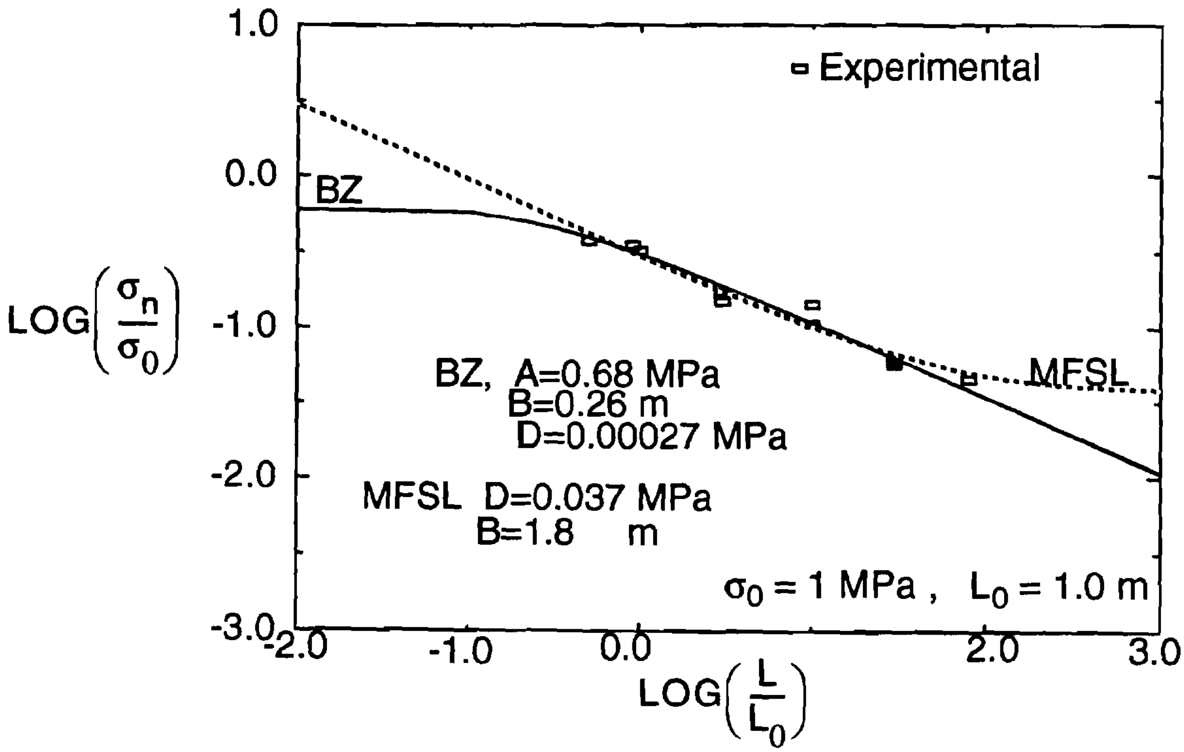


Figure 1: Nominal strength as a function of specimen size

SCALE EFFECT FINDINGS TO DATE

Strength theories of failure, if valid, predict no size effect. Yet, if failure is known to occur by strain localization and macrocrack formation, a scale effect will be discovered. The most important illustration of such a size effect is the Sanderson's much discussed pressure-area curve which predicts that the failure pressure between offshore structures and ice sheets varies as $A^{-\alpha}$. The fact is that, at the laboratory scale, much higher failure pressures are observed; however, under careful testing (and especially if cubes are tested), the damage (microcracking) that is induced prior to failure is homogeneously distributed. Such testing will lead to no size effect. However, such testing is also rather unreal. In actual ice-structure interaction scenarios, damage is not (and is highly unlikely to ever be) distributed homogeneously. In other words, non-simultaneous failure occurs and a size effect is discovered.

In linear elastic fracture mechanics (LEFM), and for tensile failure of ice sheets due solely to in-plane forces, the nominal strength decreases as $L^{-1/2}$, where L is the characteristic dimension of the structure. This is the most dramatic size effect that could be expected; in reality, as the specimen size changes from very small to very large, the size effect will be realized as there is a transition from strength failures (no size effect) to the LEFM asymptote.

The size effect can also be described as a change in the failure stress due to a change in the specimen size. LEFM predicts that the failure stress is inversely proportional to the square root of the specimen's characteristic length. To accurately predict the large scale behavior of sea ice, the knowledge of the size effect is essential. In recent studies (Adamson et al, 1995; Dempsey and Adamson, 1995; Mulmule et al, 1995), in-situ fracture experiments on sea ice were completed, spanning the transitional size and forming a link between small scale laboratory testing and large scale sea ice events. The smallest specimen had a dimension of 0.5 m while the largest specimen had a dimension of 80 m. From this comprehensive set of experiments, a size effect has been found as shown in Figure 1 which shows a dramatic decrease in nominal failure stress with a corresponding increase in specimen size. The size effect laws as developed by Bazant (BZ) and Carpinteri (MFSL) (see Mulmule et al 1995) were implemented as shown in Figure 1 and Table 1. In Table 1, based upon the large scale data from Resolute, the nominal failure strength σ_n is predicted, at the scales of 100 m, 1 km, and 10 km. The dramatic differences in the beliefs underlying these two size effect laws for large sizes is readily apparent. Interestingly, the finding by the thermal fracturing/acoustics community that the arctic ice sheets do not readily sustain tensile stress levels above 50 kPa suggests that thermal fractures, their lengths, depths, spacing and degree of openness will be the major influence on the scale effect in the transition from 100 m -1 km.

$$\sigma_n^{\mathrm{BZ}} = \frac{A}{(1+L/B)^{1/2}} \qquad \sigma_n^{\mathrm{MFSL}} = D(1+10^B/L)^{1/2}$$

Table 1: Size Effect Laws

RANGE (m)	LAW	A MPa	B (m)	D MPa	predicted σ_n @ 100 m kPa	predicted σ_n @ 1 km kPa	predicted σ_n @ 10 km kPa
0.5–80	BZ	0.68	0.26	-	35	11	3
	MFSL	-	1.80	0.037	47	38	37

Note that the constant A represents a small-scale strength value and is closely related to the tensile strength. For the BZ law, B represents the ductile-brittle transition size, where this point lies at the intersection of the strength and LEFM asymptotes. The transitional size for the MFSL law is again given by B; however, this point now apparently separates the disordered regime from the ordered (homogeneous) regime asymptotes.

The constant D represents the residual or size independent strength asymptote for very large sizes.

The size effect shown in Figure 1 indicates a less severe size effect than LEFM predicts. This can be attributed to the development of a process zone at the crack tip and other factors. It can also be seen that there is good agreement between the two laws where data is available. Discrepancies are noted when extrapolating to larger sizes.

Different Scale Effects For Different Problems: Bearing capacity failures or subsurface penetration of ice sheets leads to fracture under bending; an initial LEFM study of the related size effect has revealed that the nominal bending strength decreases as $h^{-3/8}$, where h is the ice sheet thickness (Slepyan and Bazant). The same size effect has been discovered in thermal fracturing (Bazant, 1995). The $h^{-3/8}$ size effect is the most dramatic that could occur. In reality, crack face closure serves to de-emphasize this scale effect (Slepyan et al, 1995). Time dependent deformations change the scale effect also. This is a complicated but important area of research should receive more attention.

Future Research on Scale Effects in Fracturing: Various available size effect laws have been compared by Mulmule et al (1995) and summarized above. The behavior of the these laws over portions of the available size range was examined to study the effect of change in size range as well as change of the absolute sizes. The predictive capability of the size effects laws turns out to be rather fickle. The differences found are caused *a priori* by the mathematical structure of the laws which have been constructed on the basis of specific beliefs. If a larger size range than what has been tested in the SIMI program were to become available then all the size effect laws would again span this larger size range in the same fashion as Figure 1 with the same order of disagreement in the extrapolated region. Future research on this topic does not lie within the proposition of various curve fit or size effect laws such as those just examined. There is a clear need for a quantitative basis to the predicted size effects. The latter basis will reside with approaches reflective of the true material behavior.

In other words, it is not feasible to decide which size effect law is best by comparing their ability to fit experimental data. The range of sizes are limited; moreover, other factors are predominant in very small (grain size, anisotropy, polycrystallinity, heterogeneity) and very large (thermal fractures) specimens. The important objective is identify the mechanisms underlying the different scale effects. For instance, with regard to the Phase II (columnar S2 sea ice) data (Dempsey and Adamson, 1995), the inclusion of bulk viscoelastic deformation has been found to be essential for proper numerical analysis.

There have been particularly significant findings over the last five years which offer insights as to how to bridge the scales from 10 cm - 1 km. These are:

- The scale effect summarized above in Figure 1 and Table 1 is based upon large scale fracture experiments on first year sea ice. The size range tested is 0.5 - 80 m; with further research, failure strengths should be predictable up to the scale of kilometers.

- Thermal fracturing occurs at very low stress levels, on the order of 50 kPa in tension. In other words, ice sheets apparently cannot sustain significantly higher stresses.
- The data from first year ice shows a distinct jump in the bending rigidity of the ice as the spatial scale increases above 30 m. It is hypothesized that this is a result of existing cracks distributed over the floe.

The latter two findings come from investigations primarily aimed at the km scale. Yet the scale effect discovered compares well with the thermal fracturing information and the seismoacoustic information. To bridge these scales yet more quantitatively, the spacing, openness (as opposed to rehealing) of the thermal fracturing will modify (to an unknown degree) the strength of the scale effect between 100 m and 1 km.

GENERAL SUMMARIES

In the next seven tables, general summaries are provided for all issues relevant to the 1 - 100 m scale. This chapter then concludes with the reference list.

MOST SIGNIFICANT ACHIEVEMENT AT THE SCALE 1 - 100 m

- The significant scale effect on the failure strength of first year sea ice is given by the relationship: $\sigma_n = \frac{0.68}{(1+L/0.26)^{1/2}}$.

MOST IMPORTANT OBJECTIVE AT THE SCALE 1 - 100 m

Complete the ongoing development of a nonlinear fracture model and sea ice constitutive model to make full use of the large scale fracture and constitutive measurements made to date; this, in turn, must then be used to assess and refine the scale effect predictions for the 100 - 1000m scale.

Table 2: Scale Issues in Sea Ice Mechanics

Micro Scale	Lab-Scale	Intermediate Scale	Large Scale	Meso-Scale

Materials Science ⟷ | Continuum Mechanics ⟷

Materials Science		Continuum Mechanics	
Dislocation Mechanics	Microcracking Damage Flow	Cracking Buckling Bending Crushing Thermal Fatigue	Lead Formation Pack Ice Drifting Goughing

Scale (meters)

10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5}

SCIENTIFIC OBJECTIVES

- Crack nucleation
  Anelasticity
- Fracture: size, rate, temperature effects, size effect laws, floe splitting, time dependent fracture mechanics, cohesize crack model
- Multiaxial constitutive behavior
  Compressive failure
  Ductile-brittle transitions
  Cyclic loading, damage
  Physically-based constitutive equations
  Fracture criteria vs. polycrystallinity
- Thermal Cracking
  Lead Formation
  Penetration
- Ridging

TABLE 3: SEA ICE MECHANICS PROGRAM

OBJECTIVES	• DEVELOP PHYSICALLY-BASED CONSTITUTIVE LAWS AND FRACTURE MODELS TO DESCRIBE SEA ICE DEFORMATION OVER FULL RANGE OF GEOPHYSICAL SCALES • UNDERSTAND INFLUENCE OF STRAIN RATE, TEMPERATURE, MICROSTRUCTURE AND GROWTH HISTORY
ACCOMPLISHMENTS	• COMPLETED SIZE/SCALE ARCTIC IN-SITU FRACTURE AND CONSTITUTIVE STUDIES • BENCHMARK FRACTURE-GENERATED ELECTROMAGNETIC AND ACOUSTIC SIGNATURES • FRACTURED 80m DIAMETER, 5m THICK MULTI-YEAR ICE ISLAND
IMPACT	• IMPROVED ARCTIC OPERATIONS • GUIDANCE FOR DESIGN OF NAVAL STRUCTURES ADVANCES NAVAL ELECTROMAGNETICS AND ACOUSTICS • IMPROVED TRAFFICABILITY THROUGH AND OVER ICE • IMPROVED CLIMATE MODELING

TABLE 4: SCALE EFFECTS ON THE FRACTURE OF SEA ICE

OBJECTIVES	• COMPLETE A SCALE EFFECT (0.1-100m) STUDY ON THE FRACTURE OF SEA ICE • DEVELOP FRACTURE MODELS TO DESCRIBE FRACTURE OF SEA ICE OVER FULL RANGE OF GEOPHYSICAL SCALES • UNDERSTAND INFLUENCE OF STRAIN RATE, TEMPERATURE, MICROSTRUCTURE AND GROWTH HISTORY
ACCOMPLISHMENTS	• LARGEST SCALE EFFECTS FRACTURE DATA SET (FOR ANY MATERIAL) HAS BEEN COLLECTED • SIGNIFICANT SIZE EFFECT IS EVIDENT IN FIRST YEAR SEA ICE • NONLINEAR SIZE EFFECT FRACTURE MODEL HAS BEEN DEVELOPED • SIGNIFICANT DATA SET ON IN-SITU CYCLIC/ CREEP RECOVERY LOADINGS HAS BEEN COLLECTED • FRACTURED 80m DIAMETER 5m THICK MULTI-YEAR ICE ISLAND
IMPACT	• POTENTIAL NOW EXISTS TO EXPLAIN SEA ICE DEFORMATION AND FRACTURE QUANTITATIVELY OVER RANGE OF 0.1-1000m • CAN NOW EVALUATE EXISTING AND PROPOSED SIZE EFFECT LAWS • GUIDANCE FOR OIL COMPANIES AS TO MAGNITUDE OF ICE FORCES • IMPROVED ESTIMATES OF ALL MODES OF ICE FAILURE

TABLE 5: MICROSTRUCTURAL AND CYCLIC INFLUENCES ON CONSTITUTIVE BEHAVIOR

OBJECTIVES	• UNDERSTAND CRACK NUCLEATION MECHANISMS • EXAMINE MICROSTRUCTURAL INFLUENCES AND EVOLUTION AS ARCTIC SEASON PROGRESSES • ELUCIDATE MICROMECHANICAL MECHANISMS ACTIVE DURING CYCLIC LOADING • INVESTIGATE INITIATION AND PROGRESSION OF DAMAGE UNDER COMPRESSIVE LOADING
ACCOMPLISHMENTS	• COMPREHENSIVE DATA BASE (LAB- AND FIELD-SCALE) ON THE CYCLIC LOADING RESPONSE OF SEA ICE • SIGNIFICANT 'FIRST' IN STUDY OF SEASONAL MICROSTRUCTURAL EVOLUTION
IMPACT	• IMPROVED UNDERSTANDING OF CRACK NUCLEATION AND INTERNAL FRICTION IN SEA ICE • GUIDANCE FOR DEVELOPMENT OF PHYSICALLY BASED CONSTITUTIVE LAWS

TABLE 6: CONSTITUTIVE BEHAVIOR OF SEA ICE

OBJECTIVES	• DEVELOP PHYSICALLY-BASED CONSTITUTIVE EQUATIONS FOR SEA ICE • SPECIMEN SIZE VS. MICROSTRUCTURAL SCALES • NUMERICAL CODE IMPLEMENTATION
ACCOMPLISHMENTS	• AN ASSESSMENT OF APPLICABLE NONLINEAR VISCOELASTIC AND VISCOPLASTIC CONSTITUTIVE EQUATIONS HAS BEEN COMPLETED • COUPLED FRACTURE-CONSTITUTIVE-HOMOGENEITY ISSUES HAVE BEEN ADDRESSED
IMPACT	• GENERAL PURPOSE FINITE ELEMENT CODES REQUIRE ROBUST CONSTITUTIVE LAWS • IMPROVED 'ICE FORCE' CALCULATIONS • GUIDANCE FOR LAB- AND FIELD-SCALE EXPERIMENTS

TABLE 7: MULTIAXIAL COMPRESSIVE LOADING

OBJECTIVES	• UNDERSTAND INFLUENCE OF ICE TYPE, RATE, POROSITY AND CONFINEMENT ON THE SHAPE OF THE FAILURE ENVELOPES UNDER CONTROLLED MULTIAXIAL COMPRESSIVE LOADING CONDITIONS • SCALE EFFECTS ON COMPRESSIVE STRENGTHS
ACCOMPLISHMENTS	• DETERMINED FAILURE ENVELOPES FOR SEA ICE SUBJECTED TO A RANGE OF CONFINEMENT, STRAIN RATE AND TEMPERATURE CONDITIONS • NO SCALE EFFECT ON COMPRESSIVE STRENGTH AT LAB-SCALE
IMPACT	• GUIDANCE FOR THOSE DEVELOPING PHYSICALLY-BASED CONSTITUTIVE LAWS • IMPROVED UNDERSTANDING OF PRESSURE-AREA RELATIONSHIPS AND THE ISSUE OF NON-SIMULTANEOUS FAILURE

TABLE 8: THERMAL FRACTURES AND PENETRATION

OBJECTIVES	• THERMAL EFFECTS ON ARCTIC LEAD ICE FORMATION • THICKNESS SCALE INFLUENCES ON PENETRATION
ACCOMPLISHMENTS	• FOUND BOTH THERMAL AND BENDING FRACTURES ARE THICKNESS DEPENDENT • INITIAL PENETRATION MODELS HAVE BEEN COMPLETED
IMPACT	• INCREASED IMPORTANCE ATTACHED TO RESIDUAL AND THERMAL STRESS MEASUREMENTS • GUIDANCE FOR SUBMARINE/SENSOR PENETRABILITY EXPERIMENTS

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[3]*SIMIW:* Papers in Volume 1 of the Proceedings of the Sea Ice Mechanics and Arctic Workshop, held April 25-28, 1995 in Anchorage, Alaska.

SIMI WORKSHOP PANEL ON THE 1cm-1m (MATERIALS) SCALE

Erland M. Schulson, Chairman
Thayer School of Engineering, Dartmouth College, Hanover, N.H.

David M. Cole, Co-Chairman
Cold Regions Research and Engineering Laboratory, Hanover, N.H.

Graham A.N. Thomas, Recorder
BP International Ltd., Middlesex, U.K.

Victor Smirnov, Recorder
Arctic & Antarctic Research Institute, St.Petersburg, Russia

INTRODUCTION

A major objective of SIMI is to understand the mechanical behavior of first-year columnar sea ice on scales ranging from around 1 cm to around 1 km. Here we limit our attention to the 1cm -1m scale, or the materials scale. The questions to be addressed are: What progress have we made, and what should we do next to further the objective?

To this end, we first summarize what we have learned and list the questions that arise. In so doing, we describe both experiments and modeling under appropriate headings where both approaches were followed. Where modeling alone was done we describe that work separately. We then ask how/whether this new knowledge and understanding of ice on the small scale helps to understand and predict the failure of sea ice sheets.

In presenting this summary, we refer to the work described in the workshop proceedings, unless noted otherwise.

NEW KNOWLEDGE AND UNDERSTANDING THROUGH SIMI

1. Material Characterization

A primary goal of the program is to link the physical and mechanical properties of first-year sea ice with the microstructure of the material. In pursuit of this goal, the experimental efforts at the small and intermediate scales paid considerable attention to microstructural characterization. For laboratory work, this included micrography on the scale of brine and gas inclusions in addition to observations of grain size, platelet spacing, specimen density and salinity. In-situ experiments at Barrow included similar observations, extended to include characterization of the brine drainage networks. Although much of this work was routine, an important aspect of the overall program is the consistency and rigor of the characterization at the small and intermediate scales. The detailed examination of the microstructure and fabric during the Barrow experiments, for example, provided new information on brine drainage networks, uncovered unusual brine inclusion geometries and gave useful insight regarding the loss of C-axis alignment deep within the sheet. Specifically, the micrography revealed bands near the bottom of the sheet with horizontal brine pockets extending either partially or completely across the platelets. Observations of a similar nature were subsequently made during FY'95 in the Chukchi Sea. These features may have some relationship to the brine corrosion bands observed by previous investigators (e.g., Bennington 1963). The fabric analysis indicated that the strong C-axis alignment that developed within the upper part of the sheet did not persist throughout the entire sheet. At approximately the same depth for two consecutive years, an in-flux of fine-grained material occurred. These grains were randomly oriented and grew at the expense of the aligned ice, significantly reducing the intensity of the alignment within approximately 200mm.

(i) *Microstructure*

All laboratory-grown material was fully characterized and, with the exception of alignment effects, was very similar to naturally-occurring first year sea ice (Cole). The observations made in the field documented the microstructural changes that occurred on the scale of brine inclusions (size, shape and spatial distribution) to the scale of drainage channels (spatial distribution, continuity) during the growth season. Micrographs were obtained immediately upon removal of the ice from the parent sheet. These observations were carried out in conjunction with in-situ mechanical properties experiments and provide a direct link between the microstructural characteristics of the ice and the associated creep, recovery and cyclic loading response. Specimens subjected to laboratory experiments were given detailed post-test examinations to assess the nature and extent of microstructural damage.

C-axis alignment effects on elastic and anelastic response were examined using oriented cores obtained during the experiments at Barrow. In addition to the usual characterization noted above, the C-axis distributions of these specimens are being quantified as well.

(ii) *Brine Drainage Networks*

A technique (Cole) was developed during the FY'94 experiments at Barrow for obtaining relatively thin ($\approx$ 50mm) vertical slabs that extended through the entire depth (1.4-1.8m) of the sheet. These sections provided a complete view of the brine drainage networks over a relatively large area.

The information provided by the full depth observations generated considerable interest and prompted more field work in FY'95 to explore improvements in the methodology and to make additional observations. The findings indicated a number of significant deviations from the existing lines of thought regarding these features. For the early and mid-year sheets, there was a noticeable lack of vertical continuity, with individual channels rarely extending more than 0.3 to 0.5m through the sheets. Banding structures were also clearly visible. The channels and branches were generally not open but contained fine-grained ice, and the branches were frequently not distributed symmetrically about the main channel. The spacing between the drainage networks decreased late in the season (May) and straight, open tubes were observed extending through the center of the networks. Individual as well as large groups of networks were seen to either start or end abruptly on a horizon within the sheet.

Several questions arise from these findings. What is the mechanism leading to the formation of the horizontally oriented brine pockets? What causes the in-flux of fine grains that grow to disrupt the C-axis alignment? How common is this process? What controls the development and termination of the brine drainage networks? What is the mechanism by which they refreeze with fine-grained material? To what extent does sea water circulate in these networks?

2. Compressive Failure

Compressive loading occurs during both floe-floe and ice-structure interactions. Eventually failure occurs. Compressive failure is a complicated process that involves, at the higher strain rates within the brittle regime, the nucleation, growth and interaction of cracks. At the lower rates within the ductile regime, dislocation processes and possibly dynamic recrystallization are also important. To begin, we focus on brittle behavior.

(i) *Crack Nucleation*

Prior to SIMI it was generally thought that within the relatively high-rate (albeit quasi-static in the dynamics sense) regime cracks nucleate at grain boundaries owing to tensile stresses concentrated there (particularly at triple points) from the elastic anisotropy of the material. Through SIMI that view has changed.

It now appears from three theoretical studies (by Gupta & Frost et al.; by Shyam-Sunder et al.; and by Wu et al.) that while elastic anisotropy does concentrate stress on the grain boundaries, the concentration is not large enough to nucleate cracks, even when stress concentrators like air bubbles are included and when thermal energy is considered. Instead, grain boundary sliding seems to be more important. The idea is that sliding concentrates sufficient tensile stress at either steps/ledges or triple points to nucleate cracks. Supporting this view are observations on fresh-water ice by Picu and Gupta and by Nickolayev and Schulson (1995). The latter observations also account for the across-column cracking in ice under higher confinement (more below).

Several questions arise. What is the nature of the sliding resistance? If viscoelastic, how sensitive is it to temperature, sliding speed and microstructure? What is the role of grain boundary dislocations? Also, what role does porosity play? Why is it, if grain boundaries slide, they don't seem to slide very far, given the earlier observations by Ignat and Frost (1987, albeit in fresh-water ice)? Or, does grain boundary sliding constitute a significant strain-producing mechanism in sea ice? Given that steps on grain boundaries act as dislocation sources, at least in fresh-water ice (Liu, Baker et al. 1995), can we completely rule out a role of crystal dislocations?

(ii) *Crack Growth , Interaction and Material Collapse:*

Prior to SIMI it was appreciated that whereas crack nucleation can limit the strength of ice under tension (Lee and Schulson 1988), it is not a strength-limiting step under compression. That's why the brittle compressive strength is so much larger (3-20 times) than the tensile strength. Instead, the brittle compressive strength is affected also by crack growth and interaction. These processes are not completely understood. However, SIMI has witnessed considerable progress in isolating some of the mechanisms.

An important one, given the direct observations of wing cracks in both salt-water ice and fresh-water ice (Schulson), is the classical frictional crack sliding/wing cracking mechanism. The first step here is the nucleation of cracks on planes inclined to the direction of loading. These are termed "parent cracks" and, in the light of the above discussion, probably form as the result of grain boundary sliding. Additional sliding localizes tensile stresses and initiates out-of-plane sliding tensile cracks or wing cracks which then lengthen and interact as the load rises. A macroscopic fault develops and the ice collapses. Important factors are the sliding friction coefficient (a lumped parameter that depends upon temperature and sliding speed), the parent crack size (set by the grain size) and the confining stress.

Confinement can impede all the steps in the failure process (Schulson). When both the major and minor (confining) stress are applied orthogonally under biaxial loading, moderate confinement increases the frictional force closes the wings, thereby raising the applied stresses for both wing initiation and growth. Correspondingly, the strength increases. Also, shorter wings develop, leading to a transition in failure mode from axial splitting along the direction of major loading to shear faulting in the loading plane. As the confining stress increases further, it suppresses in-loading-plane sliding altogether. Out-of-plane sliding then dominates. As a result, cracks form across the columns and the failure mode changes to spalling followed by buckling of the spalled plates should they be thin enough. Both salt-water and fresh-water ice behave in the same way.

When the confining stress is applied along the columns while the major stress is applied across, the confinement has essentially no effect at all on the failure strength or mode. In this case the ice behaves as though it were loaded uniaxially across the columns. The reason is that the along-column confining stress has little or no component on the plane of the sliding crack.

Again, questions arise. How exactly do incipient splits, faults and spalls develop into the macroscopic features that trigger collapse? How do the brine pockets affect the localization of damage and fragmentation that eventually leads to collapse of the ice? What step in the process of crack growth and interaction sets the failure stress? What is the role of pre-existing cracks on the failure stress and failure mode? How does C-axis alignment affect the failure process?

(iii) *Ductile-Brittle Transition:*

The macroscopic behavior of ice changes from ductile to brittle upon increasing the strain rate to above a critical level. The transition is important because it marks the point where the strength of the ice reaches a maximum, thereby setting the limit on ice forces for a given scenario. Interestingly, the transition strain rate in salt-water ice is about an order of magnitude higher than in fresh-water material.

Just prior to SIMI Schulson offered an explanation in terms of the competition between stress build-up and stress relaxation at crack tips, and attributed the transition to the suppression of the creep-driven stress relaxation once the strain rate reached a critical level. In quantifying the model, he invoked Riedel-Rice crack-tip creep mechanics and Ashby-Hallam wing-crack mechanics, and assumed the critical creep zone size to be proportional to the parent crack size. The model incorporates the resistance to sliding, to creeping and to cracking, as well as the size of the parent crack.

Through SIMI he tested the model. The results show that the transition strain rate decreases with increasing crack size, according to $(\text{crack size})^{-n}$, where n falls between 1 and 2. The model predicts that n=1.5. The results also show that for ice biaxially loaded across the columns the transition strain rate first increases and then decreases upon increasing the confining stress. The model predicts the same trend and gives reasonable quantitative agreement with the observations. Also, again in keeping with observation, the model predicts that the transition strain rate in saline ice is about ten times higher than in fresh-water ice, owing to a higher creep rate in the salt-water material. We have, therefore, while not a complete understanding of all aspects of the transition, at least a working model expressed in simple analytical form, built upon established mechanics and incorporating separately measurable physical parameters.

Several question arise. Are the initial wings truly proportional in size to the parent cracks? Is "steady state creep" sufficient, as the model assumes, to account for the creep zone. Is the kinetic coefficient of sliding friction the appropriate one? What is the effect of both across-column and along-column confinement on the transition?

(iv) *Failure Envelopes and Surfaces:*

The loading of an ice sheet either globally or locally will most likely not occur uniaxially, but multiaxially. Hence the interest in failure envelopes and surfaces.

Prior to SIMI Hausler (1981) had shown from tests on rather salty (10 ‰) S2 columnar ice (proportionally loaded so that ratio the three principal stresses could be varied) that confinement raises the ductile failure stress by as much as a factor of eight, depending upon whether the loading was biaxial or triaxial and upon the degree of the confining stress. Timco and Frederking (1986) performed tests on first-year sea ice, loaded across the columns and rigidly confined either across the columns in an orthogonal direction or along the columns. They showed that across-column confinement significantly increases the ductile strength, but that along-column confinement has little or no effect. And Richter-Menge (1991) showed from conventional triaxial tests that simultaneous confinement across and along the columns raises the failure stress of aligned first-year sea ice by as much as a factor of five when the ratio of the confining stress to the highest stress reaches 0.5. In other words, all of these earlier observations point to an important effect of confinement.

To understand this effect, systematic experiments were carried out (Schulson) on both salt-water and fresh-water columnar ice (unaligned) biaxially and triaxially loaded over a wide range of temperatures and strain rates spanning the ductile-to-brittle transition (within small pieces of ice). Failure envelopes (for biaxial loading) are summarized in the proceedings and failure surfaces (for triaxial loading) will be presented at OMAE'95 and at AMD-MD '95 for both ductile and brittle behavior. The results are qualitatively the same for both the fresh-water and the salt-water ice and can be summarized as follows:

When deformed slowly under biaxial loading, the ice is ductile and the failure stress increases monotonically with increasing across-column confining stress, but is essentially independent of the along-column confining stress. Also, the ductile strength increases with increasing strain rate and decreasing temperature. This behavior is attributed mainly to the response of basal plane slip to the applied stresses. The failure envelopes are elliptical in shape and can be fairly well described by Hill's criterion for the yielding of plastically orthotropic materials. Under triaxial loading fewer data are available, although it again appears that Hill's criterion is applicable. In other words, the hydrostatic component of the stress tensor has little effect on ductile failure. When rapidly deformed the material behaves in a brittle manner. Frictional processes are now important and the hydrostatic component of the stress tensor now plays a major role. Under across-column biaxial loading, the brittle failure stress increases markedly with moderate degrees of confining stress until the confining stress becomes large enough to activate out-of-plane failure. At this point the failure stress decreases slightly with further increases in confinement. As a result, the brittle compressive failure envelope for across-column loading resembles a truncated Coulombic envelope or a lamp-shade.

Under triaxial loading, the along-column confining stress affects brittle failure only when the across-column confinement is high enough to trigger the out-of-plane or spalling failure mode. In this case, the failure stress (measured as the larger of the two across-column stresses) increases sharply as the along-column confining stress increases. The brittle compressive failure surface thus is a faceted one, unlike the more rounded surface for ductile failure.

The following questions arise. How sensitive are the failure envelopes and surfaces to compressive pre-strain and to C-axis alignment? As the size of the ice feature increases, do the envelopes/surfaces for brittle failure shrink while those for ductile failure remain unchanged? What is the shape of the envelopes/surfaces under combined compressive and tensile loading? How does the loading path/history affect the envelopes and surfaces? Can the envelopes and surfaces be truly described by an associated flow rule and the concept of "strain vector normality" as preliminary results indicate?

3. Tensile Failure

Tensile loading is another important natural scenario. It occurs during ice sheet bending by loads from above and below the sheet, by thermal forcing and during the buckling of thin sheets. It also occurs during splitting.

(i) *Flexural Strength:*

The flexural strength of sea ice is governed by its tensile strength, which, prior to SIMI, had been studied off an on for many years. The principal results of the early work is that the strength decreases with increasing porosity, but, unlike the compressive strength, increases only moderately with decreasing temperature and increasing strain rate. These characteristics reflect the fact that under tension the strength of ice is limited less by plastic flow and more by the nucleation and propagation of cracks. Through SIMI, Shapiro and Weeks have established two new points.

One is that the flexural strength is sensitive to C-axis alignment. (Peyton's (1966) work suggested the effect, but the more recent work established it.) What seems to happen is that during the early stages of sheet growth, the in-plane strength (i.e., where the largest tensile stress is generated within the plane of the ice sheet) is relatively isotropic, even at depths where alignment has begun to develop. However, once the intensity of alignment reaches a certain level, the strength becomes anisotropic within the horizontal plane. Correspondingly, the flexural strength reaches a minimum when the in-plane tensile loading is along the direction of the c-axes alignment and a maximum, when perpendicular to the direction of alignment. The reason for the anisotropy appears to be related in part to the platelet-like array of brine pockets, which forms on basal planes (i.e., perpendicular to the c-axes). Along the direction of alignment, the ligaments of ice between the pockets are short and thus more highly stressed than ice elsewhere. The platelet-like arrays thus constitute preferential fracture paths.

Interestingly, the transition to a strong dependence on alignment occurs in some cases over about 0.1 m while, in others, over about 0.4 m. The sharpness of the transition depends upon the growth conditions.

The other point concerns the role of the brine drainage channels. Their effect appears to be similar to that of the platelet-like array of pores, but only stronger. Thus, depending upon the size of the test specimen and the size and number density of the drainage networks, the channels can limit the flexural strength.

From this work the following questions arise. Could part of the weakening along the c-direction be related to an intrinsically lower fracture toughness along the basal planes? Are the effects of the C-axis alignment (or brine pocket array) and the drainage channels as important when the ice is slowly deformed; i.e., where dislocation processes are more important to inelastic deformation than cracking? Is the effect of pre-compression on the flexural strength and ductility similar to that seen in the laboratory (Kuehn 1994)?

(ii) Fracture Toughness:

An important series of experiments has been performed in the field by Dempsey et al. to determine whether the size of an ice plate affects its resistance to fracture under the crack opening mode. This work is summarized in a separate section of this report. Here we only note the highlights.

The size was varied by over two orders of magnitude, from around 20 cm to 30m on edge. In addition, a floe around 80 m in dia. was split. The larger specimens were tested as floating blocks, and thus contained a thermal gradient. The data are still being analyzed, and so scientific conclusions cannot be drawn at this juncture. It can be concluded, however, that large-scale fracture experiments can be successfully carried out.

4. Cyclic Loading and Anelasticity

The first extensive series of laboratory cyclic loading, creep and creep recovery experiments on saline ice were carried out under the SIMI program (Cole). The loading paths were later replicated during the larger-scale in-situ experiments described in the 1-100 m scale section. The observations on laboratory-grown ice provided precise information on the effects of temperature, stress level, frequency and porosity on the elastic and anelastic (time-dependent elastic) response of saline ice. Additionally, the effects of C-axis alignment on the cyclic loading and creep response were examined through laboratory experiments on field cores of the aligned ice encountered during the in-situ experiments at Barrow.

A key finding is that the anelasticity is composed of two separate relaxation processes: a dominant dislocation relaxation and a relatively weak grain boundary relaxation. Although freshwater ice exhibits similar anelastic behavior, the dislocation contribution in sea ice is generally much stronger. The experiments on aligned ice showed that the anelastic response increased as the resolved shear stress on the basal planes increased, showing the importance of basal slip in inelastic processes in ice.

Laboratory experiments on material covering a wide range in salinity (and hence porosity) indicated that the dislocation-based anelastic response increased strongly with total porosity. This finding supports the notion that the dislocation density prior to straining is strongly influenced by the inclusions. The precise mechanism of this influence is still a matter of speculation. Interestingly, the kinetics and width of the grain boundary relaxation peak in the laboratory-grown saline ice were very similar to findings in freshwater ice. The cyclic loading program generated a quantitative model of the anelastic straining of sea ice expressed in terms of compliance. The model is based on the mechanisms noted above and employs physically meaningful quantities that can be obtained from independent experiments. The experiments on aligned ice are being conducted over the temperature range observed during the field cyclic loading experiments to support the model extension to high temperatures and its quantitative verification using the field results. Significantly, the anelastic behavior at higher temperatures (i.e. $> -10^{\circ}C$) appears to be fully consistent with behavior at lower temperatures, precluding the need for specialized high-temperature models.

The following questions arise. Precisely how do the growth conditions or subsequent thermal history influence the basal dislocation density (and thus compliance) of first-year sea ice? How do flaws on the scale of brine drainage networks and thermal cracks influence the elastic and anelastic behavior of an ice sheet?

5. Crack Dynamics

Another aspect of the mechanical behavior of an ice sheet is the speed of a mode-I crack as it propagates through the feature. Prior to SIMI Parsons et al. (1987) suggested that the average velocity of an unstable crack was about 20 m/s. This was surprisingly low, being around 0.5% of the speed of sound (longitudinal waves) in the material. It also turned out to be much lower than the crack velocity of about 1100 m/s that was subsequently measured in fresh-water ice (Sato and Wakahama 1992).

In connection with the Barrow field experiments Petrenko made new measurements. For the first time he employed his electromagnetic emission technique to obtain in-situ crack velocities in sea ice. He also measured the electrical resistance of the ice. The results confirmed Parson's suggestion. The crack velocity was small and ranged from around 3 to around 300 m/s, with most of the speeds falling in the range around 10-20 m/s. The upper limit was measured at quite low temperatures (-35°C at the surface). The low speeds are surprising, because mode-I crack velocities in other materials are typically 10-50 % of the velocity of sound.

Parsons attributed the low speed to a plastic zone around the crack tip. Petrenko suggests that perhaps it is related to a toughening effect of the unfrozen water. The mechanism is thought to involve not the rupture of the liquid inclusions, for the tensile strength of water is too high, but the removal by the propagating crack of the inclusion from its path.

In addition to the nature of the low crack speed in saline ice, other questions arise. How sensitive is crack velocity to temperature, microstructure (porosity, C-axis alignment, platelet spacing) and stress state?

6. Modeling

In addition to the modeling already noted in relation to crack nucleation, anelastic deformation and ductile/brittle transition, other work has been performed.

Consider damage and failure (Wu, Shyam Sunder). This work captures the underlying random microstructural heterogeneities (e.g., variations in grain size, shape ,orientation and in brine pocket array) and considers the mechanics of crack interactions. The interactions are developed in elastically anisotropic material and are used to predict the development of damage and the fracture of damaged ice at the small scale. The work emphasizes the influence of the microstructural heterogeneities on the stress/strain response and the fracture of the damaged material. The most challenging problems include: (i) extending the interaction to include complex geometries; (ii) consideration of local interactions between cracks and pressurized brine-filled pores and between cracks and creep zones in their vicinities; and (iii) developing a physically-based failure criterion based on (i) and (ii). Concerning the last point, the models should be applicable for the description of the multiple local failures or distributed damage which occurs when ice interacts with engineered structures.

Next consider constitutive equations and fracture models for sea ice (Schapery and Rodin). The work emphasizes mathematical models for linear elastic and viscoelastic deformation, as well as nonlinear and fracture behavior of polycrystals. The linear analysis predicts polycrystal behavior based on single crystal properties using an averaging approach called the self-consistent method. An important advancement is the extension of the analysis to the case of anisotropic sea ice. In this same study a creep compliance model was developed employing the elastic-viscoelastic correspondence principle. The model is expressed in terms of convolution integrals and predicts the response of columnar sea ice to arbitrary stress or strain paths. The predictions compare well with experimental observations. Finally, the work on nonlinear and fracture behavior has produced the following observations. With regard to crack tip stress fields, there is an outer stress field corresponding to the standard field derived from classical elasticity and an inner field that is consistent with the anisotropy of the grain in which the crack tip resides. The inner field is consistent with Griffith's fracture criterion, and the intensity of this anisotropic field is controlled by the grain. To determine the intensity of the anisotropic field it is sufficient to analyze a homogeneous anisotropic specimen whose elasticity tensor coincides with that of the grain containing the crack tip. Additionally, the apparent fracture energy is a strong function of the local orientation and can vary by as much as a factor of four from specimen to specimen. Future work will focus on additional model development in collaboration with Cole and Dempsey. The efforts will yield improved constitutive and fracture models that will account for realistic property gradients.

The other physically based constitutive modeling effort (Wu, Connor et al.), in addition to shedding insight into crack nucleation (see above) contributed further knowledge about the effects of microstructural variations. The probabilistic distribution of failure stress and compliance is related to the statistical variation in microstructure, and the brittle failure stress is found to be proportional to (grain size)$^{-1/2}$ in keeping with experimental observations. The micromechanisms and the resulting behavior can now be applied to the next scale level, that of indentation of a floating ice sheet. This will allow the simulation of failure based on a physical, i.e. micromechanical model.

SMALL-SCALE FINDINGS AND THE FAILURE OF AN ICE SHEET

1. Compressive Failure

(i) *Crack Nucleation:* It is a significant achievement to be able to conclude the issue of how cracks nucleate when ice is quite rapidly deformed. It means that we now have the scientific tool to predict, in principle at least, the applied stresses and the points in the microstructure where cracks will form. When combined with the knowledge of how cracks grow and interact, this new understanding presents the opportunity to build up from physical principles a true model of how ice becomes damaged and then fails under compressive loads. The challenge now is to create that model.

(ii) *Crack Growth, Interaction and Collapse:* One wonders whether the failure modes seen in the laboratory on small pieces of ice reflects the failure of full ice sheets. In particular, perhaps the splits (zero confinement) and shear faults (moderate confinement) are manifested in some field situations as non-intersecting and as intersecting leads. Perhaps the spalling and buckling (high across-column confining stress) are manifested in some field situations involving thick ice sheets as pressure ridges. If so, then we would expect the in-field failure mode to change from in-plane (i.e., leading) to out-of-plane mode (pressure ridging) as the confining stress increases above a critical level. Also, we would expect the ridge block size to be smaller than the sheet thickness. We might also expect lower in-field failure stresses, since it seems possible that thermal cracks could link up over time to act as parent cracks whose growth stress scales as (crack length)$^{-0.5}$. Sliding, say of 3-meter parent cracks under far-field, wind-driven compression could then account for the difference between the 3-10 MPa compressive strengths seen in the laboratory (where the cracks are set by the grain size and are about 6 mm in dia.) and the 100-400 kPa level now measured in both the Eastern Arctic (Tucker and Perovich 1992) and the Western Arctic (Richter-Menge et al., SIMI 1995).

This line of thinking leads to a testable hypothesis; namely, that the brittle compressive failure strength of a cracked ice plate is expected to decrease in proportion to (crack size)$^{-0.5}$.

(iii) Ductile-Brittle Transition: Consider the macroscopic behavior of an ice sheet deforming at about 1%/day ($10^{-7}s^{-1}$). Even though the sheet probably deforms plastically in local regions, the fact that it contains networks of long cracks suggests that macroscopically it fails in a brittle mode. The (crack size)$^{-1.5}$ relationship between the transition strain rate and parent crack size, established through modelling and experiment, suggests that 3 m cracks would lower the transition strain rate by a factor of about 10^4; i.e., from around $10^{-3}s^{-1}$ seen in the lab. to around $10^{-7}s^{-1}$. Longer in-field cracks would lower the transition strain rate still further.

Again this kind of thinking leads to a testable hypothesis; namely, that the transition strain rate of a cracked ice sheet is expected to decrease in proportion to (crack size)$^{-1.5}$. Both hypotheses could be tested on meter-sized blocks in which crack-like flaws are introduced.

(iv) Failure Envelopes and Surfaces: Failure envelopes under proportional loading for both ductile and brittle behavior are now available for the first time. They may be applied to help predict failure pressure and failure mode. Consider, for instance, indentation failure. Presumably, the failure pressure increases with confinement in the same manner as the compressive strength, and presumably the failure mode changes from in-loading-plane to out-of-plane as the across-column confining stress reaches a critical level. In fact, some indentation experiments were performed in the laboratory on columnar fresh-water ice, and showed the failure pressures to depend upon confining stress in the manner expected. Now the stress state and effective strain rate change with position behind the indentor. This means that elemental volumes of ice at different points within the contact zone will fail at different times, that the attendant damage will not be uniform, and that the boundary between the failed and the unfailed material will be blurry. All this will need to be carefully incorporated in engineering models.

2. Tensile Failure

The SIMI flexural strength studies began with the objective of gathering data from the small scale, laboratory experiments that could be used to calculate the response of ice sheets to flexural loads. In particular, the work was aimed at developing methods to account for the influence of the growth history of the ice (primarily as recorded in the salinity distribution) on the strength and other mechanical properties. However, we learned that the intensity of C-axis alignment and the distribution and morphology of brine drainage networks were the most important influence on the response of the test specimens to the applied loads. The C-axis alignment results in strengths that differ by a factor of about 1.5, depending on whether fracture is induced in the "strong" or "weak" direction. Further, and as already noted, variations in the geometry and scale of the brine drainage networks result in even larger variations in strength between samples with similar C-axis fabrics. The importance of C-axis fabric to the strength of ice sheets has been recognized in compression tests and fracture tests, but the potential role of brine drainage networks has not been considered. Neither of these important variables has been considered in test programs to determine the flexural strength of full ice sheets. As a result, the existing data may not be adequate to indicate the true range of flexural strengths of ice sheets that can be encountered in applications in the field.

3. Cyclic Loading and Anelasticity

The fundamental cyclic loading/anelasticity work and the related topic of failure under cyclic loading supports the analysis of ice sheet failure in the following ways. The wave-induced deformation and break-up of ice sheets and large ice floes may be analyzed as a cyclic loading phenomenon. Interpretation and analysis of in-situ stress measurements from either applied or thermally induced cycles requires a working model of the relaxation processes operating in the ice, and the anelasticity analysis provides the required model. The anelasticity work has quantified the kinetics and magnitude of the grain boundary sliding process, which is of great interest in the modelling of crack nucleation.

The anelastic strain model will improve the analysis of bulk material behavior (as distinct from the process zone behavior), providing a more reliable partitioning of energy during a complex failure process.

4. Crack Dynamics

The velocity of cracks in ice may be an important factor in the crushing and splitting of an ice sheet. For instance, crack velocity is expected to affect the size and distribution of damage and fragmentation during contact failure. Laboratory results (Smith and Schulson 1994) show that under identical loading conditions damage/cracking is much more localized around faulted zones and finer fragments form in saline ice than in fresh-water ice, differences that might now be related to the lower crack velocity through the salt-water material. Similar differences are expected in the field.

SUMMARY

The table summarizes the achievements, and lists the next steps.

SUBJECT	ACHIEVEMENT	NEXT STEP
Microstructure of First-Year Columnar Sea Ice	Characterized evolution during one growing season and related microstructure to mechanical properties.	Improve understanding of evolution, including alignment of C-axes.
Compressive Failure		
Crack Nucleation	Showed that at high strain rates intergranular cracks nucleate not in direct response to elastic mismatch, but to grain boundary sliding.	Nature of sliding resistance, and effects of temperature, strain rate and porosity.
Crack Growth/Collapse	Established that frictional crack sliding and wing cracking are important elements.	Crack interaction and the localization of damage leading to the development of macroscopic faults and spalls.
Ductile/Brittle Transition	Related to onset of crack growth, and modelled quantitatively in terms of independently measureable physical quantities to explain effects of crack size and across-column confinement.	Role of localized (crack tip) vs. global plasticity, and effect of simultaneous confinement both across and along columns; examine transition under combined compression and tension.
Failure Envelopes/Criteria	Measured and explained biaxial failure envelopes for both ductile and brittle behavior. Failure surfaces probed. Quantitative failure criteria defined.	Complete measurements of 3-D failure surfaces; determine effects of loading path/history.
Tensile Failure	Established that C-axis alignment weakens ice along direction of alignment relative to orthogonal direction in horizontal plane. Brine drainage system further weakens ice under tension, dominating other effects.	Relate to flexural failure of an ice sheet; determine whether drainage channels are weakening elements at low strain rates.
Cyclic Loading	Identified mechanisms of anelasticity, and developed quantitative physical model of the deformation. Showed that anelastic deformation increases with porosity, and that the effective modulus is a minimum at about 45° to the direction of C-axis alignment	Further explore and quantify C-axis alignment and porosity effects on elastic and anelastic deformation.
Crack Dynamics	Showed that crack velocity in first-year columnar sea ice is about two orders of magnitude lower (i.e., around 10 m/s) than in fresh-water columnar ice.	Determine the origin of the low crack velocity and examine the effects of temperature, microstructure and stress state; determine the effect of crack speed in calculating ice forces.

MOST IMPORTANT POINTS

- Established failure mechanisms: both dislocation relaxation and grain boundary relaxation account for the anelasticity of first-year sea on both the small and the large scale; grain boundary sliding accounts for high-rate crack nucleation in pore-free ice under compression; frictional crack sliding and crack interaction account for brittle compressive failure; competition between crack propagation and crack-tip creep accounts for the brittle-to-ductile transition under compression; and brine-filled pores inhibit crack propagation.

- Developed compressive failure envelopes and surfaces and found that Hill's criterion and a truncated Coulomb criterion describe the ductile and brittle failure stress, respectively.

- Found that large-scale anelasticity can be predicted from laboratory experiments, that c-axis alignment affects ice sheet compliance, and predicted that the ductile-to-brittle transition strain rate scales inversely with lead size, as $(\text{lead size})^{-1.5}$, and that the brittle compressive failure stress also scales inversely with lead size, as $(\text{lead size})^{-0.5}$.

MOST IMPORTANT AREAS FOR FUTURE RESEARCH

- Using meter-sized blocks of pre-cracked columnar sea ice loaded under controlled conditions, test predictions that the ductile-to-brittle transition strain rate scales inversely with crack size, as $(\text{crack size})^{-1.5}$, and that the brittle compressive strength scales inversely with crack size, as $(\text{crack size})^{-0.5}$.

- Determine compressive failure envelopes/surfaces and failure criteria for first-year columnar sea ice where the loading axes are inclined to the growth direction.
-
- Establish and model the relationship between sea ice growth and loading history with the in-situ anelastic and viscous creep behavior.

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Ice Loads on Fixed and Floating Structures

PANEL REPORT

K.R. Croasdale, Chairman
K. R. Croasdale & Associates, Calgary, Canada

P. Truskov, Co-Chairman
Sakhalin Oil and Gas Institute, Okha, Russia

A.T. Bekker
Far-Eastern State University, Vladisvostok, Russia

T. Murrell, Recorder
Minerals Management Service, Anchorage, USA

Introduction

Attendees at the Panel discussion numbered between 30 and 40.

The purpose of the panel discussion was **"to review current practice in ice loads and determine future research needs and priorities".** The main focus being in the context of oil and gas development in ice covered regions. In this respect, several points from the keynote presentations were noted, these were quoted as:

"Most feasibility problems for Arctic offshore hydrocarbon development have been solved ------ but significant problems remain to ensure cost-effective solutions "(A. Wang - Exxon)

"Initial structures overdesigned ------ need research to lower costs" (J.Walker - MMS)

"Need to focus on most costly items" (G. Thomas - BP)

"Biggest local concern relating to offshore development is that the enormous forces of sea ice have been underestimated"(J. Gottlieb -MMS)

The first three quotes recognize the 20 years of operational experience in ice covered offshore regions including the placement of temporary bottom-founded offshore platforms in severe pack ice regions such as the Beaufort Sea. This experience has clearly indicated that the ice load design criteria used to date has been adequate. In fact, structural response measurements conducted at several locations have generally indicated lower ice forces than predicted.

However it must be pointed out that there are various points of view on how low ice loads can go. The challenge is therefore to be able to rationalize and confirm lower ice loads than have been used in the past. Ideally this should be done with a proper understanding of the physics of ice load generation, but as in many fields, it may be necessary to rely on technically-sound empirical treatment of measured data.

The use of lower ice loads is important to lowering the costs of offshore platforms for oil and gas development in ice covered regions. But as the last of the previous quotes emphasizes, the large forces of ice need to be respected, especially in regions where no experience exists. There is also a need to demonstrate to local stakeholders that sufficient knowledge exists for safe and environmentally sound operations.

With this background the Panel suggested that the discussion proceed according to the following steps:

(1) Overview of current practice by scenario

(2) Listing of remaining key issues by scenario

(3) How can the SIMI results be applied to the key issues ?

(4) Recommended future research thrusts

The scenarios referred to above are ice load scenarios and will now be defined.

Ice Load Framework

In designing and operating offshore platforms and vessels for ice, the engineer requires to know:

- The maximum global ice load expressed as a function of probability.(This also includes a knowledge of the ice load frequency spectrum as it will affect dynamic response of the structure).

- The variability of the ice load across the area of contact, in particular the local design ice pressure (also as a function of probability.

Ice loads can be caused by a variety of ice features including continuous sheet or uniform ice, ice ridges contained in ice floes, discrete ice floes, ice rubble features, icebergs and extreme features such as ice islands. Not all regions have all these features. Indeed, an important step in designing structures for ice in a given region is to be able to specify the ice environment, especially the maximum size and thickness of ice likely during the lifetime of the structure.

Ice loads are also significantly affected by the shape of the structure and the resulting failure modes. In simple terms, ice will fail in bending on sloping structures, in crushing on narrow vertical structures, and sometimes in mixed mode failures against wide structures. The ability to predict ice loads requires that these failure modes be understood and can be predicted as a function of both ice feature geometry, ice type and structure shape and stiffness. The load magnitudes are also a function of the ice strength at the appropriate ice temperature, salinity, strain rate and size of failure zone; as well as other factors such as friction and clearing processes. Inertia effects may be important.

Figure 1 illustrates some of the complexity in the prediction of ice loads within a probabilistic framework and how the various inputs can be linked. The ice load models mentioned in the figure represent limiting global failure processes, i.e.

- Limit Stress
- Limit Force
- Limit Momentum

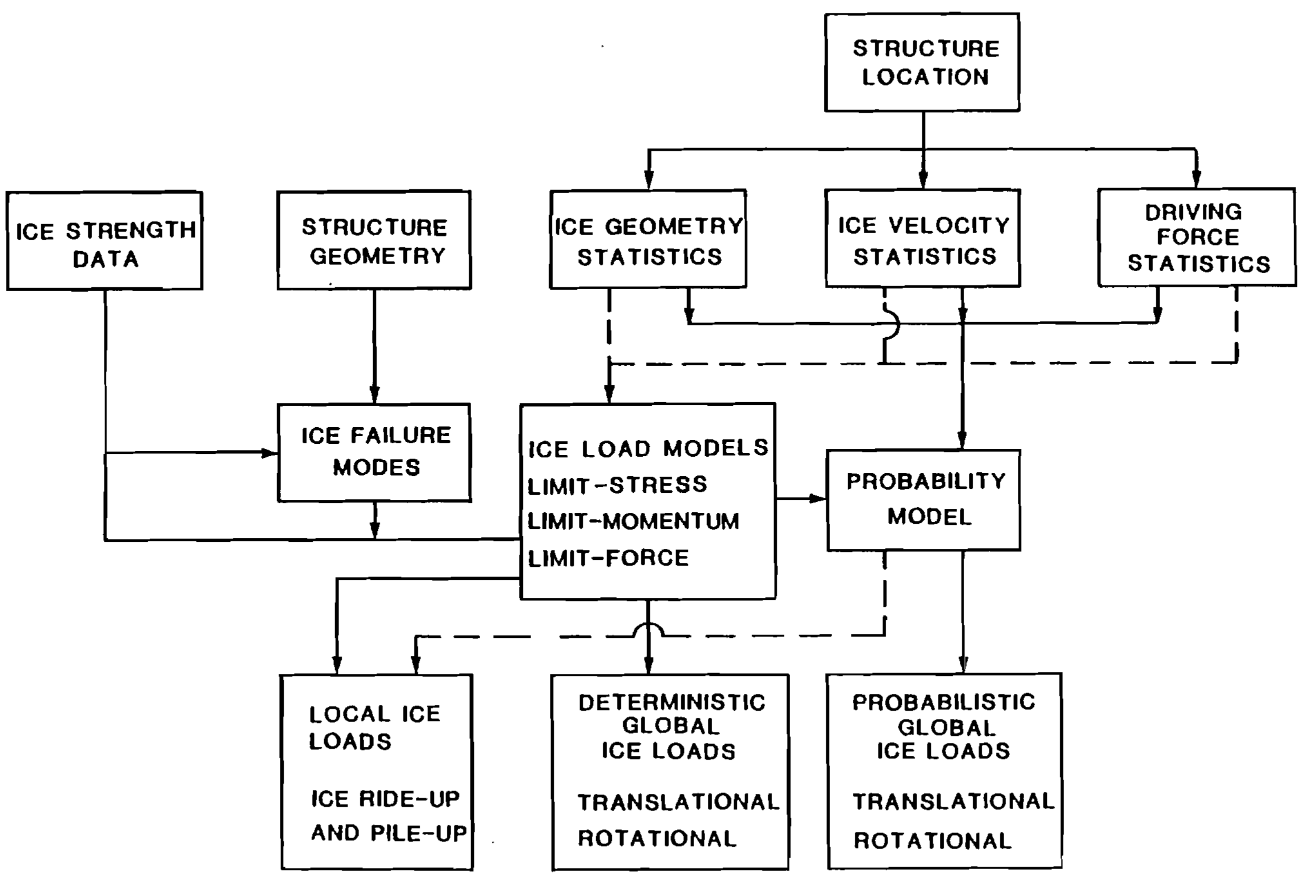

Figure 1: An Overall Logic for Ice Loads

In "limit stress", the ice load is limited by the load necessary to fail and clear the ice immediately in front of the structure over its full width. This is an upper bound condition and assumes that the ice will continue to move against the structure regardless of the forces being generated (see Figure 2).

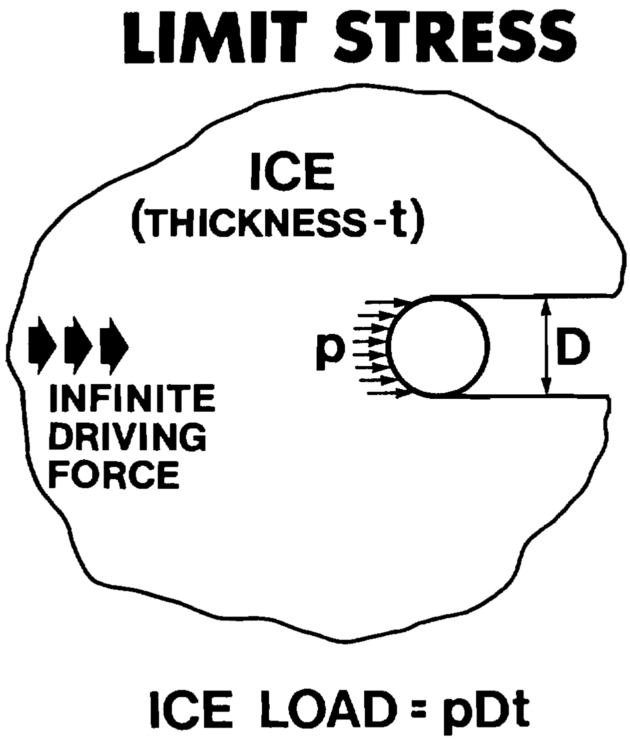

Figure 2: The Limit Stress Load

In fact, the ice load can be limited by the driving forces acting on the ice. In the "limit force" concept, shown in Figure 3, a thick ice feature is being driven by wind and current as well as pack ice stresses. In this concept, it is usual to consider that pack ice stresses are limited by ridge building forces in the pack ice.

Discrete ice features such as isolated floes, icebergs and ice islands may not have sufficient momentum to develop the full limit stress load. In such a case the contact width will be limited by the initial momentum or kinetic energy of the ice feature (Limit Momentum).

A fourth limit proposed by Blanchet (1990) is that due to floe splitting. This would apply to the situation where floes split before full envelopment (and the full limit stress load is generated).

An overall logic for how to apply these limiting load models is shown in Figure 4 (Blanchet 1990).

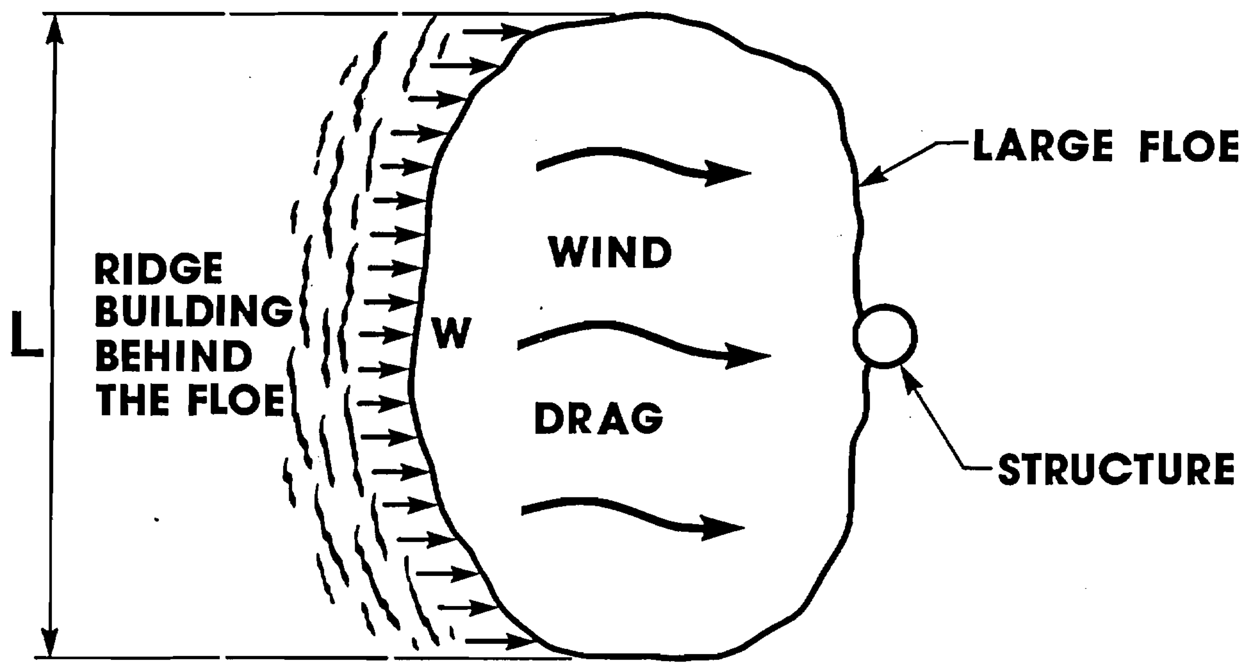

Figure 3: The Limit Force Load

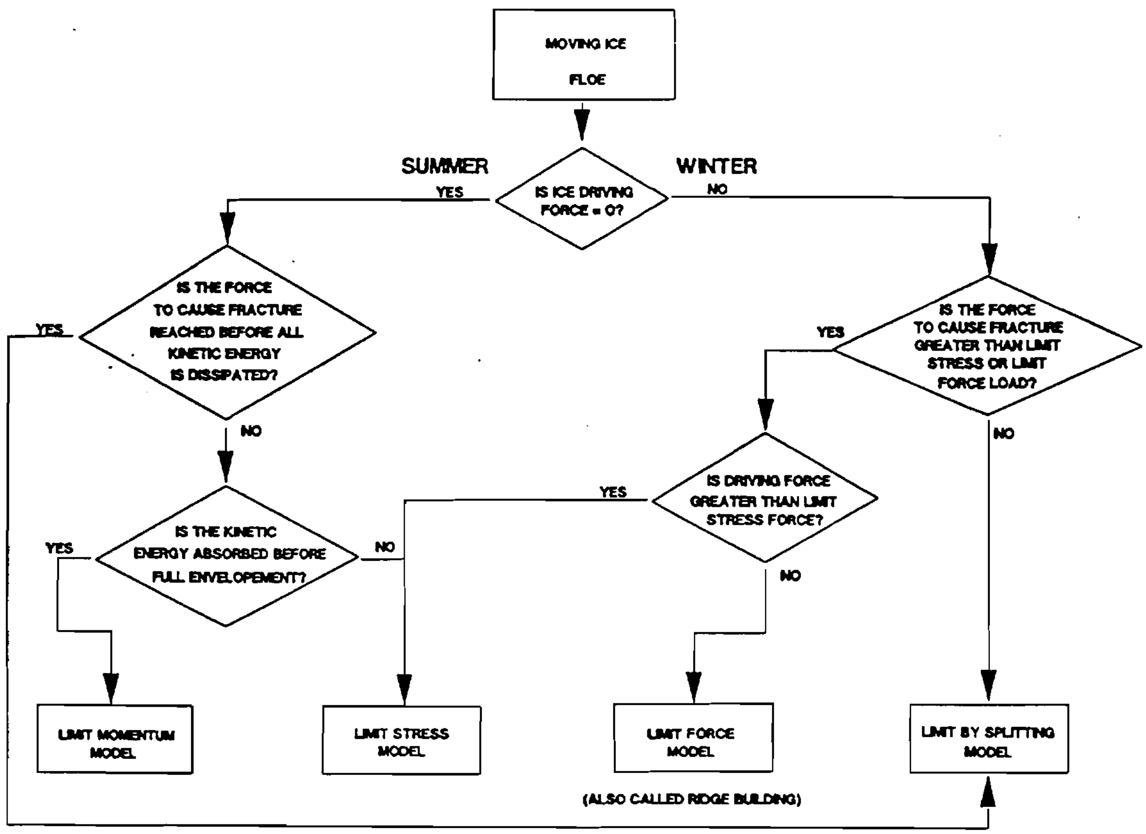

Figure 4: The Logic for the Limiting Load Scenario (Blanchet, 1990)

Current Practice

Current practice for ice loads recognizes the framework previously discussed but requires that specific calculation methods recognize the influence of structure shape and stiffness, ice morphology, ice properties, various breaking and clearing mechanisms, as well as other parameters. Calculation methods are heavily influenced by empirical methods and calibration with model tests and full scale measurements.

In North America there are currently two standards for the design of offshore platforms in ice. They are the American Petroleum Institute (API) Recommended Practice RP2N "Planning, designing and constructing fixed offshore structures in ice environments; and the Canadian Standards Association (CSA) Standard CAN/CSA-471-92 "General Requirements, Design Criteria, the Environment, and Loads", which is part of CSA Code for the Design , Construction and Installation of Fixed Offshore Structures.

Both of the above are not definitive in that they allow for various methods and inputs subject to the knowledge and judgement of the operators and regulators.

There are also Russian Codes that relate to designing structures in ice. These are more specific and have their origins in codes for bridges, dams and coastal facilities. When applied to sea ice and offshore platforms they may be conservative.

It should also be noted that specific rules are applied to the design and operation of ships in ice. These vary from nation to nation. They are often quite detailed on how ship's structures should be designed for ice loads; they are often related to ship size and power as well as to the ice conditions. The rules are quite empirical but have been calibrated by measurements of local ice pressures.

The codes, standards and rules in existence are in place to ensure safe structures, but they are not considered refined enough to allow the optimization of offshore oil and platforms to lower costs. This is mainly because in areas of uncertainty and lack of knowledge, the current methods err on the side of conservatism.

Ice Load Scenarios

Overview

In order to consider the current state of knowledge in ice load predictions, it is useful to use the previously defined framework, but with some additional detail. These are now defined in terms of ice load scenarios.

(1) Limit Stress

- Ice crushing - vertical structures - global loads
  - all structures - local ice pressures

- Sloping structures - solid ice
  - uniform ice
  - ridges
  - partially consolidated ice
    - ridges & rubble

(2) Other limits

- Pack ice driving forces (limit force)
- Momentum
- Splitting

Each ice load scenario was considered by the panel and the attendees, with the following results.

Ice Crushing - Practice

The concept of ice crushing against a vertical pier is the classic ice load problem in ice engineering and has been the subject of decades of research and numerous formulations.
It is the simplest of all the "Limit Stress" situations as shown already in Figure 2.

In simple terms the ice load (F) can be expressed as:

$$F = pDh$$

Where D is the width of the structure, h is the local ice thickness and p is the ice crushing pressure or failure stress.

Clearly, the problem is trivial if "p" can be specified, but the specification of "p" has been found to be very difficult hence the large amount of research and different approaches. For a review of the various methods of specifying "p", the Codes and Standards already mentioned should be consulted. It should be noted that methods based on indentation theories and small scale constitutive strength properties for ice appear to overpredict "p" when compared to measurements and experience. Undoubtably, there are numerous plausible explanations for this based on the recognition that ice is a brittle material at high strain rates and that in its natural state contains many existing cracks and other flaws. To date, however, the engineer's view is that no methods based on the physics of the material appear to be useable in a practical sense to predict ice crushing pressure against structures. There is also evidence that when data from a variety of sources containing different ice types, temperatures, strain rates and boundary conditions is plotted against simple geometrical parameters such as contact area it can be bounded by a simple power law (e.g. $area^{0.5}$). Such a plot is shown in Figure 5. The trend of decreasing ice crushing pressure with area is evident and this is referred to as the "size effect."

The plot shown in Figure 5 represents the most important tool of current practice which is the empirical treatment of measured data. Various organizations have different methods of interpreting such data and this leads to a spread in design values. This spread is further aggravated by the use of other empirical and theoretical methods which use small scale uniaxial strengths as inputs.

Ice Crushing - Key Issues

Based on the discussions the following key issues were identified:

(1) The size effect - do we have a reliable approach to its empirical treatment (e.g. is it controlled by area, width, thickness or a combination ?)

(2) There is still a wide spread of design values. Do we know why? How can it be narrowed?

(3) The physics of the size effect has not yet been explained—recognizing that it is extremely unlikely that there is just one mechanism over all scales, configurations, temperatures and loading rates.

(4) The crushing strength is not a material property. Therefore, the size effect may be a result of boundary effects such as non-simultaneous failure and imperfect contact. This creates a difficulty for lab-scale controlled testing in which damage is usually induced homogeneously. Perfect homogeneously induced damage will likely result in a negligible size effect. But if localization of damage occurs and a large enough size range is studied, then the size effect should be apparent.

(5) No shortage of ideas and suggestions for the size effect

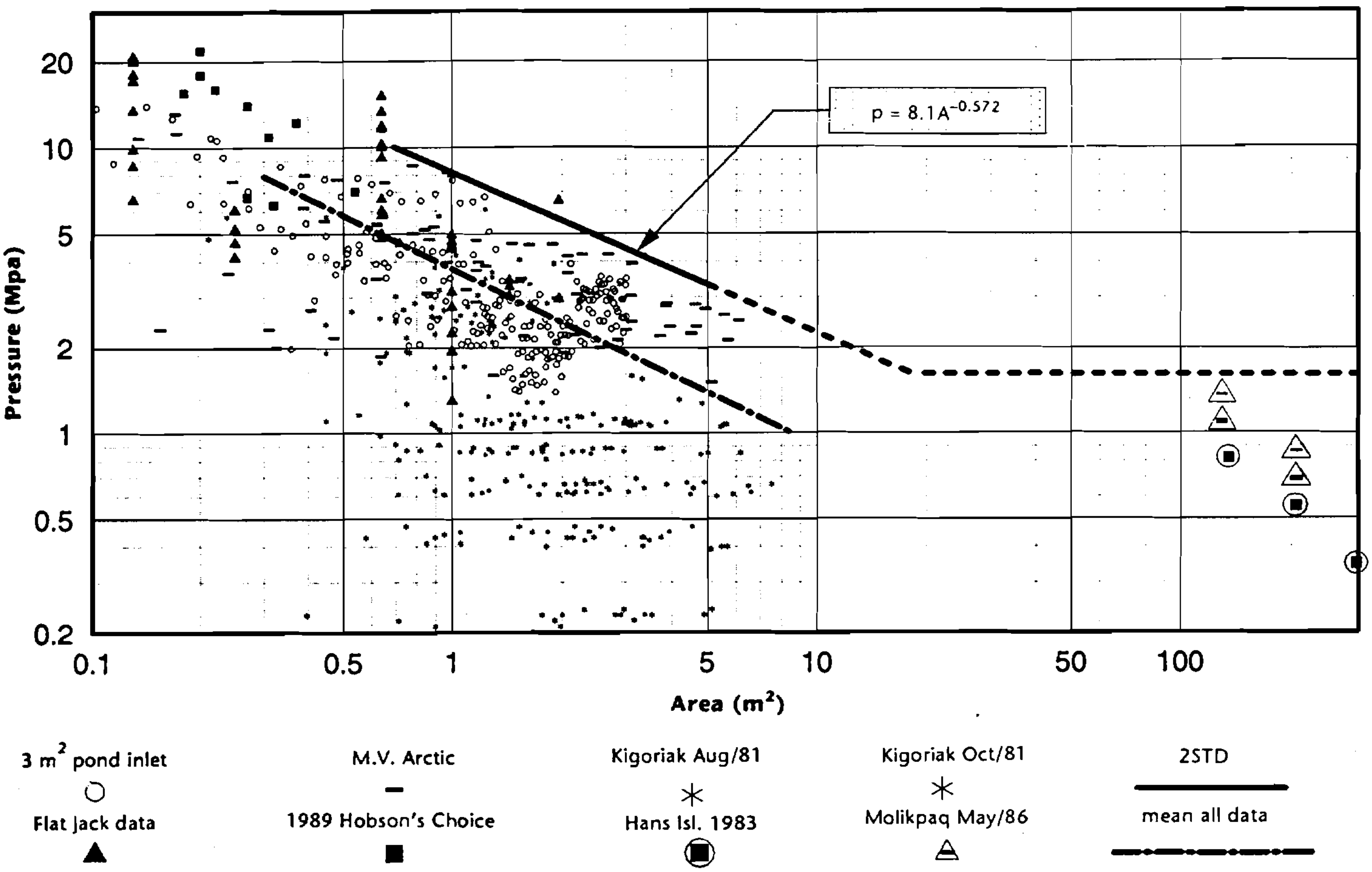

Figure 5: Ice Crushing Pressure vs Area
(CSA 1992- After Masterson and Frederking)

Ice Crushing - Application of SIMI Results

Participants in the Panel Discussion offered the following suggestions as to how results from SIMI might be applied to the issues relating to ice crushing.

(1) Use the newly measured failure envelopes for columnar saline ice obtained from multi-axial testing by Schulson's group to predict ice crushing pressures. The envelopes plot the failure stress versus degree of confinement, the strain rate and the temperature. They are significant because when combined with stress analysis of the contact zone, the envelopes allow failure pressures to be calculated. However, it has to be recognized that the results may be applicable only to local ice pressure design criteria because lab scale tests cannot account for size effects on ice crushing.

(2) Better understanding of scale on the ductile to brittle transition has been obtained. Specifically, laboratory experiments suggest that the transition strain rate decreases with increasing flaw size (l), scaling as $l^{-3/2}$. Again, however, there is a potential problem in extrapolating lab scale results to larger scales.

(3) A lower-bound for global ice pressures on large structures might be defined by interpretation of in-situ pack ice stress measurements obtained during the SIMI field program and other similar projects in Canada. The argument being that ice failure against a structure across a given width cannot be any less than measured pack ice stresses interpreted over an equivalent width. The key issue here is the interpretation of the pack ice stress measurements as a function of size of sensor, size of floe, the influence of thermal effects and distance of the sensor from the ice failure zone.

(4) Research on fracture has yielded improved understanding of size effects on fracture. Specifically, the scale effect from 0.1 to 100m on the nominal tensile failure strength is now much better understood. But the inter-relationship of this scale effect on compressive strength is not well understood.

Ice Crushing - Future Research

(1) Use the learnings from the recent SIMI laboratory tests and theoretical analyses to improve the interpretations of full scale ice load measurements, and enable their extrapolation to other situations.

(2) Test the ductile to brittle transition size effect theory on larger samples, but before doing so, it is recommended that a scheme for incorporating the results into an ice crushing pressure size effect be demonstrated.

(3) Devise quantitative verification tests for various hypotheses for size effects on ice crushing.

(4) In engineering practice, differences in the prediction of large scale ice crushing pressures continue to exist - what are the common roots ? - where do divergencies occur ? These need to be well documented and examined in order to help focus the future research thrusts.

(5) Encourage more cooperation in the field and between researchers and practitioners. The value of large scale tests and ice load measurements on actual structures cannot be overstated. Field tests however should have clear analyzable content and field teams should include researchers with lab testing experience.

Sloping Structures - Practice

Sloping structures are chosen to avoid global ice crushing in order to either (a) eliminate the higher frequency excitation associated with ice crushing or (b) reduce the global load. Whether global loads are reduced will depend on thickness of the ice, the structure diameter, the slope angle, ice to structure friction and the value assumed for ice crushing pressure in the equivalent vertical structure. Sloping piers have been used on bridges and light piers for centuries and ice breaking vessels have always had downward sloping bows. So the interaction of ice with sloping structures is fairly well understood. Currently, there are a number of algorithms for solid, uniform and ridged, ice which are in reasonable agreement and which compare well with model tests, small prototype test structures and lightpiers. (See Chao, 1990).

It should be noted that the total load due to ice failure on sloping structure is made up of both breaking and clearing terms. Their relative size will depend on structural shape. Generally as the width of the structure increases so will the clearing forces. It should be noted that most comparisons with large test data and measurements are for narrow cones. There is a lack of full scale data for wide sloping structures against which to test the current algorithms, and the potential high clearing forces are a concern. (Note that some wide Arctic exploration caissons have been built with sloping sides - initial ice failure created large rubble fields grounded on the underwater berm at -9m. In this case any advantage of the sloping face was lost after the first few interactions).

Another area of uncertainty relates to how first-year ridges fail and the loads they create (this uncertainty also applies to vertical structures). There are a number of algorithms for the loads due to first-year ridge keels (e.g. Dolgopolov and others, 1975; Prodanovic 1981: Croasdale 1980). They all treat ice rubble as a Mohr-Colomb material with cohesion and a friction angle. Depending on the model used, and the properties used calculated loads due to first year ridge keels can vary by about a factor of four. Very little full scale data is available to help calibrate the models and narrow these differences.

Finally, another area of uncertainty relating to loads on sloping structures is the effect of ice speed when it is greater than about 1.5m/s, fortunately such ice speeds are rare.

Sloping structures - Key Issues

The key issues discussed above are summarized below:

(1) Good agreement between theoretical methods, model tests, basin tests and limited full scale data- for sheet ice and solid ridges - narrow cones.

(2) Lack of knowledge of whether rubble build up is a problem - as width of structure increases.

(3) Disagreements on how to calculate loads due to first year ridge keels and ice rubble.
   - constitutive properties of ice rubble (c, ϕ)
   - failure modes

(4) Virtually no data on (3) - but some work underway.

(5) Inertia effects not well understood

Sloping Structures - Application of SIMI results

The work on first-year ridges conducted under SIMI can be useful in addressing some of the issues outlined above, more specifically:

(1) The discrete element modelling by Hopkins to simulate ridge formation could be applied to the problem of ridge disintegration when interacting with a structure.

(2) The work by Shapiro and others on the consolidation of first year ridges confirms that the consolidated layer within the ridge can reach twice the thickness of the surrounding ice sheet. The work also sheds some light on the distribution of brine within the ridge with time. This is an issue important to understanding the internal strength of first-year ridges, which is critical to predicting the ice loads which they can impose.

(3) The work by Coon and others also provides some specific data on the internal structure of a ridge. The presence of the mushy layer below the refrozen layer deserves further investigation as a possible line of weak ice. The in-situ air jack tests show promise as a technique for assessing the internal ridge strength, but further development of the method, with a larger area and displacement, is needed before meaningful data can be obtained.

Sloping structures - Recommended Research (some of this is underway)

(1) Field measurements to better define the physical and mechanical properties of ridge keels (strength - cohesion - friction angle - constitutive properties; porosity; density etc.).

(2) Large scale strength tests on ice rubble with emphasis on the effects of aging processes (both thermal and mechanical).

(3) Improved algorithms for ridge keels which recognize the differences between ice and soils from which most of them have been derived. These should be tested in controlled environments.

(4) Use of discrete and particle element modelling to assess ridge failure processes and loads.

(5) Seek opportunities to obtain full-scale load data for both uniform ice and first-year ridges (e.g. bridge to Prince Edward island).

Pack Ice Driving Forces (Limit Force) - Practice

The idea that internal pack ice stress might limit the force on structures was first raised by the ice motion modellers in the 1970s (Hibler, 1975). It became obvious however that there are ice features that can concentrate pack ice and other environmental loads, so the average geophysical pack ice stress cannot be used directly in design. It can also be shown (by experience) that for normal ice thicknesses there is usually enough driving force to cause local ice failure against the structure, and so no relief is obtained by invoking the limit driving force condition.

However, conceptually the limit does exist, especially for very thick features surrounded by thinner ice. It is further speculated that pressure ridge formation in the thinner ice will be the controlling process. (See Figure 3).

Table 1 shows how the limit stress and limit force loads compare for various sizes of blocking ice feature, thickness, strength and ridge building forces. It shows that there will very likely be some situations when the ice forces due to extreme features will be limited by driving forces. This is of interest to the engineer because the extreme design loads can be lowered.

The simple expression for the Limit Force Load (F_{LF}) is given by:

$$F_{LF} = \text{wind drag} + \text{current drag} + wL$$

Where L is the floe width and w is the maximum pack ice force (spatially averaged across the back of the floe) acting during the period when the floe is blocked (its unlikely to be a stable situation).

A difficulty in specifying the Limit Force Load has always been specifying w for design purposes. Table 2 shows a typical range of values obtained from a variety of sources.

Table 1: Typical Limit Force Ice Loads (Croasdale & others, 1992)

ICE FEATURE WIDTH (m)	TYPICAL LIMIT-STRESS LOAD (MN)	TYPICAL LIMIT-FORCE LOADS (MN)		
	Structure dia = 100 m Ice Thickness = 15 m Ice Pressure = 1.0 MPa	w = 20 kNm^{-1}	w = 100 kNm^{-1}	w = 500 kNm^{-1}
200	1500	4	20	100
500	1500	10	50	250
1000	1500	20	100	500
2000	1500	40	200	1000
5000	1500	100	500	2500
10000	1500	200	1000	5000

Table 2: Estimates of Ridge Building Forces (Various Sources)
(Croasdale and others , 1992)

SOURCE	APPROACH	RANGE OF VALUES FOR RIDGE BUILDING FORCE (kNm^{-1})
Parmerter & Coon	Ridge-building math model	10 to 30
Hibler	Large-scale ice motion modelling	10 to 100
Rothrock	As above	40 to 100
Mellor	Math model for ridge-building (2 m ice)	50
Nevel	Math model for ridge-building (1 m ice)	40 to 100
Vivitrat & Kreider	Review of rubble building & ridge-building models	150 to 700
Abdelnour & Croasdale	Narrow width model tests	up to 500
Croasdale	2-D theory for fracture and ride-up (1 to 2 m ice)	35 to 110

It should also be noted that to apply the method, the effects of the initial momentum of the ice feature need to be recognized. If this is large then a significant load may be built up from the local ice failure occurring at the structure during the period when the floe is being decelerated.

Both the Canadian and US Codes for offshore platforms mention the limiting driving force approach but provide little guidance on the specifics.

The key issues relating to the Limit Force approach are itemized below:

Limiting Driving Forces - Key Issues

(1) Average ridge building forces as a function of width and ice thickness.

(2) Effects of floe momentum

(3) Stages in pack ice interaction on back of floe - can a stationary cone form?

(4) How to define a discrete ice feature in a winter pack ice matrix (frozen in condition).

(5) Limits of application- region - ice features

Limiting Driving Forces - Application of SIMI Results

Several SIMI initiatives can be applied to address some of the above issues relating to the Limit Force approach, i.e.:

(1) A pack ice stress envelope was developed by Coon and others. This envelope is the largest 2-D stress state that the pack ice can withstand. Such a stress envelope can be used to: a) Define the effect of confining stress on the driving forces on a blocking floe. b) Help define the effect of ice conditions on these forces and enable probabilistic load calculations to be performed (by combining the stress envelope as a yield surface with wind and current distributions).

(2) The in-situ measurements of Richter-Menge and others should be analyzed to give spatially averaged ridging forces. The floe edge sensors recorded peak stresses of about 400kPa whereas the floe centre array recorded similar patterns of stress but an order of magnitude lower (i.e. about 40 kPa). It is of vital interest to know whether this is simply stress attenuation, or averaging of ridging forces across the floe width.

(3) The discrete element modelling of ridge building (by Hopkins) can be used to gain insights into the effect of ice parameters (e.g. thickness) on ridge building forces and hence on pack ice stresses. These insights can then be used in probabilistic models for the limit force ice load.

Limiting Driving Forces - Recommended Research

(1) Complete the interpretation of the in-situ pack ice stress measurements from an ice loading perspective: (i.e. to assess whether there is spatial averaging of ridge building forces across the width of influence and use existing data to establish pack ice stresses as a function of floe width).

(2) Conduct in-situ measurements to test the interpretations.

(3) Use (1) and the pack ice stress envelope developed by Coon and others to develop a 2-D limit force model which can be exercised within a probabilistic framework.

Limit Momentum - Practice

This condition has already been referred to in the Limit Force discussion, but the condition will more likely be limiting for a very thick discrete ice feature such as an iceberg. The limit simply recognizes that the ice force can be limited by the initial momentum or kinetic energy of the ice feature. The calculations are straightforward application of Newton's laws and will not be repeated here.

In terms of ice mechanics, the most important input is the ice crushing pressure as a function of the contact area, and has already been discussed under ice crushing. However, it is of interest to note that for icebergs very little data exists from which to develop an empirical ice crushing size effect curve. (However, work to correct this deficiency is underway).

Floe Splitting - Practice

Observations indicate that many large floes under stress exhibit splitting failure. It has been suggested that when thick floes interact with a structure many may split before the maximum "Limit Stress " load is reached, which will lead to a lower global load. The splitting failure mode is recognized in API RP 2N and a method is given to predict splitting failure.

Floe Splitting - Key Issues

In order for floe splitting to be used as a reliable load limit the following key issues need to be addressed.

(1) Reliability of splitting predictions (e.g. as defined in the API RP 2N) for real scale situations i.e. large floes

(2) Post-splitting loads: Even if a floe splits during ice interaction we need a scheme to assess whether the loads can continue to rise because of floe momentum and constraint of the surrounding pack ice, if present.

Floe Splitting - Application of the SIMI Results

(1) As impled above, the different splitting scenarios are not realistic yet. However, the fracture research in the SIMI program will determine the scale dependence on the tensile failure strength as well as provide a fracture model that is applicable to sea ice in the range of 0.1 to 1 km. This model can be quantitatively incorporated into a fracture-based splitting model. Questions remain regarding the actual sequence by which the splitting failures are initiated.

Floe Splitting - Recommended Research

(1) Complete the interpretation of the SIMI experimental work to develop a size effect law for fracture and splitting

(2) Develop a new theory for floe splitting using (1) (with and without surrounding pack ice).

(3) Develop a scheme for post-splitting loads based on momentum dissipation and either sequential fracturing or large scale crushing as secondary processes. This should be done with and without the presence of surrounding pack ice.

(4) Integrate the splitting mode of ice failure into a probabilistic load model (e.g. the one developed under the sponsorship of the Canadian National Energy Board). Exercise the model to assess how the inclusion of floe splitting affects the design loads for various regions. This will indicate what additional field data relating to floe splitting may be needed.

Vessels

The issues relating to ice loads on vessels have similarities and differences from ice loads on fixed and floating structures. The session did not allocate much time to vessel issues, the following listing was prepared by a vessel expert at the session (Daley), but there was little discussion.

Vessels - Key Issues

(1) Harmonization of Polar Shipping Rules
- Maximum bow forces
- Local ice pressure as function of area
- Class/area definition

(2) Design Ice Conditions
- Those influencing loads
- Those influencing performance

Clearly the issues relating to ice loads on vessels are similar to those on structures and have already been discussed. For a ship its important to get the local ice loads right because local damage can be catastrophic. But global loads for extreme ice may be less important because a ship will be able to slow down or avoid the feature. (The opposite is true for fixed structures).

Pack ice stresses are important in ship routing because it is well known that it is often ice pressure not thickness that will stop a ship.

In the above areas, the SIMI results will be of value as will also the recommended research already mentioned. No specific additional research for vessels was recommended during the panel discussion.

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SEA ICE FORECASTING
FOR SHIP ROUTING AND OPERATIONS

Robert S. Pritchard, Chairman
IceCasting, Inc.

Anatoli Polomoshnov, Co-Chairman
Sakhalin Oil and Gas Inst.

Ben W. Danielewicz, Recorder
CANMAR, Ltd.

Kyle Monkelien, Recorder
Minerals Management Service

OPERATIONS THAT BENEFIT FROM ICE FORECASTS

Some of the offshore operations that can benefit from an accurate ice forecast system are described briefly below. Accurate, well-defined forecasts and monitoring systems will reduce costs and minimize down time. They will allow for safe operations without the need to design for maximum possible loads.

It is critical to identify the best ship route to minimize transit times. Forecasts should provide information along the desired routes at distances of 10 - 500 miles. During production, a steady stream of vessels will sail between fixed ports, along routes that could differ depending on ice and weather conditions. For example, along the north and northwest coast of Alaska, 1-2 large ice-breaking LNG tankers would transit daily. A ship's progress can be affected by ice conditions (thickness, concentration, MY ice) and by ice stress. Indirectly, the ice motion, especially in areas of ice convergence, can stall vessel progress. We say indirectly because convergence is likely to lead to heavier ice conditions and higher stresses. Stress is an essential parameter because the relationship between convergence, ice conditions, and stress is not linear.

During exploration, some operators have used open water drill rigs and other vessels that were designed to withstand only limited ice forces. These operations require an alert system to warn of potential dangers. Typically, trajectories of ice that could approach the rig are estimated. Surveillance is used to identify ice that could lie along these trajectories. As this dangerous ice approaches to within pre-defined distances, the operations that may be performed are limited to ensure that there is enough time for an orderly shutdown of operations.

Pipelines are designed to avoid gouging by burying them deeper than some historically-defined ice keel depth. The cost of building a pipeline could be reduced if it could be buried at a shallower depth. An alert system could allow such shallower operations if it provided enough time to take appropriate actions in case ice with a deep keel approached. This forecast would be similar in concept to the alert systems used for drill rigs.

The design of an offshore tanker terminal must include an estimate of downtime during operations. Present thinking assumes that a long-term hindcast of ice behavior at a terminal site will provide statistics that allow the operator to estimate likelihood of downtime. Ice velocity statistics are needed. In addition, accelerations, especially the rate of change of ice drift direction at low speeds, are needed to estimate the likelihood that a tanker would not be able to keep its bow into the oncoming ice (the weathervaning problem).

The tanker terminal problem shows one of the uses of hindcasting ice behavior. The same model used to forecast ice behavior can be used with a historical data base of winds to conduct hindcast studies.

Since operations are often close to a coast, sometimes behind islands, the ice must be characterized accurately on scales of less than 10 km. The new anisotropic plasticity model described elsewhere in this report will provide this capability. In coastal areas, ice grounding can also significantly change response of the ice to wind and current forcing, and the grounding force should be included. Models should be used with caution if grounding is neglected.

Oil spill trajectory forecasting is a necessary component of an oil spill cleanup operation. It can define the likely movement and oil condition, and it can identify coastal areas that might be impacted. Such forecasts can help direct the cleanup operations. This type of modeling has been used in a hindcast mode to estimate the risk from potential drilling operations, as part of the environmental impact statements.

WHAT IS NEEDED IN FORECAST SYSTEM?

Our attention is focused on short term forecasts designed to support day-to-day operations. These forecast periods are limited to about one week because this is the limit of weather forecasts. We identify the variables or parameters that must be forecast, and the components of a reasonable forecast system. Seasonal forecasts are also needed to plan operations, but they are not discussed here because they require completely different approaches.

Two different types of forecast systems are identified: general-purpose broadcasts, and operation-specific forecasts designed to support a specific operation. The former is provided by the National Ice Center in the U.S. and by Ice Central in Canada. These general-purpose forecasts provide information on ice motion and ice conditions over large regions at regular time intervals (twice daily). The general-purpose forecasts can provide useful information to the operation-specific forecasts needed to support real-time operations. A forecast designed to support a specific operation should provide the variables in a format desired by the operator. The forecast might need to be made more frequently or on-demand. Finally, this operation-specific forecast should use data acquired at the site to initialize future forecasts, to improve model accuracy, and to estimate confidence intervals.

The system must be designed to provide the variables needed by the specific operation. These include: ice motion, including trajectories, velocity, and acceleration (rate of change in direction and speed); stress (all components, not only pressure); strain rate (convergence and divergence); ice conditions (concentration, thickness distribution); changes in ice conditions;

likely location of leads and their orientations; and likely location of ridges and their orientations. Ocean currents could also provide valuable guidance in some operations.

Confidence intervals must be provided for each variable. These should be based on uncertainty in prior simulations and forecasts. We should not allow continued use of the term *fairly good* to describe how accurately a model describes observed behavior. Valid statistical measures of error must be estimated to describe model performance. These error measures will define the forecast confidence measures.

The forecast product should be designed to satisfy the user, who may have different needs depending on the specific operation being supported. Some users will desire only brief verbal descriptions, others will desire plots of some key variables. In order for the forecast to be useful, it must be in a format that is familiar to the ship master and bridge crew, corporate headquarters, government regulator, or oil spill response team. The forecast must complement information already in hand (*e.g.*, yesterday's remote imagery), and the level of confidence provided with the forecast must be understandable to the user.

The following list attempts to outline all necessary components of a complete forecast system.

Data

Wind forecasts at 12-24 Hour Intervals (CNODDS)
Local Wind Observations
Ice Conditions (AVHRR, SAR, Ground-based radar)
Ocean conditions

Model Calculations

Interpretation of Behavior

Atmosphere, Ice, Ocean

Communications

Data Sources to Forecaster
Forecast and Explain Output to User
User Feedback Local Observations to Forecaster
User Feedback Local Accuracy to Forecaster

Location Of Forecast Operations

Forecast Headquarters
On Site

Most of these items are self-explanatory. We note, however, that user feedback is necessary to develop confidence limits. The user can provide the best estimate of prior model performance. We note also that some forecast method should be used on-site. This might be a simpler backup system that functions in case of communication failure at a critical time.

A forecast system could be mobilized in about one week if all data sources were in place, but might require a month if not.

Three classes of ice dynamics models can be used in the forecast system: statistical, deterministic, and blended.

Statistical models describe the range of behavior estimated from prior observations. Both average and extreme behavior can be estimated.

Deterministic models describe the forces acting on the ice cover, including inertial, sea surface tilt, and Coriolis accelerations, wind and water stress, and ice stress divergence. When used to describe nearshore behavior, forces from grounding of ice must be included. The ice stress is neglected in a free drift model, the simplest assumption. For the past two decades, ice stress has been described most accurately using isotropic plasticity models that describe ice conditions by its thickness distribution. Standard errors for careful simulations with wind fields developed during Aidjex are about 3 km/day. Errors increase as forecast winds are used. In the future, we expect that the anisotropic plasticity model developed during SIMI will provide the basis for ice behavior models. This next-generation model can describe behavior over scales less than 10 km, where individual leads and ridges can cause strongly oriented behavior.

Ocean currents must be included to describe water stress and tilt. To describe short-term behavior, tidal oscillations are needed. The most sophisticated ocean models can describe time-dependent behavior of the complete three-dimensional ocean, including tidal, barotropic, and baroclinic modes. Simpler vertically-averaged models can also describe some of the behavior. The more sophisticated models require very large data sets to initialize a simulation, and most of this information is only poorly known. This limitation is real, but it does not obviate the need for including accurate current information in an ice forecast or hindcast.

Blended models include both statistical and deterministic components. When well-designed, a blended model can include (at least some of) the physics described by the deterministic model, and can additionally correct for observed errors of the deterministic model.

ACCOMPLISHMENTS

The SIMI program did not directly address ice forecasting issues. However, this application did benefit from the basic research conducted under SIMI. Most importantly, the new anisotropic plasticity ice dynamics model can describe and forecast ice behavior on smaller scales than previous models. The new model can describe the formation of new leads or lead systems, including their orientations and size. All prior models are isotropic and must approximate the oriented leads as fractions of open water. Predicting lead location and orientation should be especially important for improving ship routing forecasts.

RESEARCH NEEDS

The next-generation ice model that will use anisotropic plasticity is now a well-defined concept, but continued research is needed to develop failure laws for a complete suite of full-scale processes (*e.g.*, opening, rafting, and ridging). At sub-scales, mechanisms such as frictional sliding of ice blocks over and under the ice sheet, refreezing of ice floes broken by thermal cracking and isostatic imbalance, buckling, and in-plane shearing must be described because they contribute to the full-scale processes.

A new numerical scheme must be developed, and model performance must be tested. Both zero and two dimensional simulations are needed to test model performance. In the former simulations, a homogeneous strain history is prescribed. The corresponding stress history is calculated and compared with measured stress histories. In the latter simulations, behavior of the ice cover under applied winds and currents is calculated and compared with measured ice motions, deformations,stresses, and ice conditions.

Far-field boundary conditions for the ice model must be specified, either by nesting within a large grid, or by some arbitrary specification.

More effort is needed to provide users with needed remotely sensed products, which will likely require more emphasis on analyzing existing data streams.

Sea Ice Induced Gouging of the Sea Floor

Co-chairs
Dr. W. F. Weeks, Geophysical Institute, University of Alaska Fairbanks
Dr. Albert Wang, EXXON

Recorders
Dr. Chris Woodward–Lynas, C-Core
Dr. Vladimir Ryabinin

INTRODUCTION

It was decided to discuss the general subject of sea ice induced gouging of the sea floor by considering three different questions relating to this overall problem. Specifically these questions were:

- Why should we be concerned?
- What do we know?
- What do we need to know?

The results of these group discussions are summarized in the following paragraphs. Also included is a brief mention of a few research approaches that we felt looked promising and that should be explored further, as well as comments on how the results of the SIMI program have impacted the gouging problem.

It was noted that although gouging has aspects of general scientific interest, it is essentially an applied problem that is primarily of interest to the oil industry. Therefore, although there have been continuing studies relating to iceberg induced gouging occurring off the east coast of Canada, there has been little work on sea ice gouges off the Chukchi and Beaufort Coasts of the Arctic Ocean since the drop in oil prices in the late 1980s. The exception to this statement is the Pressure Ridge Ice Scour Experiment (PRISE) which considers both sea ice and iceberg gouging and started field operations in 1992. A summary of the status of PRISE is included as an appendix to the present paper. Unfortunately the majority of the work under this program either has not as yet been completed or has not been released for publication in the open literature.

WHY WORRY ABOUT GOUGES?

The following is a list of some of the more important reasons.

- Gouging can inflict major damage to seafloor structures.

  The fact that sea ice gouging phenomenon can severely damage a wide variety of seafloor structures including pipelines, gloryholes and cable systems is amply attested to by operational experience at locations such as the Bering Straits where cable systems have frequently been damaged by gouging.

- Gouging has a major financial impact on development costs through its effect on the required depth of trenching.

  A recent study by BP breaking down the costs of offshore oil field development shows that pipeline trenching costs are by far the largest expense. This is particularly true in the arctic offshore where the trenching equipment will undoubtedly have to remain on site over the winter even though the operational season may only be 2 to 3 months during the summer and early fall, and the trench depths required may locally be at the limit of existing trenching capabilities. There are also potential problems relating to the Jones Act which may require equipment such as cutter-suction dredges to be built specifically for the U.S. Arctic.

• Permitting depends on detailed knowledge of gouging depths and frequencies.
To obtain a permit to develop a promising offshore site, the company involved must convince the permitting agency that its knowledge of gouge depths is adequate for safe development. This is generally believed to require fairly detailed knowledge of the local aspects of the hazards resulting from gouging.

• Gouging resuspends seafloor sediments.
Gouging is one of several mechanisms that can transfer both fine and coarse sediments from the sea floor to the overlying ice sheet where its incorporation can result in transport over long distances. In that current data show that hazardous materials can be concentrated in sedimentary material carried by sea ice, gouging may play a critical role in this overall process.

• Gouging contributes to the formation of hazardous ice masses.
The gouging and grounding process is a critical step in a series of ridge-building processes that lead to the formation of stamukhi and floebergs which are large locally formed ice masses that can pose hazards to offshore structures.

• Gouging contributes to the erosion of sub–sea berms that protect offshore structures.
Little is known concerning rates and overall significance of this general process except that it is undoubtedly a real hazard that could result in significant maintenance costs.

• Gouging can have an important effect on the length of the ice–free summer operational period.
The grounding process associated with gouging and stamukhi formation plays an important role in fixing and stabilizing the outer boundaries of the fast ice. The degree of stability of this grounded material can, in turn, significantly affect the timing of the breakup of the coastal fast ice zone.

• Gouging can serve as a proxy to study seabed damage caused by fishing activity.
By using natural gouges, one can avoid the expense and trouble of creating controlled gouges when studying biological destruction and recolonization associated with fishing activity. Recolonization studies on real gouges also has the potential to contribute information that would assist in the dating of recent gouging events.

WHAT DO WE KNOW?

The following summarizes some of the more important information that we believe that we know concerning gouges and the overall gouging process.

- The form of the gouge depth distribution at a given instant of time is a negative exponential.

  The gouge depth distribution function at any given time appears to be surprisingly stable and well–fitted by a simple negative exponential. This is known to be true for the Beaufort and Chukchi Seas and also for the Kara Sea. Although the maximum gouge depths are appreciably different, the same comment applies to gouges produced by icebergs off the east coast of Canada.

- The coefficients of the gouge depth distribution function vary systematically with water depth.

  The gouge depth distribution function is strongly dependent on water depth and this dependence is reasonably well–known for a few locations. Unfortunately the nature of this dependence is highly site specific. It is also believed to be strongly affected by changes in the geotechnical characteristics of the seafloor.

- Multi–gouging events observed over large areas can be related to single storm events.

  This fact has been well documented in the Canadian portion of the Beaufort Sea and is believed to be generally true.

- To obtain meaningful statistics concerning the number of gouges per km or per km^2 per year, a sampling period of several years duration is required.

  Large inter-annual variations in both the frequency and the intensity of gouging are known to be common, at least along the Beaufort and Chukchi coasts.

- The geographic distribution of gouging frequency appears to be fairly stable.

  Areas where gouging is frequent consistently show more gouging activity than nearby areas that are less impacted. This results in a consistent pattern even considering the general interannual variations mentioned above.

- Gouges generally run parallel to the isobaths.

  This statement is generally true for the coasts of the Beaufort, Chukchi, Labrador and Kara Seas as well as for the Okhotsk Coast of Sakahlin.

- The deepest, as well as the most frequent, gouges occur at water depths of between 25 and 40 m.

  The reason for this is related to the size distribution of pressure ridge keels in that keels > 40 m deep are very rare. There are two reasons why gouging is less intense at water depths < 25 m. The most important is undoubtedly the fact that the large ice masses capable of producing deep gouges ground at water depths >25 m. Also a factor is the observation that near-shore sediment motion erases gouges more rapidly in shallow water as the result of generally larger waves and stronger currents.

- Gouges are particularly frequent on the seaward side of offshore bars.

  A coupled observation is that the onshore side of such bars is frequently a 'shadow' zone with relatively few gouges.

- Gouges do not occur in deep water.

  The question here is how deep is deep enough. The deepest known pressure ridge keel observed via submarine sonar has been reported to be 50 m. However gouges having all the characteristics of modern gouges have been reported in the Chukchi Sea at water depths in excess of 60 m.

- Reasonable estimates of the forces involved in the gouging process and of sub–scour soil deformation mechanisms are available.
  It should be noted that most of this work has been carried out at Memorial University in Newfoundland in conjunction with studies of iceberg gouging and may not be totally applicable to the sea ice problem. Improving this type of information is also one of the goals of the PRISE.

- The energy balance approach appears to be of limited usefulness in gouging studies.
  Although this approach is very useful for treating the motion of pack ice, its application to gouging is still problematic because the transmission of the pack ice driving forces through a pressure ridge keel to the seafloor is not well understood at present.

WHAT WE NEED TO KNOW?

The following briefly describes some of the more important information that we believe to be required for an improved treatment of the gouging problem.

- What are the depth distributions for new gouges?
  It is important to recall that, when one examines the sea floor via a bottom sounder or side–looking sonar, one sees a mix of old and new gouges. What is needed is the distribution function that applies to gouge depths as they form. Although the information of this subject is fairly satisfactory for the coast of the Beaufort Sea as the result of the repetitive mapping of new gouges, the development of a broader data base on this subject is very desirable, particularly on regional variations in gouge distributions. As might be expected currently available data suggest that the form of the distribution is also a negative exponential but with slightly different coefficients.

- How can one accurately date gouges?
  There has been considerable discussion in the literature concerning the ages of the gouges on the sea floor, with values ranging between a few years and a few thousand years. Here it is important to remember that sea level has risen significantly since the end of the Pleistocene with a maximum value for the rise of approximately 100 m. Therefore, if the gouges in deep water are old, they could have formed at sea levels that were appreciably lower than at present and presumably do not indicate present hazards. For instance, there is a 10 m gouge that has been identified off the Canadian coast of the Beaufort Sea. Is this be considered a 'fossil' or a present hazard? It should also be noted here that in shallower water along the Beaufort Coast repetitive side–scan sonar indicates that 5 years is an average age for gouges before they are erased by sedimentary infilling. To resolve these important questions, radiometric methods for determining the ages of gouges should be developed and applied to the determination of the ages of extreme gouges located in deeper water.

- How does coastline retreat as well as the migration of offshore bars alter the distribution of new gouges?

  It is well to remember that sediment transport along the Beaufort and Chukchi Coasts is extremely dynamic with offshore bars and islands migrating at rates of up to several meters per year. The comparable situation along the coast of the contiguous States is to be found along the coast of the Carolinas. In addition major storms have been known to result in large retreats of headlands along the Beaufort coast with retreats as large as 60 m occurring in a period of several days.

- At what water depths are gouges no longer a problem?

  As mentioned earlier, accurate regional assessments of this value are extremely important in regions such as the Chukchi Sea and the Russian Arctic offshore where small differences in the value used would make large differences in the areas where either burial or armoring of pipelines would be essential.

- How can one estimate pipeline/cable burial depths for specific locations such that the risk of failure from ice gouging will be reduced to an agreed-upon suitable level?

  At present there are several different approaches to making such calculations. There is a definite need to critically evaluate these different procedures so that they can either be applied with confidence or rejected as appropriate to the specific problem and location under consideration.

- Can a method be developed that will allow one to use remote sensing methods to accurately determine the position of the soil/ice interface below grounded pressure ridges?

  We are not optimistic that this is will prove to be possible because of the very intermixed nature of ice and water that is characteristically encountered in grounded first–year pressure ridges. Unfortunately surface–based radar procedures are limited by the presence of large amounts of sea water within such ridges while EM techniques are limited by the irregular distribution of the ice in the ridge as it senses the location of the surface of the sea surface beneath the ice. One procedure that would work is, of course, steam drilling through the ridge coupled with simple direct measurements of the distance from the surface to the sea floor. The only problem with this technique is that it is hard, very messy and time–consuming work as numerous holes would have to be drilled.

- More geotechnical data is needed to assist in estimating maximum gouge depths and the rates of sediment transport along the sea floor.

  As geotechnical data is commonly site specific, more regionally distributed data is needed. Also required is a way of testing the applicability of current geotechnical models for estimating maximum gouge depths. In addition it should be noted that although quite sophisticated sediment transport models that consider both currents and waves are available , these models have never been adequately applied to the gouging problem.

- It would be extremely useful to be able to correlate surface ice features with the gouging resulting from specific observed ice motion events.

  Attempts to develop such correlations for the Canadian Beaufort Sea have, to date, proven to be unsuccessful. However, if they could be developed, they would prove to be extremely useful as both the ice surface topography and the ice motions can readily be observed via the use of remote sensing techniques.

- Procedures need to be developed to determine representative values for the strength of keels and the attack angles of the ice during the gouging process.
  This information is needed if improved approaches are to be developed for estimating both maximum gouge depths and adequate burial depths based on classical soil mechanics.

- How is possible for the highly deteriorated ice commonly found in the lower parts of the keels of first year to cut the discrete notches that are commonly found in wide gouge tracks?
  A particularly clear cut example of such notch formation was observed in gouging occurring near the Kuvlum discovery in 1992.

- How is it possible for keels to cut essentially constant depths in gouges that form while the ice mass is moving up (or down) a slope.
  At present there is no adequate explanation for this fairly common field observation.

- Is it possible to effectively apply the class of autonomous, intelligent underwater vehicles that are currently under development to a variety of problems relating to the gouging phenomenon?
  The development of such vehicles would appear to be most promising in that these vehicles should be able to undertake under–ice mapping and sampling missions that may not be possible using conventional methods. Nevertheless, it was generally felt that this technology was not, as yet, mature when the difficulties associated with working around grounded ridges are considered.

SOME NEXT STEPS

The following are some ideas or approaches that were felt to be particularly promising or important.

- It is essential that a test be made of the capabilities of the different types of gouging models to provide realistic estimates of real gouging events.
  Particularly important here are the relations between forces transmitted through the soil, the magnitude of movement and the nature of the ice mass involved. It was suggested that this be accomplished by instrumenting a full scale ice gouging event by installing sensors around a well grounded ice mass in hopes of obtaining data when the ice mass moves in the spring.

- There is critical need to develop procedures for determining gouge depth distributions for regions where sediment transport is so large that gouges are so quickly destroyed as to leave no record on the sea floor.
  This is proving to be a major problem in offshore Sakahlin where there are strong currents and an easily transportable sand bottom.

• The combined application of seismic and acoustic techniques to gouging events as currently being explored in the Kara Sea by Smirnov appears to be very promising.
This general approach should be encouraged as it provides a type of remote sensing data that are not readily attainable by other means. Consideration should be given to using these procedures during the instrumentation of the large ice mass discussed in the first item in the present section.

• An expansion of the present generation of computer simulations of pressure ridge formation should be completed in order to include varied aspects of the gouging phenomena.
Considering the difficulty of carrying out adequate field studies of gouging processes, computer simulations would appear to have considerable promise. This is particularly true considering the current highly realistic simulations of ridging that have been carried out.

• Comparative studies of ice types, ice behavior and gouging should be carried out between the Chukchi, the Beaufort and the Kara Seas with the goal of developing capabilities and confidence in applying data from one region to another.
If these capabilities can be advanced, they will prove to be extremely useful over time as we will not be required to completely re-establish the gouging data base when exploration moves into a new area of the offshore.

SIMI CONTRIBUTIONS TO THE GOUGING PROBLEM

The SIMI program has been of only limited applicability to the gouging problem. This is not a criticism as the focus of SIMI was never intended to specifically include gouging. The exception to the above statement is perhaps the SIMI work on the 1 km scale which could conceivably lead to improved simulations of keel depths which, in turn, could be used in future studies of the frequency of gouging events.

W. F. Weeks

GENERAL SUMMARY AND STATUS OF THE PRESSURE RIDGE ICE SCOUR EXPERIMENT (PRISE) - MAY, 1995

PRISE is a progressing series of interrelated, focused studies directed at solving the problem of protecting seabed oil and gas pipelines from the effects of sea ice and iceberg scour. The ultimate goal of PRISE is to **develop the capability to design pipelines and other seabed installations in regions scoured by ice, taking into account the soil deformations and stress changes which may be caused during a scour event.** The need for this capability was identified during a round-table discussion with several oil companies and the federal government in 1990 during an international workshop on ice scour held in Calgary. PRISE is an interdisciplinary, internationally-funded project and several objectives have already been completed, including small scale physical modelling studies, preliminary centrifuge tests and finite element model analyses of ice scour.

Current work includes analysis of a 20-test series of centrifuge modelling carried out to provide data for the refinement, verification and calibration of finite element models. The calibrated finite element models will in turn provide data for input into an existing soil/pipe interaction model which will be the first working tool for the analysis and design of seabed pipelines in ice-scoured environments. The combined centrifuge and engineering model studies are in progress and will be complete by the fall of 1995.

The integrated model results will then be validated against the results of observations and measurements from a real, full-scale ice scour event. Finally, the field-verified numerical model, including pipeline design guidelines, will be introduced to industry and government as a design tool that will enable the safe engineering of offshore pipelines in areas subject to seasonal ice scour.

PRISE is divided into five phases:

Phase 1: PRISE Planning and Extreme Gouge Dating Project Feasibility Study

Planning for PRISE was completed in early 1992, and resulted in definition of an executive plan for the 5 phases of the project.

The Extreme Gouge Dating Project (EGDP) was added to the original objectives of PRISE because it deals with the probability of occurrence of deeply-penetrating ice scour events. The objective of EGDP is to verify a radiometric technique that determines the absolute age of seabed sediments filling very deep scour mark troughs. By determining the age of extreme features, the return period can be calculated. With this knowledge, risk of future extreme scour events can be estimated. The EGDP feasibility study was completed in spring, 1992.

Phase 2: Extreme Gouge Dating Project

A field program was mounted in the Alaskan Beaufort Sea in summer 1992 to support the objectives of EGDP. The objectives were to make detailed seafloor maps of deep scour marks and collect cores for radiometric dating. This work was only partially successful because of severe ice problems and the availability of very limited time on the survey vessel. Although this is still an option, further work on verifying the radiometric technique was put on hold by the funding participants in favour of progressing with Phase 3.

Phase 3: Centrifuge and Numerical Modelling, Pipeline Design Guidelines

A series of 9 initial centrifuge model tests of ice scour was carried out on the Cambridge University geotechnical centrifuge in 1992. Data from these tests provided the first indications of sub-scour soil and pipeline movements and provided invaluable guidance in designing the most recent test series. The development of finite element models of ice/soil interaction were carried out at the same time. Both of these pieces of work were funded by a grant from the Natural Sciences and Engineering Research Council (NSERC) Canada which was completed in November, 1993. The most recent centrifuge modelling is in support of the development of a soil/pipe interaction engineering model. Centrifuge work began in December 1993 and was completed in March, 1995. Engineering model development began in the fall of 1994 and will be complete in mid- to late 1995. Pipeline design guidelines will be developed when the engineering model is complete.

Phase 4: Full-Scale Ice Scour Event

No data have ever been collected on ice/soil interaction forces and movements during a full-scale ice scour event. These data are crucial for verification and calibration of both the finite element models and the engineering model that will evolve from the finite element analysis. Conceptualization of a field program for monitoring a full-scale event was completed in 1992. The field program will take place after completion of Phase 3.

Phase 5: Burial and Monitoring of Experimental Pipeline

It is common practice to install and monitor experimental pipelines in on-land areas where production lines are planned, and to incorporate these data in the final design. It is anticipated that there will be a similar requirement for offshore pipelines in regions affected by ice scour. The PRISE team is seeking ways to take advantage of monitoring opportunities for a series of 6 gas production pipelines planned for installation across Baidaratskaya Bay in north Russia, the first of which may be installed as early as 1995/96. The pipeline route is subject to ice scour and may be affected by subsea permafrost.

BACKGROUND

Since 1980 C-CORE has developed an internationally-recognized expertise in the study of ice scour. Early work involved offshore mapping and statistical analysis of iceberg scour marks along the Atlantic Canadian continental shelf. This work culminated in a large, industry-sponsored field project, the Dynamics of Iceberg Grounding and Scouring (DIGS) experiment, jointly managed by C-CORE, Geonautics Ltd. and the Bedford Institute of Oceanography. DIGS was carried out in the Labrador Sea in 1985. Measurement and analysis of motions of large (several million ton) icebergs as they grounded provided the first data on behaviour and ice loads on the seabed. At the same time detailed observations made from a submersible provided the first evidence that ice crushing occurred as the keels interacted with the seabed, and analysis of scour mark structure gave indications of sub-scour soil movements. The two-volume report, published in 1988, is the first and only definitive work of its kind. Subsequent to DIGS, innovative field work involving excavation and detailed mapping of 9,000-year-old scour marks exposed on land in southern Manitoba revealed that bearing capacity-type failure mechanisms had operated in the sub-scour soils to depths greater than 5 m. The combined results from these field studies provided invaluable input constraints to the current small-scale physical and centrifuge model studies carried out as part of PRISE.

STATUS MAY, 1995

Phase 3 is continuing with the analysis of results from a comprehensive suite of centrifuge model tests of ice scour. This work has modelled the scour process in soils that approximate natural seabed situations where pipelines are planned, such as in Russia. Objectives are: (1) to model 20 scour events in clay, sand and layered clay/sand soils, (2) to describe and quantify the general cases for each soil type and to highlight the similarities and differences in the responses of the different soils to the same ice keel loads, (3) to verify physical model results against field data from modern and relic scour marks. The effects of five parameters are being assessed, including: soil type, soil condition, attack angle, scour depth and scour width.

Funding has been secured to complete the development of a soil/pipe interaction engineering model, started in the fall of 1994. This portion of Phase 3 consists of: (1) refining the existing finite element (FE) ice scour model, (2) calibration and verification of the FE model by comparing results with physical and centrifuge model results and to existing field data, (3) determination of scour-induced soil deformations and ice reaction forces through a parametric study using the FE model, (4) adaptation of an existing engineering model for soil/pipe interaction analysis to the ice scour problem, (5) calibration and validation of the engineering model against physical, centrifuge and FE model data, (6) recommendations for soil measurements during a full-scale ice scour event (Phase 4).

PRISE FUNDING PARTICIPANTS

ARCO Alaska Inc.
Chevron
Exxon Production Research Company
Gulf Canada Resources
Minerals Management Service (U.S. Dept. of Interior)
Mobil Research and Development Corporation
Mobil Oil Canada Properties
National Energy Board (Canada)
Norwegian Research Council
Petro-Canada

PRISE RESEARCH TEAM

C-CORE
Norwegian Geotechnical Institute (Oslo)
Environmental Science and Engineering, Inc. (Florida)
Woodward-Clyde Consultants (Florida)
Concordia University (Québec)
Nixon Geotech Ltd. (Calgary)
Andrew Palmer and Associates Ltd. (London)

VALUE

Because of its industry sponsorship C-CORE is able to lever significant additional funds for the PRISE study through a variety of government grant programs, thereby enhancing the breadth of the study while at the same time reducing costs for its industry partners. The combined value of Phases 1 and 2 was CAN $350,000, and was cost-shared among the funding partners. The initial Cambridge centrifuge study and development of finite element models (part of Phase 3) was funded entirely by an NSERC grant worth CAN $456,000. Current Phase 3 centrifuge modelling and development of soil/pipe interaction model CAN $428,000, to be cost-shared among funding partners and including funding from NSERC. The Norwegian Research Council has contributed CAN $135,000 towards PRISE through its sponsorship of the Norwegian Geotechnical Institute.

JOINING PRISE

C-CORE is interested in attracting new funding participants to the PRISE project because of significant cost benefits. With more participants, the individual share is reduced while each participant still receives the benefits and deliverables of a major project. For an appropriate payment new participants may join PRISE either for one of the five Phases, or for a specific element of work within a Phase (e.g. centrifuge modelling study or soil/ pipe engineering). Support-in-kind, such as relevant data sets and reports, company personnel time or survey vessel time etc., may be acceptable either instead of, or as part of, a cash contribution.

DELIVERABLES

Participants joining PRISE will receive copies of all reports, videos and model documentation produced to date, and will receive all draft and final reports produced during the period of their participation. A list of all PRISE reports is summarized below.

LIST OF REPORTS AND PROPOSALS AVAILABLE TO FUNDING PARTICIPANTS

1. PRISE - The Pressure Ridge Ice Scour Experiment: A Joint Industry Program.

2. Pressure Ridge Ice Scour Experiment (PRISE): Workshop June 13-14, 1991 (St. John's).

3. Pressure Ridge Ice Scour Experiment (PRISE): Interim Report, October 1991.

4. Pressure Ridge Ice Scour Experiment (PRISE): Draft Final Report, Phase I - Planning, February 1992.

5. Ice Scour Bibliography, compiled February 18, 1992.

6. Extreme Gouge Dating Project - Feasibility Study - Phase I (ESE/C-CORE), April, 1992.

7. Pressure Ridge Ice Scour Experiments (PRISE): Phase II - Proposal, July 1992.

8. Pressure Ridge Ice Scour Experiment (PRISE): Phase II Progress Report (draft), March 1993.

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2. Estimating impact pressure of submarine slides on pipelines (Report 524234-1).
3. Relic scour study (Report 524234-2).
4. Site investigation and laboratory testing techniques for offshore pipelines (Report 524234-3).
5. Free span problems related to offshore pipelines (Report 524234-4).
6. Freely-suspended pipeline spans and construction techniques (Report 524234-5).

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4. Comparisons of physical and numerical models of ice scour. Q.S. Yang, P.R. Lach, J.I. Clark and H.B. Poorooshasb.

For more information contact:

Chris Woodworth-Lynas, Project Manager
C-CORE - Centre for Cold Ocean Resources Engineering
Memorial University of Newfoundland
St. John's, NF, Canada A1B 3X5

Tel: 709 737 8368
e-mail: chriswl@kean.ucs.mun.ca

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OIL SPILL WORKING GROUP

Walter Johnson, Chairman
Minerals Management Service

Ed Fremouw, Acting Co-Chairman
NorthWest Research Associates

Kate Hedstrom, Recorder
Rutgers University

Stu Knoke, Recorder
NorthWest Research Associates

Attendees (except for a few in the meeting for only a short time):

Paul Barter (Kinnetics Lab), Marie Becker (CIRCAC), Gordon Cox (Amoco), Don Denbo (Pacific NW Labs), Ron Lai (MMS), Ruth Post (CIRCAC), Dick Prentki (MMS), Andre Proshutinsky (Univ. Alaska, Fairbanks), Bernie Walter (SAIC)

Introduction -- Oil spill models are needed for contingency planning, environmental impact studies, and oil spill response. Models, inputs, and outputs are tailored to which need is being addressed. Many organizations have a stake in this arena: federal government (MMS, EPA, NOAA, USCG), state governments, boroughs/counties/cities, oil industry, and environmental groups. All need good data and models to assess risks and plan cleanup. Even air quality may be an issue when cleanup by burning is planned.

The dispersion of oil under and over sea ice is adequately understood, i.e., it does not spread more than a kilometer. Dispersion during freeze-up, break-up, and in broken ice is inadequately characterized. No accurate method is available, however, to determine the quantity of oil spilled (released) under sea ice. The preferred method to deal with oil spilled in ice is to burn it off as it surfaces. Oil under the ice is expected to enhance spring melting, resulting in oil intermingled with porous ice and surrounded by still-frozen heavy ice. In pack ice the oil moves with the ice, at least as accurately as we know the ice motion. Snow cover adds insulation and causes the ice to grow more slowly. Patchy snow can cause thin patches in the ice, which trap the oil underneath. A significant ice-water shear (>15 cm/sec) is needed to cause movement of the oil relative to the ice. However, under-ice current measurements are difficult. A local spill of long duration will lead to a long stream of oiled ice. This would be hard to clean - the current wisdom is to make igniters all winter and use them in the spring to burn the oil. If oily ice moves into a region with leads, it will get incorporated into grease ice.

The oil leasing and exploration proposed is all within 75 km of shore. The Arctic oil discoveries are in water depths of less than 40 m. In the coastal waters, the ice models will require a shore-fast ice component, but none are presently available. If the ice models are meant to provide information on ice gouging, they will need better information about the bathymetry.

The components of a hindcast/forecast for the transport of oil spills would include an ice model or a coupled ice/ocean model. The working group consensus was that existing ice models perform satisfactorily on the gyre scale, the scale for which they were originally designed. Drifting buoy tracks were used to tune the parameters of these ice models, so the modelers would need other information for further validation. However, these models tend to overestimate ice motions during compact ice conditions as compared to validation data from drifting buoys.

To improve the coupled ice/ocean model, it will need fine resolution in the Arctic. The ocean model behavior will depend on whether or not the model resolves the first internal Rossby radius of deformation. If this scale is resolved (as small as 3-5 km on Arctic shelves), the results will have better eddy statistics. The ocean has greater stratification on mid-latitude shelves, leading to a larger Rossby radius, which is better resolved with somewhat coarser model grids. The islands near the Russian coast are another area where improved horizontal grid resolution is required and the ice models do not currently resolve the gap between the islands and the mainland. Improved ice models will need locally more resolution, either with nested models or with unstructured grids.

What resolution is required for the ice models? The working group felt that the 10-km ice rheology is not understood well enough at the present time. The current models use a rheology appropriate for scales greater than 100 km, although the current Navy operational model (PIPS) uses the Hibler rheology on a 25-km grid covering all the northern hemisphere ice-covered regions. The current fine-scale ice model efforts are regional; for instance, covering the Kara Sea with about 15-km resolution, using an isotropic rheology.

An ice ridging sub-model, such as Mark Hopkin's model, can provide valuable information to the large scale models, but additional improvements will be required if accurate forecasts of land-fast ridging are to be obtained. It should be possible to find ridges using Synthetic Aperture Radar and use that information in the forecast after the actual spill. Synthetic Aperture Radar from satellites can also be used as a source of new ice velocities, especially since radar works through clouds.

OIL SPILL WORKING GROUP SUMMARY

WHAT WE KNOW NOW

1. Improved coupled ice-ocean models for central Arctic have been constructed.
2. Nested ocean and ice model techniques have been applied to Arctic problems.
3. Improvements in the convection parameterization in ocean models has been shonw to accelerate the melting rate of ice.
4. Improved wind fields from atmospheric models has been applied for input to ice-ocean models.

MOST IMPORTANT AREA FOR FUTURE RESEARCH

Small-scale (2 to 10 km) ice-ocean model development and validation, including the anisotropic parameterizations of ice mechanics, to properly characterize the nearshore ice motion since oil transport is primarily by ice motion.

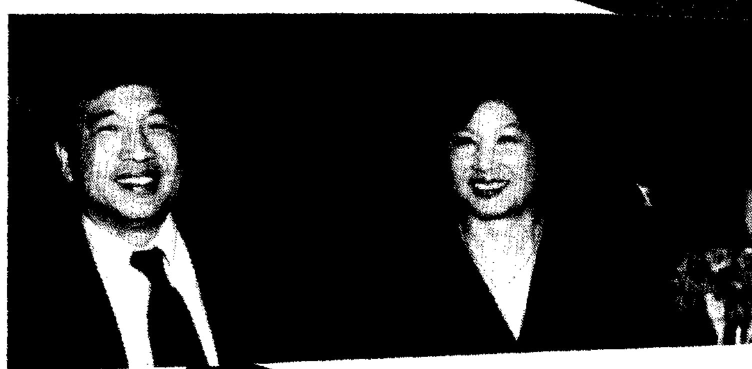
OTHER AREAS FOR FUTURE RESEARCH

1. Data to characterize ice spreading (ice bottom roughness, ice surface roughness, location of broken ice and open water) and oil spreading and weathering in ice-ocean models.
2. Nested ice-ocean models.
3. Local bathymetry and winds data for potential spill locations.
4. Validation of ice motion models using SAR ice motion products.
5. Fast-ice models to include freeze-up, break-up, accelerated melting due to the presence of oil, river inputs, and tidal effects.
6. Models and data regarding the behavior of oil-water emulsions and their in-situ ignition process for clean-up by burning.
7. In-situ oil spill clean-up equipment tests and demonstration projects in the Arctic using real oil and in sea ice.







2. Part II - Invited Speakers and Posters

2.1 Speakers on Tuesday, April 25, Opening Session

"Industry-Government Cooperation in Ice Mechanics and Modeling," Albert Wang (Exxon)

"Program for Energy Research and Development (PERD), Ice-Structure Interaction Program," Ibrahim Konuk, (National Energy Board of Canada)

"MMS Programs," Jeff Walker (MMS)

"Application of Ice Cover Mechanics in Design and Operations of Marine Structures," Jukka Tuhkuri, (Arctic Offshore Research Centre, Helsinki Univ. of Tech.)

"Ice-Structure Interaction Research and Arctic Development," Ben Danielewicz (Canadian Marine Drilling)

"BP Programs," Graham A. N. Thomas (BP International Ltd.)

These presentations are summarized on the following pages.

2.2 Invited Speaker at Banquet, Thursday, April 27

"A Review of Select Exploration and Development Activities in State Nearshore Areas," James Hansen, Manager of Oil and Gas Leasing Program, Alaska Department of Natural Resources.

A summary of this presentation follows the above summaries.

Arctic Modeling
(with a View Toward Government- Industry Cooperation)

A. T. Wang
Exxon Production Research

Topics

- Historical Cooperative Research Projects
- Arctic and Subarctic Areas of Interest to Industry
- Arctic Modeling Status and Research Needs
- Areas for Possible Government-Industry Cooperation

Remarks:

- The focal points of this presentation are the status of arctic (ice) modeling, technological challenges, research needs, and government-industry cooperation. I will cover the three key components of arctic modeling: data, models, and model validation.
- In view of the Clinton administration's recent emphasis on government-industry cooperation, cooperative research is a timely subject.
- One of the main objectives of this workshop is to report the results of ONR's Sea Ice Mechanics Initiative (SIMI). SIMI is an extensive five-year ($12 M) research program. The program examines and develops arctic models at different scales and attempts to build bridges between the models. Both government and industry are interested in arctic models of all scales, from the micro scale to the meso scale.
- Both government and industry have successful records of arctic research. One of the early large government research programs was the Arctic Ice Dynamics Joint Experiment (AIDJEX), conducted in the Beaufort Sea in the 1970's. From AIDJEX to SIMI, there has been continuing government attention to the arctic seas. Arctic and subarctic seas are vital to our national interest.
- In this talk, I will mention several cooperative research projects, some of them supported by both government and the industry. These successful projects demonstrate to us that there is much to be gained by all participants in a joint research effort.
- In the last thirty years close to one thousand cooperative research studies were conducted by the industry. Government has supported many of these joint industry projects.
- In the mid 1980's the primary geographic areas of interest were the U.S. and Canadian arctic. In the 1990's, there has been more activity in the arctic and subarctic seas of the former Soviet Union.

Government-Industry Cooperation (Past Examples)

- ONR Sea Ice Mechanics Initiative
- Polar Sea/Polar Star Voyages
- Chukchi Sea Ice Gouge Data Collection Programs
- Beaufort Sea Multi-year Ice Properties Program
- CRREL Ice Test Program
- MIT Sea Ice Mechanics Research Program
- Dartmouth Ice Program

Remarks:

- There is no unique way of cooperation.
- For example, in the ONR Sea Ice Mechanics Initiative (SIMI), industry representatives were invited to serve on an advisory committee to provide input to the program. There has been wide industry support and participation in workshops like this one. The SIMI program also provided funding for some of the JIP's initiated by industry.
- Polar Star and Polar Sea voyages were carried out a number of years in the Alaskan Bering, Chukchi and Beaufort Seas. The U.S. Coast Guard provided icebreakers, while industry provided fuel and paid for instrumentation and data analysis costs. The voyages provided useful ice condition, ship performance, and ice pressure data to industry and government. The voyages also provided training opportunities for the vessel crews.
- In a Chukchi Sea ice gouge data collection program, the USGS collected data and the industry paid for data analysis.
- In the multiyear ice properties program and the most recent CRREL ice test program, the U.S. Army CRREL was subcontracted to carry out research work for industry. The expertise of the CRREL researchers really helped industry better understand multiyear ice properties. Industry funding has also benefited CRREL.
- Both government and industry supported the MIT and Dartmouth ice research programs

Regions of Interest

- Alaska. BP is currently studying the possible development of the North Star/Seal Island prospect in the Alaskan Beaufort Sea.

- Sakhalin. Offshore Sakhalin is one of the most active subarctic regions for possible hydrocarbon development. Last June, Sakhalin Energy Investment Company (4M&S) reached a production sharing agreement with the Russian government for the so called Sakhalin 2 project. Recently, Exxon and SODECO have completed negotiation with representatives of Russian Federation and Sakhalin Oblast for Sakhalin 1 development. In the Sakhalin Tender 3, Exxon obtained the exploration right for two northern blocks, and Mobil and Texaco won the exploration right for one of the southern blocks.

- Pechora Sea. About ten Western companies are interested in oil prospects in the onshore and offshore Timan-Pechora area. An offshore tanker terminal is being studied by these companies. In the study, icebreaking tankers along with other concepts are being considered for exporting oil from the Pechora Sea to the market place.

- Other regions. Other offshore arctic and subarctic regions of interest include the Russian Barents Sea, Kara Sea, Canadian Grand Banks (Hibernia), northern Caspian Sea, and China's Bohai region.

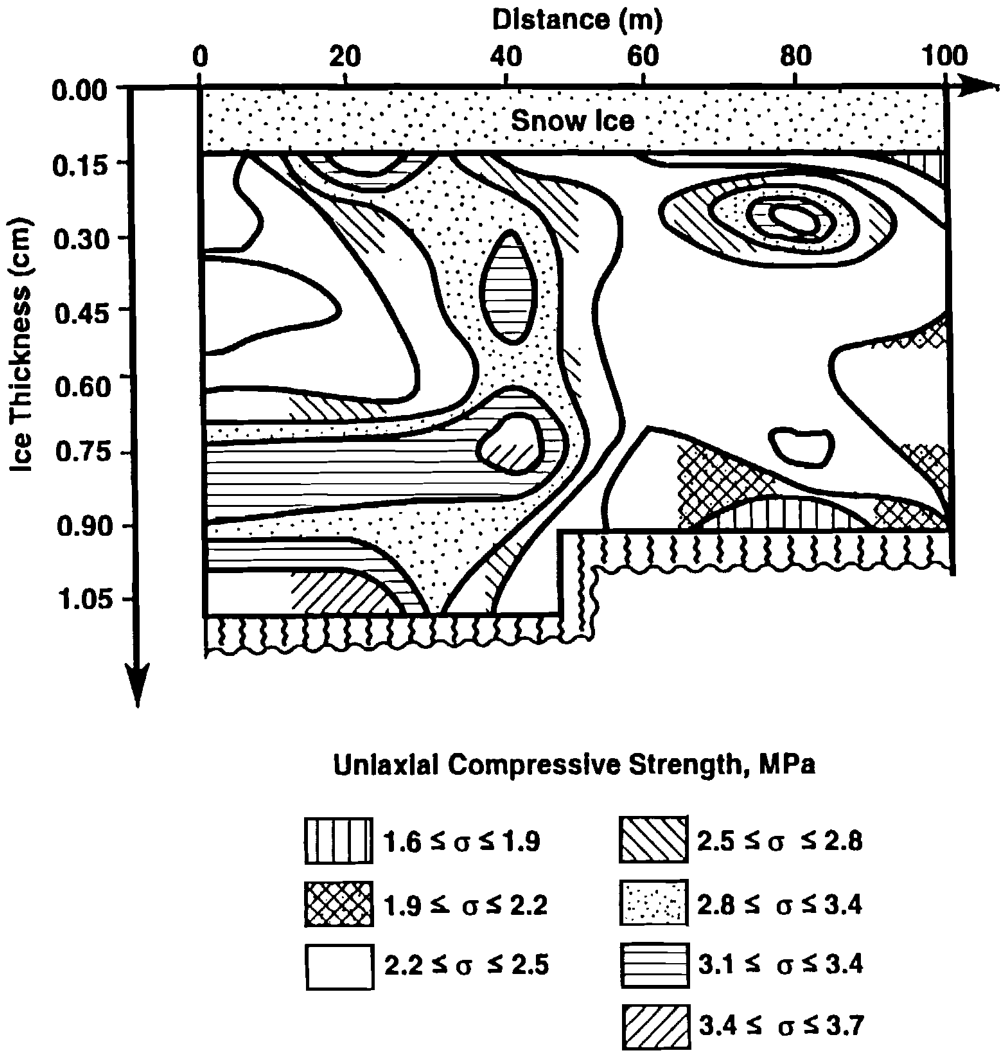
Areas of Interest of Arctic Research

- Ice Properties
- Ice Loads
- Marine Transit and Operations
- Data Gathering Strategy/Survey Tool Development
- Ice Forecast and Ice Monitoring
- Ice Gouges

Remarks:

- Areas of interest include ice properties, ice loads, marine transit and operations, data gathering strategy and survey tool development, and ice forecast and monitoring. I will address the ions of the first four items will be presented later. Therefore, I will only discuss ice forecast and ice monitoring.
- Ice forecast is important to the operation of arctic structures and vessels. A sound ice forecast system can contribute significantly to exploration, production, maintenance, and re-supply activities. It is also important to the emergency alert, escape, evacuation, and rescue operations.
- Ice monitoring is an indispensable part of ice forecast. In the 1980's, the operators frequently monitored the ice conditions by using SAR and SLAR flights. Such flights are not cost effective for some remote areas. Furthermore, in bad weather, the flights may be canceled. In recent years, two SAR satellites were launched by the Europeans and Japanese. RADARSAT, the Canadian SAR satellite will be launched in the near future. Satellite downlink equipment is available. In terms of hardware, real progress has been made since the mid 1980s.
- However, the ice centers in North America, Europe and Japan are only interested In the ice conditions of a relatively small geographic area. For example, there is very little coverage of offshore Russia by existing SAR satellites. Also, there are very few trained specialists in Western countries to properly interpret SAR data for CIS regions.

Ice Property Tests



- **Extensive small-scale tests have been conducted**
- **Significant progress made on the understanding of small-scale ice behavior**
- **Ice strength data analyses focused on extreme values**
- **Large-scale tests were few, results not well analyzed**
- **Prediction formulas often based on small and scattered data bases**
- **Partially consolidated ridges not well studied**

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Remarks:

- Significant progress has been made in our understanding of small-scale ice behavior.

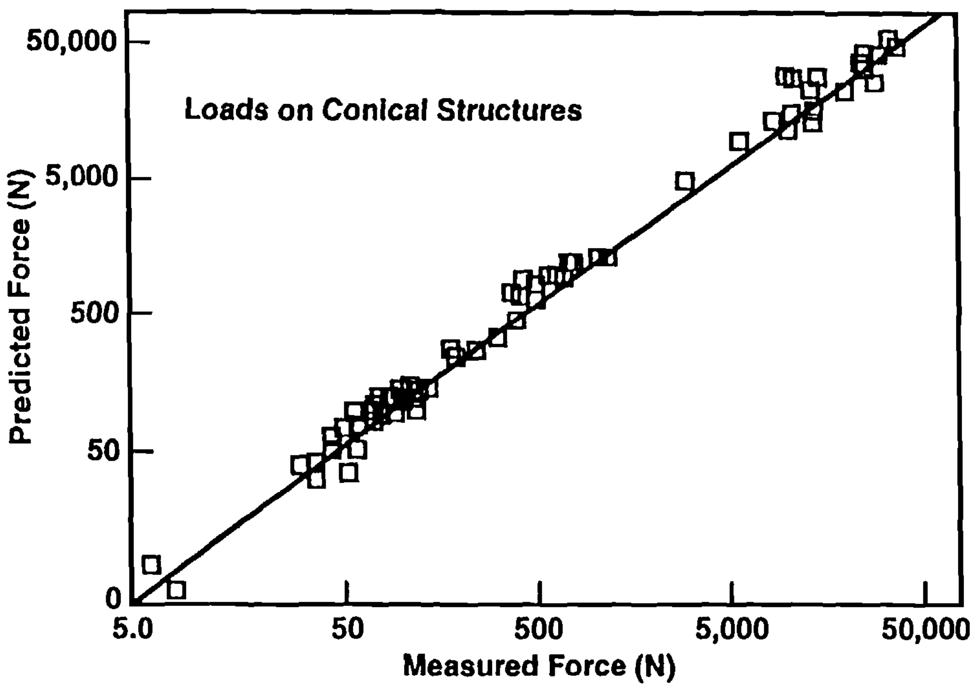
- In term of ice strength, most analysts attempted to develop formulas for extreme ice strengths. Such formulas are useful for specifying ice pressure on a small area. However, the relationship between the small-scale extreme ice strengths and global ice loads is not clear.

- The figure to your left (Truskov's Sakhalin ice strength figure) shows a large ice-strength variation in sheet ice. The data were obtained from offshore Sakhalin Island by our Russian colleagues in the Sakhalin Oil and Gas Institute. The lead researchers, Drs. Truskov and Polomoshonov, are in the audience. Since ice typically fails at the weakest point, the high inhomogeniety of ice strength should be taking into consideration for design ice load computations for subarctic regions.

- Most researchers do not use the data obtained by others. Most published analytic formulas are based on a small data base.

- Ice rubble and first year ice ridge are not well studied. Most existing ice rubble property data are laboratory data, rather than field data.

Ice Loads on Cones



- Formulas developed and adopted by API and CSA yield similar results
- Computed values comparable to model tests results
- Limited large-scale data (Kemi I and Mitsui cone)
- Paritally consolidated ridge load and loads on high-angle cones not well understood.
- Uncertainties exist on ice-structure interactions (e.g., adfreeze bond, friction coefficient, etc.)

Remarks:

- Since the 1970s, formulas have been developed to compute sheet and ridge loads on cones. A few of these formulas were adopted by the API RP 2N and the Canadian Standard. The ice loads calculated by these well-accepted formulas are, in general, close to one another.

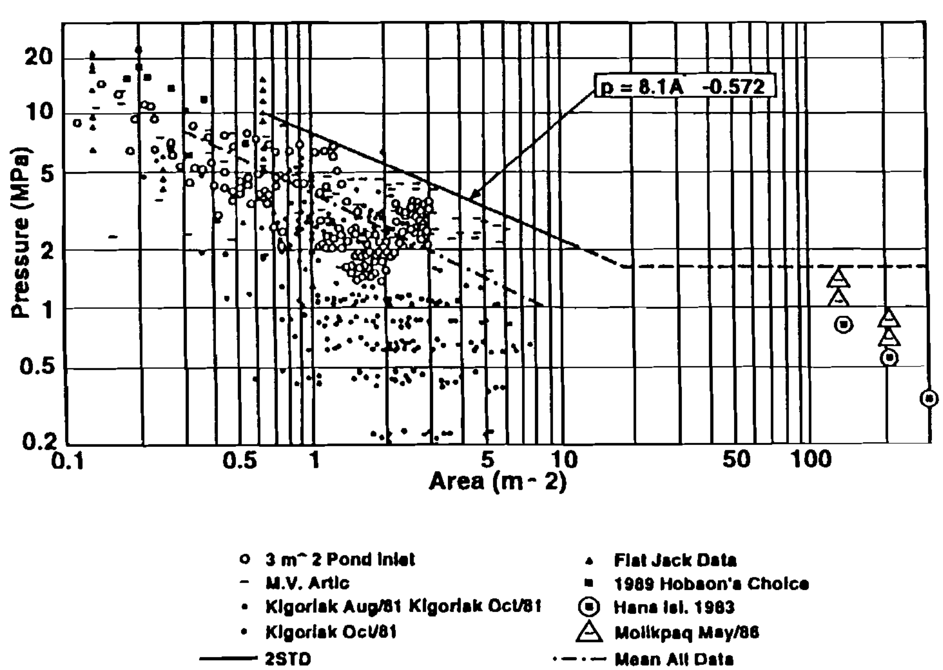
- In the last 30 years, a number of model tests were conducted in various ice basins, including Exxon's ice basin in Calgary. As shown by the figure to your left, calculated loads measure well against model test results. The largest model cone had a water line diameter of about 3 m. A production cone probably will have a water line diameter of 50-100 m.

- Currently, large-scale data are very limited for cone structures. The Kemi-I Lighthouse had a waterline diameter of about 10 m. Kemi-I data, which are not of top quality, seem to indicate that existing formulas are basically sound.

- Ice load formulas on cones are well-established in the West.

- There are uncertainties concerning ice loads generated by partially consolidated ridges and ice rubble. Formulas have been developed. However, relatively little validation effort to verify these formulas has been undertaken.

Ice Crushing Pressures



- Dictate global loads of vertical-sided structures and local loads of all structures
- Consensus lacking on pressures over large areas
- Full-scale data are limited
- Major research area by governments / universities
- Impact on subarctic development options less severe than on arctic development

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Remarks:

- Ice crushing pressure dictates local ice loads of all structures. It has been studied very extensively since the 1940's. The early efforts were focused on ice loads on bridge piers.

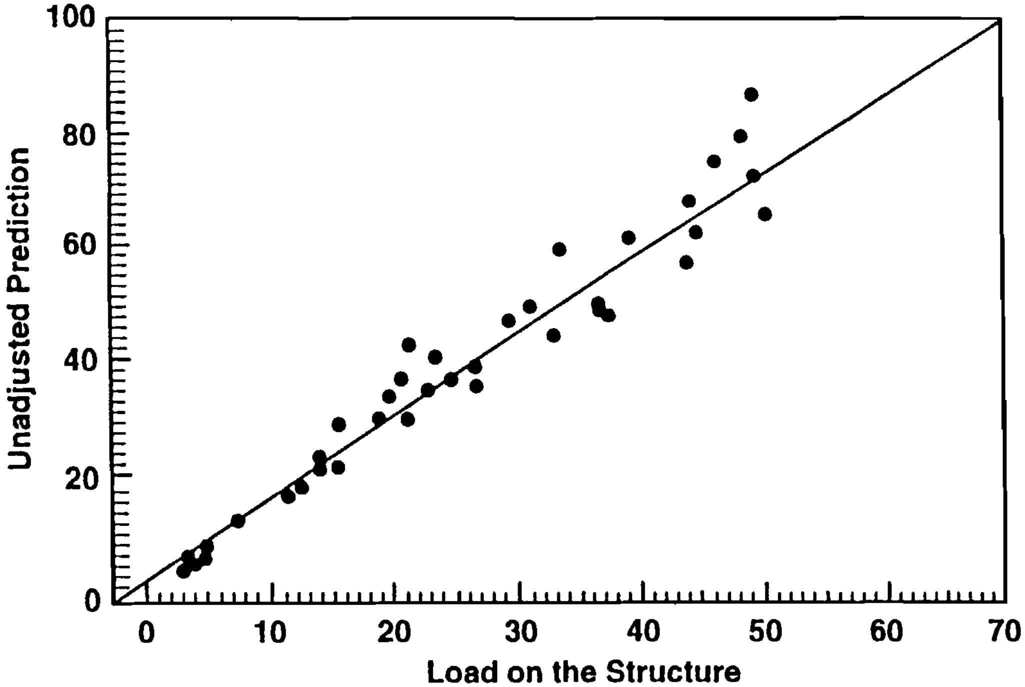
- Both small-scale and medium-scale ice crushing pressures were well studied through controlled experiments. As shown in the figure to your left, small-scale ice crushing pressures are very high.

- Large-scale ice crushing pressure data have been collected from drilling structures, icebreakers, natural islands, lighthouses, and bridge piers. Since large-scale data were not obtained through controlled environments, they are frequently difficult to interpret. The global pressures measured from structures are typically lower than those obtained through small-scale experiments.

- Currently, there is a lack of consensus on how to reconcile the large-scale measurements with the small-scale test results. There is also a debate on the so called size effect.

- Despite the uncertainties, the fact remains that no exploration/production structure designed for arctic conditions has ever been severely damaged due to the forces generated by an ice cover.

Ice Loads on Multilegged Structures



- Approaches discussed by API and CSA codes
- Loads dependent on structure geometry
- Ice jamming and rubble forming concerns
- Theory not fully developed
- Model tests play a critical role
- Model test results are sometimes difficult to interpret

Remarks:

- Ice loads on multilegged structure are dependent on the number of legs, the sizes of legs, leg spacing, and ice dynamics.
- Approaches to compute loads are given in API Recommend Practices and CSA codes. However, a general formula is yet to be derived. Such a general formula would be useful for structure screening purposes.
- When a particular structure shape is determined, model tests can be conducted to improve and fine-tune design ice forces. Model tests can also be used to better understand ice jamming and rubble forming.
- However, model test results are sometimes difficult to interpret. As far as I know, no model ice currently exists that can fully reflect large-scale ice behavior.

Ice Transit

- Arctic transit has been studied by the U.S., Canadian, Russian, and Finnish governments and the industry for many years
- Success has been reached in the Bering, Beaufort, and Baltic Seas, and the Russian Northern Sea Route
- Further studies needed to ensure cost-effective year-round safe transit of tankers, cargo ships, and supply vessels
- Multiple vessel classification systems pose a hindrance for international joint effort
- Real-time forecast and monitoring are not easily available for some regions
- Improvement of quantification of ice conditions and vessel performance is needed

Remarks:

- In the 1800's and early 1900's, the (Russian) northern sea route and the (American) northwest passage were studied by Russian and American adventurers.
- Russian vessels have been transiting through the Northern Sea Route since the early 1930's. The successful transits and operations of Manhattan, Polar Star, Polar Sea, M. V. Arctic and other icebreaking vessels in the U.S. and Canadian arctic seas are also encouraging.
- For petroleum development, one may need year-round transit that has a tight schedule. Cost-effectiveness is another concern.
- Every country has its own classification of ice vessels and its own marine transit codes. This is a problem for international cooperation and transit through national boundaries.
- To maintain year round transit, it would be helpful to have a good ice forecast and monitoring system. As mentioned earlier, it is fairly difficult to monitor the ice conditions in certain remote regions at the present time.
- For planning purposes, it is useful to use certain types of simulation programs. Improvements in quantification methods for ice conditions and vessel performance are needed to support the development of better marine transit simulators.

Areas for possible Cooperation

- Large scale : Ice driving forces, transit-related research
- Structure scale: Ice loads
- Medium scale: Rubble properties, ice fracture
- Small scale: Indexing, fundamental properties/behaviors.
- Tool development: AUV, Upward-looking Sonar

Remarks:

- In the very large scale, ice driving forces are of interest to the oil companies as well as the government. Five field programs were undertaken by the U.S. and Canadian governments in the late 1980's and early 1990's. More data collection and model development efforts are needed to better quantify ice driving forces. Ice driving forces are of interest to oil companies, because ice driving forces in the subarctic regions may limit ice loads on structures. To the governments, ice driving forces are critical to the understanding of global ice dynamics, lead formation, etc.
- In structure scale, ice loading problems, such as the scale effect of ice crushing pressure, are of interest to both industry and government.
- In the scale of a few meters, ice rubble properties need to be studied in the field and laboratories. Ice rubble and partially consolidated ridges have a wide presence in both the arctic and subarctic regions.
- In the small scale, continued research is needed to better understand the fundamental properties of ice. Since large scale ice experiments are costly, some prediction formulas (based on small scale ice measurements) are needed to predict large-scale ice properties.
- Finally, we need more and better tools to collect data in ice environment. For example, a viable option needs to be developed to collect ice gouge data in sandy soils where ice gouges may be infilled very quickly. The development of remote undersea vehicle may be useful to collect ice data, including ice gouge data. Upward-looking sonar has been successfully deployed by the Canadians for several years. Improvements on the existing upward-looking sonars can be made to enhance their performance and cost-effectiveness.

Conclusions

- Significant progress has been made in sea ice mechanics/arctic modeling in the last 30 years
- Most feasibility problems for offshore arctic hydrocarbon development have been resolved
- A significant number of problems remain unresolved in order to ensure sound engineering and cost-effective solutions
- Cooperative research should be seriously considered by all parties to leverage their resources

<u>Remarks:</u>

- Looking back to the late 1960's, significant progress has been made in terms of model development, data collection, and model validation.
- The successful deployment of production and exploration structures and icebreaking vessels indicates that there are no feasibility problems for arctic and subarctic hydrocarbon development.
- Benefits of cooperation includes
  - Costs and resources sharing benefit all participants
  - Wide areas to look for common interest, from micro scale to meso scale
  - Concentrated effort reduces redundancy and eliminates waste
  - Make large-scale projects more feasible
  - Increase the use of data centers and facilities

Program for Energy Research and Development

(PERD)

Ice-Structure Interaction Program

Ibrahim Konuk
Engineering Branch
National Energy Board
Calgary, Alberta T2P 3H2
Canada

Introduction

Program on Energy Research and Development Ice-Structure Interaction Program is the leading research program in Canada, sponsoring applied research on ice-structure interaction. The program budget is about $1000k and is managed by the Engineering Directorate of the National Energy Board (NEB).

The scope of the program includes ice mechanics and its engineering applications in areas that are covered by the regulatory mandate of NEB.

The program supports the following subprograms:

Field Data Collection
Development of New Ice Mechanics Models
Probabilistic Framework Model for Prediction of Long Term Processes
Pack Ice Driving Forces
Ice Induced Vibrations of Wide Structures
Ice Loads on Conical Structures.

Regulatory Responsibilities of the National Energy Board

The National Energy Board (NEB) has regulatory responsibility for all oil and gas exploration, drilling and production facilities, and activities, in the Northern Territories including offshore Arctic Ocean. NEB is also responsible for regulating the construction and operation of pipelines that cross provincial or international borders.

The principle objective in regulating exploration, drilling, development, and production activities is:

(a) To ensure the safety of the workers on the site or facility;

(b) To ensure that all reasonable steps are taken to protect the environment; and,

(c) To ensure that the production practices do not result in the oil and gas resources being lost or wasted.

These objectives are achieved through ensuring that proper design and operating criteria are used. In fulfilling its responsibilities, NEB develops, administers and enforces a number of sets of regulations which establish the approval process and prescribes standards that must be met in order to obtain an approval. Generally, these standards are selected or developed in consultation with technical experts in the oil companies.

NEB also cooperates with industry in the development of new design codes and standards which may be referred in the regulations.

PERD Ice_Structure Interaction Program is a major part of an extensive research program to develop new design and analysis methods to improve effectiveness of the regulation to make the Canadian oil and gas projects cost effective. NEB also sponsors research to develop new materials and structures and new construction techniques to keep the Canadian industry competitive.

Field Data Collection Subprogram

Over the last decade, a large amount of data on ice-structure interaction has been collected from field observations and measurements. They do not, however, cover the full range of ice-structure interaction scenarios and are not in sufficient detail to be used in the verification of ice structure interaction models.

In previous years, this program have focused on field programs related to the Beaufort operations; however, the program is now refocused to attempt to conduct field programs in the two regions of Canada; Beaufort Sea and Grand Banks. The near term expectations for field development are highest in these regions and therefore, related research needs have remained to be high priority.

At present, iceberg impact forces are calculated using iceberg strength values based on small-scale tests. Most recent work using indentor equipment on a grounded iceberg in Pond Inlet only tested areas up to three square metres. Experience with the loading of sea ice on arctic structures, however, indicates that the effective strength of ice is reduced as the contact area is increased. If a large iceberg were to strike a fixed platform, the contact area of the crushed ice would be in the range of 300 to 600 square metres. The effective strength of this large contact area would probably be much lower than the results from small-scale tests suggest. This program will collect field data which will be used in the development of models that will allow us to determine the effective strength of icebergs over medium and large areas.

In addition to that the growler and bergy-bit interaction with floating structures is a major issue for Grand Banks. The data is collected by this program is required for developing design methods for bergy-bit impact since the production systems will have to be designed to tolerate certain levels of ice impact loads in order to achieve an optimum efficiency.

This program also serves to attract additional funds available from other sources such as industry and other government organizations towards the collection of data relevant to our research needs. It will thus support the development of ice structure interaction models that are required for the design of facilities for the expected field developments.

One of the most recent joint industry research programs sponsored by this subprogram conducted a field investigation to determine the effect of splitting on ice loads.

Development of New Ice Mechanics Models

Ice structure interaction processes, the associated forces and how they impinge on offshore structures are not fully understood. Laboratory tests show that the local ice pressures can exceed 6 Mpa whereas the pressures derived from large scale interactions can get as small as 1 Mpa. At this point, there is no rational model that explains this phenomena satisfactorily by using physics, mechanics, material science or other similar methods. Therefore, predictions of ice forces are mostly based on empirical relationships and simplified analytical procedures.

In order to increase the understanding of ice structure interaction phenomena and to better predict ice forces, a significant amount of research work is required in the development and verification of analytical and numerical methods for deterministic and probabilistic prediction of ice pressures and resulting loads based on physics or rational mechanics approaches such as fracture mechanics, plasticity theories, damage theories, etc.

In recent years, both industry and government have utilized considerable resources to collect large scale ice load data to develop practical design methods that can be used for calculating ice loads on arctic structures. As part of one of the projects sponsored by PERD funds, some of this data has been collected in a database.

Under this project, the large scale data collected by the field programs will be systematically analyzed from the viewpoint of developing unified analytical and numerical ice load calculation methods that can be applied to practical design problems.

This program will also attempt to examine and reconcile the issues surrounding the differences among industry and research groups with respect to design ice loads for arctic offshore drilling or production structures.

Probabilistic Framework Model for Prediction of Long Term Processes

Ice loads govern the design of most drilling and production structures in the Canadian Arctic and East Coast. The magnitude of ice loads depends on various site specific and regional environmental parameters. Use of deterministic methods to predict long term ice forces provide too conservative estimates.

As a matter fact, the current CSA Code requirements for offshore structures are based on statistical design concepts. It is therefore necessary to develop probabilistic methodology for determining loads and simulating long term ice/structure interaction events.

In the past, this project supported the development of several Monte-Carlo based poisson type stochastic models. One of these models, BOREAS 3.1, is now commercially available to industry and engineering consulting community. A study of the sensitivity of poisson type models to the input parameters is currently in progress.

The other major task to be completed is to conduct a critical evaluation of various types of stochastic models and compare them with poisson type models such as BOREAS.

Pack Ice Driving Forces

In 1984, Croasdale proposed a limiting driving force approach to the determination of ice loads. It applies in the case of a large ice feature such as an ice island fragment or multi year floe being pressed against an offshore structure by environmental driving forces. If an offshore structure were to be completely enveloped by such an ice feature the forces on it would be very large. The available environmental driving forces (pack ice pressures and wind and current drag acting on the ice feature), however, may not be sufficiently large to produce full envelopment of the structure. This provides a logical means for selecting a global design force less than that which would be inferred from the ultimate crushing strength of the ice.

A key element in the above approach to the determination of global ice forces is knowledge of the magnitude of the pack ice driving forces. It is speculated that these pack ice forces are governed by ridge building mechanisms in the thinner ice of the pack. A number of analytical models exist for the prediction of ridge building forces, but they range over almost 2 orders of magnitude. If the actual values are in the lower part of this range, Croasdale (1984) has demonstrated that they would limit the maximum forces acting on a structure. Therefore it is necessary to obtain field data on the magnitude of pack ice driving forces.

By measuring in situ pressures in multi-year floes in regions of convergence in the polar pack it is possible to determine pack ice driving forces. The pack ice to the west of the Queen Elizabeth Islands is a suitable location for such measurements. The forces measured will be related to environmental conditions so that measured values can be extrapolated to various regions in the Arctic.

A pilot study on pack ice driving forces has already been carried out (Croasdale et al. 1986). Under this study, transducers capable of measuring low level in situ stress (<100 kPa) were developed. The feasibility of the measurement techniques were demonstrated and ridge building forces appeared to be in the lower part of the anticipated range. The need for an improved understanding of how the transducers performed was indicated.

The subprogram is expected in the coming year to produce a complete analytical model to predict design loads on structures resulting from pack ice force loading scenario, detailing the complete analysis of all stress results and relating pack ice stresses to environmental conditions.

Ice Induced Vibrations of Wide Structures

Over the past several years, NRC has developed and used technology to determine the loads experienced by a structure undergoing ice-induced vibrations. This technology has been used to predict the ice loads and foundations loads on the bridge piers of the Great Belt Link bridge in Denmark. Also, it has been used to determine the conditions under which sever ice-induced vibrations would occur on the JZ-20-2 platforms used in the Bohai Bay, China. The comparison of the model test results with full-scale information shows remarkable agreement. In this modelling technique, several of the properties of the structure are modelled. The stiffness, natural frequency and damping are modelled in the full horizontal plane, in the in-line, transverse and rotational directions. The modelling system developed at NRC is very versatile, and a wide range of stiffness and natural frequency values can be modelled.

With this modelling technology, the questions related to ice-induced vibration of a wide structure such as the Molikpaq can be addressed. A model of the Molikpaq will be constructed which will have the correct scaled values of *global* natural frequency, stiffness and damping in the horizontal plane. In addition, the model will be constructed as a segmented model comprised of a number of vertical strips each with their own values of natural frequency, stiffness, and damping. With this technique, additional information will be obtained on the load distribution on the model.

Ice Loads on Conical Structures

Conical forms at the waterline are used to protect structures such as oil production platforms, bridge piers, and lighthouses from large ice forces. To design for safety, cost effectiveness and protection of the environment, precise information is required about the magnitude and nature of ice loads. Recent research has resulted in methods to estimate ice forces on conical structures, but some questions remain unanswered. The influence of ice speed, cone angle, friction coefficient, and structure diameter have not been fully resolved.

The present project combines physical modelling with analytical and numerical methods to solve the problems. In addition, full-scale data will be used for correlation purposes. This unique combination of approaches will ensure success.

APPLICATION OF ICE COVER MECHANICS IN DESIGN AND OPERATIONS OF MARINE STRUCTURES

Kaj Riska and Jukka Tuhkuri
Helsinki University of Technology, Ship Laboratory
Espoo, Finland

ABSTRACT

This paper reviews some of the recent research on ice cover mechanics performed at the Helsinki University of Technology. The aim of that long term work has been to identify, formulate and analyse the physical processes that take place when a ship proceeds in an ice covered sea area or when ice moves against an offshore structure. Many of the physical processes identified have been tackled by computational methods in order to analyse these problems. In the present paper the research problem is divided into four scales: large scale, medium scale, small scale, and micro scale. In the large scale logistic problems and risk are analysed. The medium scale is the scale of a ship and in this scale interaction with idealised ice conditions are studied. Ice forces as an average pressure on a small area are the scope in small scale studies and the micro scale work concentrates on ice structure contact. This paper also discusses the ice action on offshore structures based on the same division into scales. Finally, recommendations for future work are given. These include the more recent ideas of interaction between the scales, parameterisation of ice conditions, and ice failure mechanics in the micro scale.

1. INTRODUCTION

The aim of this paper is to give an overview about how the physics of ice cover is applied in engineering studies of ships and other structures in ice. A further aim is to formulate a framework for future research in this area: What kind of information of ice cover should be provided to an engineer or an operator in order to increase the efficiency and safety of a ship or structure performing a given mission. This paper focuses to the work performed in Finland and at the Ship Laboratory of the Helsinki University of Technology.

The information about an ice field relevant to engineering studies can be divided into categories and subsequent sub-categories. It has turned out to be practical to divide the problem into four scales as listed in Table 1. These four scales have been introduced in order to set paradigms for research efforts and it is acknowledged, that there are also other ways to give a structure to the research problem in hand. As an example, one can divide these scales further down: A researcher working in a scale smaller than the micro scale might be interested in the dislocations in ice.

It is important to emphasise that the different scales interact with each others. The initial values for parameters and the boundary conditions for a problem in one scale are defined by earlier processes in the same scale and also by processes in other scales. Processes in one scale are synthesis of processes in smaller scales, but detailed information of all the scales smaller than the present one is not necessary. For example, when analysing a ridging process, it is sufficient to know when the ice cover breaks into discrete blocks and we do not need to know about grain size events. However, the interaction between scales underlines the importance of analysing the ice-structure problems as processes consisting of discrete events in different scales as will be discussed further below.

One of the central issues in this paper is the identification and description of the most important processes in ice cover and the subsequent parameterisation of ice conditions in different scales. It is far from clear what parameters are the important ones for different ship-ice processes. Table 1 lists the ice parameters that have been used in earlier studies, but more work is needed in this area.

In the following sections the four categories of ship-ice problems identified in Table 1 and also the interaction aspect are reviewed. The emphasis is on the large and micro scales. In the end of this paper, recommendations for future work are given. As our aim is to review the work performed at the Ship Laboratory of Helsinki University of Technology, we do not give a general literature review.

Table 1. The scales in engineering operation in ice covered seas.

Scale	Problems	Ice parameters
Large	Logistic analyses Risk analyses Transportation system design	WMO's egg code Equivalent ice thickness
Medium	Ice resistance Manoeuvring Ship structural design Ice action on offshore structures	Size of distinct ice features Bending strength Thickness
Small	Ice load on structures Average ice pressure Ice bending and buckling Ice ride-up and pile-up	Average ice strength
Micro	Ice-structure contact	Fracture parameters Micro structure of ice

2. LARGE SCALE

For a ship operating in open water only, the large scale problems are, for example, definition of the wave spectra for the lifetime of the vessel and the corresponding structural response. The classical problem is the fatigue strength of the hull beam when the ship encounters 10^8 waves during her lifetime. In other words, a naval architect wants to determine the load statistics for a given ship with a given operation profile. From that statistics then the extreme values of structural response, the probability of damage, etc. can be calculated.

For ships operating in ice covered seas there are not similar widely accepted methods to analyse the lifetime response. In order to develop one, the ice conditions must be parameterised and the ship's response in these ice conditions must be calculated. A probabilistic methodology has been developed by Kujala (1994) to calculate the lifetime ice loads. His approach was developed for ships operating in the Baltic Sea and is based on the following assumptions:

- An equivalent level ice thickness, which takes the ridges into account, is used as the ice parameter.
- The long term statistics of ice cover thickness and coverage are used.
- Statistical parameters of hull loads are obtained by comparing measured loads with the equivalent ice thickness.
- It is assumed that the extreme values follow a Gumbel I asymptotic distribution.

Long term distributions of ice loads calculated by this method comply with the measured ones for cargo ships navigating in the Baltic. Figure 1 gives the calculated load on a frame of the cargo vessel MS Arcturus in the Baltic Sea. The effects of the navigation area and time are shown: The further north of the longer time the vessel sails, the higher the loads.

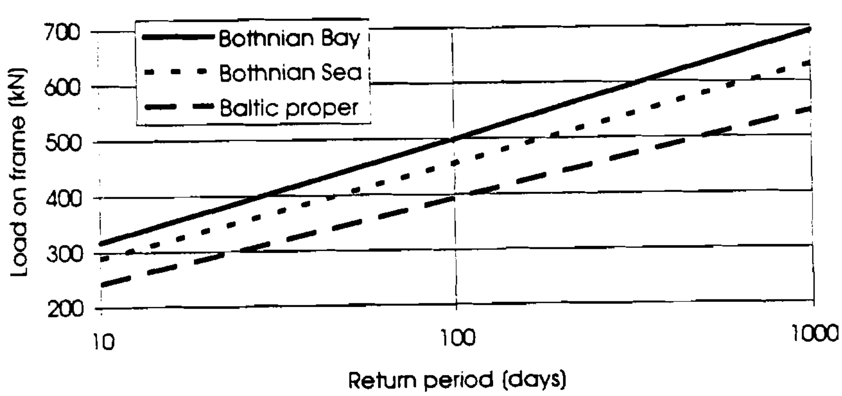


Figure 1. Calculated load on a frame of MS Arcturus navigating in the Baltic (Kujala, 1994).

Another active research area with scope in the large scale is ship trafficability. The ability of a ship to proceed in ice depends on many factors. Its machine power and the ice resistance in different ice conditions form the basis of this ability. An icebreaker escort, a possibility to observe the ice conditions ahead of the ship, and crew experience in ice navigation influence also the performance of a ship in ice. There is not one single quantity which describes the ship ability to proceed in ice. A quantity suggested is the *efficiency of speed.* It is the average speed from one point (A) along the route to another point (B) divided by the average of the instantaneous speed proceeding from A to B. Determination of this quantity and its dependence on ice conditions, route selection, application of remote sensing methods, etc. forms the target of ship trafficability studies. In these studies the parameterisation of ice conditions is of central importance and requires further work. The effect of ice conditions to ship operations, in this case to the demand of icebreaker assistance along the North East Passage, is shown in Figure 2.

For cargo ships the speed is not the only factor effecting the efficiency of transportation. Also the amount of cargo transported has to be taken into account. For this purpose we can use the *transport efficiency Q*, which can be defined as

$$Q = \frac{DWT \cdot v}{P} \qquad (1)$$

where DWT is the deadweight, v is the mean speed, and P is the installed power. Figure 3 shows the observed transport efficiencies of seven cargo ships operating in the northern Baltic. These efficiencies were obtained during one voyage per vessel (Lehtinen, 1993).

Ship trafficability can also be studied by transit simulation where the ship's resistance and speed are calculated when the ship proceeds from one point to another. Monte-Carlo method has been used to set an ice cover consisting of level ice and a number of ridges. Although simple, such a simulation can be used to compare different navigation strategies: blind navigation where the route is the shortest way and active navigation where, as an example, decisions can be made to go around an obstacle and not through it. Such tactical navigation is an area where more research should be directed. One of the must interesting questions is the use of remote sensing in tactical navigation.

As stated above, in both the operability studies and in the analysis of the long term response of a structure, the parameterisation of the ice cover is important and requires further work. In general, the parameters used to describe an ice cover should be a structured set (i) observable by remote sensing methods, (ii) predictable by mesoscale ice dynamics models, and naturally (iii) applicable to practical engineering problems. A research aim should be to define an *ice state* in an analogous manner as sea state is defined. Such a set of parameters would be of great importance for marine operators in forecasting the ice conditions expected during any particular task.

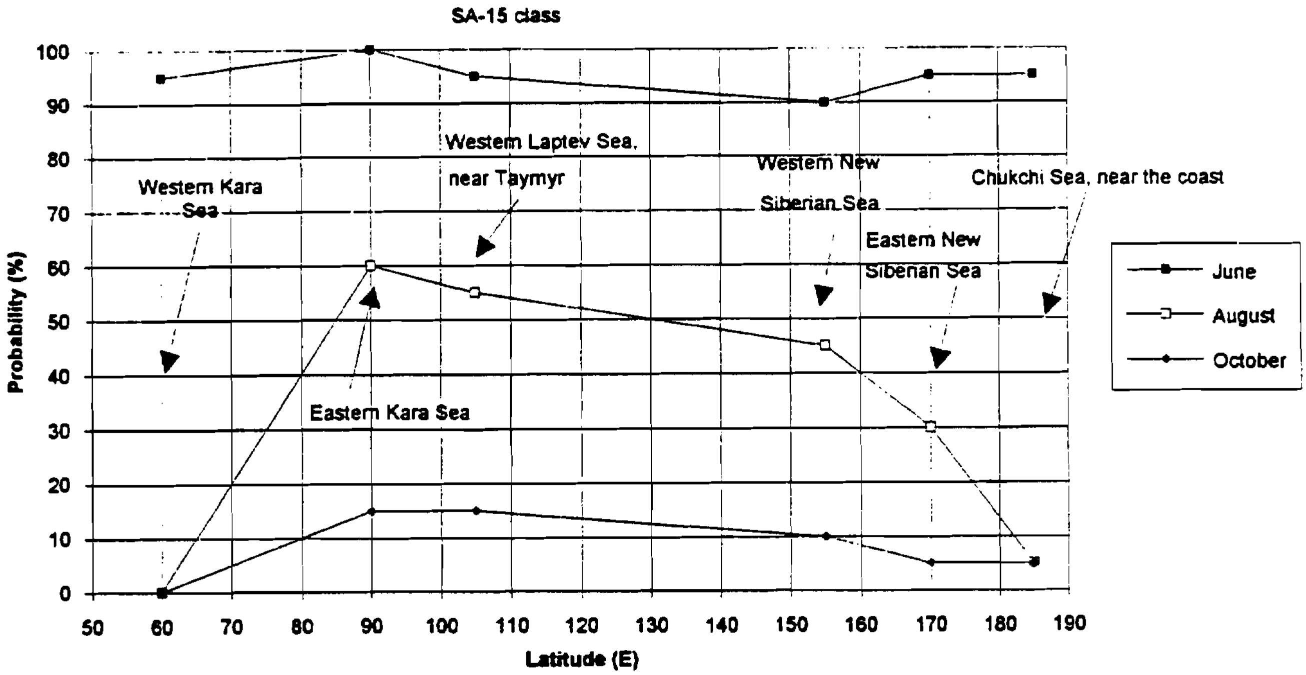


Figure 2. The probability of ice conditions demanding icebreaker assistance for a Norilsk-type ship along the North-East Passage (Buzuev, 1992).

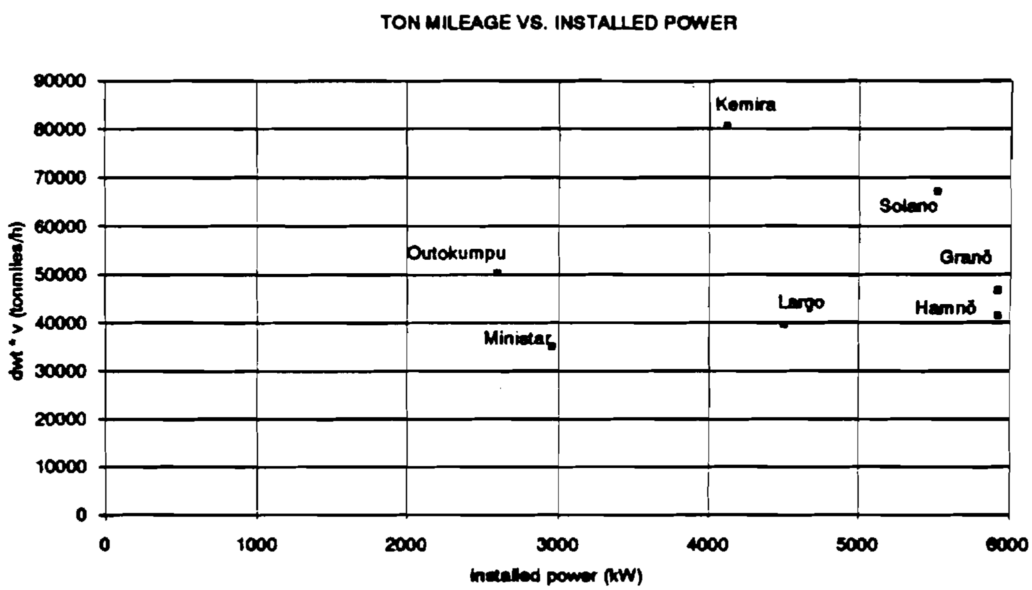


Figure 3. The transport efficiency of cargo ships operating in the northern Baltic during winter 1993 (Lehtinen, 1993).

3. MEDIUM SCALE

With the medium scale we refer to a scale in which an ice feature can be idealised, for example, as level ice with uniform thickness, as a regular shaped ridge, or as a massive floe. A lot of research effort have been dedicated to develop calculation methods for ice resistance and ship manoeuvring capability in this type of idealised conditions. The early analyses were mainly empirical and the ice parameters that were used included bending strength and thickness (Enkvist, 1972).

The more recent research in this scale include experimental and theoretical studies on, for example, ice impact on a landing craft bow (Varsta, 1983), motion dynamics of a ship ramming against a massive ice floe (Riska, 1987), ship resistance in a channel with and without compression (Kujala et al., 1991), and a ship in compressive ice (Kujala et al., 1993).

The ice parameters in the medium scale have also been studied. Veitch et al. measured the thermodynamics of an ice ridge in the Baltic Sea (1991a) and in an ice tank (1991b). The measurements consisted of cross-sectional drilling and long-term temperature recording. Figure 4 shows the shape of a measured ridge together with the thickness of the consolidated layer. Lehtinen (1993) has reported measurements of the profiles of channels.

A process that is common for both an ice field and ice-structure interaction is pile-up of ice or ice ridging. In ridging we have only ice-ice contacts, but in a pile-up process the same ridging occurs against a structure that can be a stationary off-shore structure or a ship stuck in a compressive ice field. As it is difficult to observe the ridge build-up process in the field, ridging experiments have been performed in an ice tank (Lensu and Green, 1995).

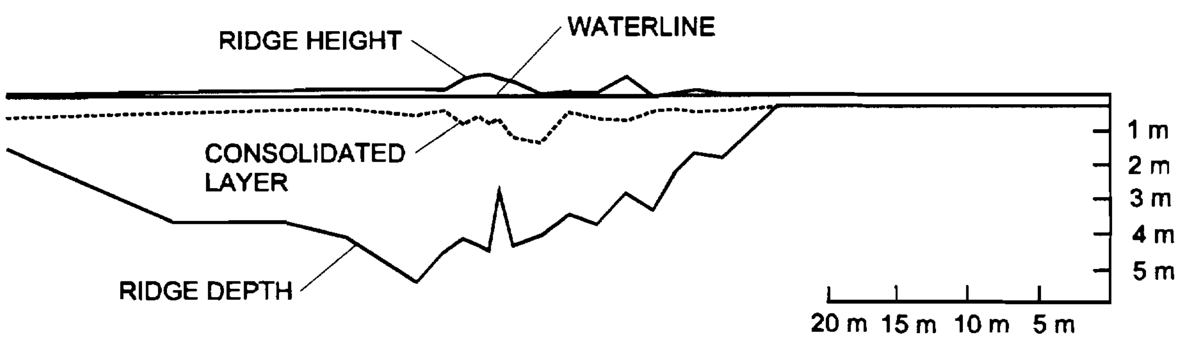


Figure 4. The shape of a measured ridge and thickness of the consolidated layer (Veitch et al., 1991).

4. SMALL SCALE

While ice resistance and motion dynamics of a vessel are considered as medium scale processes, analysis of the average pressure over the ice-ship contact area can be considered as a small scale process (Table 1). The average ice pressure has been observed to decrease with increasing geometrical or rather apparent contact area. This observation holds true for different contact geometries. (For a review of this problem often described by a pressure-area curve, see, for example, Riska (1995).) The load on a ship is obtained then by integrating the average pressure over the contact area (Varsta, 1983, Riska, 1987). At present, this approach is used in many standards for structural design of ships and off-shore structures.

During the years there has been a trend of increasing the design ice pressure p for ships and decreasing the design contact area, or height h in a two-dimensional presentation. However, the understanding of the design load caused by ice contact ph has not changed. Figure 5 shows the models for ship-ice contact in the Baltic.

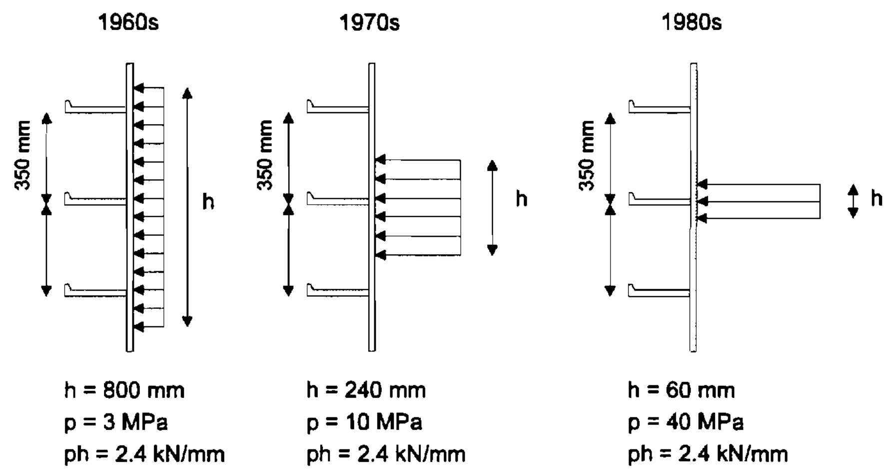


Figure 5. Development of the ice pressure p and contact height h used in structural design for ships in the Baltic.

5. MICRO SCALE

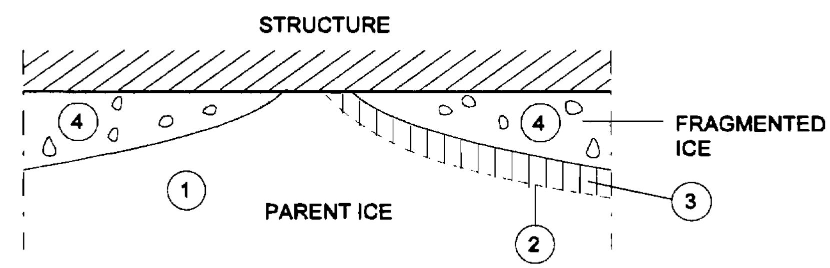
Recent developments in the analysis of ice-structure contact have suggested that in order to understand the physics of ice-structure contact, the approach of average pressure used in the small scale studies is not sufficient. For example, when analysing local deformation and strength of ship shell, the "true" ice pressure distribution should be taken into account. As an example, the local response of ship plating is very different whether we assume a 350 mm or a 60 mm contact height (Figure 5). For advanced ship structures like sandwich structures, this local structural response may be the most important one (Tuhkuri, 1995a).

Joensuu and Riska (1989) observed in the landmark laboratory experiments that in the brittle failure of ice, the contact between ice and a structure is transmitted through a small area of high pressure. Similar observations were later made during field tests onboard an icebreaker (Riska, 1991). Daley (1991) developed a computational process model for this type of brittle failure. In his model it is assumed that the ice edge fails by a repetitive flaking process which turned out to be chaotic. These lines of thought have been developed further by Tuhkuri (1993, 1994, 1995b) both experimentally and theoretically. The new aspects include further analysis of formation of crushed ice and the effects of this pulverised material to the flaking process.

Figure 6 shows a schematic presentation of the brittle ice-structure contact as observed in the laboratory experiments by Tuhkuri (1995b). In this figure we can observe an area of direct contact between the structure and ice and areas of contact through a layer of crushed ice. An important observation is the distinct boundary between the parent ice and the pulverised ice. There is active research going on to explain the processes resulting into this type of ice-structure contact.

Another still unanswered question is what are the parameters that define the brittleness of ice if flaking is typical to brittle failure. A multitude of experiments have shown that the ice in contact with a structure can fail in many ways. Figure 7 illustrates a simple division into crushing failure (microcraking only), intermediate failure, and flaking failure (no microcraking). The indentation speed and temperature have been proposed as the major parameters controlling these failure modes, but at least also confinement effects the process (Tuhkuri, 1995b).

A THREE STAGE CONTACT MODEL



1. IN THE INTACT PARENT ICE (1), A MACRO CRACK (2) AND A FLAKE (3) FORM.
2. A FLAKE (3) FAILS TO FORM A MASS OF CRUSHED ICE
3. THE CRUSHED ICE (4) FORMED FROM FLAKE (3) AND EARLIER FLAKES IS COMPRESSED, COMMINUTED AND EXTRUDED

Figure 6. Schematic presentation of the brittle ice-structure contact as observed in laboratory experiments by Tuhkuri (1995b).

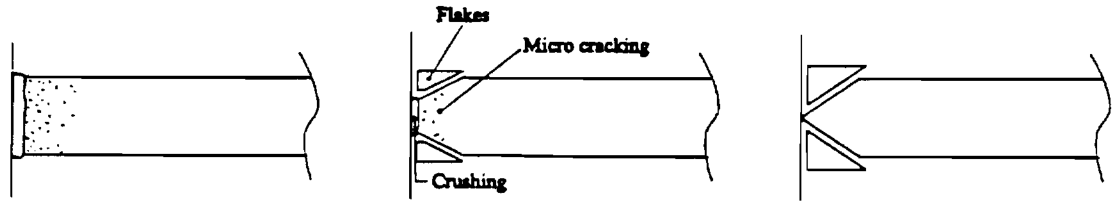


Figure 7. A sketch of the cross section through ice illustrating the crushing, intermediate and flaking failure (modified from Saeki and Ozaki, 1979).

6. INTERACTION BETWEEN SCALES

In the ice load model by Daley (1991) an ice edge failure was treated as a hierarchy of failures, each being superseded by a 'lower level' failure. In Daley's model, all the failure events were shear failures. Daley and Riska (1994) proposed a conceptual framework for ice loads which generalises the Daley's hierarchical edge failure model to ice failures in other scales. In this framework the ice failure is viewed as a process comprised mainly of a series of discrete events, rather than as a continuous process.

Figure 8 illustrates the hierarchy of limits that occur when an ice sheet strikes a structure. When the floe edge strikes the structure, local shear failure occurs until the vertical contact force is large enough to cause a flexural failure and a new contact edge forms. The force required to cause shear failures is increasing between two flexural failures. Also the force required the cause the flexural failure grows with each failure, because the previous pieces brace the free edge. The third limit is described as the rubbling limit and refers to the force required to build a rubble pile. The force increases as the size of the rubble pile grows. Also this pile-up process has a limiting process and the load will not grow to infinity. Daley and Riska (1994) propose that this type of hierarchies of limits, or limits-within-limits, are an essential aspect of any ice-structure problem and should be taken into account in ice load models.

7. RECOMMENDATIONS FOR FUTURE WORK

In the preceding chapters ice-ship problems in four different scales were reviewed. Many of the issues discussed are the subject of active research and some are not. Below a list of the research topics that the authors consider the most important is given.

Large scale

- Ship operability studies
  - efficiency
  - simulation
  - active / passive navigation
  - use of remote sensing in tactical navigation
- Ice cover parameterisation
  - remote sensing
  - definition of the parameters

Medium scale

- Ice ridges
  - formation of ridges, pile up against structures
  - thermodynamics of ridges, consolidation

Micro scale

- Flaking mechanics, fracture mechanics
- Microcracking

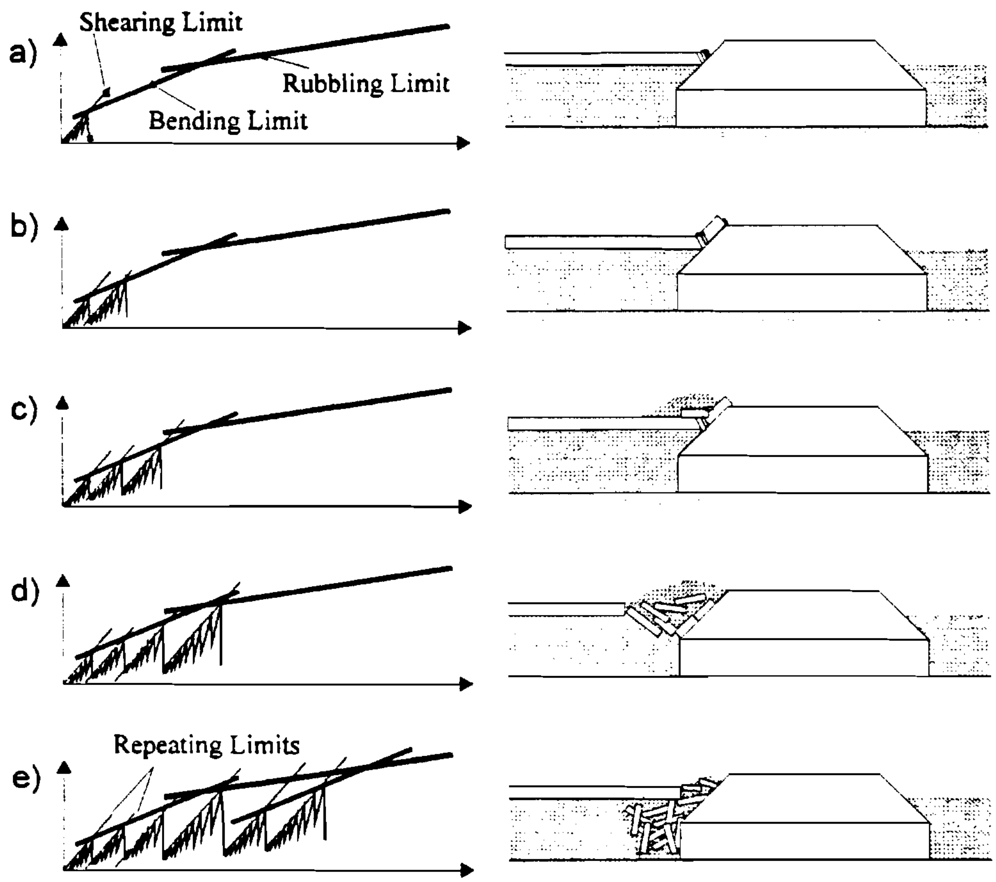


Figure 8. Floe-structure interaction showing hierarchy of limits (Daley and Riska, 1994).

ACKNOWLEDGEMENTS

This review reflects the ice research carried out in the Helsinki University of Technology but a number of the results were obtained through close co-operation with Finnish, Canadian, and Russian researchers and organisations.

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ICE-STRUCTURE INTERACTION RESEARCH AND ARCTIC DEVELOPMENT

Kennedy, K.P., Fitzpatrick, P.J., Hewitt, K.J. and Danielewicz, B.W.
CANMAR
Box 200, Calgary, Alberta T2P 2H8

Prepared for

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1.0 INTRODUCTION

Continued ice-related research and development has been a major factor in CANMAR's successful offshore arctic drilling operations. Year-round drilling in the Beaufort Sea has evolved from the dredged sand islands of the early 1970s through to the fully mobile bottom-founded SSDC in 1986. Development of these structures was made possible, in part, by intense data collection on the ice environment and specific research programs.

Given the oil price regime of 1994, there is a perception that economical production development in arctic waters is infeasible. While this would be valid in the early 1980s, significant advances have been made in our understanding of ice-structure interaction over the past 15 years. These advances are primarily the result of operating experience and full-scale research programs.

For example, first-year ice interactions with artificial islands in the late 1970s indicated that average ice failure pressures were generally less than 1 MPa, an order of magnitude lower than that predicted by laboratory compressive strength tests. Similarly, the Hans Island Multi-year Impact Experiments (1980, 1981 and 1983) demonstrated that global ice forces generated by 6 m thick multi-year floes were significantly lower than anticipated. Equivalent average failure pressures of around 0.1 to 0.2 MPa were observed for contact widths up to 200 m. These results demonstrated that ice loads on wide structures were much lower than previously thought.

2.0 TRENDS IN ARCTIC STRUCTURES

In the early 1980s, it was thought that an exploration structure for a water depth of 60 m in the Canadian Beaufort Sea had to be protected by a sand berm around 1 km in diameter and some 30 m thick (**Fig. 1**). At that time, ice features of less than 30 m thickness were thought to deliver a load of about 1 500 000 tonnes (15 000 MN) to an unprotected platform. These huge loads resulted from the extrapolation of small-scale laboratory compression tests directly to full-scale scenarios.

During the 1980s, full-scale ice load measurements on exploration structures and research programs such as Hans Island confirmed that global loads were significantly less than previously though. Indeed, the most probable largest, credible ice load experienced by any unit operating in the Beaufort Sea is believed to be only about 10 000 tonnes (100 MN). This is in line with the present (1994) 100-year global design ice load for a 100 m wide structure in 30 m of water of about 100 000 tonnes (1000 MN).

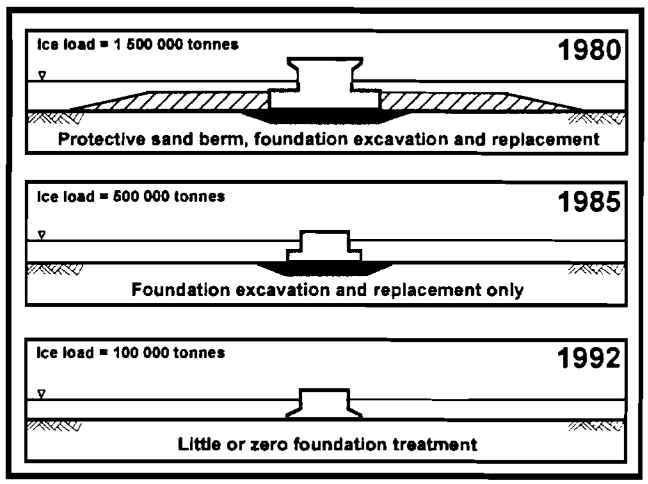


Fig. 1 Evolution of arctic structures in the Canadian and US Beaufort Sea (Fitzpatrick, 1994).

The combination of operational experience and full-scale research programs has resulted in a global load reduction factor of around 15 since the early 1980s (**Fig. 2**). This obviously has a direct bearing on the global size and cost of arctic production structures. The reduction factor of around 2 for local loading has resulted primarily from using more realistic strain rates and treating the load in a probabilistic manner rather than as the absolute maximum crushing pressure possible. New arctic production systems developed by CANMAR make strong use of these results and the results of a recent structural steel research program. Further details on the summaries given below can be found in the referenced papers at the end of this document.

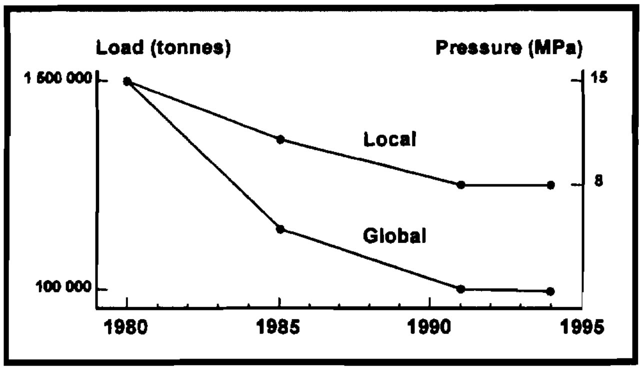


Fig. 2 Then and now... Beaufort Sea global and local ice loads from 1980 to 1994 (Fitzpatrick, 1994).

3.0 ICE-RELATED RESEARCH AT CANMAR

The results of the Hans Island experiments remain the only true full-scale measurements of multi-year ice forces on wide structures. While this data set is an important element of our design methodology, CANMAR continues to support research in many areas of ice-structure interaction. The following are brief summaries of some of this recent work.

3.1 SSDC Monitoring Studies

CANMAR's mobile bottom-founded exploration structure offers a unique opportunity to measure ice interactions at full-scale. Since the SSDC's first deployment in 1982, ice monitoring programs have been carried out at six drilling sites . Global loads interpreted from ice-pressure panels on the SSDC are low, the highest around 10 000 tonnes (100 MN). Our experience suggest that direct measurement of global ice loads with pressure panels is not reliable. Loads interpreted from ice instrumentation are 2 to 3.5 times higher than those interpreted from geotechnical response (see **Fig. 3**). This suggests that the magnitude of actual ice forces on wide arctic structures is even lower.

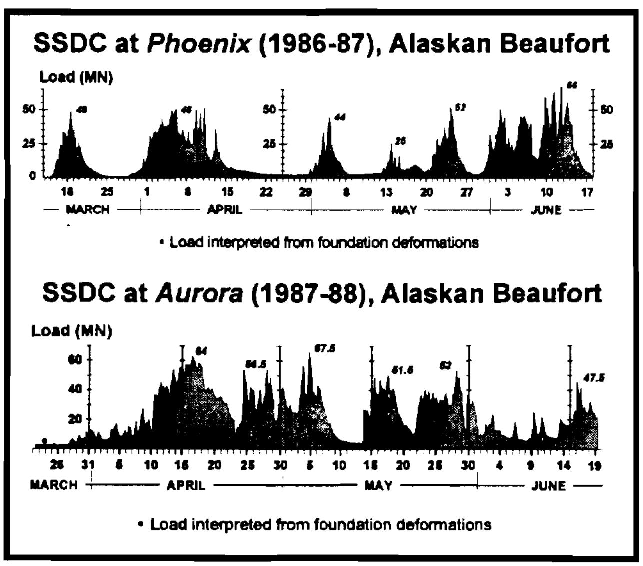


Fig. 3 Interpreted global first-year ice loads from ice panels and foundation deformations (Hewitt et al., 1994).

3.2 First-year Ice Loads Database

This proprietary database allows a deterministic approach to estimating first-year ice loads on wide arctic structures. The database includes over 14 000 data points determined from re-analysis of 16 separate data sets dating back to 1966. Most of the data was collected during ice monitoring programs on Beaufort Sea structures. The database has been used to secure permits for year-round drilling operations.

3.3 Lighthouse Ice Force Measurements

In 1990, CANMAR, as part of a joint-industry partnership, sponsored a series of ice force measurements at the Norströmsgrund lighthouse in the Gulf of Bothnia. These measurements were coordinated by VBB VIAK AB and will provide full-scale ice load data for use in non-simultaneous failure and dynamic ice-structure interaction models.

3.4 Medium-Scale Indenter Experiments

In 1989 and 1990, medium-scale ice indentation tests were carried out in multi-year ice at Hobson's Choice Ice Island. CANMAR was a participant in the jointly funded project. The emphasis of these tests was to improve estimates of design ice failure pressures and to study recent ice failure theories. Pulverization of ice and extrusion of crushed ice was recognized as the primary mechanism for the dynamics observed during the tests. Results also suggest that very high local pressures develop in "hot spots" over the contact area, while the average indentation pressure is considerably lower.

3.5 Statistical Properties of Sea Ice Thickness

In 1991, CANMAR sponsored a re-analysis of submarine sonar under-ice profiles for the southern Beaufort Sea. This work, undertaken by CAMBRIDGE POLAR CONSULTANTS, focused on developing a more complete description of the ice regime to produce reliable statistics. Probability densities were developed for level ice thickness, ridge draft and spacing, lead spacing and multi-year floe diameter.

3.6 Beaufort Sea Floe Size Distribution

A comprehensive review of a variety of floe size studies was carried out for CANMAR by CANATEC CONSULTANTS LTD. Of the 22 studies examined, nine were determined to provide reliable multi-year floe size information. These were then organized to provide data sets for use in probabilistic ice load models for the North American Arctic Offshore.

3.7 Ice Floe Splitting Theory

Methods to estimate global ice loads on offshore structures are based primarily on loading scenarios that assume crushing is the dominant failure mode. Observations of full-scale interactions, however, suggest that floe splitting is a common failure mechanism, whereas pure ice crushing is comparatively infrequent. By incorporating the statistics of global splitting failures, it is anticipated that design multi-year ice loads for production structures, such as the 100-year load, can be further reduced.

In 1989, Canmar and Mobil Research and Development Corporation sponsored development of a fracture theory suitable for use in probabilistic models. This theory was developed by Dr. J.P. Dempsey of Clarkson University.

3.8 Large-Scale Ice Fracture Experiments

In 1990, a two-phase jointly-funded research project was initiated to calibrate, using large-scale data, the analytical splitting model developed at Clarkson University. Phase 1 of the project was completed in January, 1992 near Calgary, Alberta.` Fracture toughness, elastic modulus and other properties were measured for thirteen freshwater ice specimens over a scale range of 1:85.

Based on the success of Phase 1, large-scale fracture tests were conducted in Phase 2 in April, 1993 near Resolute, Northwest Territories. Square fracture specimens ranging in size from 0.5 x 0.5 m to 80 x 80 m, the largest known fracture specimen of any material, were fractured under controlled loading in 1.8 m thick sea ice. The results will then lead to calibration of the floe splitting model and incorporation into probabilistic design ice load models.

Canmar has recently contracted Clarkson University to perform additional data analysis of the Phase 1 and Phase 2 data sets. This work should continue into 1996.

3.9 Loading and Mooring of Tankers at Arctic Structures

The objective of this project is to produce analytical tools for interpreting the performance of systems and procedures used in mooring and loading of tankers at arctic offshore structures. The project deliverables are analytical models in spreadsheet format. Model inputs are user-specified environmental conditions and equipment configurations. Model outputs are time requirements and downtime estimates.

The project objectives are being met in three stages:

- *Establishment of the Current State-of-the-Art* based on international operator reports and a workshop designed to examine the effectiveness of current technologies.
- *Scale Model Testing at the Institute for Marine Dynamics* to supplement the current state of knowledge about the effect of structure size and ice direction change on the behavior of a tanker moored at a structure in moving ice.
- *Analytical Model Development*, an extension of earlier Canmar work for the Canadian Coast Guard, by applying new modeling concepts and extending them with the information collected in the first two stages of this project.

The total cost of the project is C $340,000 (US $240,000). The Canadian Transportation Development Commission has sponsored C $150,000 of the cost and the remainder is being shared by 12 industry participants. The project began in October, 1994 and is scheduled for completion in June, 1995.

4.0 STATE-OF-THE-ART STEEL STRUCTURES

Another important element in Canmar's approach to the design of arctic production structures is the redefinition of the state-of-the-art in steel design. When Canmar designed and built its first arctic bottom founded structure, the best design methods available at that time were used. However, it slowly became apparent that this approach, while highly efficient for temperate zone structures, was conservative when applied to platforms intended for ice-infested waters.

4.1 The Research Program

The degree of conservatism proved difficult to estimate and impossible to verify by theoretical or finite element methods. Canmar set the scope for, and funded, a major full and partial scale testing program. The results of the program (completed in 1992) have proven that steel weight savings of 25% to 30% are possible. When ease of construction is combined with weight savings, the total cost savings for the basic structure exceed 30%. Canmar's platform concepts incorporate these results in steel weight estimates.

Four basic types of test were carried out. The material tested was EH 36 steel, as produced by an on-line accelerated cooling process (the same as in the SSDC's support base structure, the MAT). The first two tests (**Fig. 4**) were plate and stiffener tests with normal (perpendicular) hydrostatic pressure loading. These results are directly applicable to the outside wall and the base of an arctic structure. The last two tests (**Fig. 5**) were in-plane loading tests. The findings here can be used to improve the design performance of the internal bulkheads, which transfer global loads to the foundation.

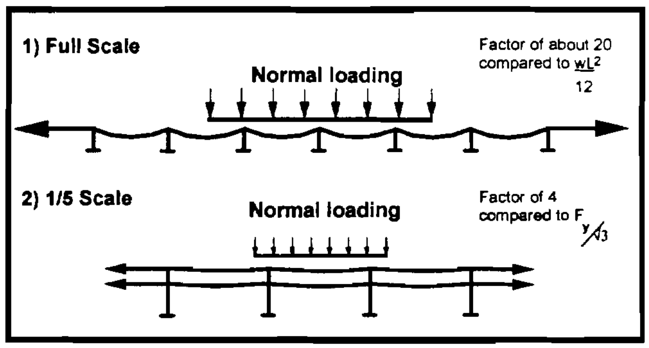


Fig.4 Plate and stiffener tests.

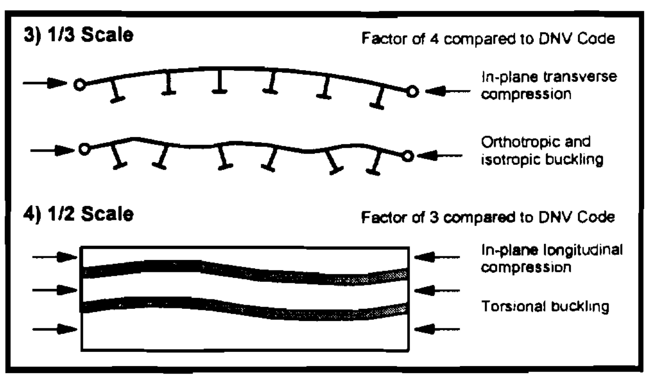


Fig. 5 In-plane, longitudinal and transverse tests (Fitzpatrick, 1994).

4.2 Concept Types

In the early 1980s, some 60 or 70 different concepts for arctic production structures were on the drawing board, ranging from monolithic gravity structures to floating units with ice melting systems.. The concepts that have survived are essentially very simple. **Fig 6** illustrates four different concept types. The bottom two represent the present state of the art. The others appear attractive at the outset, but a closer look brings some flaws to light.

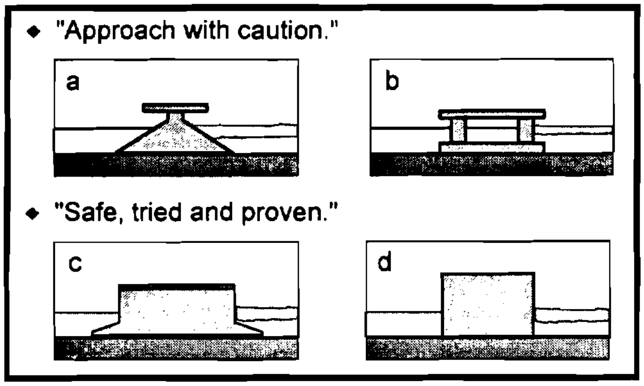


Fig. 6 Concept types (Fitzpatrick, 1994).

Cone Shaped Structure (Fig 6a)

When ice loads were thought to be high (500 000 tonnes plus), there was incentive to break the ice by bending, thus reducing the horizontal load and the size of the platform. With the lowering of design loads to around 100 000 tonnes, the driving force for the proving of this concept type has dissolved. At this load level, the conical structure would be relatively small in mass and vibration effects could be expected to play a significant part in the design evaluation. The structure would also be relatively difficult to construct and too small to provide any significant oil storage.

Columnar Structure (Fig. 6b)

In areas without multi-year ice and where ice and wave loads are comparable, it is tempting to try a "load transparent" structure, similar to the jacket structure philosophy in the more usual "wave only" environment. Such a structure could not store oil in any quantity, would suffer stability problems due to its low mass, and may experience ice bridging between the columns. As well, the concept may suffer from vibration, the degree of severity of which is difficult to assess.

Monolithic Cantilever Structure (Fig. 6c)

The structures shown in Fig. 6c and Fig. 6d look so simple that they beg the comment that there must be a more efficient way. Experience to date would suggest that this is not the case. Where the foundation is of competent clay, base area is the main criterion for horizontal stability (hence the area efficient cantilevers). Such structures do not depend solely on gravity for resistance and are generally a little smaller in volume and mass requirements than those that sit on sand foundations, (except where storage requirements are so massive that the horizontal loads are inconsequential).

Cuboid Structure (Fig. 6d)

If the foundation is a soft clay, the most effective solution is to remove a substantial portion and backfill with dense sand. Since the resistance mechanism is friction, base area is not critical and weight alone becomes the predominant requirement. Earlier concepts of this nature had an octagonal rather than square shape, as this was considered to be more streamlined. Experience has not indicated that the slow, erratic, non-fluid like loading nature of heavy ice is affected one way or the other as a result of streamlining. Construction and general arrangement details are greatly simplified by a square layout and since no great load advantage is achievable, the concepts might as well be right-angled.

5.0 TYPICAL CONCEPTS FOR SPECIFIC AREAS

The details of different solution types are now presented for three different arctic regions with site parameters as shown in **Fig. 7**. The foundation choices are for illustrative purposes only and while they are quite possibly representative, they are not indicative of each entire region.

	Canadian Beaufort Sea	US Beaufort Sea	Pechora Sea
Water depth	30 m	30 m	15, 20 & 30 m
Multi-year ice	yes	yes	no
First-year ice	yes	yes	yes
Maximum wave	9 m	9 m	10, 12 & 14 m
Foundation	poor	good	good

Fig. 7 Typical regional site parameters (Fitzpatrick, 1994)

5.1 Canadian Beaufort Sea

After examining many possible general arrangements, and taking into account optimization of resupply and the space requirements of daily production rates in the region of 100 000 bbls per day, a topsides plan area of 10 000 m^2 was considered suitable for this location. A second deck, immediately beneath and with the same area, was also considered necessary. The next requirement was that the platform should be stable. This aspect required that consideration be given to the design ice load and to the foundation resistance capacity (**Fig. 8**).

With a factor of safety of 1.5, the foundation must provide a horizontal resistance of 150 000 tonnes. At this particular location, the thickness of the recent soft sediments is about 10 m with a sand stratum of around 25 m beneath, which in turn is underlain by a stiff cohesive clay. Leaving the soft upper sediments in place would require an enormous base area, much greater than that provided by the dimensions required for the topsides. If, however, the 10 m of weak clay (250 000 m^3) is excavated and backfilled with sand, the platform can achieve stability by weight alone. The friction coefficient of competent sand is about 0.6, so to provide a resistance of 150 000 tonnes, the net weight on the bottom after the deduction of the effects of buoyancy should be not less than 250 000 tonnes. This can be achieved by a simple

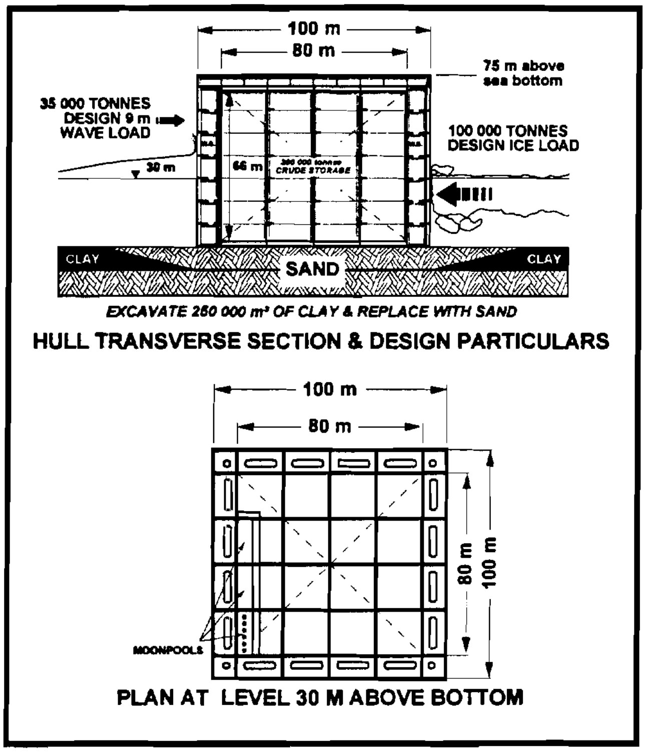


Fig. 8 Canadian Beaufort Sea production and storage platform (Fitzpatrick, 1994).

boxlike structure with a freeboard of about 45 m. The unit must be ballasted fully at all times with a liquid that has a specific gravity of about 0.8 or more in order to maintain required contact force. Stability and topsides requirements are satisfied by a structure 100 m x 100 m x 75 m high.

If we allow a 10 m perimeter all the way around the structure, permanently ballasted with seawater as a protection against accidental high speed ramming by a ship, plus a double bottom and double deck at the top of the platform for further security, then the internal volume available for crude storage is about 300 000 tonnes or 2 000 000 barrels. This capacity is essentially free as the structure must be this size anyway in order to resist the design ice load and provide working area for the topsides facilities. Storage volumes greater than this amount come at a premium, since it would become a governing factor in the sizing of the structure.

Three principal factors are simultaneously catered to and no one criterion dominates the design. To recap, the three factors are 10 000 m^2 deck area; 150 000 tonnes foundation resistance for 100 000 tonnes ice load; and 300 000 tonnes of non-segregated storage for crude oil production.

5.2 US Beaufort Sea

The environmental design criteria in this general area are virtually the same as in the Canadian Beaufort. In the deeper areas of the Chukchi Sea (50 to 60 m) they are somewhat worse - in the order of 50% more for ice and greater again for waves. The only significantly different factor affecting the conceptual design is that of foundation strength, since all the other main parameters are unchanged. Storage requirements are also less onerous since the US Beaufort is closer to pipeline and openwater transportation.

Foundations in the mid-US Beaufort consist generally of firm clays with undrained shear strengths of 1500 psf (75 kPa) and up. At the surface interface there is a strength loss due to hydraulic and/or ice scour interaction. The provision of a square, grid-like, bladed skirt system about 2 to 3 m high and spaced at about 6 to 10 m on the underside of the structure enables the strength of the competent material 1 m or so below to be fully mobilized.

The structure has a similar 10 m, water only, perimeter to that shown in the earlier cuboid concept; a feature that is suggested for all storage concepts (**Fig. 9**). Because of the lesser volume required, the "free" storage capacity is about 200 000 tonnes (1 500 000 bbls). While this is less than in the Canadian concept, the reduction trades off nicely with the shorter product transportation distance.

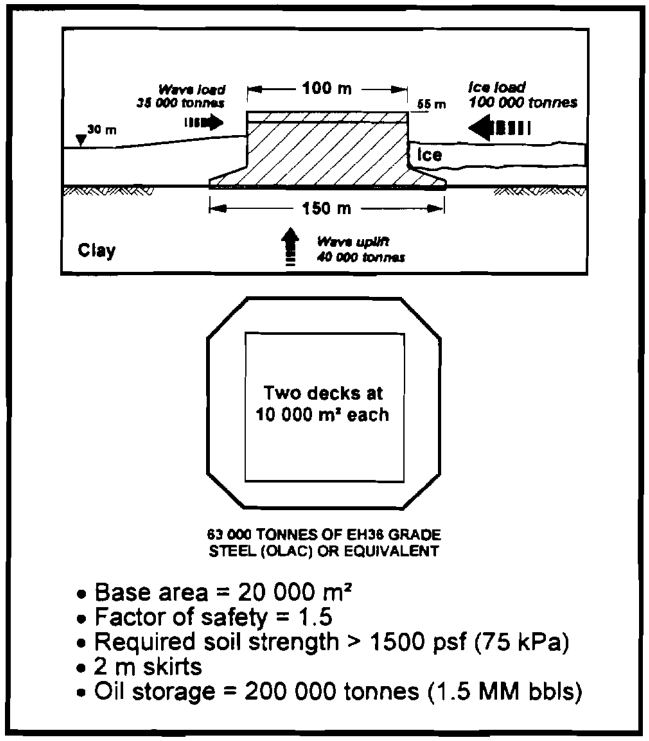
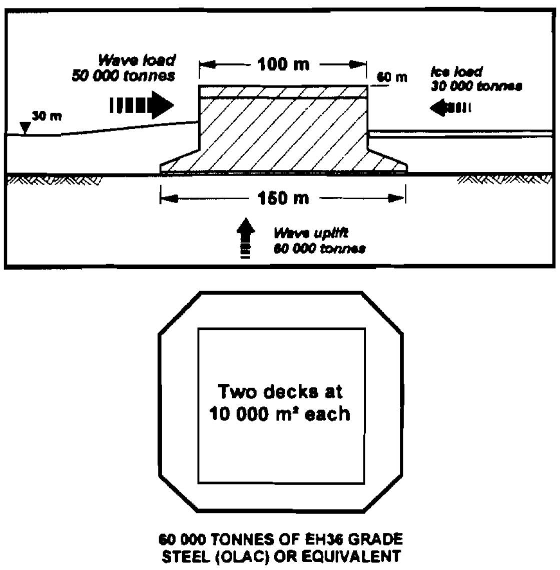


Fig. 9 US Beaufort Sea production and storage platform.

5.3 Pechora Sea Concepts

Wave loads and ice loads are similar in magnitude in the Pechora. The maximum design wave, about 15 m, is higher than in the US and Canadian Beaufort, but there is no multi-year ice and the features that form are the product of only one season's freezing. Somewhere around the 15 to 20 m water depth, wave and ice loads tend to be equal. Below this depth, ice loads are greater. Deeper than that, waves govern.

In the Pechora Sea, reduction of the waterline diameter below 100 m reduces the wave and ice loads almost linearly. There is a point at which this linearity drops off, particularly where ice loading conditions are concerned, but it is well below this dimension (100 m) where this occurs. For these reasons, it is difficult to pick a typical size of structure suited for the Pechora. In general, platform size will be strongly dictated by functional requirements, in particular those of storage. Two main structures are possible. The first (**Fig. 10**) has been adapted, transferred, and modified slightly from the US 30 m water depth concept. Because the buoyancy loading from the 14 m design wave is higher, the structure needs to be a little taller, resulting in a slight potential storage increase to 225 000 tonnes (the 10 m ballast tank is still included around the perimeter). However, because of the less stringent ice loading conditions, the overall steel weight requirement drops slightly relative to the US case. The major difference is that the minimum foundation strength requirement has been halved due to the reduction of the global load from 100 000 to 50 000 tonnes.



- Base area = 20 000 m²
- Factor of safety = 1.5
- Required soil strength > 750 psf (37 kPa)
- 2 m skirts
- Oil storage = 225 000 tonnes (1.7 MM bbls)

Fig. 10 Pechora Sea production and storage platform (30 m)

In the second concept, the water depth has been reduced and the neck narrowed to 85 m. This combined reduction lowers the global load by about 20% and the storage capacity is now about 140 000 tonnes (1 MM bbls). The deck area and the minimum foundation strength requirements remain the same, but the structure requires significantly less steel to construct. In fact, as one goes shallower and if the deck area and storage requirements are radically reduced, the minimum size platform (that would be stable) could probably be constructed from as low as 10 000 tonnes of steel.

5.4 Steel versus Concrete

Before any bottom-founded structures of significant size were deployed in the Arctic, there was a general feeling that concrete had the edge on steel. Local ice loads were thought to be phenomenally high, thus favouring thick walled concrete. Steel plastic catenary mechanisms were not well understood and steel weight requirements were consequently high and costly to fabricate. Also, steel was thought to be inadequate (in terms of notch toughness) for the harsh arctic environment. Today, for the most part, the pendulum has definitely swung in the other direction for reasons of cost, draft restrictions, long-term performance, constructability and hydrostatic stability (see Fitzpatrick, 1994).

6.0 SUMMARY

- Design, global ice load reductions and structural research have greatly reduced platform costs.
- Monolithic steel gravity platforms are the most cost effective platform solutions for the Arctic offshore.
- The installed costs given in **Fig. 11** are exclusive of topsides facilities and the equipment necessary for the control and storage of crude, but include towing and installation and foundation preparation where appropriate. In the Pechora case, the costs given are for guidance purposes only, as the structures will more than likely be constructed in Russia

	Water Depth (m)	Steel Weight (tonnes)	Top Deck Area (m²)	Crude Storage (tonnes)	Cost (MM $US)
Pechora #1	15	10 000	2 000	20 000	50
Pechora #2	20	40 000	7 000	125 000	120
Pechora #3	30	60 000	10 000	225 000	170
US Beaufort	30	63 000	10 000	200 000	175
CAN Beaufort	30	75 000	10 000	300 000	225

Fig. 11 Summary chart for different concepts

- Cost estimates were established subsequent to quotes from a Japanese shipyard with previous arctic experience. They reflect an early 1993 projected view of mid-1990s construction costs. Fabrication in Japan was assumed at a basic rate of 300 000 yen per fabricated tonne. The exchange rate used was 128 yen to 1 US$, which gave a unit rate of $2350 per tonne. This was raised to $2500 per tonne to allow for extras. Adjustments should be made accordingly.

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Sea Ice Mechanics Initiative Workshop
Anchorage, Alaska - 23 - 27 April 1995

BP PROGRAMS

Presentation by
Graham A.N. Thomas, BP International Limited

Introduction

In the 1980's the BP Group (including Sohio and BP Alaska) performed research into arctic technology from offices variously in San Francisco, Dallas and London. BP was active in oil industry arctic research in Alaska and Canada, participating in the majority of Joint Industry Projects and with several unique projects.

With imminent arctic offshore developments failing to materialise, due to continuing low oil prices and the forecast of uneconomic rates of return on capital, BP along with other oil companies redeployed its specialist technologists. The focus shifted to building on the strengths of BP's existing operations in the Prudhoe Bay area. BP's technology strategy is focussed on the use of technology and knowledge, wherever they exist, rapidly to add value to the core business activities of creating options, making decisions and allocating tasks.

This brief presentation is therefore in two parts, namely pre-1988 and the 1990s. In-between, some arctic research continued related to northern Norway.

Pre-1988: US/Canadian Arctic Research

In the 1980s, BP/Sohio research and technology development for the arctic offshore was aimed at primarily confirming the feasibility of exploration and eventual production, and latterly with focus on reducing the cost of drilling exploration wells. Four areas were addressed, and some of the principal aspects in those areas were as follows:

<u>Ice:</u> fundamental ice mechanics, properties of sea ice and spray ice, ice environment characterisations and mapping, ice load calculation methodologies, ice scouring;

<u>Structures:</u> concepts for exploration structures and for production structures, perimeter ice-resisting structural elements;

<u>Pipelines:</u> deep trenching, permafrost impact, multi-phase flow, monitoring and leak detection, landfall options;

<u>Geotechnics:</u> seabed characterisations and mapping, structure foundation options, permafrost impact.

More generally for transportation options in addition to pipelines, ice transit with ice-capable tankers was studied.

In addition to the many joint industry projects in which Sohio, BP Alaska or both participated BP/Sohio had some particular program of its own, including:

- Katie's Floeburg (1985): field experiment in the Chukchi Sea based on a seasonally-grounded stable ice rubble field (Katie's Floeburg) to investigate the 'winter blocking' ice load. 'Winter blocking' occurs when a large thick multi-year ice feature surrounded by pack ice becomes lodged against a structure.

- Hans Island (1986): following participation in the successful programs in 1981, 82 and 83 BP/Sohio returned to Hans Island in 1986 with improved instrumentation in order to gain more information on the multi-year ice floe 'summer impact' scenario.

- Spray Ice (to 1986): various projects over several years, including field trials to create grounded ice structures ('islands') in the arctic offshore in up to 12 water depths. The technology was eventually used by others to successfully drill exploration wells.

- Sohio Arctic Mobile Structure (SAMS - early 1980s): some engineering design was completed for a mobile exploration drilling structure for shallower (e.g. 15 m) water depths.

- Stepped Pyramid Structure (mid-1980s): various concept development studies were completed for BP/Sohio's preferred structure concept for deeper (up to 60 m) water depths and mobile winter ice.

- Ice Rubble Generator (early/mid-1980s): a concept to extend 'spray ice island' technology to deeper water depths (up to 20 m) by using a temporary grounded structure to generate and capture ice rubble from mobile early-season first year ice.

- Arctic Plough: design development and field trials were completed for deep trenching and burying of seabed pipelines.

1988 - 1990: Norway - Barents Sea

Although interest in offshore Alaska waned, interest in potential lease acquisitions offshore northern Norway continued. BP was an active participant in IDAP (the Ice Data Acquisition Programme). And in conjunction with Statoil, BP performed some bi-lateral studies including:

- Ice Accretion: field study and data analysis of ice accretion on a semi-submersible drilling rig operating in the Barents Sea

- Satellite Image Analysis: nine years of satellite image data were analysed to determine ice concentrations and movement patterns in the Barents Sea, to assist in determining (a) design ice events and (b) early warning systems for ceasing operations and moving off station.

Post-1990: Field Developments and Continuous Improvement

BP's approach in the 1990s is one of improving existing operations, and of moving step by step to new field operations and development. Steps along this path include:

- Milne Point: acquisition and operation of the Milne Point field;

- Niakuk Field: a small field developed and now producing from a gravel island in Prudhoe Bay, between the Prudhoe and Endicott fields;

- Badami Field: engineering is in progress for the development of a field some miles east of Prudhoe bay. Badami is to be developed from an onshore site with extended reach drilling to the offshore field. One of the challenges is to install and operate a chilled pipeline in permafrost; there is useful transfer of technology from the Canadian arctic experience;

- Prudhoe Bay Gas: options for export of Alaskan Gas to the Pacific Rim could be via pipeline to a Northern or Western Alaskan port. In order to meet this challenge, the port and tankers would need to handle ice infested conditions. The alternative under consideration would be a pipeline to Valdez;

- Northstar: following acquisition of the Northstar/Seal Island prospects, conceptual engineering studies are in progress to identify the significant cost reductions necessary for economic viability. If viable, Northstar will be the first 'truly' offshore (i.e. no causeway) arctic production development. BP is committed to work with the state and federal authorities to secure a safe and economic development plan.

FUTURE NEEDS

Cost Reduction

The prime future need is to reduce costs. Technical feasibility for arctic offshore developments in current lease sale areas has today largely been established. Field development concepts can be engineered with high confidence but further work is needed to make these concepts relevant and cost effective.

BP's experience in the North Sea is that significant cost reductions can be achieved through:

- New Relationships: new ways of doing business with contractors, including partnerships and alliances, and in sharing risk and reward so that all parties are aligned with the project objectives; and with regulators, state and federal authorities, maintaining a dialogue and seeking their guidance so that acceptable solutions are developed.

- Integrated Teams: ensuring that the various specialist staff e.g. from drilling, reservoir, facilities and commercial, are integrated into a team that is aligned to deliver on the targets set; each member seeing the impact of particular decisions on the whole;

- Breakthrough: challenging conventional approaches in order to generate the step-changes necessary to make arctic offshore development economic.

- Understanding the Cost Drivers: analysing the elements that contribute to total cost and focussing on the key elements.

Sea Ice Technology

For technology generally, the need is for continuous improvement. Improved use of existing technology combined with incremental use of new technology is the general way forward.

In the field of sea ice mechanics, the need is for probabilistic models for calculating design ice loads. Such models should account for the ice properties, the ice environment, and the ice/structure interaction scenarios so that risk-based design ice loads for various structures in various locations can be minimised with confidence.

Full scale field measurements of ice loads on structures, with adequate recording of scenarios and key parameters, will assist. It is likely that these are obtained economically when such data gathering is 'piggy-backed' on operating facilities. The first facilities may be expected to be designed conservatively. When sufficient data is gathered, design criteria can be revised with confidence arising from operating experience.

There is the experience of the North Sea where field measurements have provided confidence in the environmental characteristics, The design wave heights have been safely reduced to reflect the statistics of what is actually measured.

More specifically, the ice 'Pressure/Area' effect shown by Sanderson in the 1980s has been developed by Masterson and Frederking (1993) and is to be published in the 1995 edition of API RP 2N "Recommended Practice for Planning, Designing and Constructing Structures and Pipelines for Arctic Conditions". This highlights that at 'structure-scale' (> 50 m^2 say), ice/structure interaction pressures from just a few large scale data points are available to guide designers. Probabilistic global ice load models, with or without constitutive relationships for sea ice, are calibrated against these few data points and conservative assumptions must therefore be made. The need is for more documented and analysed full scale data. Using sea ice/ice load models appropriate to the scale and verified against field data, design ice loads for various structure types such as vertical caissons, sloping cones, stepped pyramids and gravel islands may be estimated without undue conservatism.

A Review of Select Exploration and Development Activity in State Nearshore Areas

James Hansen, Manager of Oil and Gas Leasing Program,
Alaska Department of Natural Resources

Presented to: Sea Ice Mechanics and
Arctic Modeling Workshop
Anchorage, Alaska
April 25-28, 1995

Introduction

After giving you a brief overview of state government's structure, regulatory role and responsibilities for managing subsurface oil and gas resources, I would like to direct your attention to some examples -- from nearshore North Slope producing fields -- where technology is contributing to lowering costs in such a way to help make relatively small fields economic to produce.

Extremely high operating costs in arctic Alaska are a result of the remoteness, the harsh environment, and the costs of meeting stringent environmental standards. Research projects have been and continue to be conducted on every aspect of the onshore and offshore environments, including studies on wildlife, fisheries, and habitat; tundra re-vegetation; hydrology; insect relief; whale migration; waste management and pollution control; nearshore water circulation patterns and salinity; permafrost; ice gouging; weather; storm surging; ice mechanics; and many more. These studies provide much of the foundation for selecting cost-effective construction techniques, making siting decisions, and providing monitoring and mitigation options.

I believe the research studies and applied technologies generated from the paticipants in workshops such as this have played and will continue to play an extremely important role in balancing the costs of extracting valuable energy resources from arctic areas against the goal of minimizing adverse impacts to land, sea and wildlife.

The current production in the Beaufort Sea is all land based. That is, the oil and gas is produced from onshore drilling pads utilizing extended reach drilling technology or from drilling pads connected to shore by gravel-filled, breached causeways. We have yet to see the first bottom-founded production platforms in the Beaufort Sea, but hope that this eventuality will be realized in the future. So, although I don't have any startling new information on ice engineering techniques in the deeper OCS waters, I do hope to show you what is working in the shallow, nearshore envirionment.

Introduction

Good evening, I'm Jim Hansen, Chief Geophysicist for the Division of Oil and Gas for the State of Alaska. I'm standing in for Commissioner Shively who had other commitments and couldn't be here today. He does send his best wishes, however.

Tonight I'm going to touch on two topics--the role of state government in oil and gas activities, and current production activities near and in the Beaufort Sea.I thought it might be a good idea first to explain how we are structured; it will put some of the names I'm going to use in perspective:

Governor Knowles heads the Executive Branch of Alaska's state government. In addition to his staff, several commissioners report directly to him. For our purposes here, we will be concerned with the commissioners who head up what we call the three resource agencies. That is the Commissioner of the Department of Natural Resources, the Commissioner of the Department of

Environmental Conservation and the Commissioner of the Alaska Department of Fish and Game. Commissioners lead various departments.

Each Department is made up of divisions who are, in turn, headed by directors. I am in the Division of Oil and Gas, the division with the responsibility for oil and gas lease sales and lease management activities. I report to the director, who reports to Commissioner Shively and he, in turn, reports to the governor.

In my division, we are concerned with oil and gas leasing on state-owned lands, both on and off-shore. It is the process where Alaska generates more than 85-percent of its income. The economy here is driven primarily by the activities and production of a single industry. We have almost forty-years experience administering oil and gas leases and we are learning more every year.

Concerns

There's a lot we don't know about the ecology of the arctic, especially the offshore environment. And, as we proceed with exploration activities, we are careful to do what we can to minimize the impact of our presence. We have a well thought-out method to do that which I'll discuss a little later. You should know, however, the results of research conducted by groups such as this make significant and continuing contributions to our knowledge and we applaud your efforts.

To protect the arctic environment and the way of life of our arctic residents, extraordinary steps are taken to ensure that our activities do not interfere with the subsistence way of life or create damage unnecessarily. You might like to know how we address some of the issues - real or imagined.

In the Beaufort Sea, when bowhead whale are migrating through an exploration area, we apply and enforce seasonal drilling restrictions.
All non-essential activities are suspended and those that continue must be coordinated with local whaling groups. One company (Texaco) has estimated that a "warm stand-by" status as the whales pass adds $660,000 per day to the cost of operations.

In an attempt to determine if industrial noise and other disturbances disrupt migration patterns or make hunting more difficult, we have required research to determine the effect of exploration activities on the whales. We were concerned that displacement from their migratory path or feeding areas could lead to long-term displacement with unknown consequences. But, that appears not to be the case.

We are especially concerned with drilling in broken ice or within a spring lead system. A spill or blowout under those conditions has not happened - and we don't want it to. Lessees who conduct drilling operations during these times must participate in the Oil Spill Research and Development Program. They must be trained in accordance with Minerals Management Service standards relating to well-control equipment and techniques and they must have an oil spill contingency plan approved by the state.

Spill preparedness plans require planning standards for all exploration facilities. The objective is to be able to contain or control and clean-up a realistic maximum discharge within 72 hours. A "realistic maximum discharge" depends upon the size of the involved facility and is set by formula. For an exploration or production well, it is 16,500 barrels.

Lessees must submit a detailed plan of operations to the division for written approval before initiating any exploration or development activity, whether on or off-shore. An approved plan of operations becomes the permit by which the division regulates the activity. It also provides us with an opportunity to add stipulations that might not have been relevant at the pre-lease stage. The ability to do this is especially important as technology changes. State leases in Alaska are generally valid for ten years and a lot of good things can happen in a relatively short period of time. We want to be able to apply the best available technology at any time it becomes obtainable.

Let me give you a few examples of how we have been able to improve our presence on the North Slope by advances in technology. Within the past twenty-years the spacing between wellheads has been reduced 91%. As a result, the surface area required for gravel pads has been reduced 75%. A typical drill site now takes up less than 9 acres compared to an average of 65 acres in 1970.

The area required for contractor services has been reduced 95%. Buildings in Deadhorse, the service center for the Prudhoe Bay field, cover more than 1,050 acres while a newer facility designed for the Kuparuk oil field covers only 55 acres.

Gravel roads for pipeline construction have been eliminated completely and exploration drill sites are now constructed of ice rather than gravel. Drilling fluids are disposed of through underground injection and the design and permitting of centralized waste management facilities has resulted in a 95% recycle rate for associated wastes.

Reserve pits have been eliminated (or perhaps needed only on a temporary basis), and fewer drill sites are required due to recent advances in directional drilling - the horizontal reach is about 15,000 feet; in 1981 it was about 5,000 feet.

As a result, industry is now drilling into the offshore Niakuk Reservoir from an onshore location at Heald Point northeast of Prudhoe Bay. As a result, they have been able to avoid the problems associated with off-shore drilling and eliminate the need for a subsea pipeline.

We like the progress that has been made, and look forward to more as time goes by.

I mentioned that we impose various stipulations and mitigation measures. Some of them directed toward off-shore activities might be of interest to you.

We are concerned with problems associated with water currents, storm and ice scouring, and subfreezing conditions. As a result, continuous-fill causeways are prohibited and non-continuous fill causeways are permitted only after consultation with ADF&G and ADEC - and then only after we determine that it's necessary for field development and no other alternative exists.

When approved, they must be designed and sited to prevent detrimental changes to nearshore oceanographic circulation and water quality characteristics such as salinity, temperature and suspended solids. They must be designed to provide for the free passage of marine and anadromous fish and they are not permitted in the mouths of rivers or deltas.

Our leases carry stipulations requiring pipelines for the transportation of oil and gas. And, following the installation of a pipeline of sufficient capacity, crude oil cannot be transported by surface vessel from off-shore production sites (except in an emergency).

If a pipeline is not feasible and vessel transportation must be used, ships used to carry hydrocarbons must conform with the standards established by the Port and Tanker Safety Act of 1978, as well as any other applicable laws and regulations.

When conducting offshore geophysical surveys, explosives may not be used in open water areas. This type of operation is restricted as necessary to comply with the provisions of the Marine Mammal Protection Act and the Endangered Species Act as they relate to the Bowhead whale.

Disposal of wastewater from gravel islands, ice islands or other semi-permanent or bottom-founded structures is regulated by a federal permit (NPDES), while disposal of domestic wastewater onshore is regulated by federal standards under Section 312 of the Federal Water Pollution Control Act.

I mentioned that we have a well thought-out process to minimize the impact of our presence. With imperfect knowledge, I'm sure that mistakes are made, but we put plenty of time and effort into doing it right.

The state's oil and gas leasing process follows certain procedures which must be completed within specific timelines before decisions are made. The public and those involved are informed of each step in the process and their input is encouraged.

The Leasing Process

In general, the leasing process works like this:

4 - 6 years before a sale is held - a call for nominations is sent to the oil companies asking them to identify areas that they are interested in. Nominations are reviewed and new proposed sale areas are identified by the department (DNR).

3_ - 5_ years before a sale is held - we solicit comments from local governments, state and federal agencies, the oil industry, environmental organizations and any affected coastal districts and the public.

3 - 5 years before a sale is held - additions and revisions are outlined in a published Five-Year Oil and Gas Leasing Program which is presented to the Alaska legislature every two years in January. It is also made available to the general public.

3 to 3_ years before a sale is held - we issue a second call for comments. It is again sent to local governments, state and federal agencies, the oil industry, environmental organizations and affected coastal districts and the public.

2 years before a sale is held - we do a preliminary land status review. We also issue a call for nominations for specific acreage for inclusion in the sale area. Based on the land status review and input from industry, the sale area may be revised.

1_ to 2 years before a sale is held - a final call for comments is issued. It requests specific environmental and socioeconomic information as well as other regional concerns. It is again sent to local governments, state and federal agencies, the oil industry, environmental organizations , any affected coastal districts and the public. At this point, the state agencies are asked to provide necessary mitigation measures to alleviate or reduce potential adverse impacts. In addition, public information meetings are held with borough and/or municipal planning groups, other concerned organizations and citizen groups.

1 to 1_ years before a sale is held - we initiate a tract-specific land title research. At this point, a lease sale area may be revised based on environmental and socioeconomic information; comments received from local, state and federal agencies, organizations and the public;
available geological and geophysical information; and the results of the land title search. Preliminary tract maps are prepared, and the department publishes a preliminary best interest finding which establishes the scope of the review, sets out issues and facts regarding the proposed sale, and contains the proposed mitigation measures based upon the comments received. It also includes the bidding method, royalty rates, minimum bid, the term of the lease and any other terms considered appropriate.

In that document, we discuss the potential effects that could result from exploration, development, and production within the sale area, as well as problems that could be encountered when hydrocarbons are transported from the area. Included, too, is an analysis of the state's compliance with the Alaska Coastal Management Plan and any coastal district plan that might be involved. On the North Slope, that would be the North Slope Borough Coastal Management Plan.

9_ months before a sale - notice of the issuance of the BIF is sent to local governments, state and federal agencies, the oil industry, environmental organizations, affected Native organizations, local libraries and the public as well as any affected post offices. In addition, legal notices and display ads are placed in newspapers and service announcements are sent to local radio and television stations.

8 to 9 months before a sale is held - the department conducts public hearings in the affected communities during a 60-day public comment period. Comments received, along with the department's response, are included in the final finding.

Following the review, a decision is made whether the proposed sale is in the best interest of the state. Assuming that to be the case, additional stipulations and mitigation measures may be imposed as a precondition to leasing. Stipulations and mitigation measures may be requested by ADF&G, ADEC, one or more of the federal agencies, an affected coastal district or the general public. We are required by law to consider and respond to each comment received. Our goal is to reduce or eliminate reasonably foreseeable adverse effects.

5 months before a sale is held - based upon comments received after the preliminary best interest finding is issued, the department makes a final determination as to whether the sale will be held, the tracts that will be offered, and what measures will be required.

4_ months before a sale is held - a Notice of Intent to Issue is sent to local governments, state and federal agencies, the oil industry, environmental organizations, and the public as well as post offices in the affected area. Once again, legal notices are placed in newspapers and sent to local radio and television stations.

3_ month before a lease sale is held - a Final Best Interest Finding and Director's Decision is made available to the public. As before, notices are sent and final tract maps and legal descriptions are made available.

1 to 2 months before a lease sale is held - a final land status check is conducted and notifications are made if there are any adjustments to the tracts to be offered.

Day Zero - the lease sale is held on the scheduled date.

1 to 10-days after the sale - the apparent high bids are analyzed and the Commissioner decides whether or not to accept high bids. Winning bidders are notified.

Assuming a bid is accepted, the lessee is granted an exclusive right (subject to the provisions of the lease) to drill for, process and dispose of oil or gas from under the leased lands.

However, <u>each</u> subsequent activity on a lease is subject to a plan of operations, authorized by a Lease Operations Approval and each approval becomes a separate file for the life of the lease.

Lease operations approvals identify specific measures, design criteria and construction standards that will be employed to meet the provisions of the lease..

These approvals are subject to review by state and federal agencies as well as an Alaska Coastal Management Plan consistency review. They are also available for public review and comment. As you might expect, there is not always harmony, but we have a pretty good method to handle disputes. Internally, we have what is called an elevation process.

Assume, for example, that two agencies cannot agree on a method or perhaps the wording on a proposed stipulation. The first attempt for a solution is handled at the director level. If that doesn't work, the problem is "elevated" to the three resource commissioners. That is, DNR, ADEC and

ADF&G. If the commissioners cannot agree, the final step is an appeal to the governor - but that seldom happens.

Externally, we have the Coastal Policy Council. They are a nine-person body appointed by the governor (resulting from the ACMP) who have certain policy and decision-making powers affecting activities in the coastal districts. In the event of what is perceived to be an improper decision, an affected coastal district, a state agency or the citizen of an affected coastal district - or the project applicant may file a petition for review by the Coastal Policy Council. The CPC has the power to prescribe a new review by remanding the problem back to the planning process. I have never seen that happen.

In some cases, a proposed activity requires completion of a federal environmental impact statement before approval is granted. Only when proposed operations comply with state and federal laws, and the provisions of the lease, is approval given. Agencies, members of the public, and industry are encouraged to comment on any part of process.

In conclusion, you can see that we have an expensive and complicated leasing, permitting and compliance process that works well most of the time. As more knowledge is gained it will work even better. The most important thing, we think, is the involvement of the various state and federal agencies, the various coastal districts and the public. We encourage their participation and that is the reason the whole system works as well as it does.

A Review of Oil and Gas Activity in State Nearshore Areas

1. Map of Northern Alaska from the Chukchi Sea to Canada

National Petroleum Reserve (NPRA)

Arctic National Wildlife Refuge (ANWR), currently closed to petroleum exploration and development

State owns the submerged lands extending out to 3 miles from the coastline, the federal gov controls area beyond the 3-mile limit (federal OCS)

Central region -- the major North Slope oil fields -- entirely state owned
Prudhoe Bay--12 BBO (recoverable), 23 TCF, discovered in 1968

Extensive exploration since--resulted in a number of additional large and small deposits, commercial and noncommercial in this region

Peak North Slope production in 1988 was 2 million bopd; avg. for 1995 --estimated just under1.6 million bopd

Offshore OCS exploration has not been as successful

Most notorious failure was the Mukluk prospect, drilled and abandoned in 1984 at a cost of nearly $2 billion.

More recent exploration failures include the dry holes in the Chukchi Sea and Beaufort seas

Two discoveries -- Hammerhead & Kuvlum

ARCO originally claimed Kuvlum could hold 1BBO; presently it's deemed uneconomic to develop.

Currently, there is no production from the Alaska OCS submerged lands.

2. Central North Slope Area Oil Fields

Shows major producing North Slope oil fields

A number of these accumulations are located right on the shoreline, providing technological challenges to their development.

The shoreline fields rely on gravel-fill, breached (or non-continuous) causeways and long-reach directional drilling technology to tap the reservoirs.

2a. Causeways must be breached:

to maintain the nearshore oceanographic circulation for preservation of water quality characteristics such as salinity, temperature and suspended solids.

to provide for the free passage of marine and anadromous fish

Causeways are not permitted in the mouths of rivers or deltas.

2. Examples of current developed fields using onshore drilling pads and extended reach drilling to tap offshore reserves are Milne Point and Niakuk.

Future similar developments may occur at Badami and Point Thomson to the east of the Endicott field and at recent discoveries at Kalubik in the Colville River area.

Milne Point Field

Milne Point field discovered in 1969 -- lies just north of the Kuparuk field, originally estimated to contain 60 MMBO

Initial production began in November, 1985 and the field was shut in from January of 1987 until April of 1989.
BP has begun a major development project; BP's goal is to raise the daily production from 20,000 bopd to about 50,000 bopd by 1997.

A substantial portion of the new production will come from reserves at NW Milne lying 2 to 3 miles offshore, utilizing extended reach wells

This additional accumulation is estimated to contain about 80 MMBO

3. Niakuk Field

Discovered in 1985; entirely offshore in about five feet of water.

Total recoverable oil is estimated to be 58 million barrels.

Total production for 1995 is estimated at 3.4 million barrels of oil and 2.5 billion cubic feet of gas.

The field was put on line in April of 1994 producing about 15,000 bopd. All production is through directionally drilled wells from Heald Point.

4. Niakuk Drillsite Cross Section

Heald Point's original elevation was about 15 feet above sea level.

The gravel pad for the drillsite extends five feet above the existing tundra. For protection from erosion, the side slopes, which extend into the adjacent waters, have a grade of 7:1. This gives a freeboard of about 20 feet which is sufficient for protection against storm surge waves & ice.

4a Before

4b After

5. Pt. McIntyre field (just north of PB)

Uses both shore based drilling and a causeway connected to an offshore drilling pad,

Discovered in 1988

Production began in October, 1993 with initial rates of about 75,000 bopd eventually increasing to 100,000 bopd.

Production in 1994 was about 35 million barrels of oil and 4.9 billion cubic feet of gas.

Total recoverable oil is estimated to be about 340 million barrels.

Two production gravel pads, PM1 and PM2.

PM1 is located on the existing Pt. McIntyre exploration pad onshore

PM2 is located on the West Dock Causeway; built for 60 total well slots. Currently 24 producing oil wells have been drilled.

6a Endicott Field

Endicott located offshore and just east of Prudhoe Bay.

The field was discovered in 1978 and was the first offshore arctic production of oil and gas in Alaska.

Developed by constructing two offshore gravel islands (with about 6.8 million cubic yards of gravel),

Drilling was started in April of 1986 with one rig on each island and the field commenced production in Oct 87

Initial rate for the field was approximately 40,000 bopd

Production was increased to a maximum of about 115,000 bopd in 1992.

Current projected production for 1995 is 94,000 bopd

As of February, 1995 -- total of 95 development wells have been drilled with 92 of them still producing.

6b. Wintertime

1. Map of Northern Alaska from the Chukchi Sea to Canada

To move further offshore into deeper water to develop discoveries like Northstar (Seal Island), Hammerhead and Kuvlum,

independent offshore facilities will most likely have to be developed

buried pipelines to shore facilities or tankers will be necessary to bring the crude oil to market.

7. Central North Slope Area Oil Fields (BADAMI)

Badami accumulation located primarily offshore beneath shallow waters in Mikkelsen Bay.

1990 discovery

Discovery well produced oil at a sustained rate of 4,250 bopd and 2.6 MMcfpd of gas

Estimated reserves -- up to 100 million barrels.

Development plans include:

> **A gravel-fill dock about 2,400 feet long to be constructed from the shoreline into about 10 feet of water in Mikkelsen Bay**
>
> **Onshore production well pad and onshore development facilities.**

A buried 28-mile long 20-inch chilled-oil pipeline from the producing facilities to a tie-in with the existing Endicott line onshore.

The buried, chilled-oil pipeline, including river crossings, is estimated to cost about $60 million.

Early estimates indicate an elevated line would cost nearly twice that amount.

The Badami line would represent the first chilled-oil production pipeline on the North Slope.

Buried pipelines are the standard in regions of the country with unfrozen soils. In the arctic, however, any buried line must be insulated to provide for the integrity of the frozen soils.

The crude will be chilled to a temperature of about 30° F using an oil chiller module at the Badami Main Production Facility.

The waxy fraction of the oil becomes suspended in a granular form within the crude stream, and has a very simlliar density to the parent oil -- this will reduce solid wax deposition within the pipeline.

The oil will be reheated to temperature of about 120° F at the Endicott Pipeline tie-in by two 16 million Btu/hr crude heaters.

8. Pipeline X-Section

The pipeline will be buried in permafrost soils about three feet deep in select, screened backfill material, covered with native backfill and bermed over with additional backfill material.

The pipeline trenching operation will be conducted on top of an ice road averaging about 4" in thickness.

After One Thaw Season

After Restoration

If Badami is developed and if this proposed chilled pipeline is built, it will provide valuable information on the application of this technology to buried subsea pipelines in the Beaufort Sea.

9. Northstar Unit (Seal Island)

The Northstar/Seal Island accumulation, discovered in 1984, is located about 4 miles offshore of Gwydyr Bay.

Original discovery made from an artificial gravel island built in 1982 in 39 feet of water -- the island rose 22 feet above the surface.

A second island (Northstar) built in 1985 in 45 feet of water. Each island had about 400 feet surface diameter and over 800 feet at the sea floor.

Wells tested oil with some test rates exceeding 5,000 bopd.

Estimated to contain about 180 MMBO

BP will be evaluating development plans for this accumulation

One option may be to take a very close look at the Badami chilled oil, buried line.

Pipeline would have to be laid deep enough to avoid ice gouging

10. CIDS (Concrete Islnd Drilling System)

I would now like to take a couple of minutes to address how the state government regulates these activities.

11. Flow Chart

Governor heads the Executive Branch of Alaska's state government.

Several commissioners report directly to him.

Concerned only with the 3 resource agencies

Each Department is made up of divisions which are, in turn, headed by directors. I am in the Division of Oil and Gas, the division with the responsibility for oil and gas lease sales and lease management activities.

The director reports to Commissioner and he, in turn, reports to the governor.

AOGCC

OIL SPILLS & WHALES

PLAN OF OPERATIONS -- agency review / public comment

To protect the arctic environment and the way of life of our arctic residents, extraordinary steps are taken to ensure that O&G activities do not interfere with the subsistence way of life or unnecessarily create damage

In the Beaufort Sea, when bowhead whale are migrating through an exploration area, we apply and enforce seasonal drilling restrictions.

All non-essential activities are suspended and those that continue must be coordinated with local whaling groups.

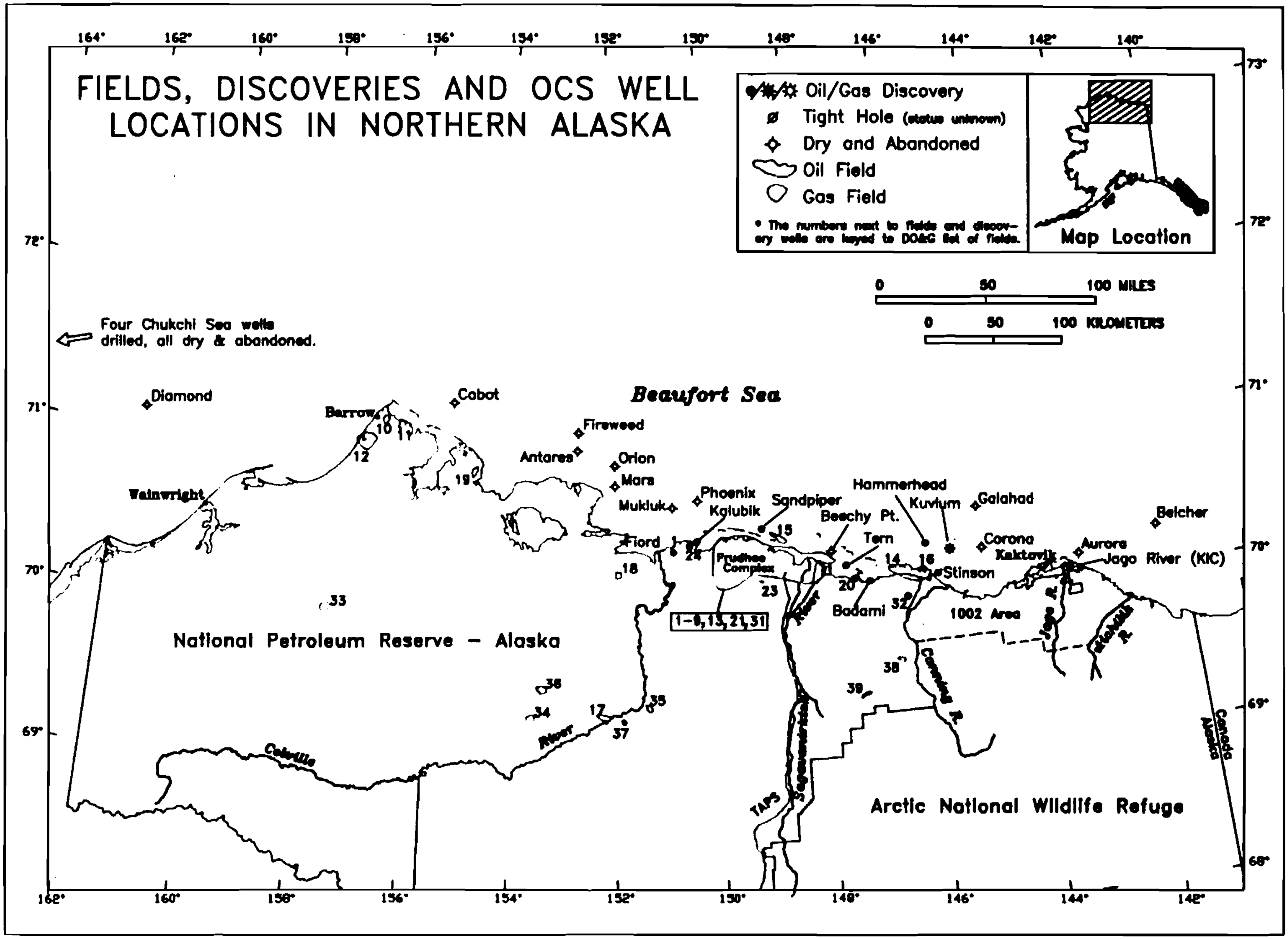
One company has estimated that a "warm stand-by" status as the whales pass adds $660,000 per day to the cost of operations.

We are especially concerned with drilling in broken ice or within a spring lead system.-- difficulty in containing an oil spill

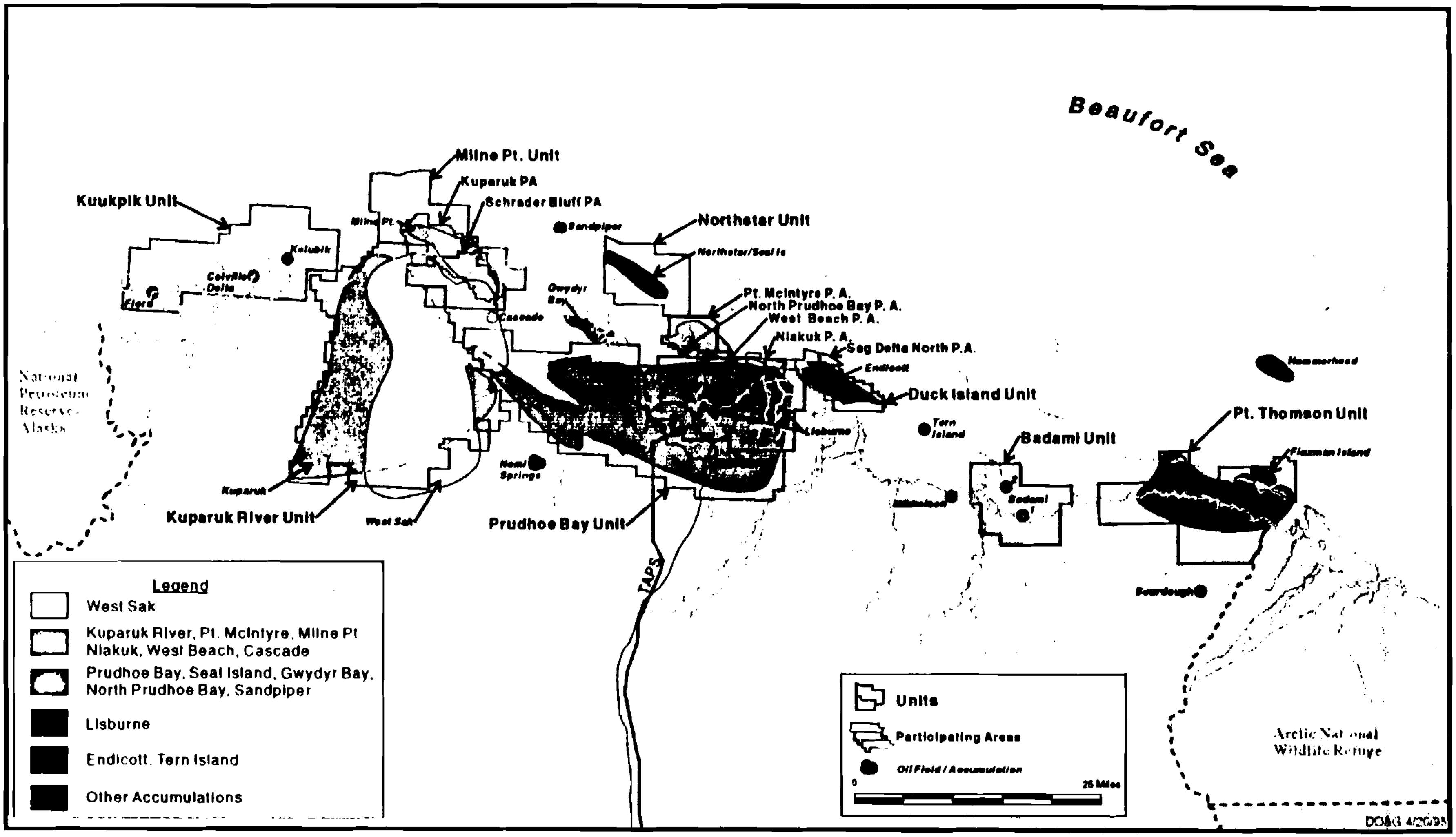
Spill preparedness plans require planning standards for all exploration facilities. The objective is to be able to contain or control and clean-up a realistic maximum discharge within 72 hours. For an exploration or production well, this is 16,500 barrels.

Lessees must submit a detailed plan of operations to the division for written approval before initiating any exploration or development activity,

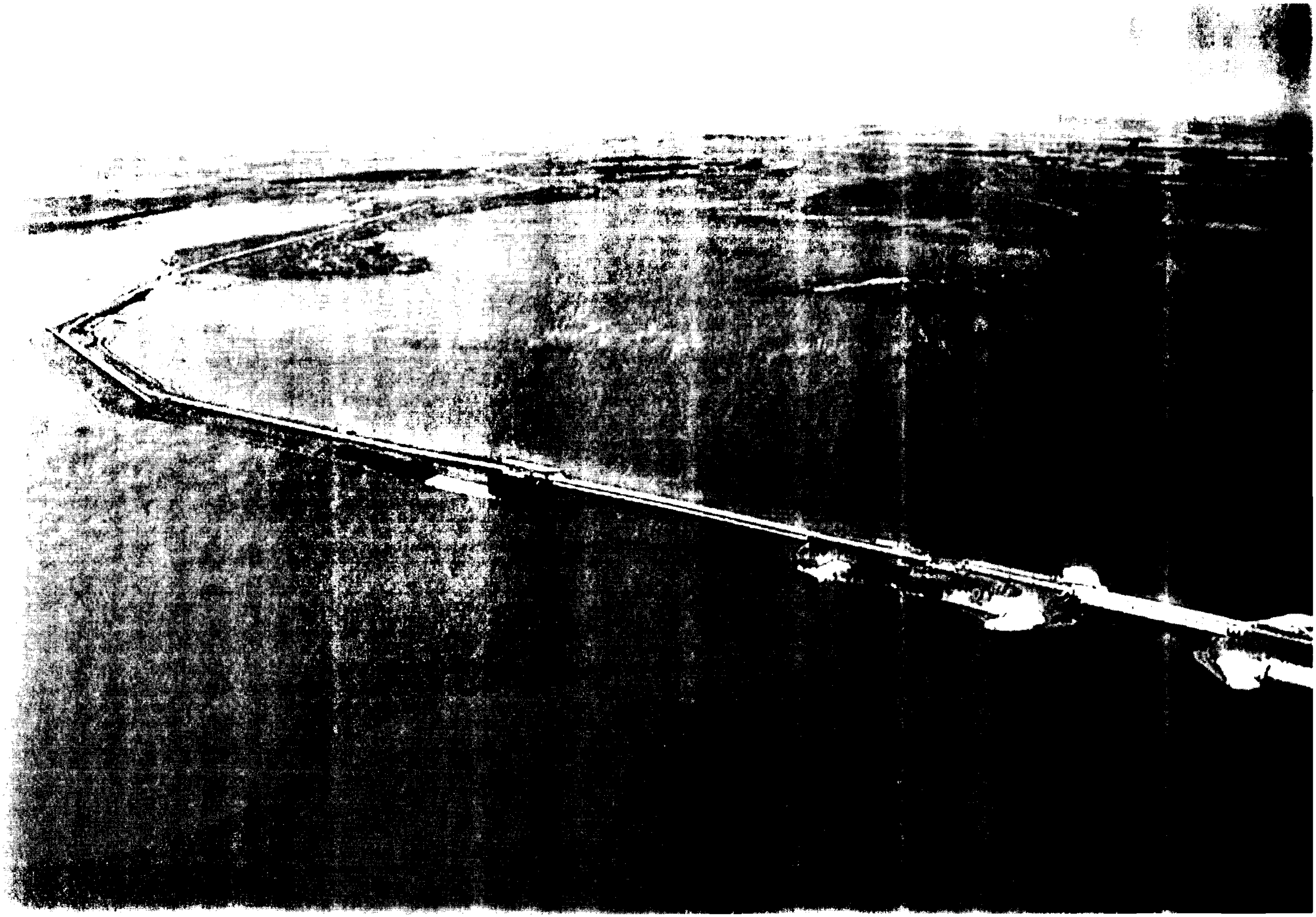
Plans are reviewed by the Resource agencies, and sent out for public comment



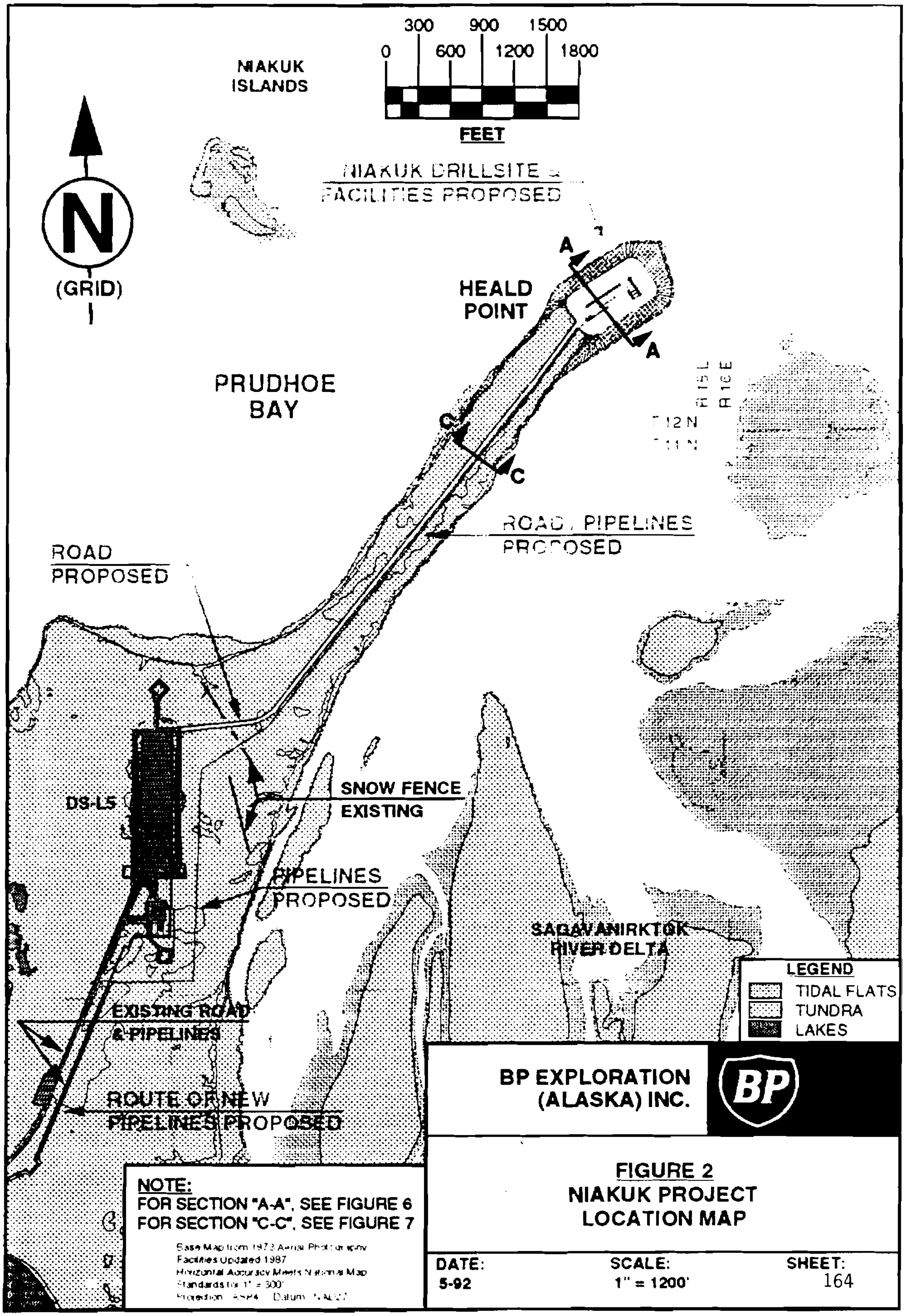
1. Map of Northern Alaska from the Chukchi Sea to Canada



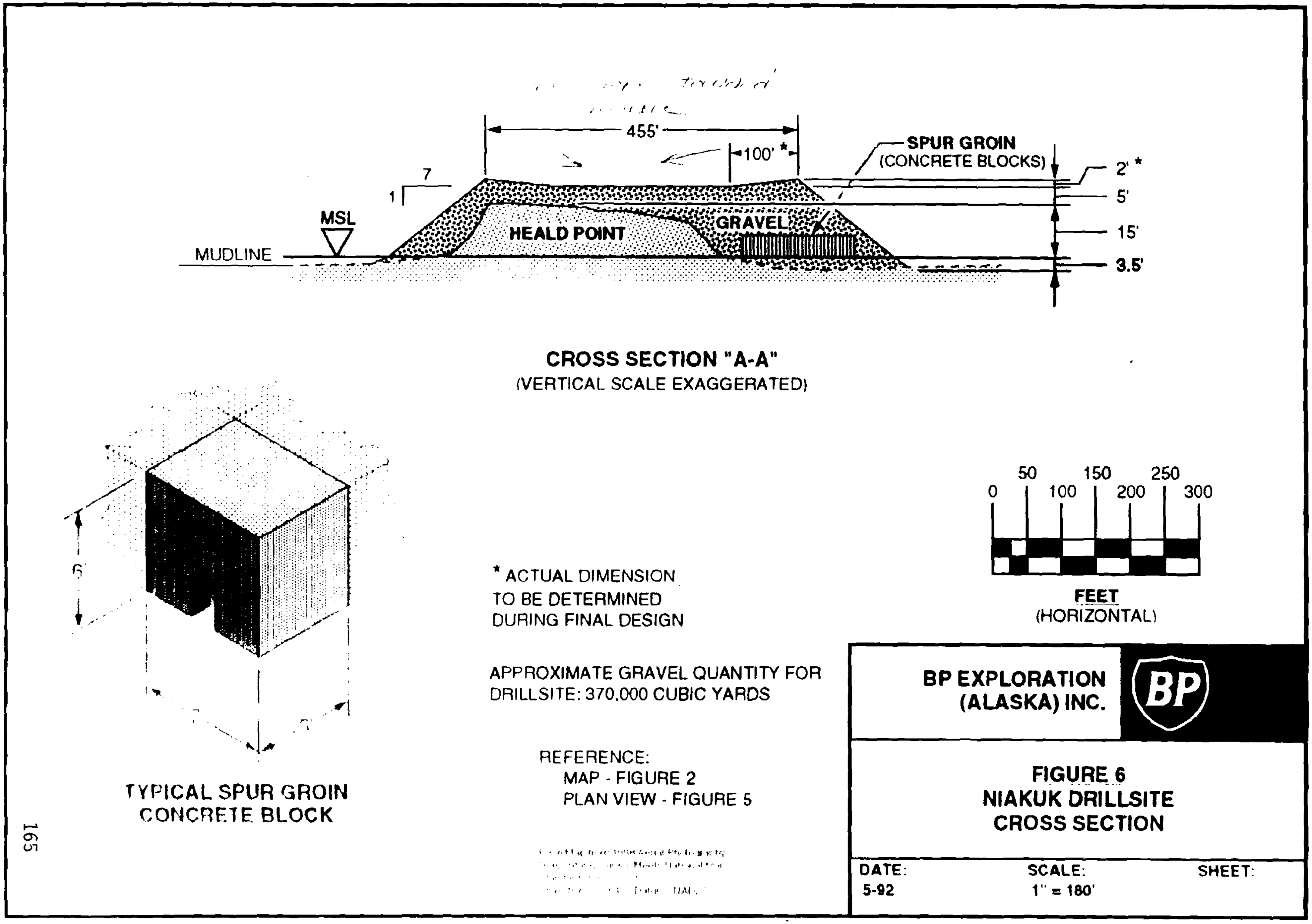
2. Central North Slope Area Oil Fields



2a. Endicott Causeway

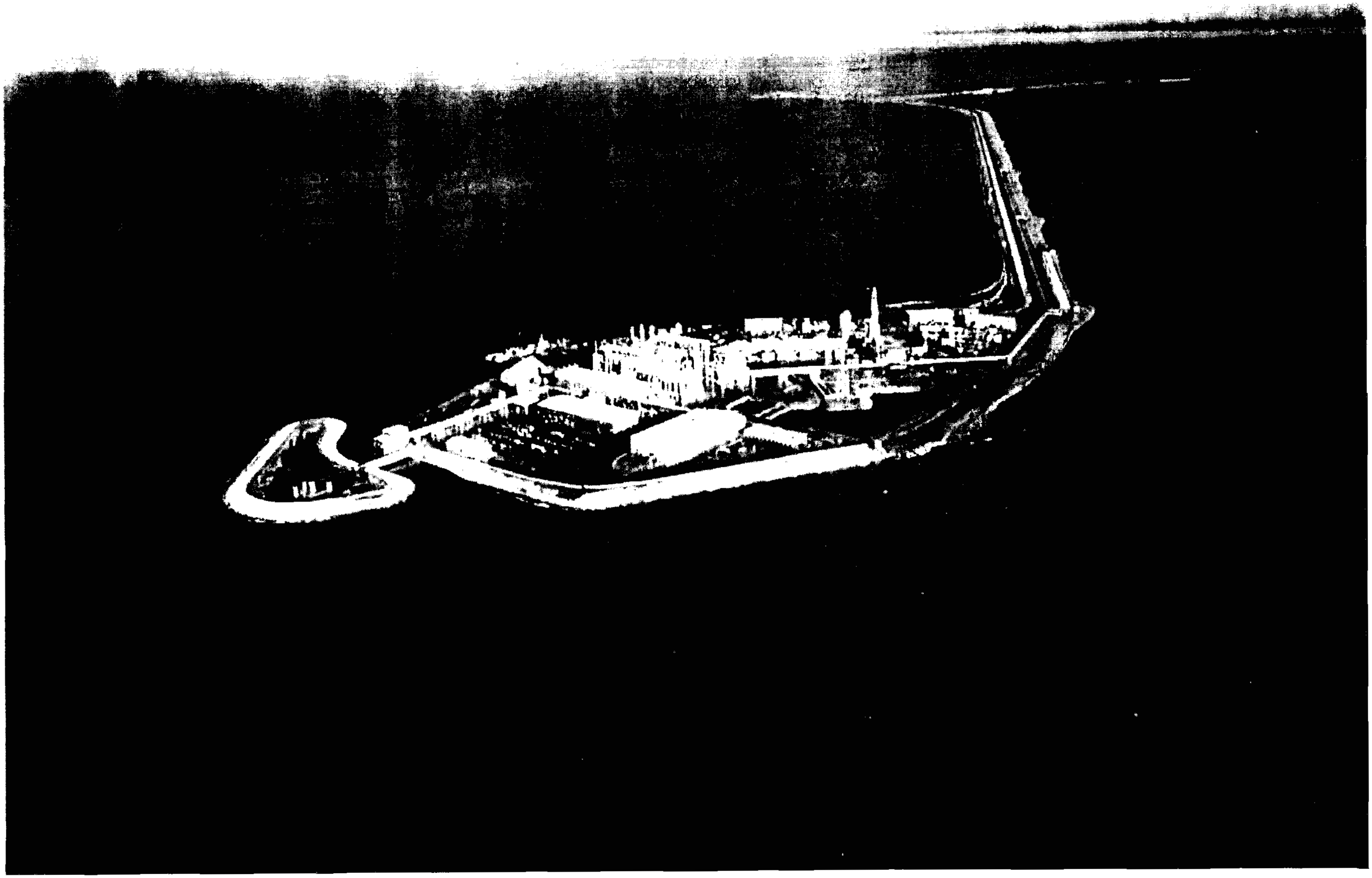


3. Niakuk Field



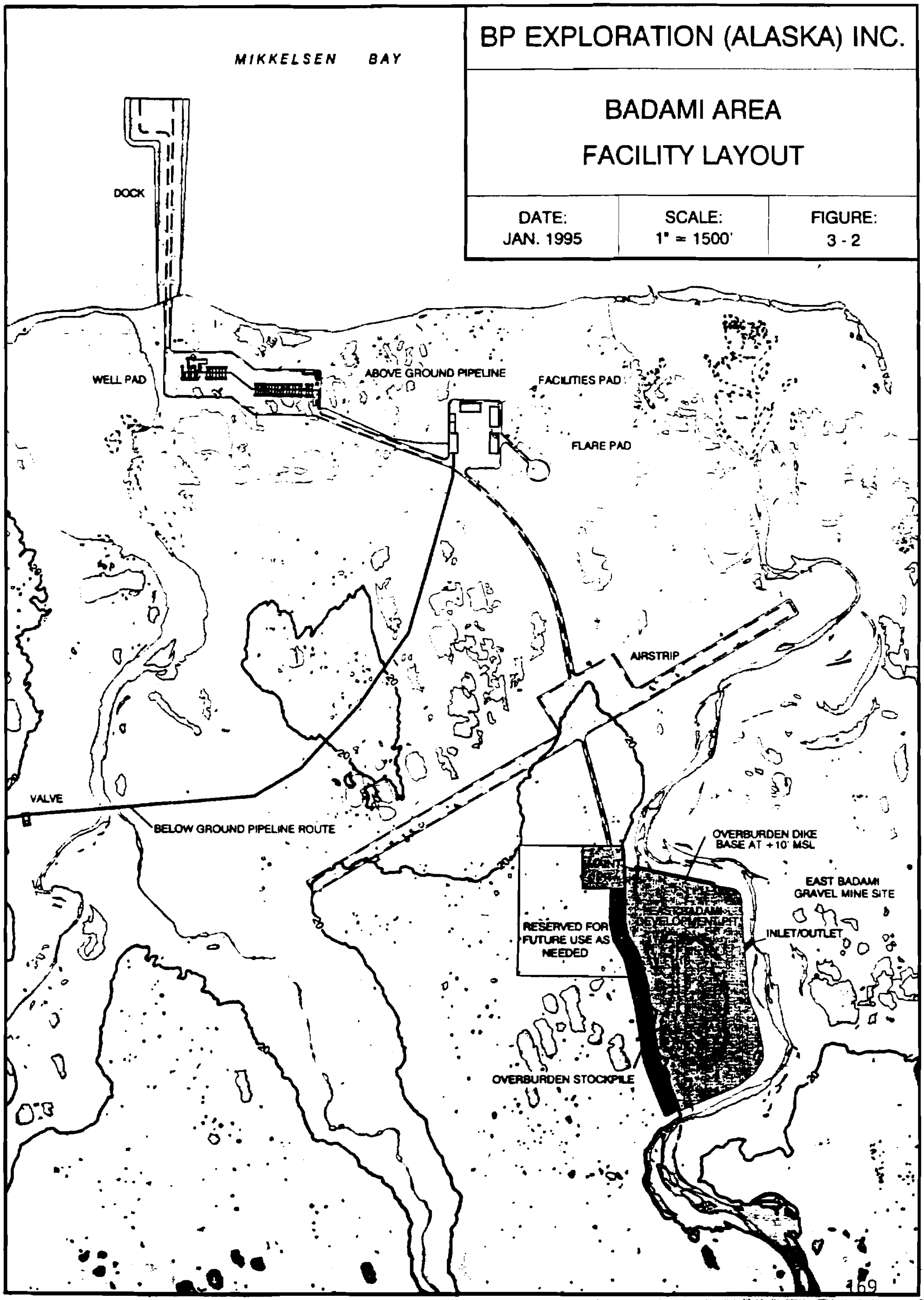
4. Niakuk Drillsite Cross Section

5. Pt. McIntyre Field (just north of PB)

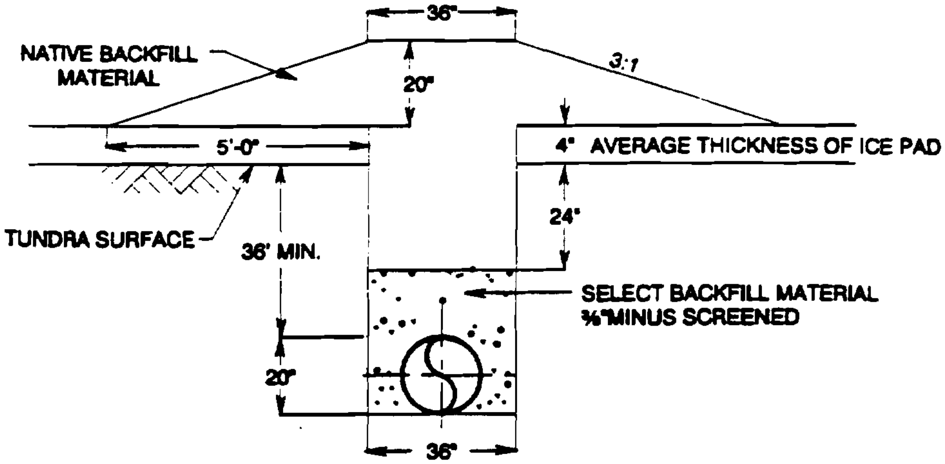


6a. Endicott Production Facility

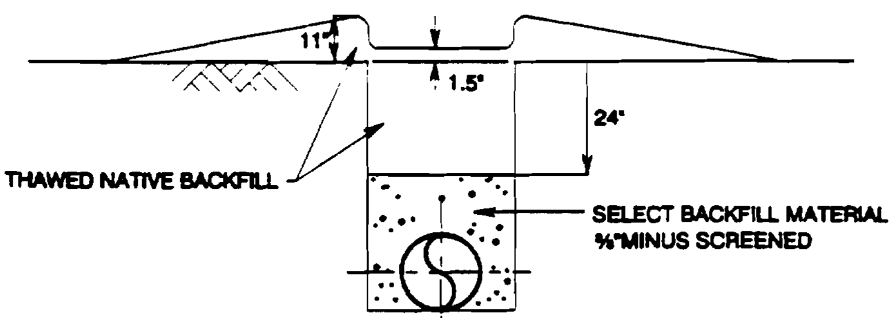
6b. Endicott in Wintertime


BP EXPLORATION (ALASKA) INC.
BADAMI AREA
FACILITY LAYOUT
DATE:
JAN. 1995
SCALE:
1" = 1500'
FIGURE:
3 - 2
MIKKELSEN BAY
DOCK
WELL PAD
ABOVE GROUND PIPELINE
FACILITIES PAD
FLARE PAD
AIRSTRIP
VALVE
BELOW GROUND PIPELINE ROUTE
OVERBURDEN DIKE
BASE AT +10' MSL
EAST BADAMI
GRAVEL MINE SITE
RESERVED FOR
FUTURE USE AS
NEEDED
INLET/OUTLET
OVERBURDEN STOCKPILE

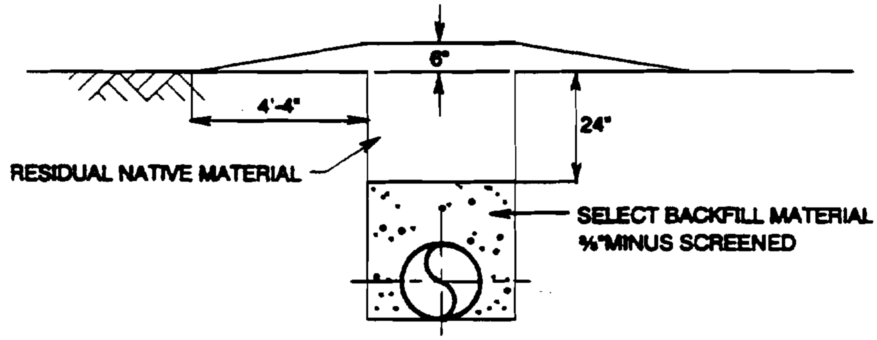
DITCH CONFIGURATION-25% (BY VOLUME) ICE CONTENT IN EXCAVATED MATERIAL



APPROXIMATE SHAPE AND CONTENT AFTER BACKFILLING



APPROXIMATE SHAPE OF DITCHLINE AFTER ONE THAW SEASON ASSUMING
NO LOSS OF RESIDUAL MATERIAL



APPROXIMATE SHAPE OF DITCHLINE AFTER THAW & RESTORATION
ASSUMING 30% LOSS OF RESIDUAL MATERIAL

ASSUMPTIONS

1.) 30% BULKING IN EXCAVATED MATERIAL THAT WILL REMAIN AFTER BACKFILLING
2.) 90% OF BULKING WILL DISAPPEAR AFTER FIRST YEAR THAW
3.) 90% OF THAW SETTLEMENT WILL OCCUR AFTER FIRST THAW SEASON
4.) AVERAGE THICKNESS OF ICE PAD - 4"
5.) AVERAGE LOSS OF RESIDUAL MATERIAL AFTER MATERIAL AFTER THAW-30%
NOTE-THIS WILL BE DUE MAINLY TO MIXING WITH THE SURFACE VEGETATION NEAR THE DITCH

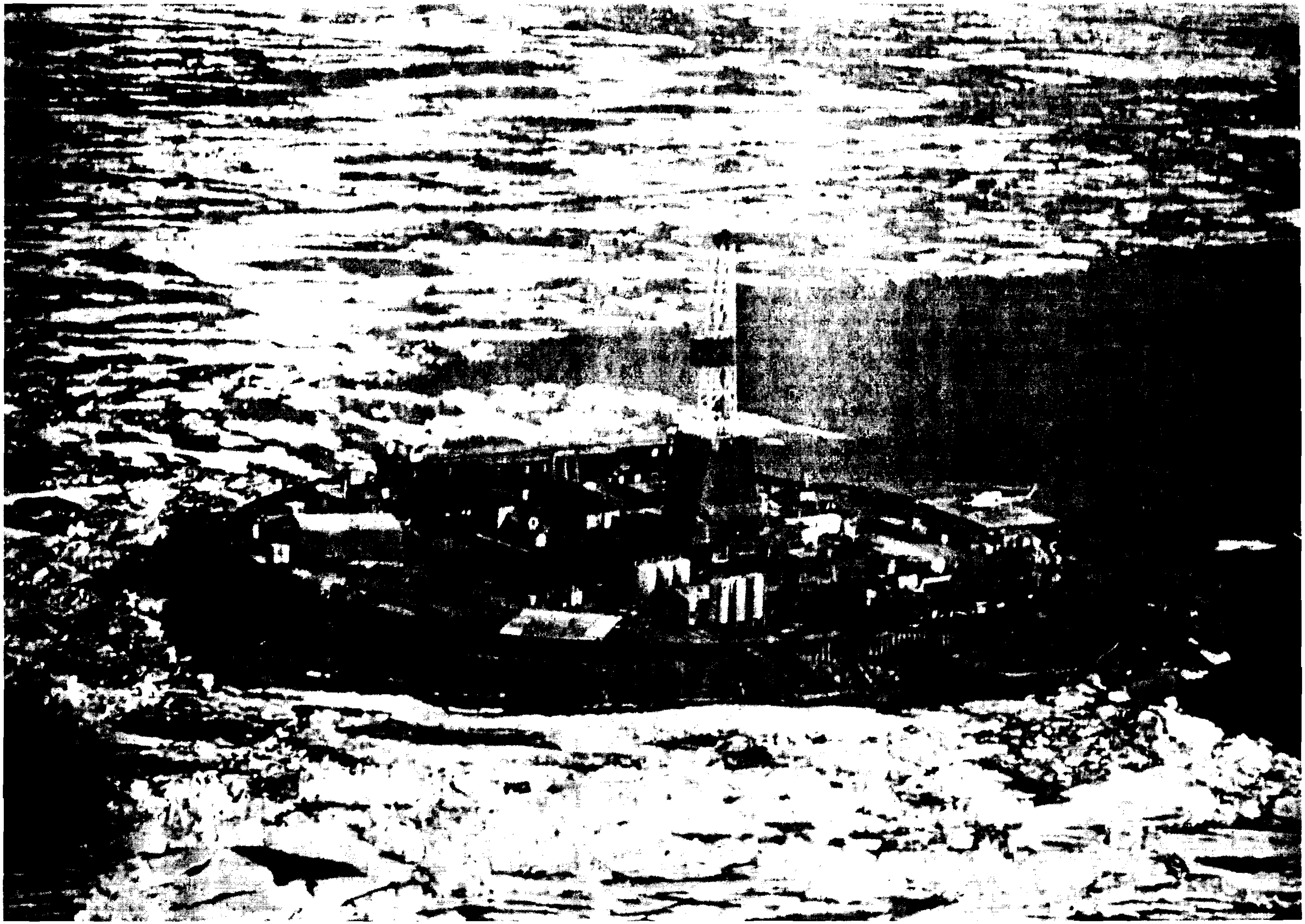
BP EXPLORATION (ALASKA) INC.

BADAMI PIPELINE DITCH
CROSS SECTION BEFORE AND AFTER
THAW AND BULK SETTLEMENT
(25% ICE CONTENT)

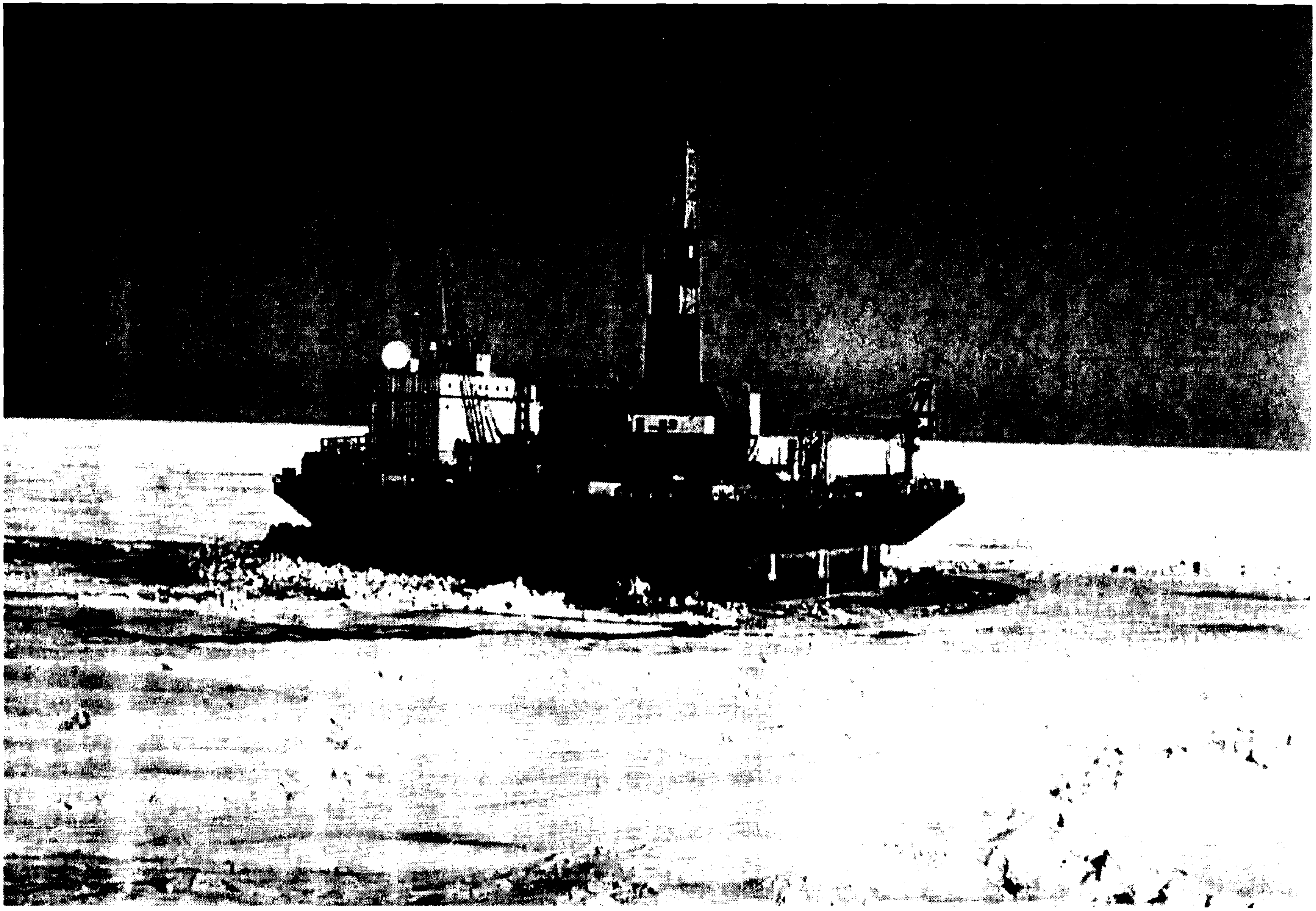
DATE:	SCALE:	SHEET:
JAN. 1995	NOT TO SCALE	3 - 11

8. Pipeline X-Section

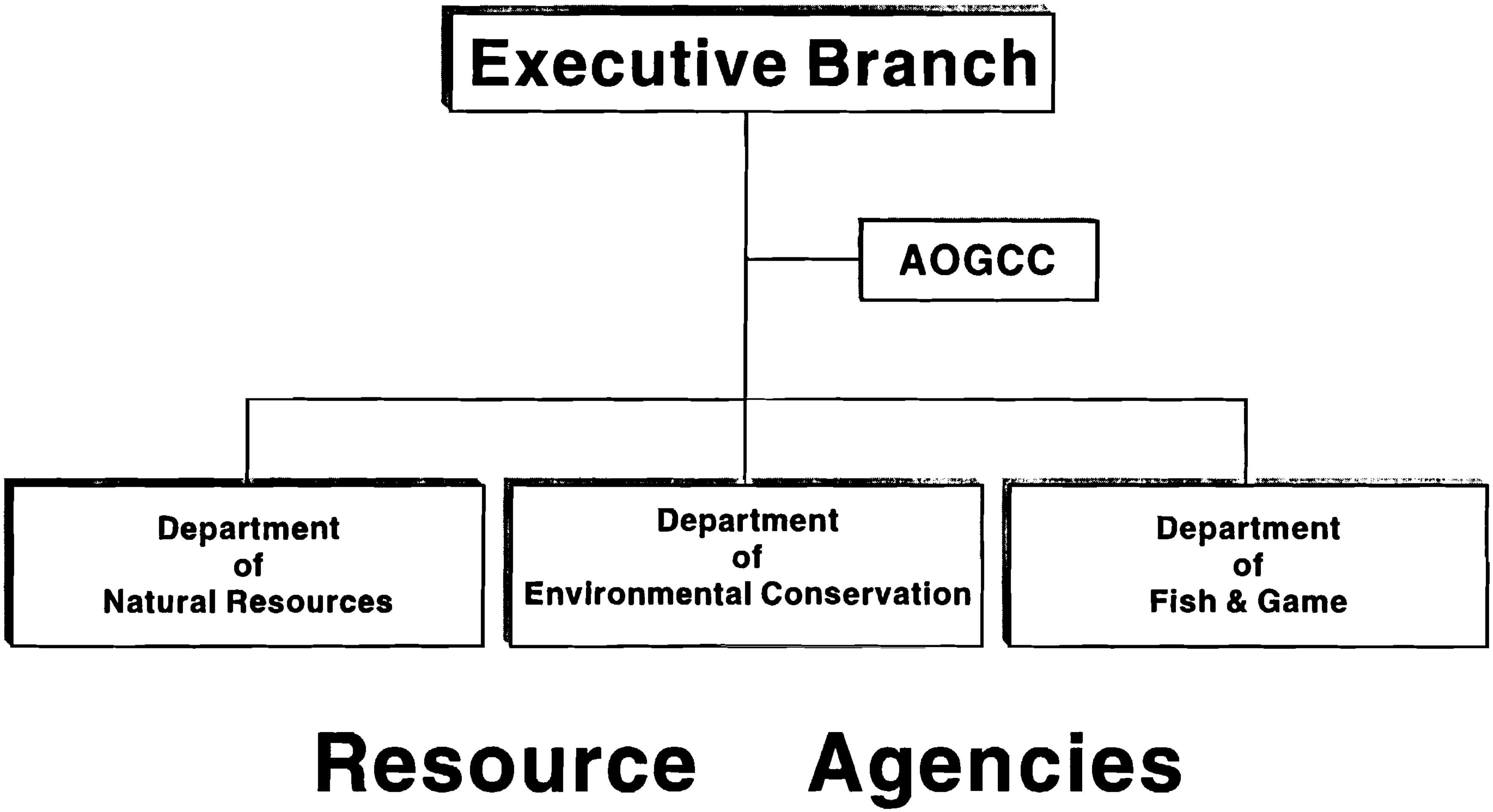
ex12477.dgn



9. Seal Island - Manmade

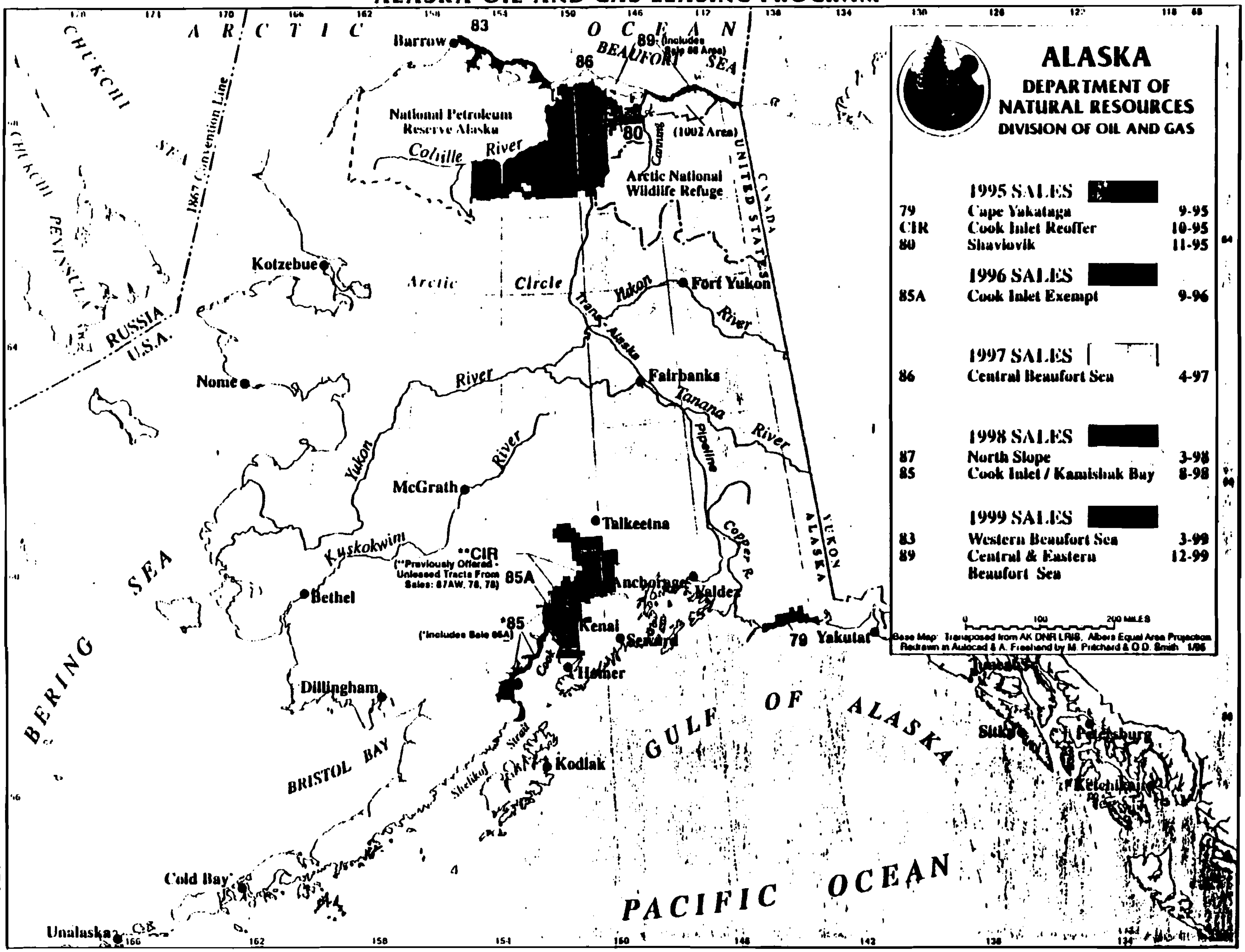


10. Concrete Island Drilling System - CIDS



11. Flow Chart

ALASKA OIL AND GAS LEASING PROGRAM



2.3 SIMI Papers not Included in Volume 1

This section contains four papers by SIMI researchers that were not included in Volume I of the Proceedings:

"Ice Surface Oscillation Measurements on SIMI using Strain, Heave and Tilt Sensors," Peter Wadhams and Stephen C. S. Wells, Scott Polar Research Institute, Cambridge, UK.

"AUV Operations in the Arctic," J. G. Bellingham, J. J. Leonard, J. Vaganay, C. A. Goudey, D. K. Atwood, T. R. Consi, J. W. Bales, H. Schmidt and C. Chryssostomidis, Mass. Inst. of Tech.

"Multipath Navigation in the Arctic: A Feasibility Test," Max Deffenbaugh, Henrik Schmidt and James G. Bellingham, Mass. Inst. of Tech.

"Performance Assessment of the High Resolution GPS Ranging System," Max Deffenbaugh, Henrik Schmidt and James G. Bellingham, Mass. Inst. of Tech.

Ice Surface Oscillation Measurements on SIMI Using Strain, Heave and Tilt Sensors

Dr Peter Wadhams (PI), Stephen C.S. Wells, Sea Ice Group, Scott Polar Research Institute, Lensfield Road, Cambridge, CB2 1ER, UK.

Abstract

A sensor system measuring three directions of acceleration, two orthogonal directions of tilt and three surface strains was deployed during all phases of SIMI. Ice surface oscillations were observed at all times. The spectra usually have a dominant peak at about 16-30 s period, representing swell and infragravity waves penetrating from the open ocean, but at times of strong winds waves of 6-12 s period occurred due to local forcing of wind pressure over ice. In addition, occasional outbreaks of very short period (1-3 s) wave energy were observed, which appear to be associated with nearby pressure ridges. Some specific experiments were done during the spring experiment to examine the nature of these waves.

Introduction

Oscillations representing energy from a variety of sources can be observed whenever sufficiently sensitive instruments are deployed on sea ice. We have measured such oscillations and their directional spectra in many parts of the Arctic and Antarctic using arrays of strainmeters, tiltmeters and accelerometers. The purpose of deploying such arrays on SIMI was to examine whether any components of these oscillations can be associated with ridge building processes as independently detected by other kinds of sensor (e.g. stress gauges).

Using systems which measure three directions of horizontal acceleration, two orthogonal directions of tilt and three surface strains in a 120° rosette we performed a long series of long-term (days or weeks duration) and short-term (hours) measurements during all three phases of SIMI: the installation phase (Sept-Oct 1993), the early winter experiment (Nov-Dec 1993) and the spring experiment (April 1994). Instruments were also left to record continuously between the installation phase and the early winter experiment.

The initial deployment was at two edges of a multi-year floe, in close proximity to CRREL stress arrays, with four additional strainmeter arrays deployed in the interior of the floe. The floe edges bordered refrozen leads, one of which closed during the installation phase to create a pressure ridge. A series of 19 experiments was conducted during the installation phase, then the systems operated almost continuously for 7 subsequent weeks, monitoring six sites with 7 strainmeters and 4 heave-tilt systems.

During the spring camp, 24 short-term experiments were conducted over eight days at sites around the camp, using a pair of heave-tilt systems to examine the nature of short-period oscillations observed during earlier experiments. A single strainmeter was also deployed.

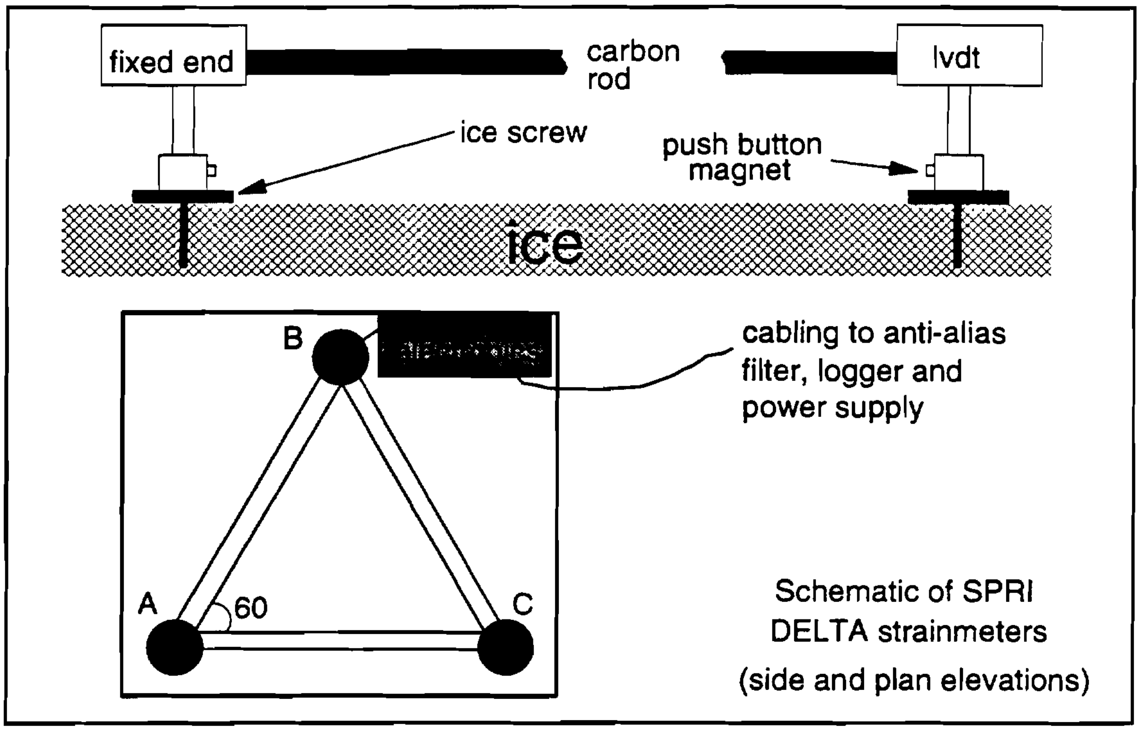


Figure 1 SPRI/BP Delta Strainmeter.

Experimental Method

Sensors Deployed Three types of sensor were deployed during the SIMI field program. Acceleration measurements were made using three orthogonally mounted Schaevitz accelerometers (±2g). Tilt measurements were made using orthogonally mounted Tilt Technology ELH-46 (±5 degree) and ELH-47 (±0.5 degree) sensors. The tilt sensors were mounted on a levelling platform. These two sets of sensors were housed in a single Zarges box. Strain measurements were made with BP Delta Strainmeters. See Figure 1. All signals from the sensors were fed through an amplifier box where gain and zeroing were set and then filtered through anti-alias filters, either built in house (for data transmission by VHF) or via two Alligator Technology Anti-Alias Filter cards mounted in a PC (for data transmission by landline). Deployment configurations are given in Figures 2 and 3.

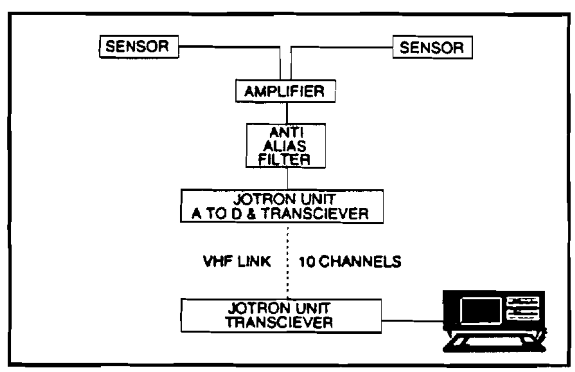


Figure 2 SPRITel schematic

Data logging and control was by the SPRITel program (written in house) for the VHF telemetry and by the SIGNAL CENTRE program (produced by the company of the same name) for the landline telemetry. These programs allowed the monitoring of 10 and 32 data channels respectively. Data were stored in binary formats and further compressed using the L'Harc and PKZip utilities. Downloaded data were stored on 3.5" (1.44Mb) floppy disks and on 3.5" (21Mb) floptical disks. During phases 1 and 2 (the winter camp) signals logged using these systems were sampled at 3.0Hz and filtered with a cutoff at 1.5Hz. Details of the all the sampling frequencies used during the winter and spring camps can be found in Tables 1-3.

During the winter camp and the spring camp some data logging was also done at the sites using Squirrel loggers. In this case the sample rate was at 3.3Hz

Two of the heave and tilt sensor packages were constructed for the SIMI program, and two older systems overhauled. The SPRITel software was designed and written and additional specialist SIGNAL CENTRE software modules commissioned for the project.

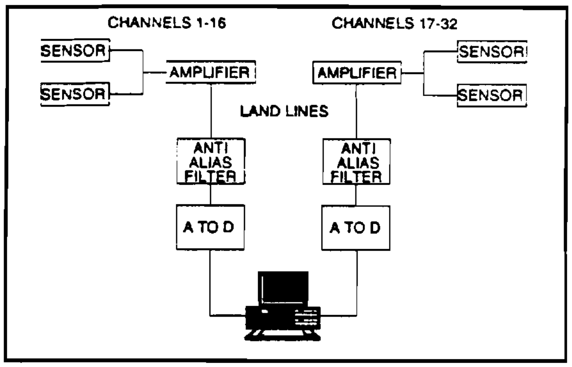


Figure 3 SIGNAL CENTRE schematic

Sensor Locations Sensor locations and layouts for the fall and winter experiments are shown in Figure 4. The hut in this figure is the "Wadhams/MIT hut" (location F3) on the standard map of SIMI West Camp. Sensors were not moved once deployed though the method of data communication did change for some sites from VHF to landline telemetry.

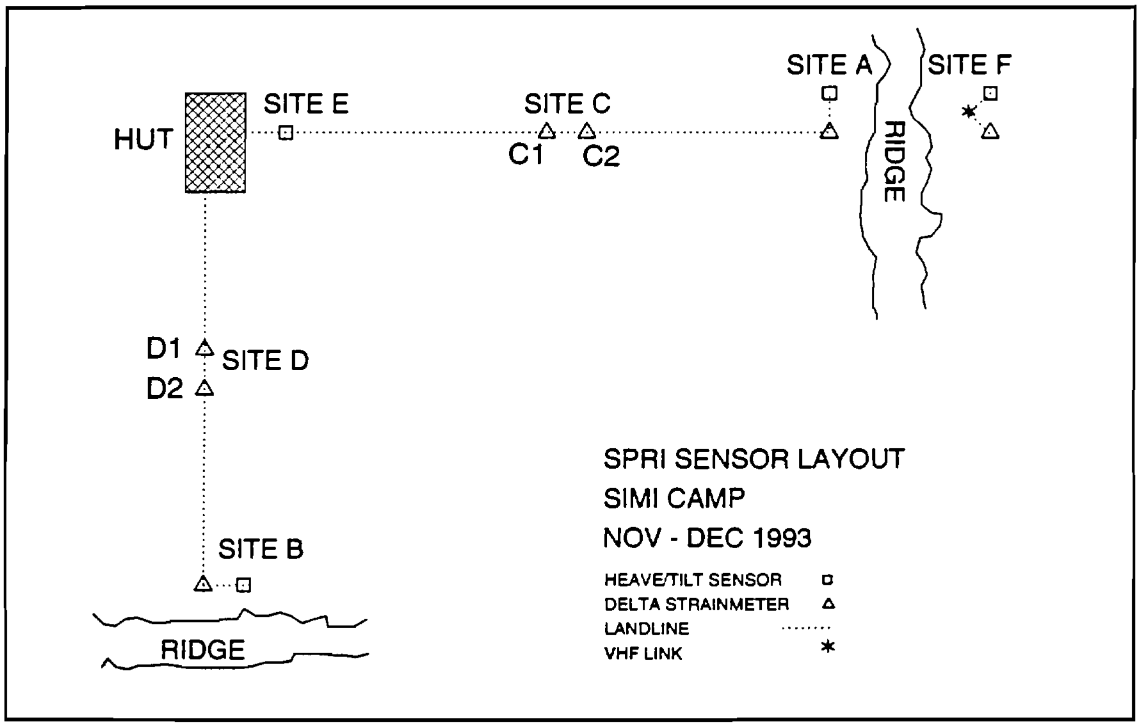


Figure 4 Sensor locations for Fall/Winter Camp. Telemetry configuration for phase 2.

During the spring camp the sensors were deployed around ridges close to the camp. A typical configuration for the sensors is given in Figure 5, though the actual layout varied for each experiment. The sensors were also deployed in support of the controlled load measurements of Pritchard and Coon (NWRA) and in an experiment with Farmer (IOS).

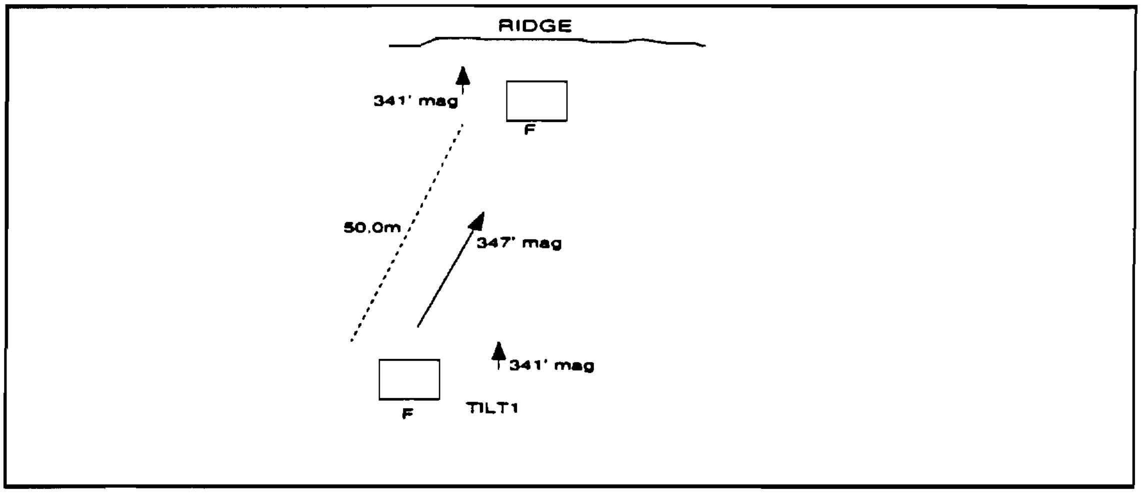


Figure 5 Typical experimental layout for two heave and tilt systems, Spring Camp.

Data Sets The data sets held are described in the tables on the following pages. The fall/winter experiments defined as phase 1 are in Table 1, phase 2 in Table 2 and the spring camp, phase 3, in Table 3.

Data Analysis Data analysis required the recovery of the data from the archived formats in which it was stored and the removal of spurious spikes and steps introduced by the re-zeroing of the instruments. The data were then corrected for any gain changes made during the experiment and the instrument and filter calibrations applied. Cross-correction of the data was also required, for example to remove errors introduced by tilt of the ice in both the accelerometers and the strainmeters.

Preliminary Results

The strain and flexure records typically show oscillations which have energy at a number of preferred frequency ranges. Three frequency ranges were dominant. Long period oscillations (16-30s) represent swell and infragravity waves penetrating from the open ocean, probably either the very distant Greenland Sea or (in late summer) the closer Chukchi Sea; attenuation within the ice due to creep induced by flexure wipes out all the more normal ocean wave periods. Shorter period waves of 6-12s period are generated locally within the ice by wind pressure when the wind speed exceeds the minimum group velocity for flexural-gravity waves. Finally, very short period waves (1-3s) were also observed sporadically, with no existing explanation for their mode of generation.

During the spring experiment specific tests were carried out to determine the origin and nature of these short period oscillations. Typically the set-up was as Figure 5, with simultaneous recording from a sensor package alongside a ridge and another 50m or 100m away. Unfortunately the spring experimental period was "quiet" in the sense that no ridge-building events occurred near the camp and no strong local winds were experienced. Inspection of spectra from the records shows that short period oscillations were less prevalent during these experiments. It is clear, then, that they tend to be associated with "active" periods when deformation is occurring within the pack.

Figure 6 shows a composite set of 19 spectra of tilt from experiment 93-13 conducted on 28 September 1993. Each spectrum was obtained from a 68-minute tilt record. Two features are apparent in the series of spectra:-

1. The main type of energy present is very long period swell-like infragravity wave energy with an energy density and a peak period (26.3 - 28.6 s) which remain remarkably steady through the whole 21-hour experimental duration.
2. On two occasions a burst of energy is seen at very short periods. The larger spike in the figure actually consists of two very narrow spectral peaks, with periods of 3.2 s (smaller peak) and 2.8 s (larger peak). The smaller spike which occurs 3 hours later has a single peak at 2.8 s.

Figure 7 shows a single spectrum from this series which includes the double spike of short period energy. Once again the narrow swell-like energy peak is evident, at 28.6 s, and it is also clear that on this calm day there was no energy present at wind-wave periods (6-12 s). The period of the swell-like peak is much longer than typical swell periods in the open sea and must represent infragravity waves which have penetrated great distances through the ice such that all shorter periods (initially containing more energy) will have been attenuated away by creep losses. The twin spikes of the very short waves are extremely narrow and represent short-lived bursts of energy at two distinct frequencies, one of which recurred after 3 hours but which did not then reappear during the remainder of the 21 hours.

Figure 8, by contrast, shows a composite set of tilt spectra from experiment 93-17, done on the following day (29 September) at the same site. Here there is no occurrence of short-period energy, while the long period wave energy varies greatly during the experiment, growing as the day progresses.

Figure 9, one of the individual spectra from this series, shows that the long-period swell peak lies at a much longer period than for experiment 93-13 (67 s), and the swell spectrum is somewhat wider. This implies that infragravity waves in ice vary both in energy and in peak period, which tends to refute two hypotheses which have been made about such waves, i.e.

1. That there is a uniform infragravity wave spectrum in the Arctic Ocean reflecting a similar uniform "background radiation" in the world ocean, which is difficult to detect in the open ocean because of the dominance of shorter period waves;
2. That the ice picks out a preferred resonant period at which this infragravity wave energy is concentrated, which is a function of area-averaged ice thickness (a suggestion by Russian investigators).

Figure 10 shows two pairs of spectra from attenuation experiments carried out during spring 1994. Each spectrum comes from a tiltmeter placed either alongside a ridge or 50 m from it, in the configuration shown in fig. 5. The experiments were done on 17 April (21A) and 18 April (25). The spectra are offset by a factor of 10^2. It can be seen that all the spectra are remarkably flat, with no definite energy peaks. Experiment 21A shows more long-period energy near the ridge than 50 m from it. Experiment 25 shows overlapping spectra, but with some evidence of additional energy at very short period in the 50 m spectrum, with a wide peak centred at 1.45 s period which only shows about twice as high as the surrounding spectral levels.

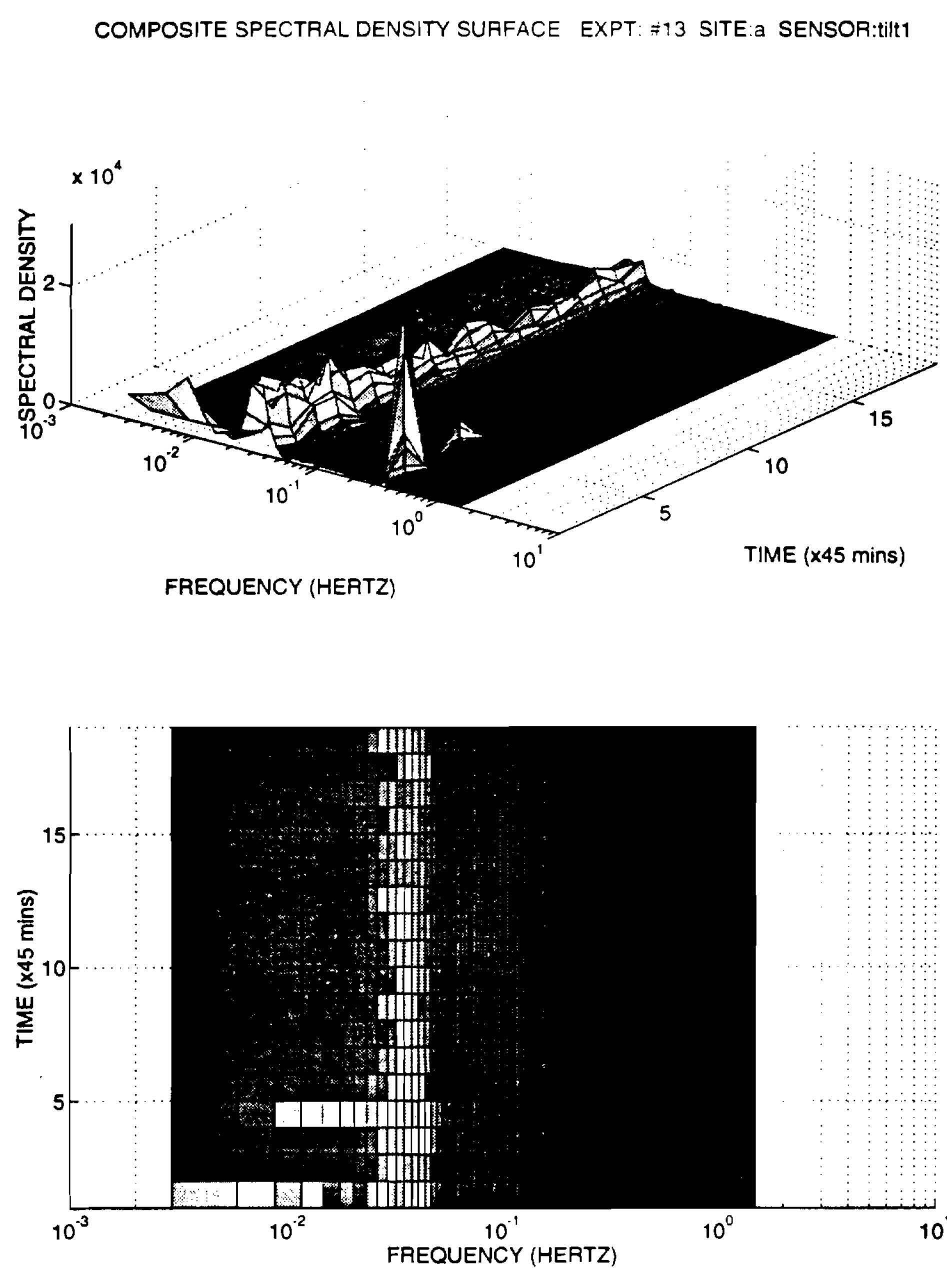


Figure 6 Experiment 93-13. Tilt Sensor, Site A.

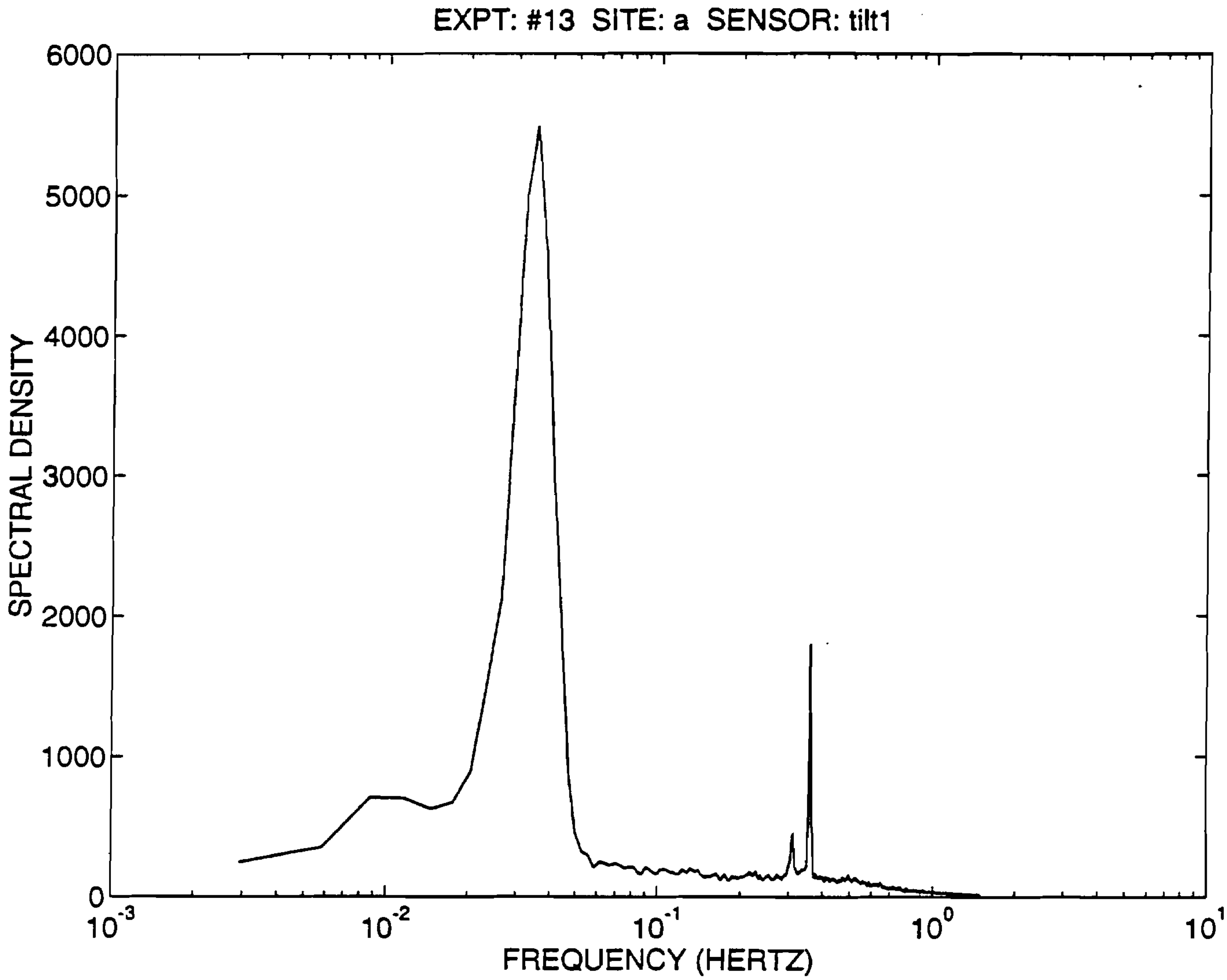


Figure 7 Experiment 13 tilt sensor energy spectrum showing short period waves.

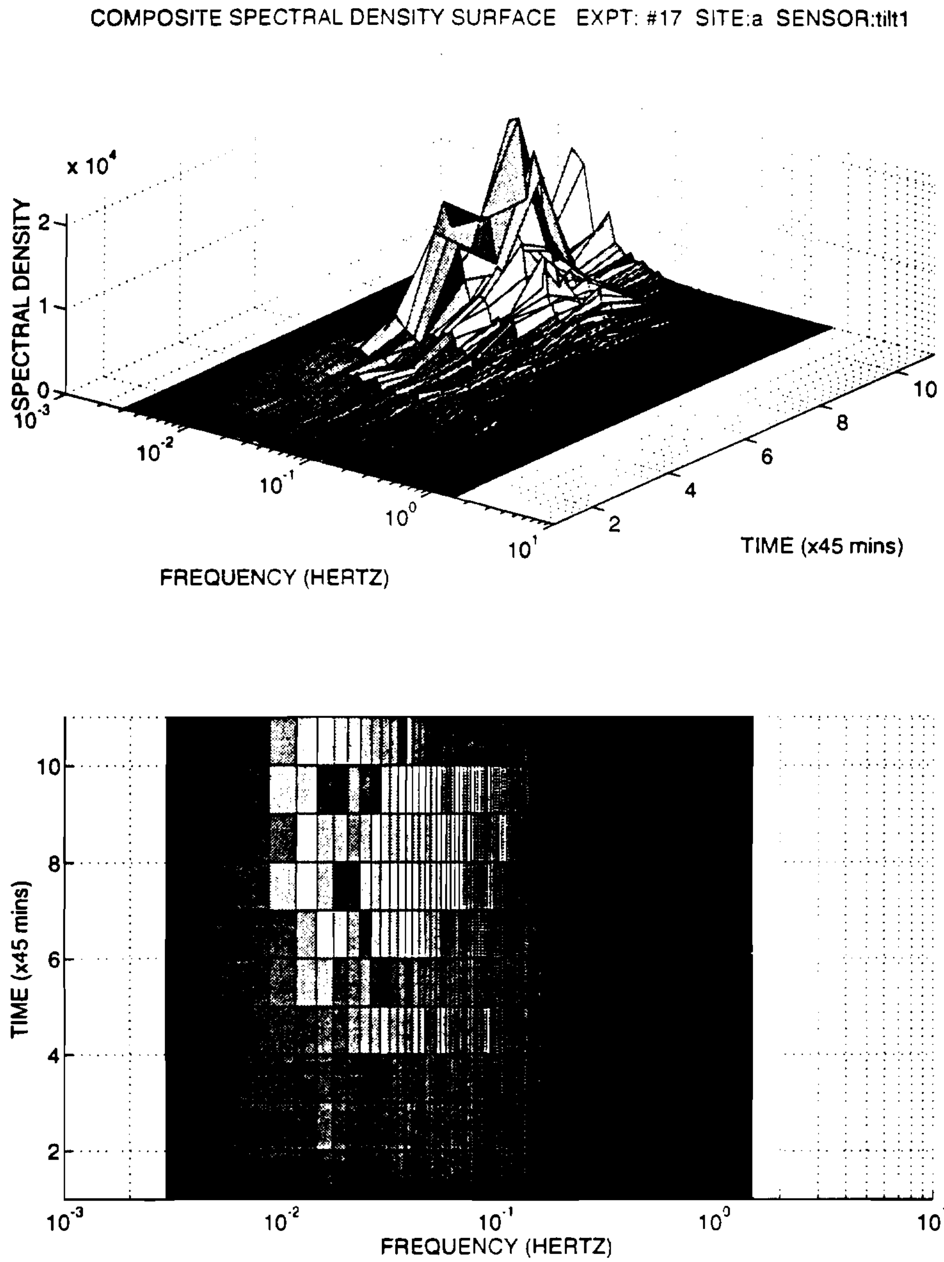


Figure 8 Experiment 93-17. Tilt sensor, site A.

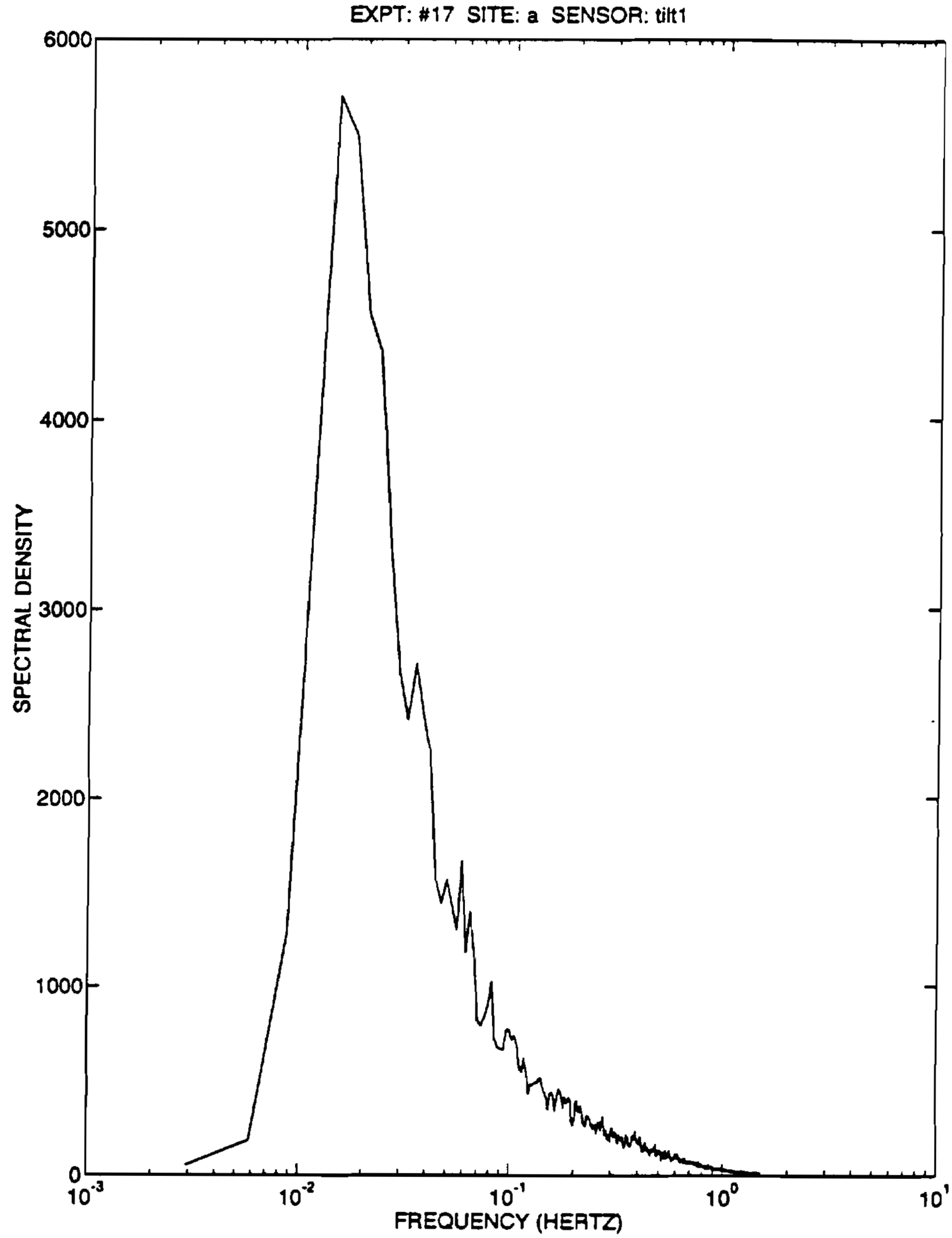
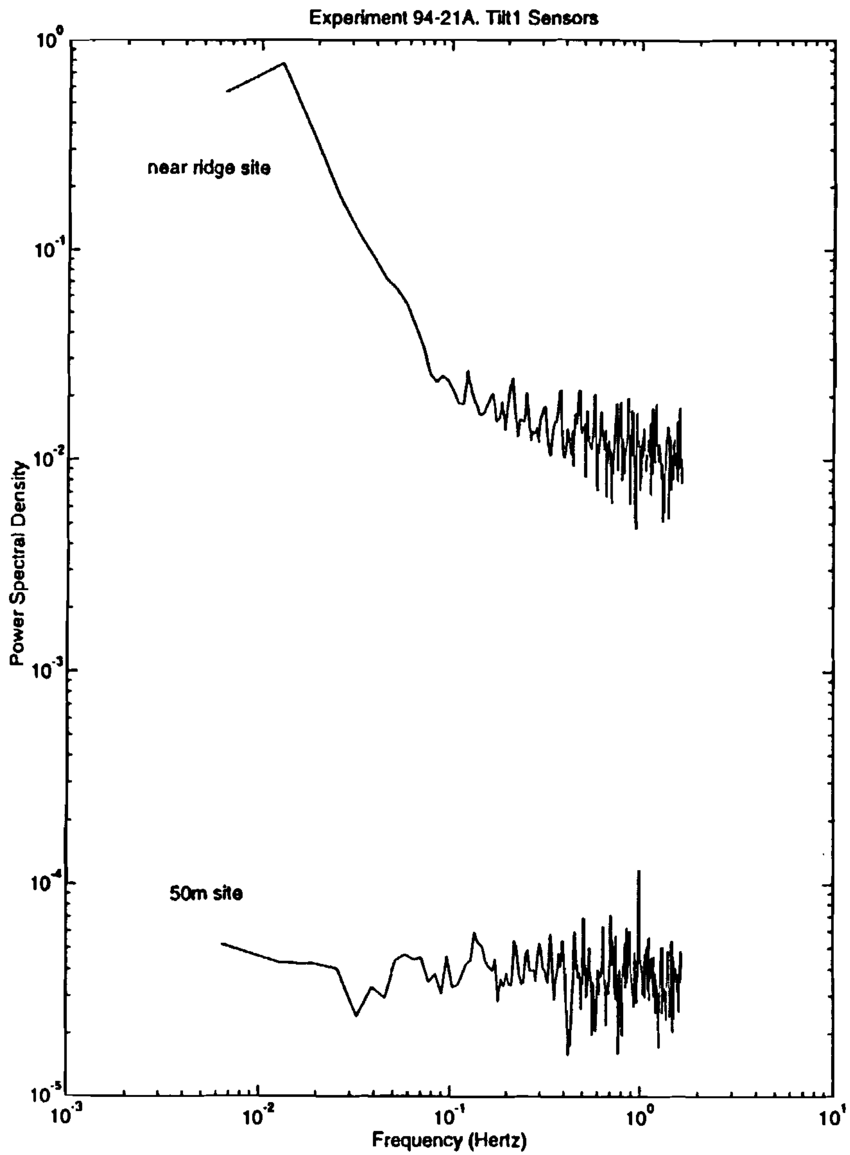


Figure 9 Experiment 17 tilt sensor enrergy spectrum showing only long period waves.



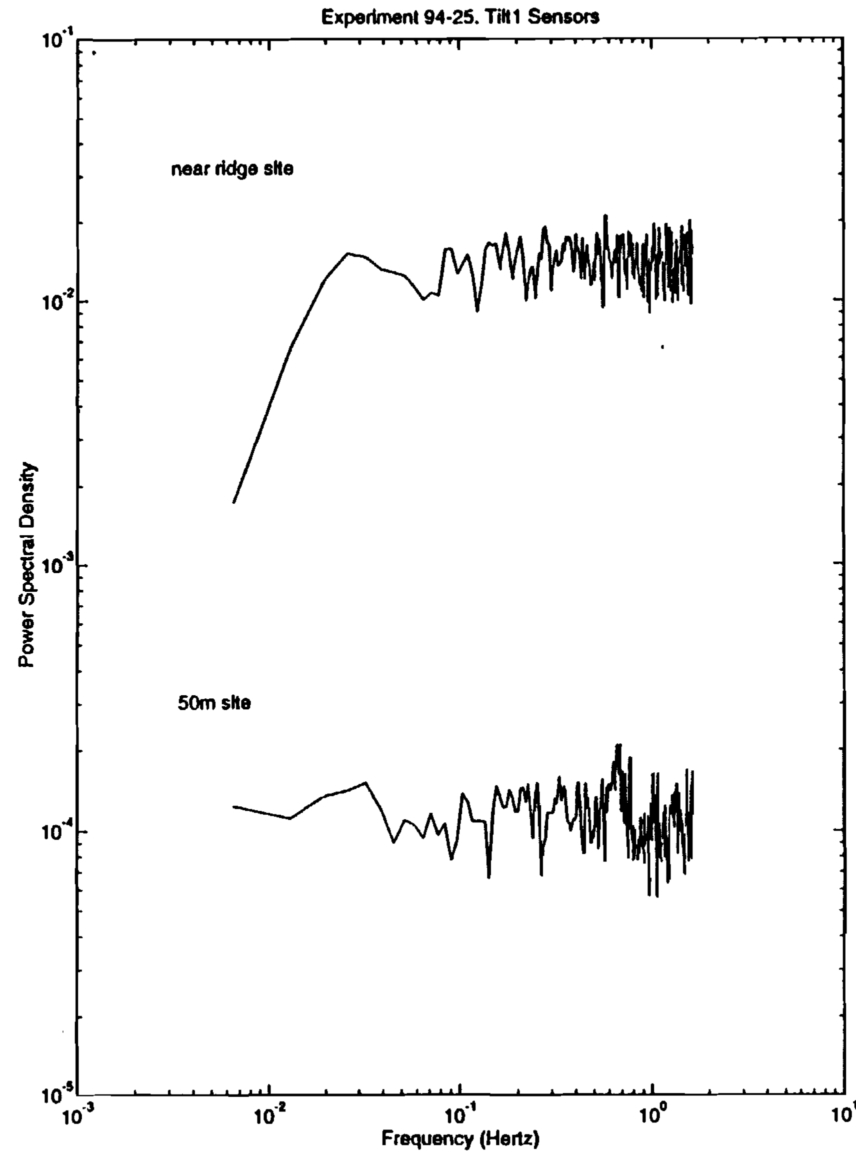


Figure 10 Two pairs of spectra from attenuation experiments conducted near ridges

Analysis of the data is still in progress. Results presented so far raise more questions than they answer. In particular, the variability of the long period energy is of the greatest interest, and further analysis of these datasets will yield new insight into the background of longest gravity waves in the ocean. The short period wave energy, which may well be associated with ice deformation events, proved to be very sporadic, occurring in short bursts mainly during fall; we hope to correlate these with deformation events recorded by CRREL stress gauges and buoy arrays. Some possible explanations which have been proposed for the existence of short period waves are:-

1. Slippage of one floe past another whilst under simultaneous compression and shear, resulting in a "stick-slip" process (Bogorodskiy and Smirnov, 1982). These have also been termed "relaxation self-excited oscillations" by the AARI group.

2. Bobbing or pitching oscillations of the floe induced by the unbalanced pushing upwards or downwards of newly fractured ice blocks which add to the structure of a growing pressure ridge. Each new block stimulates a few cycles of resonant floe response. The bobbing period T for a body of draft h, neglecting added mass and damping coefficient, is

$$T = 2\pi (h/g)^{1/2} \qquad (1)$$

and the three periods reported here (3.1 s, 2.8 s, 1.45 s) are bobbing periods for ice of draft 2.58 m, 1.92 m and 0.52 m respectively. The first two could be realistic figures for the floe involved.

3. They arise from the ridge acting as a torsional oscillator under the driving stress of unstable under-ice current shear.

Mechanism 1 requires the icefield to consist of individual floes, separated by open water, which are very dynamic and shear past one another. The SIMI region approximated to this morphology only at the very beginning of the installation phase. Mechanism 2 is associated with active ridge building. Mechanism 3 has no association with ridge building but simply depends on the ice-water shear current being significant and being oriented in an appropriate direction relative to the ridge; this is often, but not always, associated with strong local winds.

Further analysis of the dataset in conjunction with concurrent stress, deformation and meteorological data should enable these questions to be resolved.

Reference

Bogorodskiy, V.V. and V.N. Smirnov (1982). Relaxation processes in Arctic ice fields. *Dokl. Akad. Nauk SSSR, 250,* 24-26.

EXPT	START (GMT)		FINISH (GMT)		SITES LOGGED (Y/N)					
	DATE	TIME	DATE	TIME	A	B	C	D	E	F
93-1	22/09/93	00:13	22/09/93	18:14	Y	N	N	N	N	N
93-2	23/09/93	00:05	24/09/93	00:01	Y	N	N	N	N	N
93-3	23/09/93	22:26	23/09/93	18:08	Y	N	N	N	N	N
93-4	24/09/93	21:35	24/09/93	22:38	Y	N	N	N	N	N
93-5	24/09/93	23:09	25/09/93	00:10	Y	N	N	N	N	N
93-6	25/09/93	00:25	25/09/93	03:14	Y	N	N	N	N	N
93-7	25/09/93	03:17	25/09/93	18:18	Y	N	N	N	N	N
93-8	25/09/93	23:05	25/09/93	23:28	Y	N	N	N	N	N
93-9	25/09/93	23:30	26/09/93	02:36	Y	N	N	N	N	N
93-10	26/09/93	04:18	26/09/93	18:00	Y	Y	N	N	N	N
93-11	26/09/93	18:07	27/09/93	00:36	N	Y	N	N	N	N
93-12	28/09/93	01:20	28/09/93	02:50	Y	Y	N	N	N	N
93-13	28/09/93	04:13	28/09/93	16:19	Y	Y	N	N	N	N
93-14	28/09/93	21:44	29/09/93	00:37	Y	Y	N	N	N	N
93-15	29/09/93	00:03	29/09/93	08:36	N	N	Y	N	N	N
93-16	29/09/93	05:46	29/09/93	07:38	Y	Y	Y	N	N	N
93-17	29/09/93	08:41	29/09/93	16:38	Y	Y	Y	Y	N	N
93-18	29/09/93	18:50	29/09/93	21:26	Y	Y	Y	Y	N	N
93-19	24/09/93	18:01	29/09/93	23:25	Y	Y	Y	Y	N	N

Table 1 Phase 1. Fall Experiments.

EXPT	START (GMT)		FINISH (GMT)		SITES LOGGED (Y/N)					
	DATE	TIME	DATE	TIME	A	B	C	D	E	F
93-20	30/09/93	19:30	31/10/93	09:30	Y	Y	Y	Y	N	N
93-21	01/11/93	****	test only	****	Y	N	N	N	N	N
93-22	01/11/93	****	test only	****	Y	N	N	N	N	N
93-23	03/11/93	****	test only	****	Y	N	N	N	N	N
93-24	03/11/93	****	test only	****	Y	N	N	N	Y	N
93-25	04/11/93	05:25	04/11/93	----	Y	Y	Y	Y	Y	N
93-26	04/11/93	08:33	04/11/93	----	Y	Y	Y	Y	Y	N
93-27	05/11/93	02:28	05/11/93	----	Y	Y	Y	Y	Y	N
93-28	05/11/93	06:53	08/11/93	23:34	Y	Y	Y	Y	Y	Y
93-29	09/11/93	00:00	29/11/93	00:53	Y	Y	Y	Y	Y	Y

Table 2 Phase 2.Winter Experiments.

EXPT	START (G.M.T.)		FINISH (G.M.T.)		LOGGING FREQ. (Hz)	ANTI-ALIAS FILTER (YES/NO)	LOGGING SYSTEM
	DATE	TIME	DATE	TIME			
94-1	12/04/93	01:03	11/04/94	05:00	3.3	Yes	Squirrel
94-2	12/04/94	09:30	12/04/94	17:40	3.0	Yes	SpriTel
94-3	12/04/94	19:22	12/04/94	20:52	3.0	Yes	Squirrel
94-4	13/04/94	07:30	13/04/94	20:00	3.0	Yes	SpriTel
94-5	13/04/94	no data	13/04/94	no data	10.0	Yes	no data
94-6	13/04/94	19:30	14/04/94	16:30	3.0	Yes	SpriTel
94-7	14/04/94	19:36 23:25	14/04/94	19:47 23:45	10.0 10.0	Yes Yes	SpriTel SpriTel
94-8	15/04/94	02:09	15/04/94	04:09	3.0	Yes	SpriTel
94-9	15/04/94	05:30	15/04/94	07:15	3.0	Yes	SpriTel
94-10	15/04/94	08:00	15/04/94	19:00	3.0	Yes	SpriTel
94-11	15/04/94	21:08	15/04/94	23:30	3.0	Yes	SpriTel
94-12	16/04/94	00:15	16/04/94	02:30	3.0	Yes	SpriTel
94-13	16/04/94	03:43	16/04/94	05:32	3.3	Yes	Squirrel
94-14	16/04/94	06:55	16/04/94	12:00	3.3	Yes	Squirrel
94-15	16/04/94	19:54	16/04/94	21:39	3.3	Yes	Squirrel
94-16	16/04/94	23:53	17/04/94	00:40	3.3	Yes	Squirrel
94-17	17/04/94	01:11	17/04/94	03:19	3.3	Yes	Squirrel
94-18	17/04/94	18:05	17/04/94	19:53	3.3	No	Squirrel
94-19	17/04/94	08:53	17/04/94	13:43	3.3	No	Squirrel
94-20	17/04/94	20:28	17/04/94	22:19	3.3	No	Squirrel
94-21	17/04/94	22:30	18/04/94	00:15	3.3	No	Squirrel
94-22	18/04/94	01:30	18/04/94	02:15	3.3	No	Squirrel
94-23	18/04/94	03:20	18/04/94	04:15	3.3	No	Squirrel
94-24	18/04/94	04:30	18/04/94	05:30	3.3	No	Squirrel
94-25	18/04/94	06:26	18/04/94	07:40	3.3	No	Squirrel

Table 3 Phase 3. Spring Experiments

AUV OPERATIONS IN THE ARCTIC

J. G. Bellingham, J. J. Leonard, J. Vaganay, C. A. Goudey, D. K. Atwood, T. R. Consi, J. W. Bales, H. Schmidt, and C. Chryssostomidis

Massachusetts Institute of Technology, Sea Grant College Program
Cambridge, Massachusetts 02139

Abstract

This paper describes the challenges of designing an autonomous underwater vehicle system for surveying the underside of the Arctic ice canopy and results of initial tests. The objective was to launch and recover an autonomous underwater vehicle through the ice to make measurements of the topography of the underside of the ice canopy. Ultimately, transits of up to ten kilometers and mapping operations over an area of one square kilometer are desired, however the tests described here were limited to the immediate vicinity of the launch/recovery ice hole.

Introduction

The requirement for a cost effective under-ice survey capability was high-lighted by the Arctic Sea Ice Mechanics Initiative, sponsored by the Office of Naval Research. For this initiative, a capability to rapidly characterize the under-side of the ice in a region of ice activity was desired. Rapid response is necessary since ice activity lasts on the order of a day. In the past, data concerning the topography of the ice have been obtained by a variety of means, including sidescan sonar mounted on submarines [Sear and Wadhams, 1992] and mechanically-scanned sonars inserted through holes drilled in the ice [Conners et al., 1989]. AUVs offer a complement to these methods of data acquisition, providing a larger area of coverage via a single ice hole, at a much lower expense than a nuclear submarine.

There is ample precedent for employing AUVs for Arctic operations. The UARS (Unmanned Arctic Research Submersible) was used to obtain under-ice topography in the early 1970s [Francoise and Nodland, 1972]. More recently, the Seashuttle vehicles [Light and Morrison, 1989] have been demonstrated in the Arctic as a very small, economical platforms. The International Submarine Engineering ARCS vehicle was designed to operate under ice [Brooke, 1981], as is the Marconi Test Bed AUV currently under development [Tonge, 1992].

Prior to vehicle operations, a number of preparatory activities are required. First, a hydro-hole measuring at least 1 x 2.5 meters in size must be formed for launch and recovery. The hydro-hole will be maintained in a heated tent, and will provide a base for vehicle operations. Second, an array of acoustic beacons must be deployed from the ice sheet. The acoustic beacons will be used as elements of a long-baseline array for AUV navigation.

The mission chronology is:

1) Mission parameters downloaded to vehicle, including position of ice-mounted navigation beacons.
2) Vehicle deployed through a hydro-hole in base camp.
3) Navigation to the active region to perform its mapping mission.
4) Perform under-ice mapping.
5) Return to base camp for recovery and data retrieval.

Recovery was achieved by an arrangement similar to that used for the UARS vehicle [Francoise and Nodland, 1972]. An ultrashort-baseline (USBL) navigation system was employed for homing the vehicle on a net suspended under the ice. The vehicle carried a set of barbs on its nose with which it entangled itself in the net.

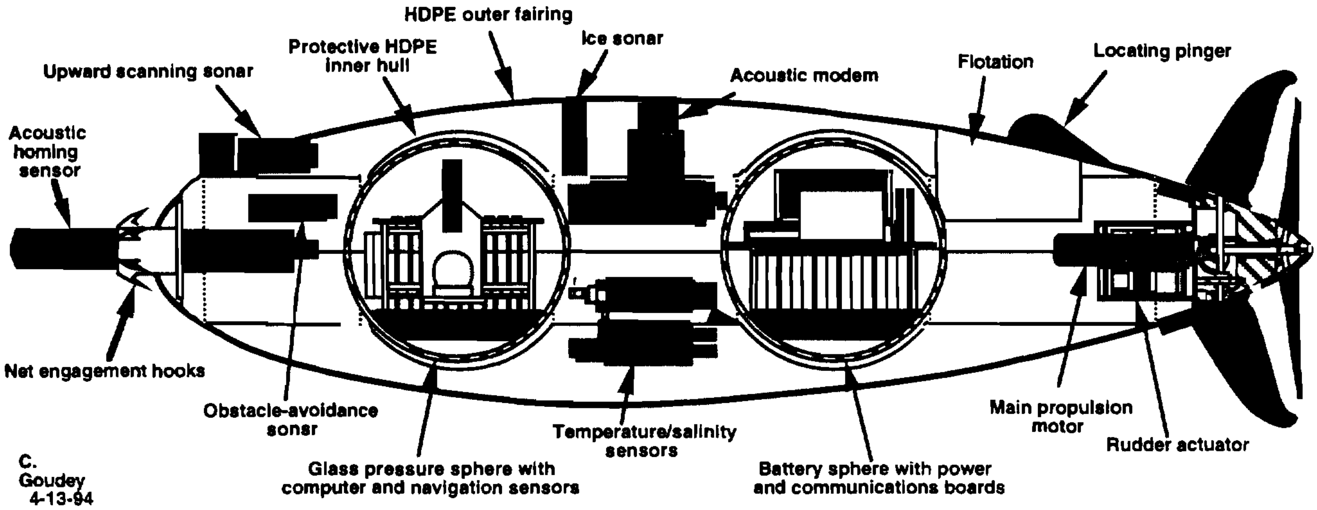


Figure 1: Arctic configuration of Odyssey II. Mission sensors are the scanning sonar at the nose, and the temperature and conductivity sensors located in the center of the vehicle.

Vehicle Description

The logistical complexities of operating in the Arctic are such that a small vehicle with a minimum support requirement is extremely attractive. Odyssey II is second generation survey class autonomous underwater vehicle, designed as an intelligent mobile instrument platform [Bellingham et. al, 1992]. Comprised of a low-drag fairing with a single ducted propeller and cruciform control surfaces, Odyssey II is 2.2 meters long, and has a maximum diameter of 0.6 meters (see Figure 1). The fairing is free-flooded, and contains the main pressure housings, which are two glass spheres. In the present configuration, the vehicle has an endurance of eight to twelve hours, depending on the operating speed and the duty cycle of subsystems such as the acoustic modem.

The primary onboard computer is built around a Motorola 68030 microprocessor [OR Industrial Computers]. In addition to the main computer, a network of small microcontrollers (Motorola M68HC11) is used to distribute "intelligence" to sensors and actuators. The present vehicle state sensor complement includes a three-axis fluxgate magnetometer [EMDS], three-axis accelerometer and angular rate sensors [Systron-Donner], a pressure transducer [Paroscientific], and a water speed sensor. Two ST500 obstacle avoidance sonar and an ST200 altimeter sonar [Tritech] are also integrated into the vehicle. An acoustic modem [Datasonics] has undergone preliminary testing on Odyssey II, and will become a standard device.

For Arctic operations, Odyssey II had no drop weights. However, two drop weights are attached for deep-water operations. The first is used to speed descent of the vehicle to its operating depth, while the second is used to speed ascent in a normal mission, or to force ascent in an emergency. The drop weights can be released either by command from the main vehicle computer, or on the initiative of a second "watchdog" computer which monitors the main vehicle computer and the progress of the mission. The watchdog operates as a backup to the main computer, to ensure vehicle recovery when all else fails.

A transponder, a radio beacon, and a strobe are used to provide a means of locating the vehicle. All three location aids operate off of power sources independent from each other and the rest of the vehicle electronics to ensure operation even if vehicle batteries run low. The radio beacon and strobe are used for locating the vehicle on the surface. An ultrashort-baseline (USBL) system is used on the surface to track the transponder. Both LXT and Trackpoint II systems [ORE] have been used to track Odyssey II from the surface.

Attitude Heading Reference System

For operations in the Arctic, Odyssey II measures its orientation with a sensor package which measures magnetic intensity, angular rate and acceleration for all three axes. The vehicle attitude and heading are taken from the angular rate and acceleration sensors only. Drift in the heading of the inertial system is corrected by the magnetic measurement. Periods of high magnetic activity could compromise accuracy, however this was not encountered during our operations. The earth's field was monitored at the camp throughout the mission, so that post-mission correction of heading errors could have been made. While significant heading errors can degrade vehicle performance, they generally do not jeopardize recovery chances, as in the terminal phase of the mission the vehicle uses the acoustic homing beacon as the directional reference.

Homing

A commercial USBL system, the LXT [ORE], was integrated into the vehicle to provide a homing capability for under-ice operations. The LXT measures both direction and range to up to two acoustic beacons Detection of beacons at ranges on the order of two kilometers was obtained in the Arctic. While power consumption of the system is high (40 watts), the USBL need only be turned on for the recovery phase of the mission (cf Figure 2). While vehicle position can be determined from range and bearing to one beacon, the ability of the vehicle to track two beacons at a time also allows for a range-range solution for the vehicle position (i.e. spherical navigation, cf Figure 4).

Algorithms

The layered control work previously developed on Odyssey I and on Sea Squirt has been substantially improved and implemented on Odyssey II. A full description is omitted for lack of space, however achievements include:

- creation and demonstration of simulation-to-vehicle software path in which code run in Macintosh simulation is transferred directly to vehicle, tested in a vehicle-in-the-loop simulation, and then used for vehicle field operations.
- extensive testing of vehicle dynamic and mission level control in field operations, including demonstration of nine new behaviors designed for Arctic vehicle operations.
- communication with the vehicle via a commercial acoustic communication system, including interrogating individual subsystems and examining mission data files.

The elementary unit of layered control is the behavior. A behavior receives sensory input and generates commands. Each behavior is responsible for a specific mission objective. For example, the objective of an obstacle avoidance behavior is to prevent the vehicle from hitting objects. A layered control command structure consists of a number of behaviors with different objectives. The command outputs of the behaviors are resolved into the final command that is sent to the vehicle. At present, a total of 18 behaviors have been written for Odyssey II, with a little more than half those behaviors employed in the field. These include:

depth_envelope: ensures that the vehicle does not exceed a maximum depth or climb above a minimum depth, and prevents the vehicle from approaching too close to the bottom.

arctic_depth_envelope: the same as depth_envelope, except that instead of preventing the vehicle from approaching the bottom, it keeps the vehicle from colliding with the ice canopy.

detect_collision: monitors the output of the accelerometers to detect a jerk (i.e. the time derivative of total acceleration) which indicates a collision.

mission_timer: ensures that the vehicle shuts down after expiration of a set time.

acquire_heading: causes the vehicle to turn to a desired heading.

modem_communicate: loads messages for the modem to send indicating the progression of the mission and detection of any failures.

setpoint: commands the vehicle to attain a given heading, depth, and speed for a given length of time.

setvector: commands the vehicle to attain a given heading, pitch, and speed for a given length of time.

waypoint_2d: commands the vehicle to attain a given location in space using long-baseline navigation.

set_rudder: causes the vehicle to set its rudder to a given deflection for a period of time.

survey_dead_reckon: commands the vehicle through a grid survey using dead-reckoning navigation.

survey_with_nav: commands the vehicle through a grid survey using long-base-line navigation.

homing: commands the vehicle to home on an acoustic beacon using the ultrashort-baseline navigation system.

homing_directed: commands the vehicle to home on an acoustic beacon from a particular direction, and to try again if an approach is missed.

deep_homing_directed: the same as homing_directed, but also causes the vehicle to approach the beacon on a climbing path, to ensure the vehicle stays deep as long as possible.

race_track: commands the vehicle to alternately home on first one then another acoustic beacon for a given number of cycles.

An important feature of the Odyssey II vehicle control software is the vehicle state structure. This structure contains descriptions and values for sensors and behaviors. It also contains the configuration of the active layered control structure (i.e. the priority and argument values for active behaviors) and the output command structure. The state structure serves a number of important functions: it provides a single global structure which once accessed provides the entire vehicle state to a function or process. It also provides the template for both data logging and data analysis.

Summary of Runs (Winnipesaukee & Arctic)

Lake Winnipesaukee, New Hampshire

Odyssey II was tested extensively under-ice in lake Winnipesaukee in New Hampshire. During five weeks of operations of the vehicle under 18 inches of ice, the following was accomplished:

- The basic vehicle subsystems - power, propulsion, steering, communication, and control - were tested.
- Handling techniques were developed for launching and recovering Odyssey II through the ice.
- The ultra-short baseline navigation system used for acoustic homing behaviors was characterized.
- Several trajectory-generation algorithms for homing the vehicle into the recovery net were

tested. The most promising was implemented in a "missed-approach retry" mode.

- Lost-vehicle strategies for locating and recovering a vehicle away from the ice hole were successfully tested. Acoustic and radio beacons were used to locate the AUV.
- The attitude heading reference system was characterized to evaluate its performance in high-magnetic-inclination environment found in the Arctic.

Beaufort Sea, Arctic

In the Arctic, Odyssey II was repeatedly deployed and recovered through 6' of ice. The AUV performed a series of "out-and-back" missions to demonstrate its ability to home into the recovery net using an ultrashort baseline navigation system. Several trajectory generation algorithms for homing the vehicle into the recovery net were tested and the most promising implemented in a "missed approach-retry" mode. The ultra-short baseline navigation system used for homing was also employed for long-baseline navigation, thus providing a backup navigation system. An ROV was used to observe and document AUV operations under ice. Other activities during Arctic operations included making preliminary maps of the ice canopy along the vehicle track, demonstrating lost-vehicle location and recovery strategies, and demonstrating an attitude heading reference for high magnetic inclination environments. Acoustic communication was demonstrated from the AUV to receivers as far as 10 km away (WHOI collaborators).

Figure 2 shows a 3D vehicle track for one of the Arctic runs. Figure 3 shows the measured profile of the under-ice canopy along that track. The AUV was traveling at approximately 3 knots. The vehicle begins at the origin, and travels out by dead reckoning. When the vehicle turns, the USBL system picks up the transponder in the recovery net and the position is updated (causing the jumps visible in the vehicle track. The portion of the vehicle track extending to the northeast is an artifact of dead-reckoning being continued despite capture of the vehicle in the recovery net.

In addition to the AUV, we deployed a small ROV (a Benthos Mini-Rover) from our ice-tent. Our experience showed the benefits and difficulties of tethered vehicles in the Arctic. We found that the ROV provided an ability to see what was going on beneath six feet of ice which was quite helpful in several stages of the experiment. In addition, we used the ROV to scout the around the ice hole and located ice keels that extended as much as 15 meters below the ice surface. In the process of carrying out this reconnaissance, the tether lodged on a protrusion from the ice keel, clearly demonstrating the hazards of operating tethered vehicles underneath ice. Finally, we note that the limited length of an ROV tether prevents it from providing the 10-km lateral excursion required for the ice mechanics experiment.

Conclusions

The capability described here is the first stage of a larger effort to develop a cost effective means to monitor the Arctic ocean. By addressing the issues fundamental to operation of unmanned underwater vehicles in the Arctic, our intent is to set the groundwork for longer term vehicle operations. Future work will focus on addressing difficulties encountered in the two scheduled tests, and on the development and incorporation of more sophisticated sensor packages for under-ice mapping and water column characterization.

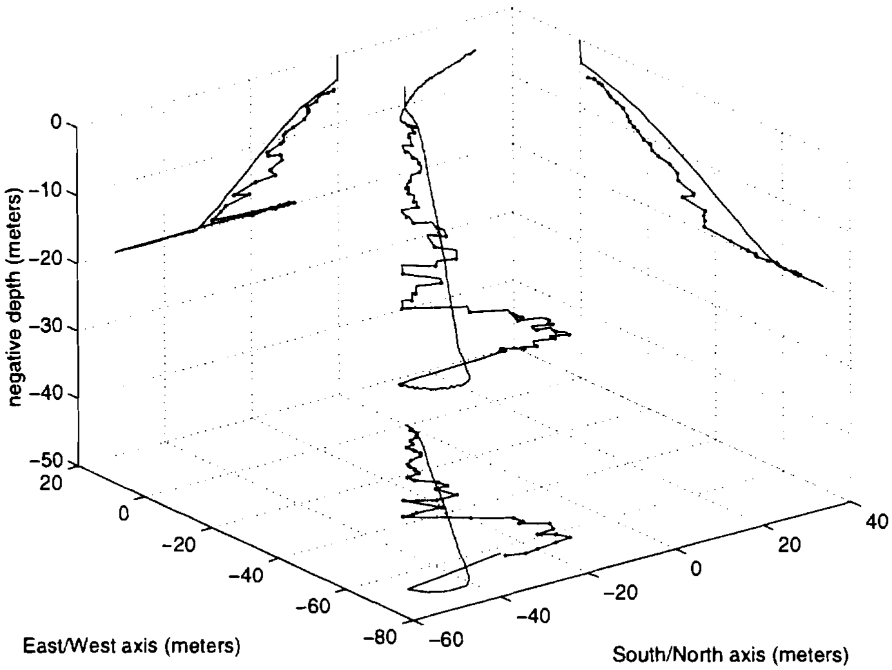


Figure 2: This plot shows Odyssey's trajectory during one of the Arctic runs. The vehicle starts at position (0,0), and proceeds to the southwest while diving down to 20m. On turning, the vehicle acquires the homing beacon, and resets its dead reckoned position. The sucessive updates cause the jumps visible in the vehicle track. The portion of the vehicle track extending to the northeast is an artifact of dead-reckoning being continued despite capture of the vehicle in the recovery net. The 3D trajectory is also projected on three orthogonal planes to clearly show the extend of the motion along each reference axis.

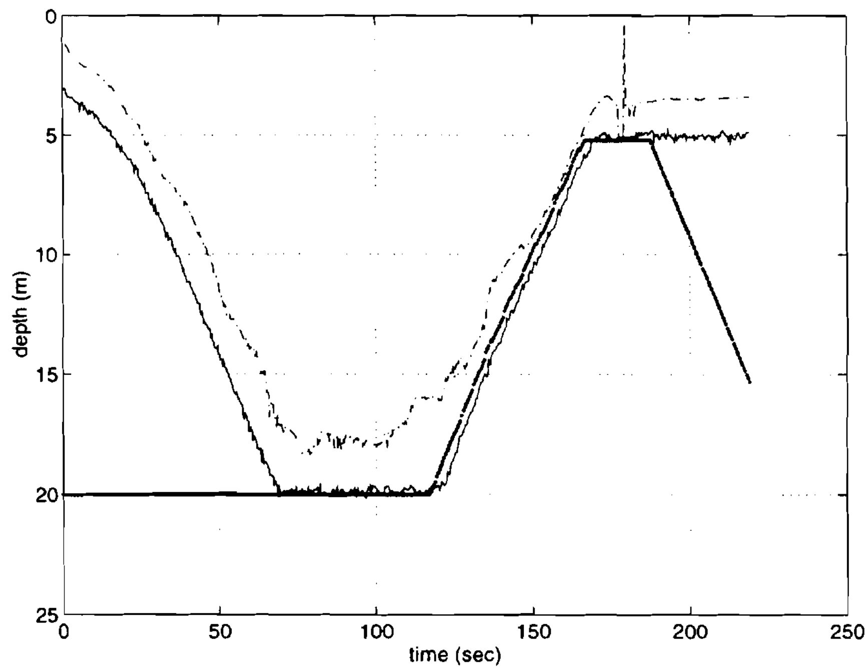


Figure 3. This figure shows a plot of the depth of the Odyssey II vs. time for one of the Arctic runs. The measured depth of the vehicle is shown as a solid line and the commanded depth is shown as a dotted line. The output of the vehicle's upward-looking 200 kHz sonar is shown as a dashed line, giving an indication of variations in the under-ice topography.

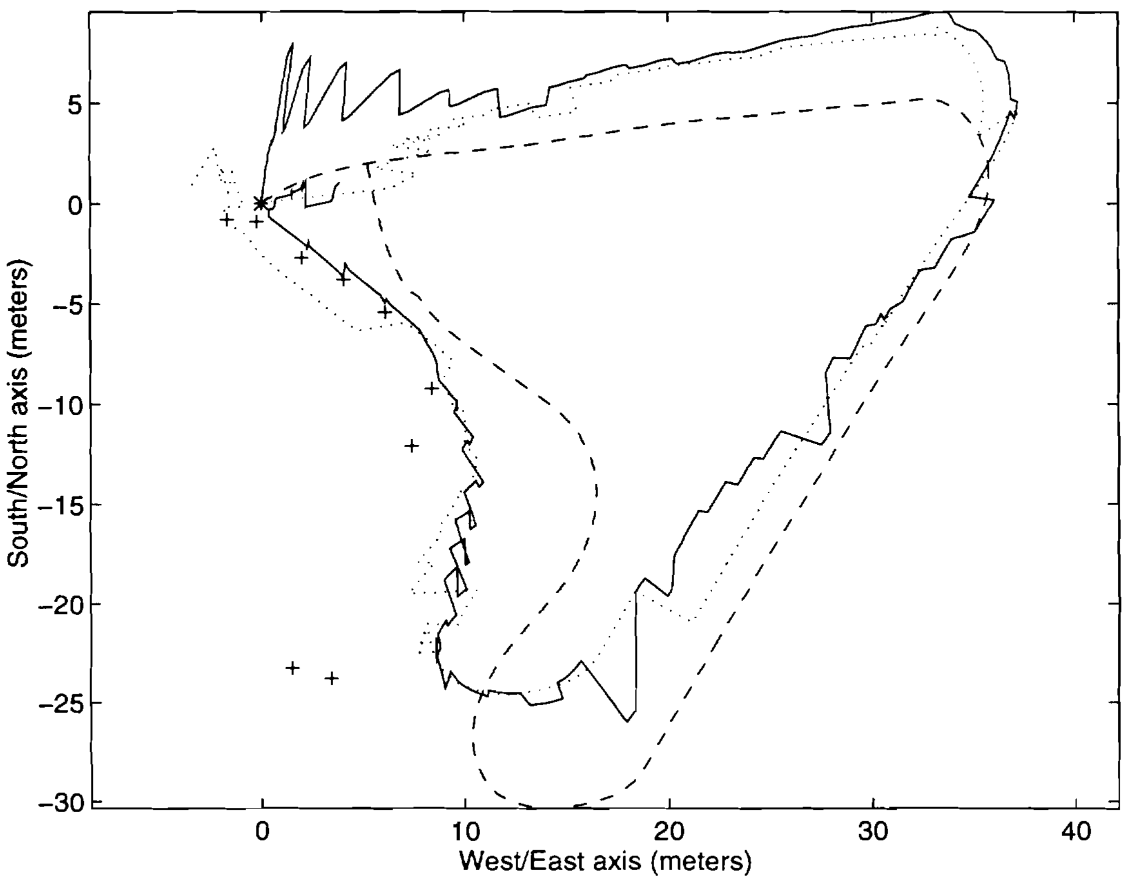


Figure 4: Odyssey is able to compute its position in many different ways thanks to its sensor suite. This plot shows the vehicle trajectory, estimated by four different methods, in one of the many runs executed at lake Winnipesaukee. 1) dashed: dead reckoning. 2) dotted: Two beacons are tracked by the USBL hydrophone located in the vehicle nose. The measured ranges have to pass a validation test before being used to compute a fix which is used to update the dead reckoned position. 3) solid: A Kalman filter uses the ranges to the two beacons, as they arrive, instead of waiting for a couple of ranges. Each new range measurement is used to correct the predicted position (dead reckoning) and improve positioning accuracy. 4) crosses: The range, azimuth and elevation of the homing beacon, measured by the USBL hydrophone, allow computation of the beacon's position in the vehicle frame. Given the orientation of the vehicle measured by its Attitude and Heading Reference System and the beacon's depth, the position of the vehicle can be computed

Acknowledgments

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Multipath Navigation in the Arctic:

A Feasibility Test

Max Deffenbaugh, Henrik Schmidt, and James G. Bellingham

MIT Sea Grant
Autonomous Underwater Vehicles Laboratory

ABSTRACT

Accurate acoustic positioning over a large operational area requires either many acoustic beacons or the ability to use navigation beacons at extended ranges. The useful range of a navigation beacon in the Arctic tends to be limited by multipath. Multipath creates problems for navigation when small changes in sound speed cause the first arrival in the multipath arrival sequence to fade. The next arrival is then mistaken for the first one, and a range error results. The utilization of the full multipath arrival sequence enables a navigation system which is robust to the fading of a subset of those arrivals. A feasibility test for such a multipath navigation system is described here.

I. MULTIPATH NAVIGATION

Acoustic navigation is a crucial capability for operation of underwater vehicles beneath the Arctic ice. Unfortunately, the oceanography of the Arctic is such that a shallow sound channel forms just beneath the surface, as seen in Figure 3. This sound channel creates multipath conditions reminiscent of shallow water propagation. Multipath can be problematic for traditional acoustic navigation systems which use only the first arrival in the multipath sequence for ranging. If this first arrival is unexpectedly absent due to a small change in the sound speed profile, a range error will result. A navigation system which is able to utilize multiple arrivals in a multipath environment can be made robust to the fading of some subset of those arrivals. Such a system is described here, and results of a feasibility test conducted in conjunction with the SIMI project in Spring, 1994 are presented.

II. SYSTEM OPERATION

In the multipath navigation system described here, the received acoustic signal is broken down into a set of arrivals--one arrival for each eigenray connecting source and receiver. While characteristics of the received signal as a whole change in a non-linear fashion with modest variations in vehicle position or sound speed profile, the travel times for the individual arrivals composing the received signals will tend to behave linearly in response to normal changes. This means that if the received arrivals can be identified with a modeled set of eigenrays, a linear inversion can be performed to find the model parameters based on the modeling error for each eigenray. The operation of the navigation system is shown in Figure 1.

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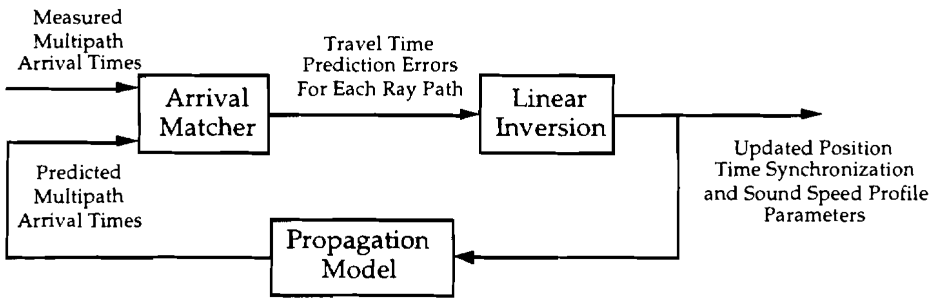

Figure 1: Multipath Navigation System.

The system seeks the set of parameters (vehicle position, time synchronization error between the vehicle and beacon clocks, and possibly parameters describing the sound speed profile) for which the predicted set of multipath arrivals from all beacons best matches the measured multipath arrivals. The Arrival Matcher attempts to associate each measured arrival with an arrival predicted by the propagation model. Each such match that can be made gives a travel time prediction error for the matched eigenray. A linear inversion is then performed to determine the model parameter errors from the arrival time errors.

Treating the received signal as a set of individual arrivals which move linearly with changes in parameter values instead of as a single "signature" characteristic of a particular parameter choice, but which changes non-linearly for realistic parameter errors, allows a linear inversion to be used to determine parameter values instead of simulated annealing or some other time-consuming multidimensional optimization technique. This time savings makes real-time multipath navigation feasible even with computer hardware which could be carried by a small AUV.

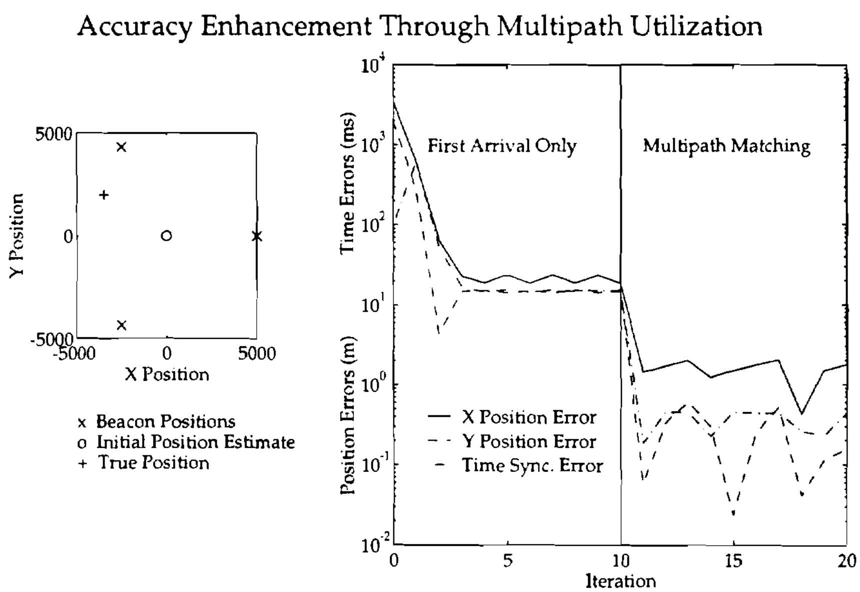

Figure 2: Performance Enhancement from Multipath Utilization.

Figure 2 demonstrates the improvement in navigation resolution which can be achieved through multipath utilization in a fading environment. [Deffenbaugh, 1993] In this simulation, beacons were deployed at the positions indicated by 'x' above. The navigation system was given an initial position estimate ‘o’. The true position was ‘+’. The navigation system was then asked to determine its true position. After 10 iterations using first arrivals only, it still had errors on the order of 10m in position and 10ms in time synchronization between the vehicle and beacon clocks. When allowed to use the multipath structure, the position and time synchronization accuracy improved by about a factor of 10.

III. EXPERIMENT DESIGN

The success of the system depends on the ability to distinguish individual arrivals in the multipath structure and then to associate these arrivals with certain modeled eigenrays. An experiment was designed to demonstrate this capability. An acoustic beacon was deployed through the ice at ranges of 3km, 6km, and 10km from the base camp, while a receiver at the base camp recorded the beacon signal. The beacon transmitted a 63-bit BPSK coded pseudorandom noise sequence with two cycles of an 11.4kHz center frequency per bit. To achieve time synchronization, both the beacon and the receiver had GPS receivers. At one minute intervals, both units also recorded their GPS positions and the satellites used to acquire the positions. When both receivers use the same satellites, their *absolute* position errors are nearly equal, and a highly accurate *relative* position can be obtained. This "poor man's" differential GPS system is described in greater detail in a separate article in this volume [Deffenbaugh, 1995]. Finally, a CTD cast was taken to determine the sound speed profile. The ray trace below shows predicted ray paths at 0.5 degree intervals between -10 and 10 degrees. The circles on the chart show the ranges and depths where measurements were made.

Range	Depths		
3km	15m	30m	60m
6km	15m	30m	60m
10km		30m	

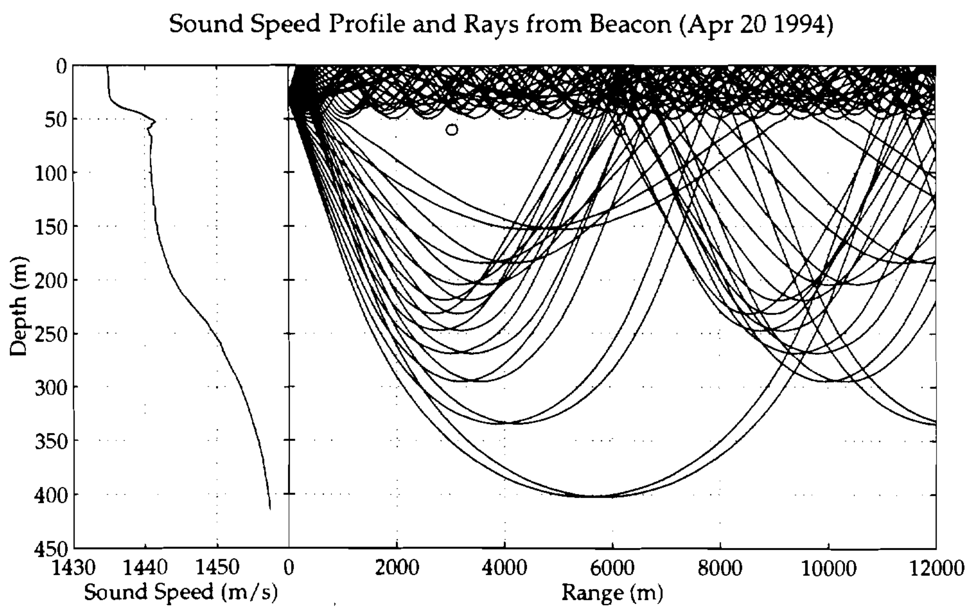

Figure 3: Sound Speed Profile and Rays at 0.5 Degree Spacing.

The ray tracing model of Figure 3 predicts that the 3km range 60m depth receiver is in a shadow zone, and true to the prediction, no signal was detected at this location. This large shadow zone near the transmitter demonstrates the importance of taking acoustic propagation conditions into account when designing navigation systems.

The receiver at 3km range and 30m depth, however, should be well within the surface channel. The signal received at this location is analyzed in Figure 4. The waterfall plot at the top of Figure 4 shows the magnitude of the channel impulse response at 5 minute intervals. The individual arrivals here are quite distinct, and the arrival location is stable. These sample impulse responses are summed and displayed at the bottom left of Figure 4. Superimposed on this figure are 'x's at the arrival times predicted using a ray tracing model. There is an unexpected arrival present in the measured signal at 2.122 seconds. Unexpected arrivals are frequently seen due to slight errors in the sound speed profile.

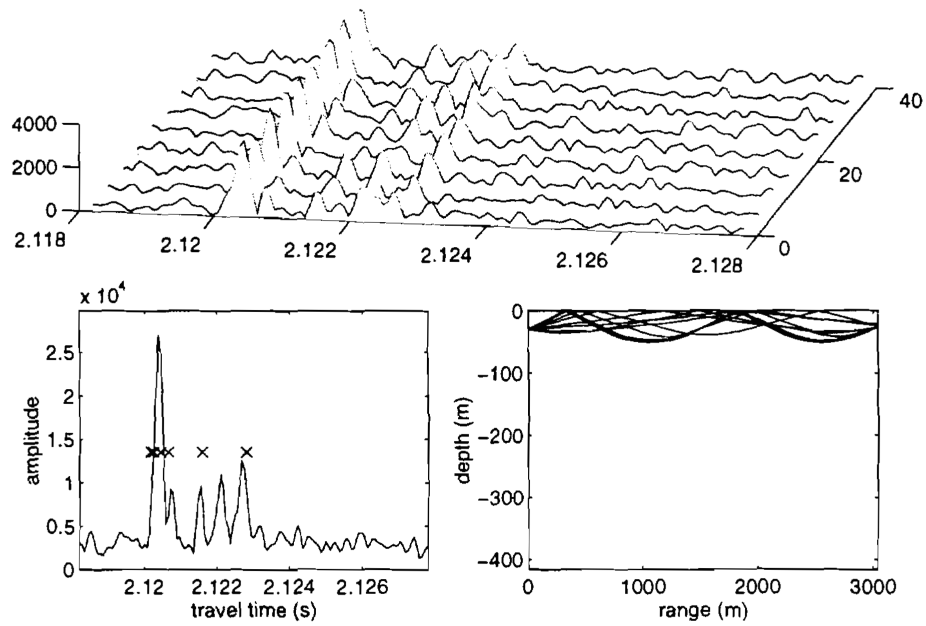

Figure 4: Received Signal Analysis (3km range 30m depth).

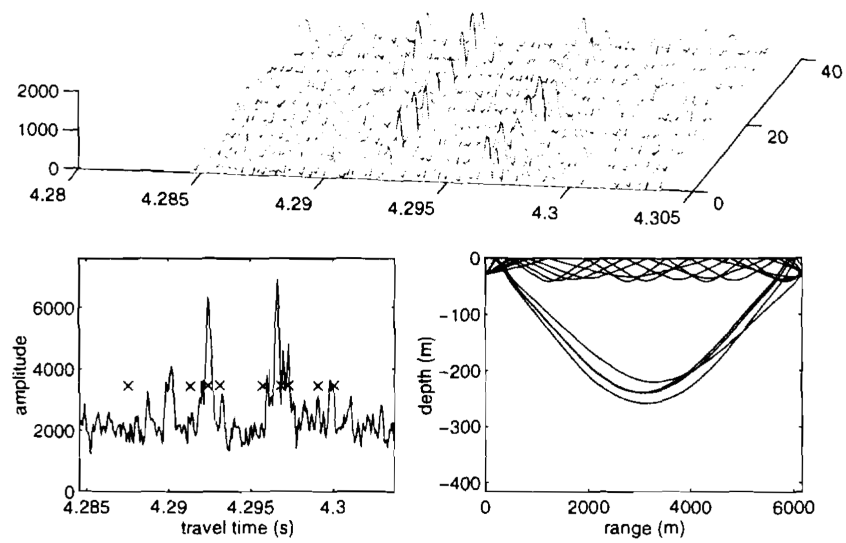

Figure 5: Received Signal Analysis (6km range 30m depth).

In Figure 5, a similar analysis to that of Figure 4 is performed for the receiver at 6km range and 30m depth. At this longer range, some deep paths are seen in addition to the shallow surface paths, as is predicted by the ray trace in Figure 3. In the last two traces shown in the waterfall plot of Figure 5, a new first arrival emerges at 4.29 seconds which was not present five minutes prior. Such an event would cause position errors for a system which relied on only the first arrival for navigation. The use of the whole multipath structure, in combination with the ability to ignore certain arrivals which do not match the model makes the multipath navigation system robust to this sort of change in the received signal.

In Figure 6, the received signal for the 6km range, 60m depth source is analyzed. The ray tracing model predicts only deep rays at this location, however, some of the surface channel arrivals are also seen in the received signal. (The last arrival peak corresponds in time to surface channel arrivals.) The presence of surface channel arrivals at this depth indicates an error in the sound speed profile. In particular, the local maximum of sound speed at 50m depth is most probably a transient feature that had gone away by the time this data was taken. If this sound small peak were removed, the surface channel would extend deep enough to effect a source at 60m depth.

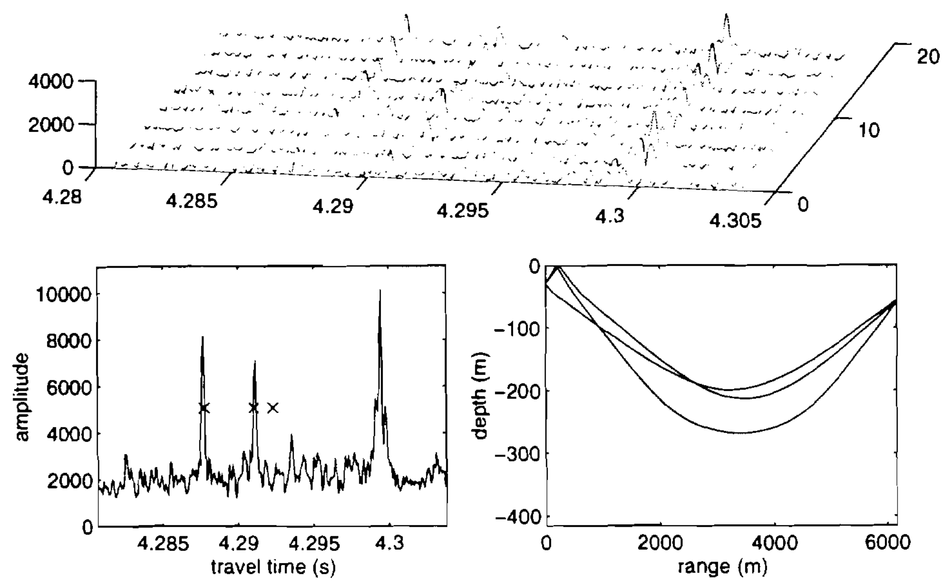

Figure 6: Received Signal Analysis (6km range, 60m depth).

IV. CONCLUSION

The application of the multipath navigation technique presented here is dependent on the ability to represent the received acoustic signal as a set of distinct arrivals and to then associate these arrivals with modeled eigenrays. The data collected suggests that this is possible in the Arctic environment, though it is crucial that the system allow the possibility that all arrivals may not find matches.

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Performance Assessment of the

High Resolution GPS Ranging System

Max Deffenbaugh, Henrik Schmidt, James G. Bellingham, and Donald K. Atwood

MIT Sea Grant
Autonomous Underwater Vehicles Laboratory

ABSTRACT

Sub-meter relative position accuracy is demonstrated for standard C/A Code GPS receivers separated by 1km. The dominant source of C/A Code GPS position error is the random timing error added to each satellite transmission. When positions of closely spaced receivers are determined from the same satellites, the absolute position errors are approximately the same, and the relative position is very accurate. This technique was applied in the Arctic to positioning of an acoustic beacon relative to a base camp location. The beacon and the camp both had a C/A code GPS receiver. At one minute intervals, GPS positions and the satellites used to obtain the positions were simultaneously recorded at both locations. After retrieval of the beacon, the instances when position pairs used the same satellites were selected, and relative positions were calculated from these measurements. The resulting relative positions had a standard deviation of 3.9m, and with averaging over 100 measurements, the standard deviation was reduced to less than 50cm.

I. EXPERIMENT DESCRIPTION

During the SIMI project, Fall 1993, an acoustic beacon was deployed at a 1km range from an ice camp on the same ice floe. GPS receivers at the camp and at the beacon simultaneously recorded their positions at one minute intervals over a 26.5 hour period. During this time period, the ice floe was seen to drift approximately 15km. Figure 1 shows the track of the ice camp, the lower (southerly) track, and the track of the beacon.

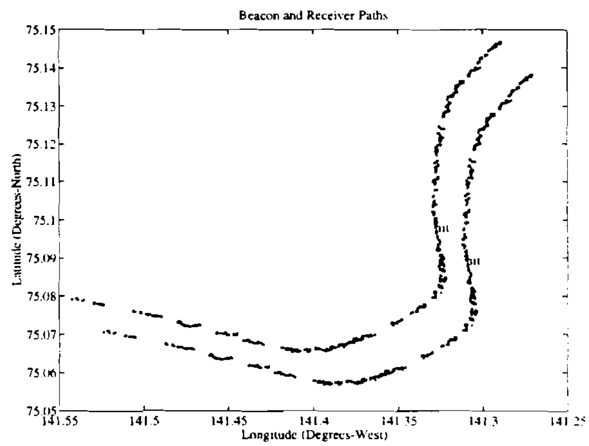

Figure 1: Path of Beacon and Camp

The size of the field shown in Figure 1 is 11.1 km (N-S) by 8.6km (E-W). Blank spots in the paths correspond to time intervals when the two receivers were operating from different satellites. About 60% of the position fixes which the two systems acquired were found to be from the same satellites.

II. RANGE MEASUREMENT ERRORS

The dominant source of C/A Code GPS position error is the random timing error added to each satellite transmission. If two receivers use the same satellites to determine their position and they are sufficiently close together that the common time errors from the satellites manifest themselves as equal size position errors, then the effects of the time

This work is supported by the ONR Arctic Programs Office. The author is supported by an NSF Graduate Fellowship under Grant #RCD-9154652

errors will cancel when the relative position is found. The resulting precision of the range measurement is shown in Figure 2. The estimated standard deviation of individual range measurements is 3.9m.

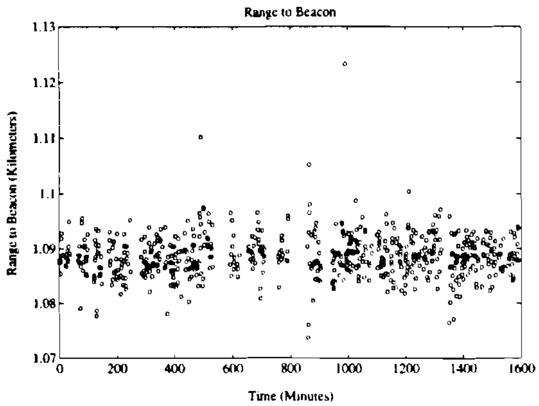

Figure 2: Range Estimates from Camp to Beacon

III. BENEFITS OF POSITION AVERAGING

Consecutive range measurement errors (1 minute apart) have a correlation of 0.25, and range measurement errors with greater temporal separation show no detectable correlation. Since the relative beacon motion is negligible and the noise is nearly uncorrelated, position averaging yields greatly improved ranges. The estimated standard deviation of the range estimate as a function of the number of samples averaged is shown in Figure 3. Shown as a dashed line is the $N^{-1/2}$ theoretical decrease in standard deviation if the samples were independent.

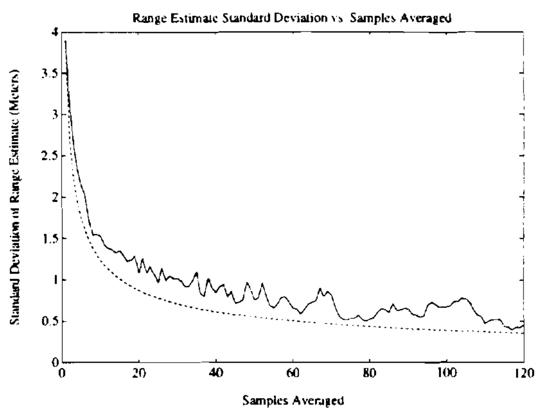

Figure 3: Decrease in range estimate standard deviation with increased sample averaging.

IV. ACCURATE BEARING MEASUREMENT

From the position differences, the bearing to the beacon from the camp can be calculated. This bearing is plotted for the duration of the experiment in Figure 4. The time rate of change in bearing is the angular velocity of the ice floe. The constant change of bearing for the first 1100 minutes indicates a constant angular momentum. Evidently a collision occurs at about minute 1100 which imparts a change in angular momentum to the ice floe. The global positions of the camp and beacon at minute 1100 are labeled "hit" in Figure 1.

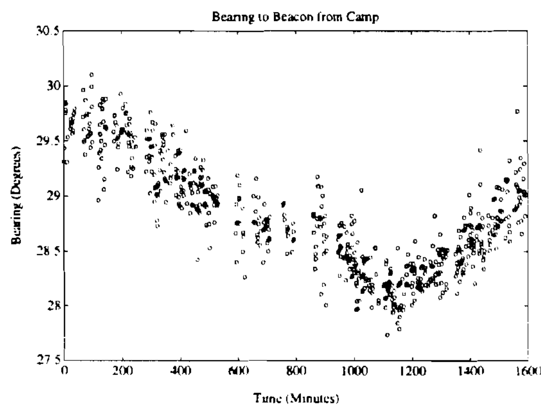

Figure 4: Bearing from Camp to Beacon

IV. CONCLUSION

Relative positions between closely spaced objects can be accurately measured by differencing C/A Code GPS receiver positions when the position measurements are based on the same satellites. For GPS units at 1km separation, the standard deviation of the resulting position difference was found to be 3.9m. When relative positions change slowly, averaging over time can decrease the standard deviation of the relative position error to less than half a meter for GPS units at 1km separation.

APPENDIX: SUBSEQUENT TESTS

In April 1994, GPS positions were recorded at 3km, 6km, and 10km ranges. At these longer ranges, the two GPS receivers did not choose the same satellites as frequently. The GPS receiver computes its position using measurements from four satellites. The percentage of samples in which both receivers chose the same four satellites is given in the table below. The percentage of samples in which 0, 1, 2, and 3 common satellites were chosen is also provided. The duration of the GPS record on which these percentages are based is noted for each range.

		Common Satellites				
Range	Time	0	1	2	3	4
3km	1 hr.	0%	16%	20%	64%	0%
6km	2 hr.	0%	8%	15%	76%	0%
10km	7 hr.	<1%	9%	38%	46%	6%

Many GPS receivers allow the user to specify which of the visible satellites should be used. It would be desirable to coordinate satellite selection, either via a radio link or with a selection algorithm which switched through all the available satellites in such a way as to increase the chance of both receivers selecting the same satellites at some time.

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2.4 Poster Session

The poster session took place on Tuesday afternoon (April 25); however, the posters remained in place until Thursday, April 27. This allowed additional time for attendees to view and discuss the work.

Most of the poster information from SIMI investigators is contained in Volume 1 of this proceedings. Four additional SIMI papers are contained in Section 2.3 of Volume 2.

The authors and titles for the posters are listed below alphabetically by first author. Approximately half of the posters were presented by researchers not involved in the SIMI program. These researchers were given the opportunity to provide information about their posters for inclusion in this volume. If an abstract or additional information on the poster are included in these proceedings, the volume number is noted in the far right column.

Author(s) and Title	Location of Information
Anderson, Robert M., and Burton L. Markham, "Submarine Force Support of Arctic Science: The SCICEX Program."	Vol. 2
Ba žant, Z. P., Y.-N. Li, M. Jirásek, Z. Li, and J.-J. Kim, "Effect of Size on Distributed Damage and Fracture of Sea Ice."	Vol. 1
Bekker, A. T., "Ice Structure Dynamic Interaction: Destruction Ice Model."	Vol. 2
Bekker, A. T., and S. G. Gomolsky "Determination of the Ice Strength for Calculation of the Ice Load."	Vol. 2
Bellingham, J. G., J. J. Leonard, J. Vaganay, C. A. Goudey, D. K. Atwood, J. R. Consi, J. W. Bales, C. Chryssostomidis, "Under Ice Survey Operations with AUV Odyssey."	Vol. 2 in Sec 2.3
Cole, D. M., "Field and Laboratory Experiments and Modeling of the Constitutive Behavior of Sea Ice."	Vol. 1
Cole, David M., Lewis H. Shapiro, Wilford F. Weeks, Carl Byers, John P. Dempsey, Robert M. Adamson, Victor F. Petrenko, and Oleg V. Gluschenkov, "The Barrow Experiments."	Vol. 2
Connor, J. J., S. Shyam-Sunder, A. Elvin, D. Choi, and J. Kim, "Physically Based Constitutive Modeling of Ice."	Vol. 1
Coon, M. D., D. C. Echert, and G. S. Knoke, "Sea Ice Mechanics from 20 cm to 80 km."	Vol. 1
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Video tapes were shown as part of the poster session. The presenters and titles were as follows:

Dirk Kristensen,	"UNOLS/NSF Arctic Research Vessel - Ice Model Tests."
S. Rajan,	"Temporal Evolution of Compressional Wave in Sea Ice."
Pavel Truskov and Anatoli Polomoshnov	"Arctic Buoy Experiments in the Sea of Okhosk."
Chris Woodworth-Lynas	"Ice Scour, Camden Bay Alaska."
Chris Woodworth-Lynas	"Dual Bucket Seabed Sampler."
Max Coon, Stu Knoke, and Skip Echert	"Ice Stick and Slip near the SIMI Camp."

Submarine Force Support of Arctic Science: The SCICEX Program

Robert M. Anderson and Burton L. Markham
Naval Undersea Warfare Center Detachment
Arctic Submarine Laboratory

ABSTRACT

Nuclear submarines have operated in the Arctic on a variety of military missions for nearly 40 years. During these deployments, there have been limited opportunities to support civilian scientific research. The USS PARGO supported increased civilian Arctic scientific research in a 1993 deployment, SCICEX-93. Due to the success of that mission, combining the military needs of the Navy and the Arctic data collection needs of the scientific community has become a reality. In June of 1994 the Navy, the National Science Foundation, the United States Geological Survey, and the National Oceanic and Atmospheric Administration signed a memorandum of agreement to allow the use of U.S. Navy submarines for scientific research in the Arctic. This agreement formalizes a relationship between the continuing critical military missions of submarines and the scientific research that is conducted as a second priority.

SCICEX-93 was the first cruise of a nuclear-powered submarine to the Arctic in which the U.S. scientific community was openly invited to participate in the planning and implementation of the cruise. During SCICEX-93, in one month, the scientists collected data throughout the Arctic resulting in the most complete snapshot of the Arctic environment ever collected by an expedition. Results from this enormous data collection effort are now appearing in the literature.

The resulting memorandum of agreement commits these agencies to perform and fund at least five other such Arctic science cruises at the rate of one per year. The Submarine Force provides the ship and its associated costs, while the scientific agencies provide the equipment and funds for installations, data acquisition and analysis, data classification review, and technical adviser services. Each future SCICEX will have a different thrust area, such as, water chemistry, geophysics, etc. The USS CAVALLA is presently deployed on SCICEX-95, the first of these cruises. The CAVALLA is carrying scientists from the University of Alaska, the University of Texas, Oregon State University, and Columbia University. They will spend at least 45 days under the ice (more that twice the amount of time spent in 1993) and perform a dozen different experiments. The broad area announcements for the 1996 and 1997 cruises will appear soon.

ICE - STRUCTURE DYNAMIC INTERACTION: DESTRUCTION ICE MODEL

Bekker A.T., Far-Eastern State Technical University, Vladivostok, Russia.

The Process of the Ice-Structure dinamic Interaction of a drifting ice cover with sea structures is accompanied by ice distruction and formation ice forses, having complicated, as a rule, probabilistic character. The character of ice distruction may be different depending on geometric parameters of interacting elements, dynamic and cinematic parameters of the process. The complication of discription this process is condition by its complication and high changeableness of the properties of the sea ice as material. The numerical model discribing proccess of distruction ice sheet, is accompanying by split of ice pieces, was offered. Such kind of ice destruction is sufficiently tipical for this problem. The numerical model is bazed on use distruction specific energy of ice as criteria ice destruction.

This model let to discribe as initial penetration process of structure into ice sheet, as and cutting process. The model was verified on rezults of experimental research by auther. The rezults of comparison gave satisfactorify coincidence of the absolute significance contact forsce and its freguencies.

This model let to decide dynamic problem of the ice structure interaction. The rezults of numerical reseach is gave.

Determination of the ice strength for calculation of the ice load.

A. T. Bekker, S. G. Gomolski
Far- Eastern State Technical University, Vladivostok, Russia

Analys of the factors influenceing on the determination of the ice strength was made. It was ascertainmented the boundery conditions of the compression model test of the ice cylinders influence on the ice strength very much.

The boundary conditions on contact of samples with jam plate under the testing can be realized corresponding to the absence of friction, infinite friction or finite friction. With the aim of analysis of boundary conditions on stress and strain state the cylinder with dimensions d=h was considered, where d is diameter and h is height. The finite element method was used to find the stresses in the gravity centers of elements under different boundary conditions.

An analysis of stress and strain state showed that the stress distribution under zero friction was considerably differ from the same with friction. Under the finite and infinite friction the dangerous stress and strain state is formed close to points on the bound of loaded sides. The equivalent stresses were determined for this regions according to different strength theories. The stress analysis showed that if the failure is formed under the same stress level than the registed forces at the failure moment are considerably differ leading to large range of strength values for material.

THE BARROW EXPERIMENTS

By

David M. Cole
US Army Cold Regions

Lewis H. Shapiro, Wilford F. Weeks, and Carl Byers
University of Alaska

John P. Dempsey and Robert M. Adamson
Clarkson University

and

Victor F. Petrenko and Oleg V. Gluschenkov
Dartmouth College

Abstract

As part of ONR's Sea Ice Mechanics Accelerated Research Initiative, a group of researchers collaborated in a set of field measurements to investigate the evolution of the physical and mechanical properties of first-year sea ice through a growth season. The primary objectives of the work were to:

1) Examine the influence of sample size on the strength and constitutive behavior of first-year sea ice through in-situ experiments;
2) Improve our understanding of the interrelations between physical and mechanical properties; and
3) Perform analyzable in-situ experiments on well-characterized ice for use in verifying models based on small-scale isothermal behavior.

To address these concerns for young, mid-winter, and spring ice conditions, replicate sets of loading experiments and physical-properties observations were made in November, 1993; March, 1994; and May, 1994. Each set consisted of in-situ fracture, creep, creep-recovery, and cyclic-loading experiments at a site in Elson Lagoon near Barrow, AK. Small-scale isothermal laboratory measurements of flexural strength were also made.

The efforts of the various authors are given in greater detail in their contributions to Volume I of the Workshop Proceedings.

SEA ICE DEFORMATION AND STRESS, A COMPARISON ACROSS SPACE SCALES

M. D. Coon, D. C. Echert, and G. S. Knoke
Northwest Research Associates, Inc.

J. E. Overland and S. Salo
Pacific Marine Environmental Laboratory

R. S. Pritchard
IceCasting, Inc.

D. A. Rothrock and H. L. Stern
Polar Science Center, University of Washington

ABSTRACT

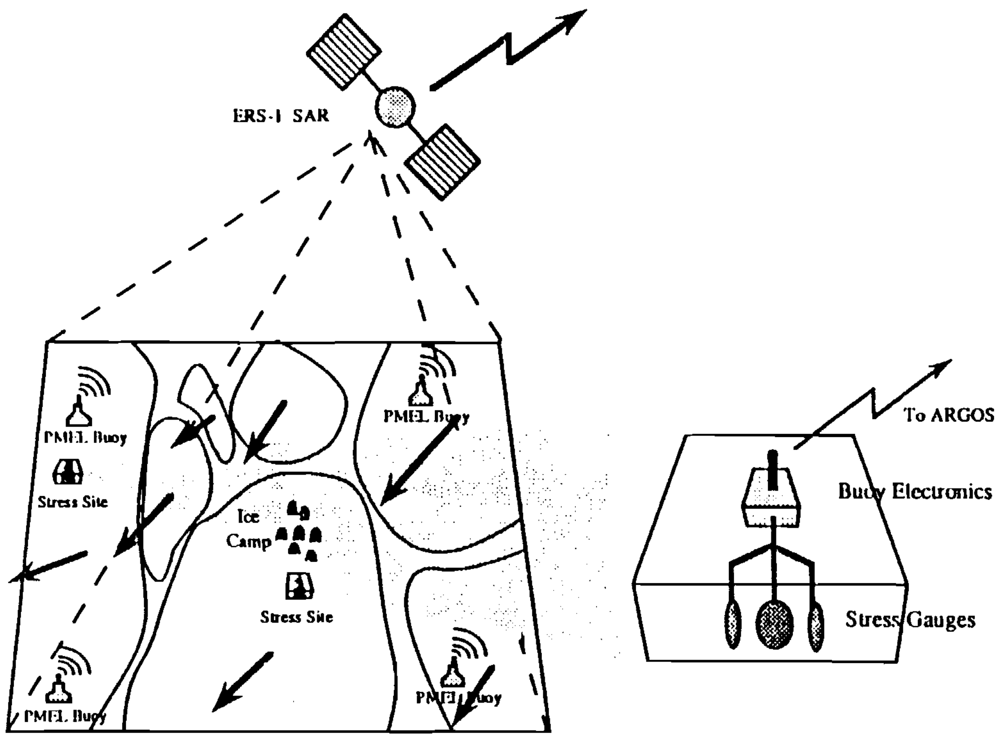
For the first time, simultaneous measurements of sea ice stress on both sides of a lead, ice motion from sequential SAR imagery, and ice motion from drifting GPS/Argos buoys are compared. The lead, which appeared early in Day 35 (Feb. 4), 1994, was observed, relative motions were calculated across and along the lead direction, and stresses were transformed to this same coordinate system. The lead orientation and approximate location were determined from SAR images of the pack ice surrounding the SIMI camp, as well as net ice motion at 3-day intervals. The ice motion around the lead was provided in greater temporal detail by an array of drifting GPS/Argos buoys producing hourly positions. Sea ice stress was measured on each side of the lead using flatjack sensors. The ice motion normal to the lead and the ice stress normal to the lead are compared as well as the shear ice motion and the ice shear stress.

Shortly before the lead opening motion is apparent in the ice motion data, the ice stress state abruptly changed from biaxial compression to uniaxial compression with traction on the lead near zero. We thus measured the stress conditions at lead creation as sheared compression; there was no tension at the time. We observe excellent correlation between ice motions measured with SAR products and drifting buoys. The SAR products provide greater spatial detail and a more precise definition of the orientation of the lead while the drifting buoys provide greater temporal detail. We also conclude that a properly installed 20-cm stress gauge in a single floe can provide a reasonable measurement of the large-scale (50-km) pack ice stress resultant.

We thank R. Colony, R. E. Moritz, and L. McNutt for their helpful technical discussions concerning these data.

Overview of Experiment

These results closely follow the experiment plan described in Section IV of "Contemporaneous Field Measurements of Pack Ice Stress and Ice Strain Measurements from SAR Imagery," by Coon, Knoke, Echert, and Stern (in Proceedings of OCEANS'93, Victoria, B.C., October, 1993). The schematic below, first published in 1991, accurately describes the overview of this 1994 experiment. Note that three satellite systems (ERS-1, GPS, and Argos) were utilized in this experiment.



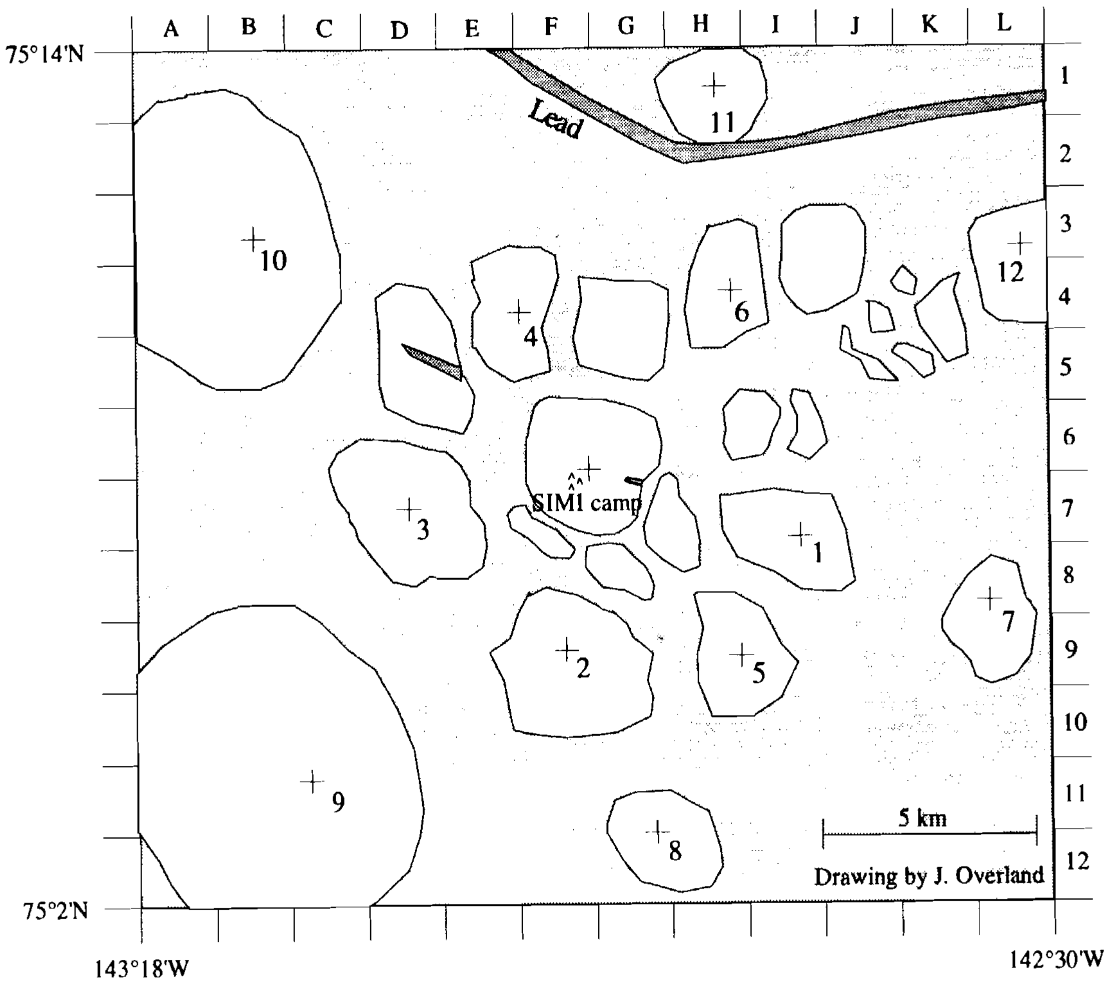
Ice Stress Measurement Sites and Buoy- and SAR-Derived Ice Vectors

In-Situ Stress Measurements

Vicinity of SIMI West Camp

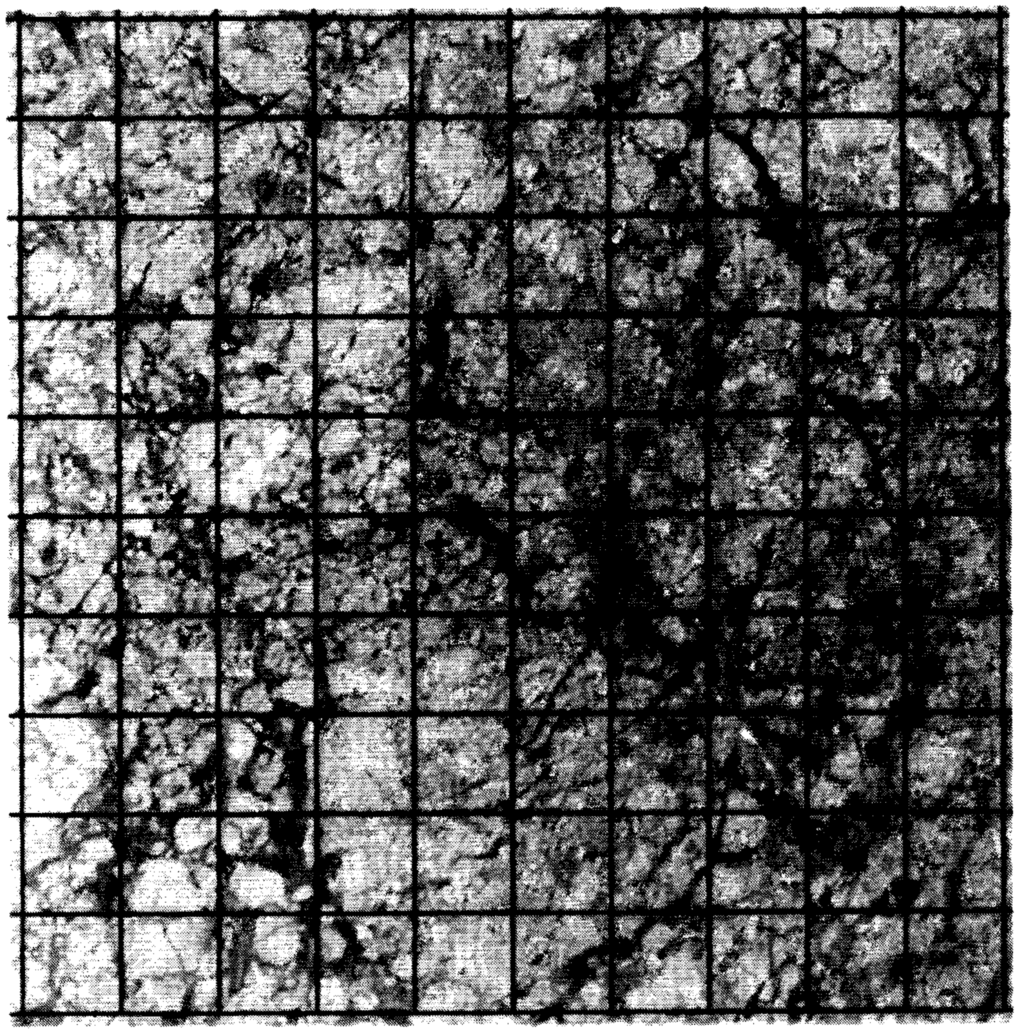
The map shows the locations and numbers of the main floes around the SIMI Camp (later called West Camp) in September 1993. The gray areas indicate small floes, rubble ice, and new ice between the large, multiyear floes. Each plus-sign (+) indicates the site of a PMEL GPS/Argos buoy deployed in September. NWRA stress buoys were deployed on Floe 4 (E4) and at the SIMI camp (F5) in November 1993.

Map 1. Vicinity of SIMI West Camp, September 1993.



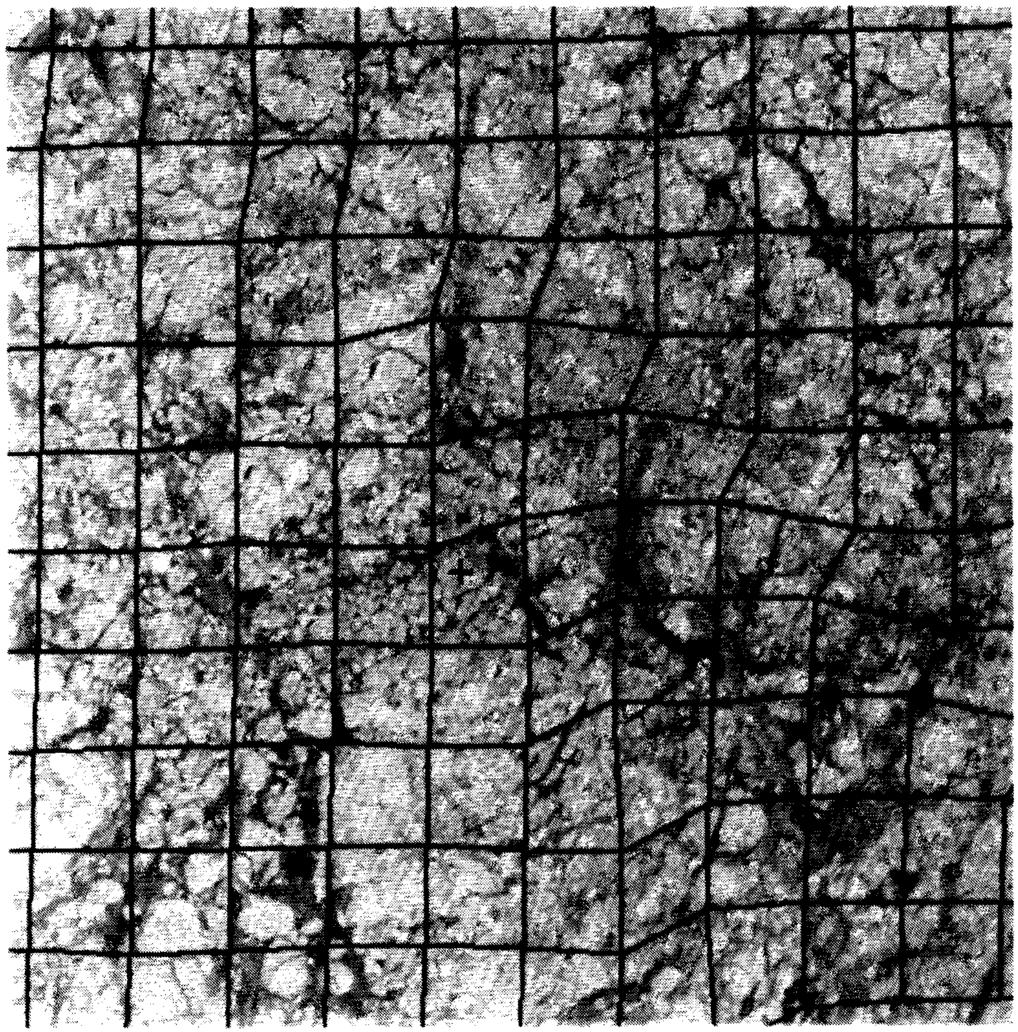
Synthetic Aperture Radar (SAR) Image with SIMI Camp

This is a synthetic aperture radar (SAR) image acquired by the ERS-1 satellite on February 4, 1994 (Day 35). The SIMI Camp is marked with a plus-sign (near the middle of the image). The grid lines have a spacing of five kilometers, so the whole scene is about 50 x 50 kilometers. The image is Copyright ESA 1994.



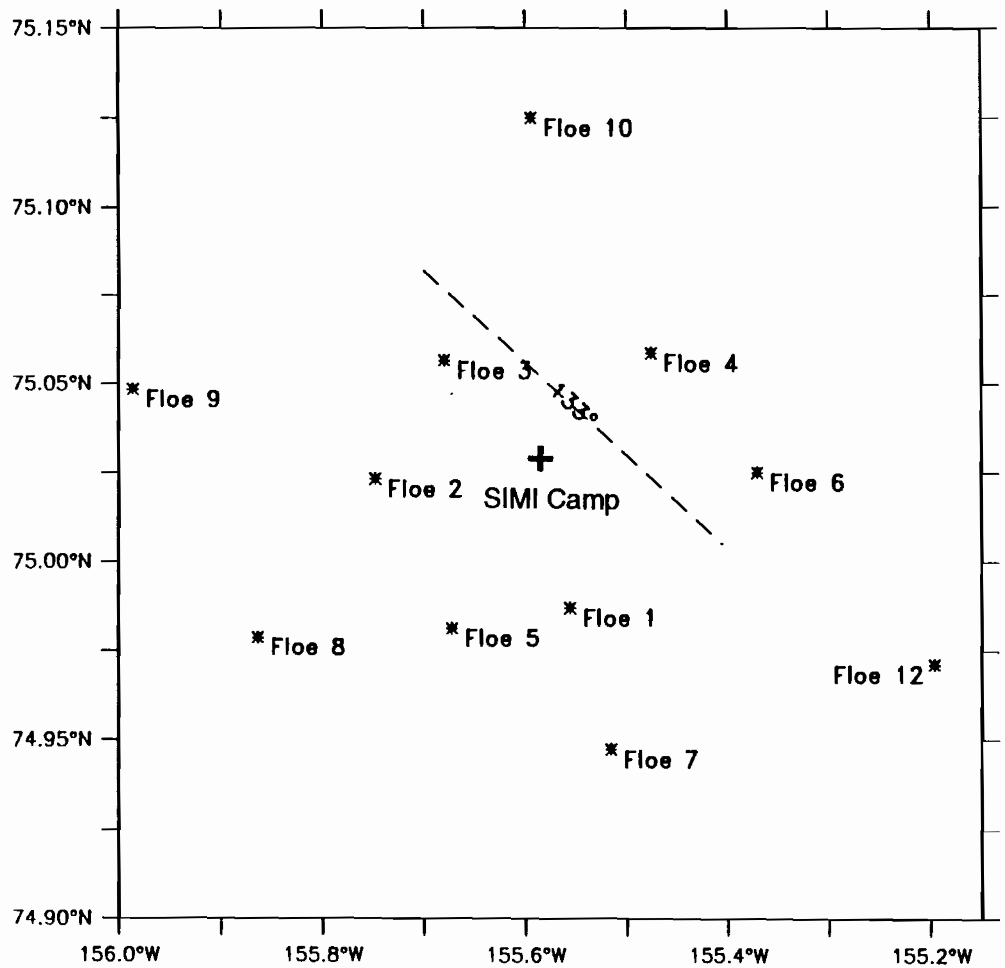
SAR Image with Deformed Grid

This is a SAR image acquired on February 7, 1994 (Day 38). The SIMI camp is again marked with a plus sign (near the middle of the image). The slightly deformed grid shows how the configuration of the sea ice has changed over the three day period. This deformed grid was obtained by an automatic ice-tracking procedure that uses area correlation to find corresponding features in two SAR images. The image is Copyright ESA 1994.



Positions on Day 35, 1994

This figure shows the positions of the PMEL GPS/Argos buoys at the SIMI camp and on the floes around it at 0000Z on Day 35 (February 4), 1994. We also include the orientation (though not necessarily the accurate position) of a lead which separated Floes 4, 6, 10, and 12 from the camp.

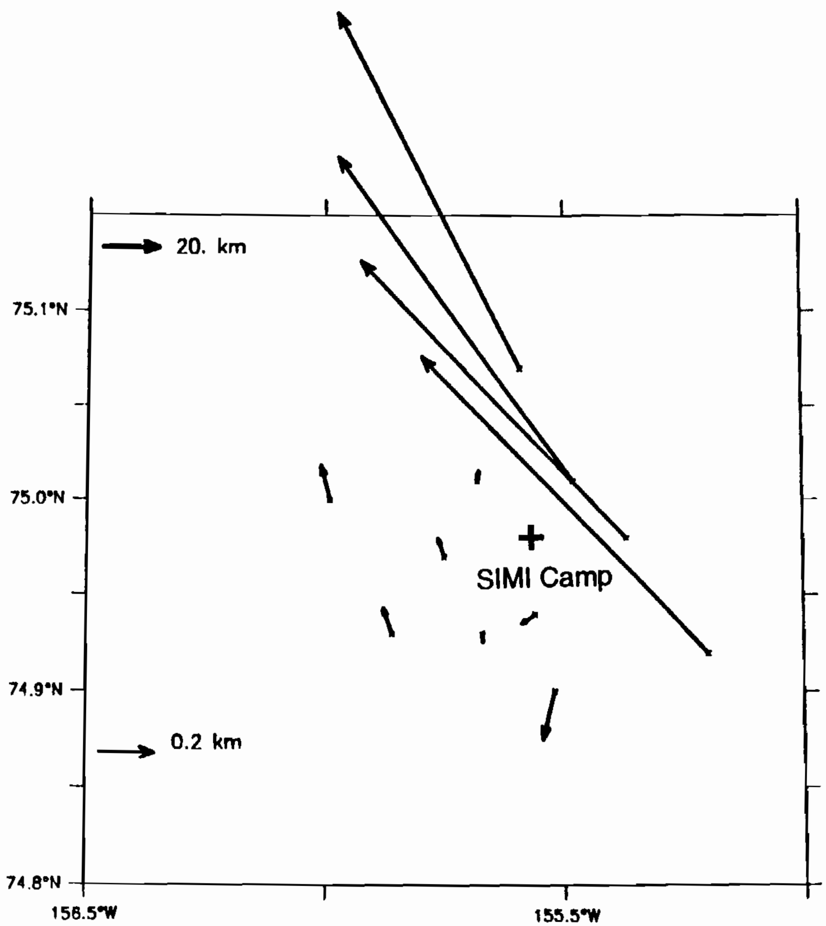


Positions on Day 35, 1994

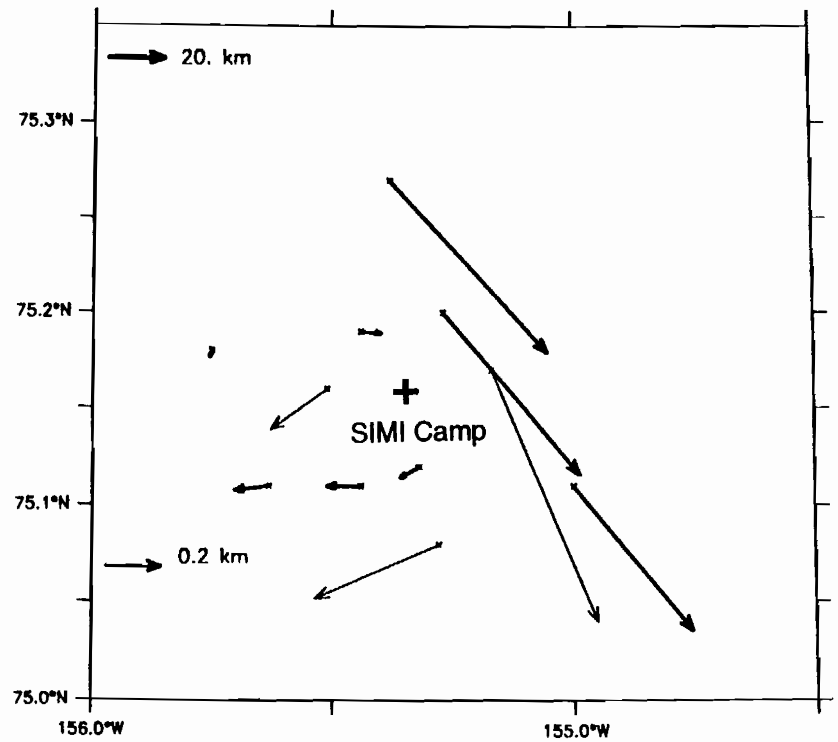
Relative Displacements

These figures depict 3-day displacements of the GPS/Argos buoy array relative to the displacement of the SIMI camp (plus sign). The left figure is Day 35 to Day 38; the right figure is Day 38 to Day 41; the figure axes and the buoy positions are latitude and longitude. The velocity vectors, scaled by the 0.2 km arrow in the lower left corner, indicate buoy displacements relative to the SIMI camp. These arrows are bold if the displacements were obtained from GPS data only and thin if the displacements use any Argos or splined data.

Note the relative displacement of Floes 4, 6, 10, and 12 to the northwest between Days 35 and 38, followed by relative displacements in the opposite directions during the next three days.



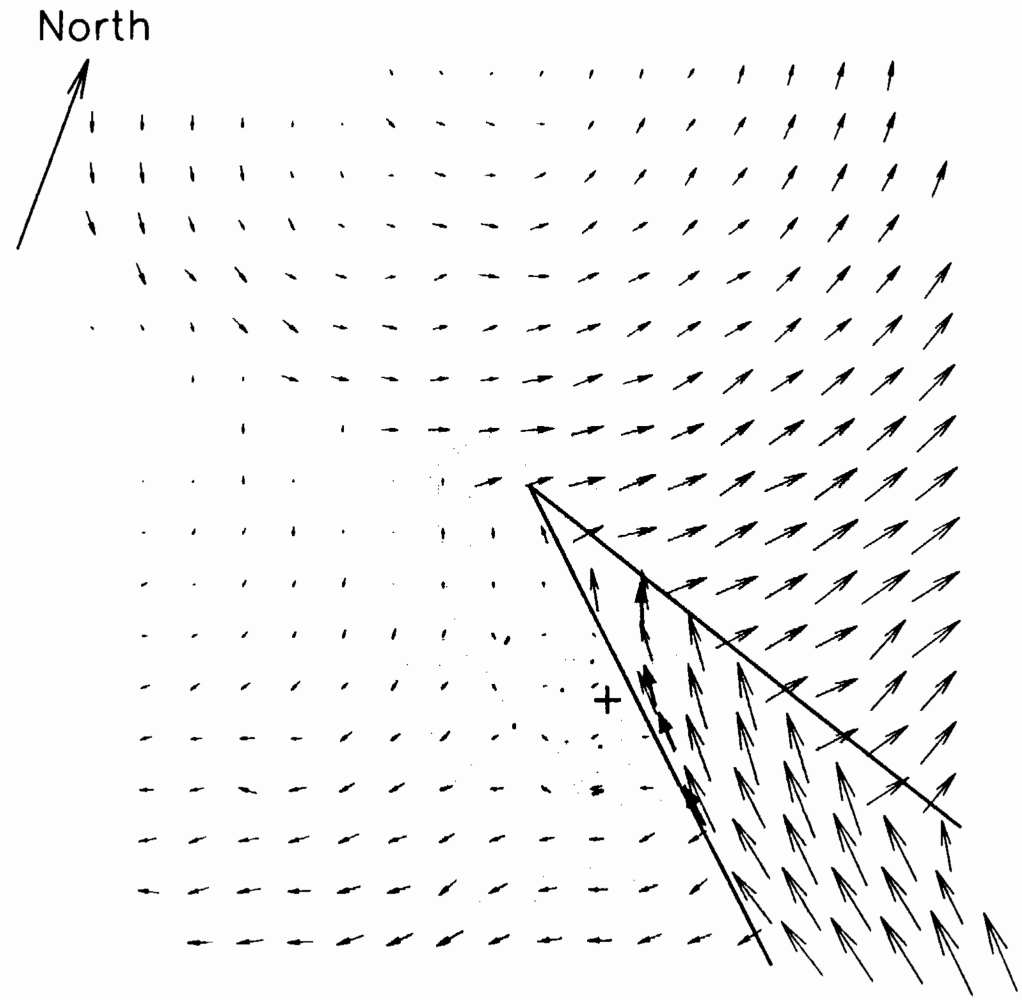
9403500–9403800 Relative Displacement



9403800–9404100 Relative Displacement

Vector Ice Motion Comparison

This figure shows SAR displacement vectors for Days 35 to 38 relative to the SIMI camp (plus sign) on the same 5-km grid as before but for an area of about 85 x 85 kilometers. The gray area corresponds roughly to the portion of the SAR image shown before. The majority of the arrows are displacements derived from the sequential SAR images (exaggerated by a factor of three). The darker arrows show the motion of the PMEL buoys relative to the main camp over the same three-day period (also exaggerated by a factor of three). The two intersecting lines denote the velocity discontinuity lines, implying active leads or ridges. The angle from North to the active lead near the main camp is approximately 133 degrees. These data show excellent correlation between ice motions measured with SAR products and drifting buoys.



Jump in Normal and Shear Velocity Across the Lead

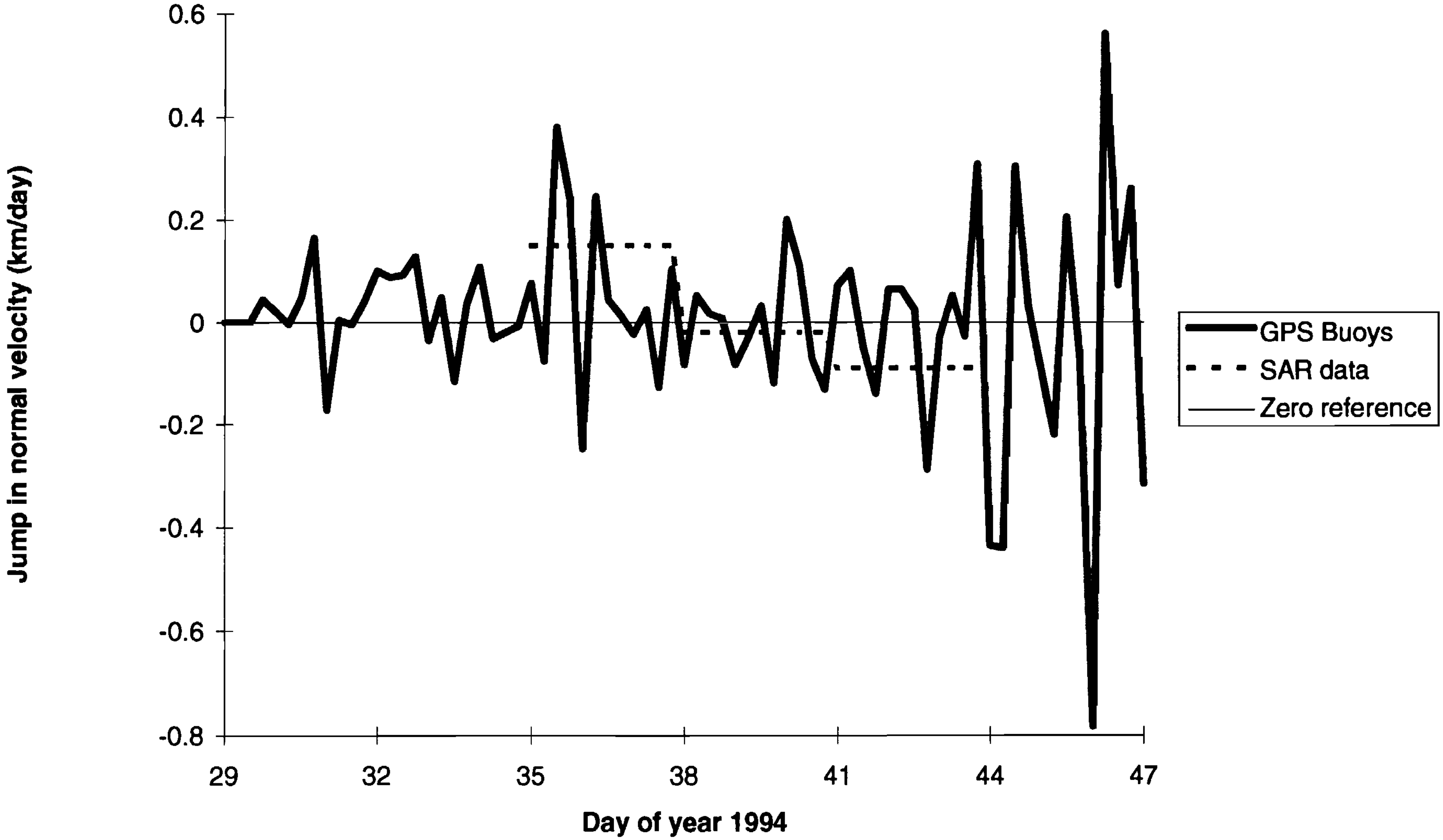
Here we combine data from PMEL's GPS/Argos position buoys with data derived from SAR images. The following two figures compare the jumps in ice velocity normal to the lead and the jumps in shear velocity.

In calculating the ice motions from GPS buoy data, we sub-sampled the relative displacements (buoy displacement - main camp displacement) every six hours and rotated the components to the lead coordinate system. We then averaged the normal and shear components for the far-side buoys on Floes 4, 6, 10, and 12 and subtract the average components for near-side buoys at the main camp and on Floes 1, 2, 3, 5, 7, 8, and 9. A positive shear motion is southeast (Heading 133°T); a positive normal motion is northeast (Heading 043°T).

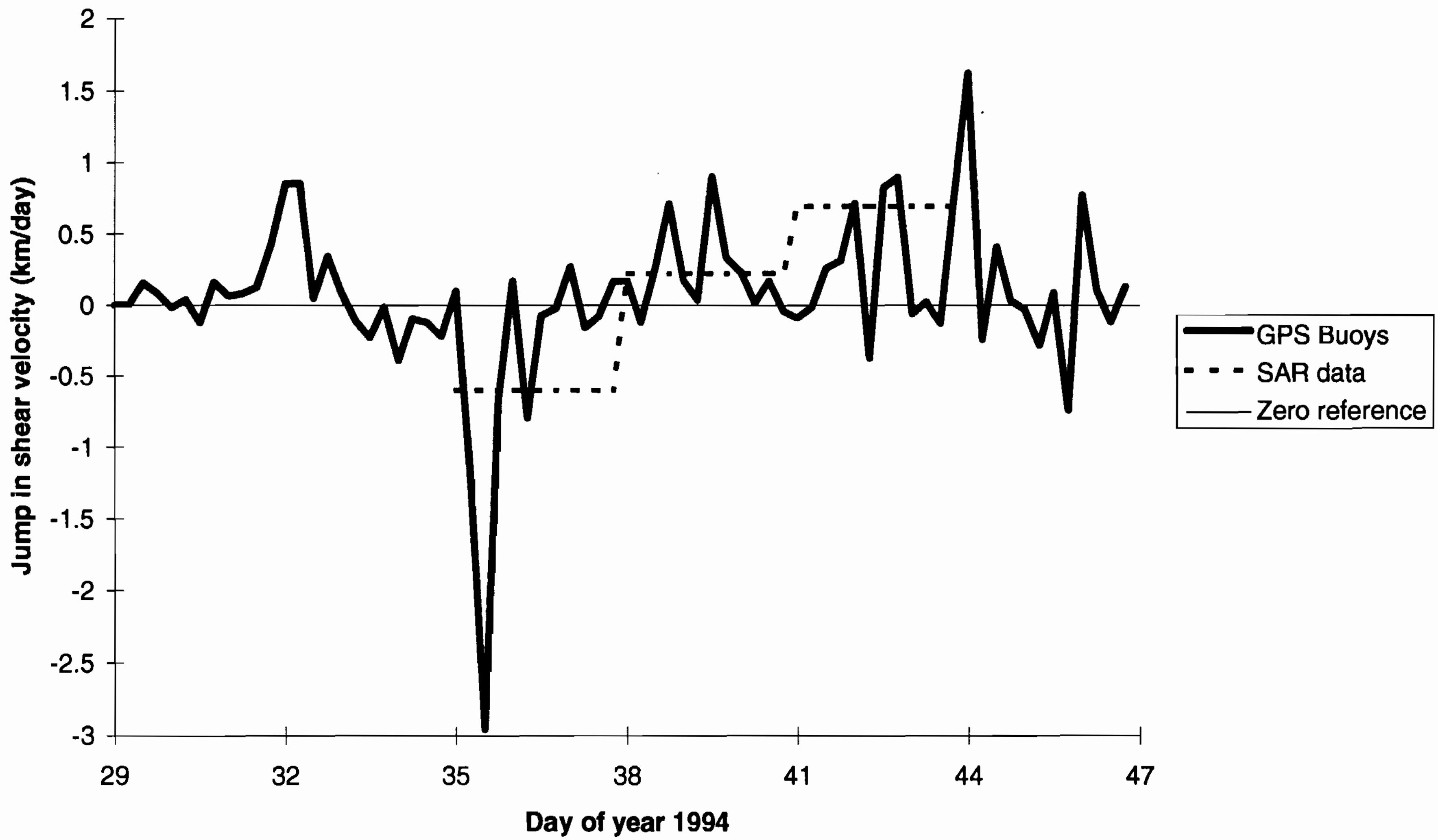
In calculating the ice motions from SAR products, the velocity jump across the lead was resolved into components parallel (shear) and perpendicular (normal) to the lead. The velocity jump is the difference of the average velocities of ten locations on the far side of the lead from camp and of ten locations on the same side of the lead as the camp.

Most of the relative motion toward the northwest occurred in roughly 12 hours of Day 35, while the southeastward motion occurred more gradually. The jump is shear velocity was larger that the jump in normal velocity for both events.

Jump in normal velocity across the lead derived from 6-hour GPS positions and jump in normal velocity across the lead derived from 3-day SAR images



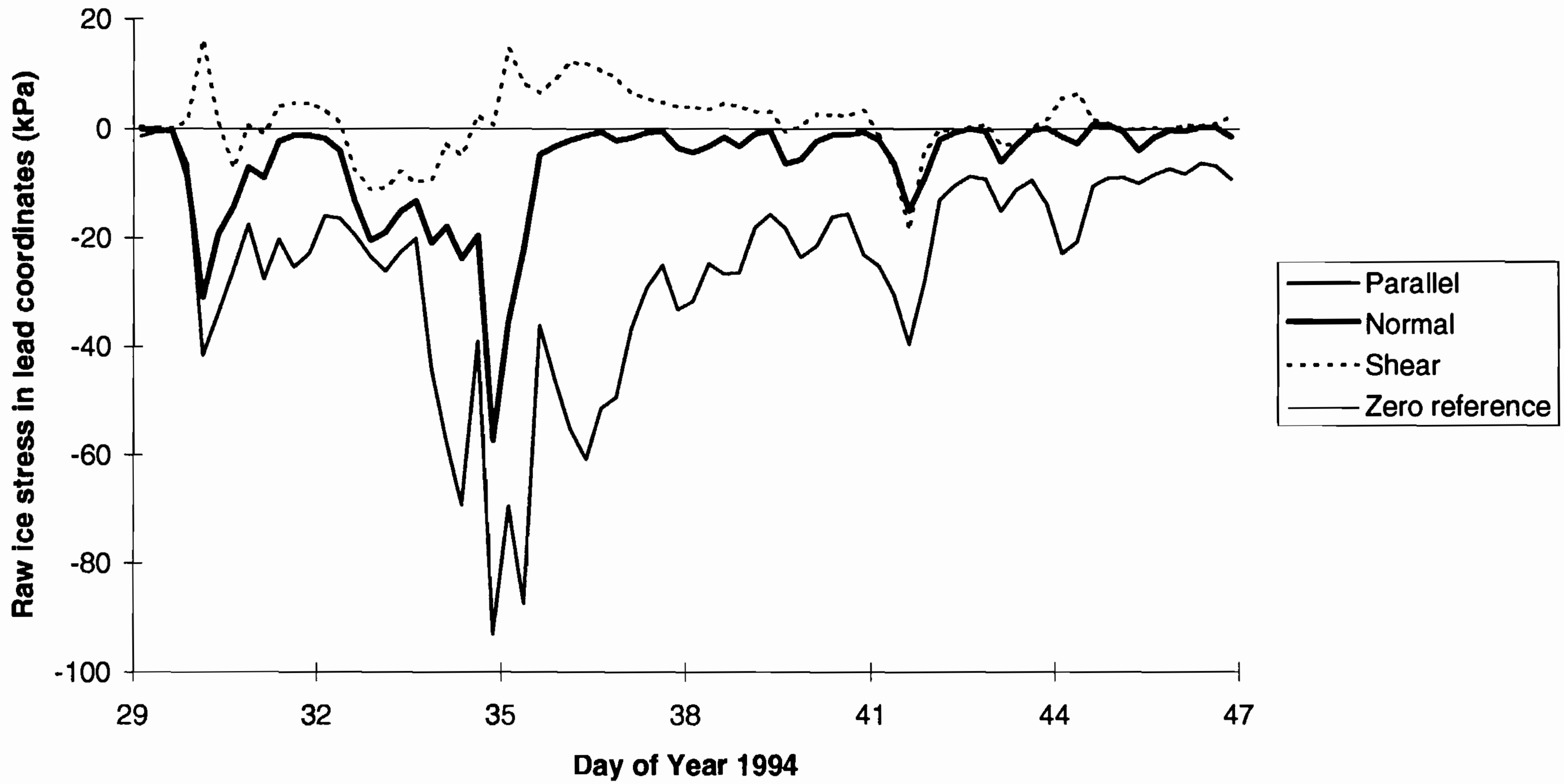
Jump in shear velocity across the lead derived from 6-hour GPS positions and jump in shear velocity across the lead derived from 3-day SAR images



Sea Ice Stress Measured at Floe 4 Expressed in Lead Coordinates

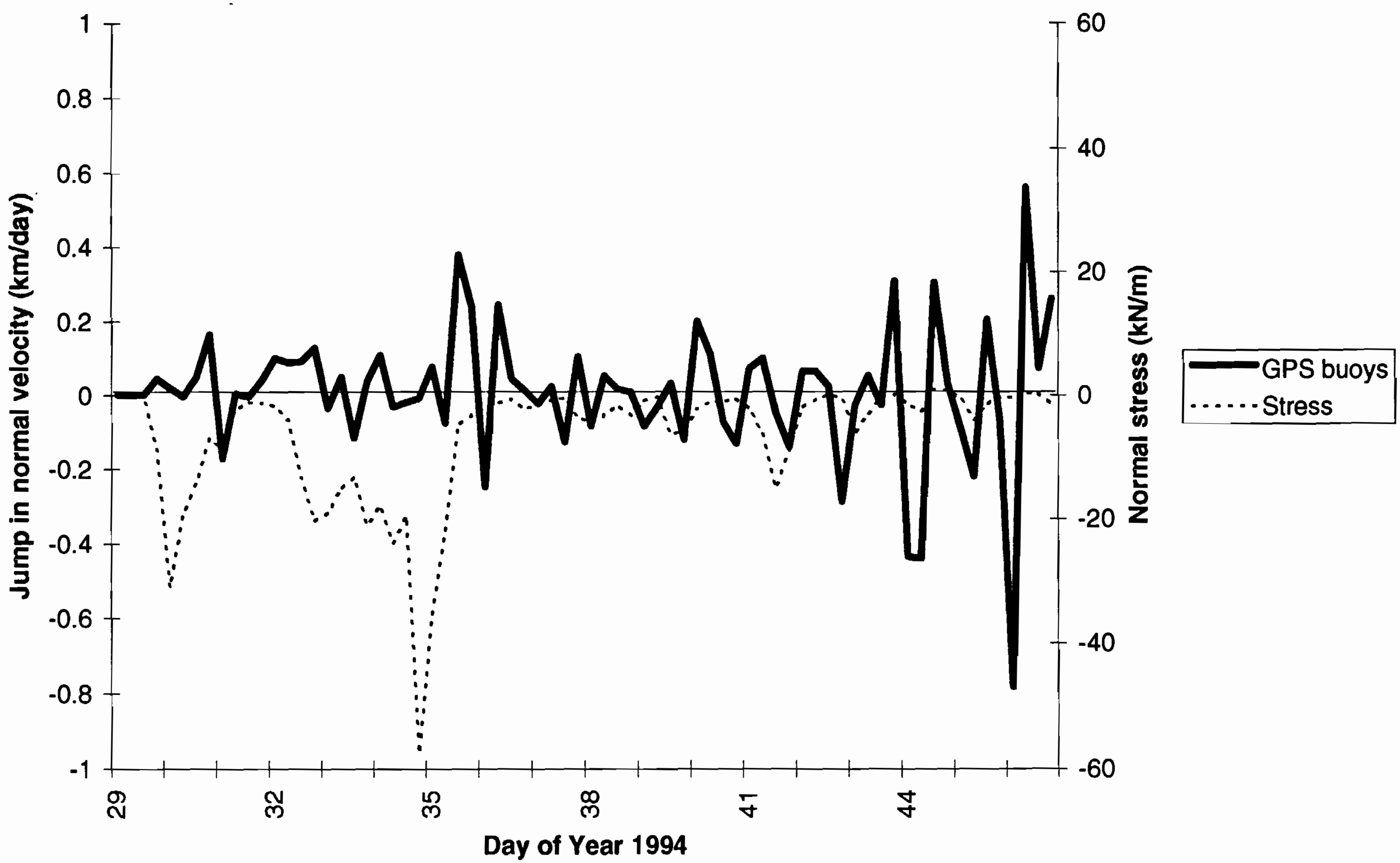
Sea ice stress was measured in Floe 4 in three directions in the horizontal plane using flatjack ice stress sensors. Coordinate transformations of 6-hour averaged data yield the parallel, normal, and shear stresses in lead coordinates shown below. The term 'raw ice stress' indicates that we have not included the effects of the inclusion factor of the stress sensor in the ice.

Shortly before the beginning of Day 35 (when the lead activity was apparent in the ice motion data), the ice stress state abruptly changed from biaxial compression to uniaxial compression. The traction on the active lead near zero for at least 11 days following lead creation. Note that there was compression in both directions when the lead was created at the beginning of Day 35, indicating shear failure of the pack ice, not tensile failure.



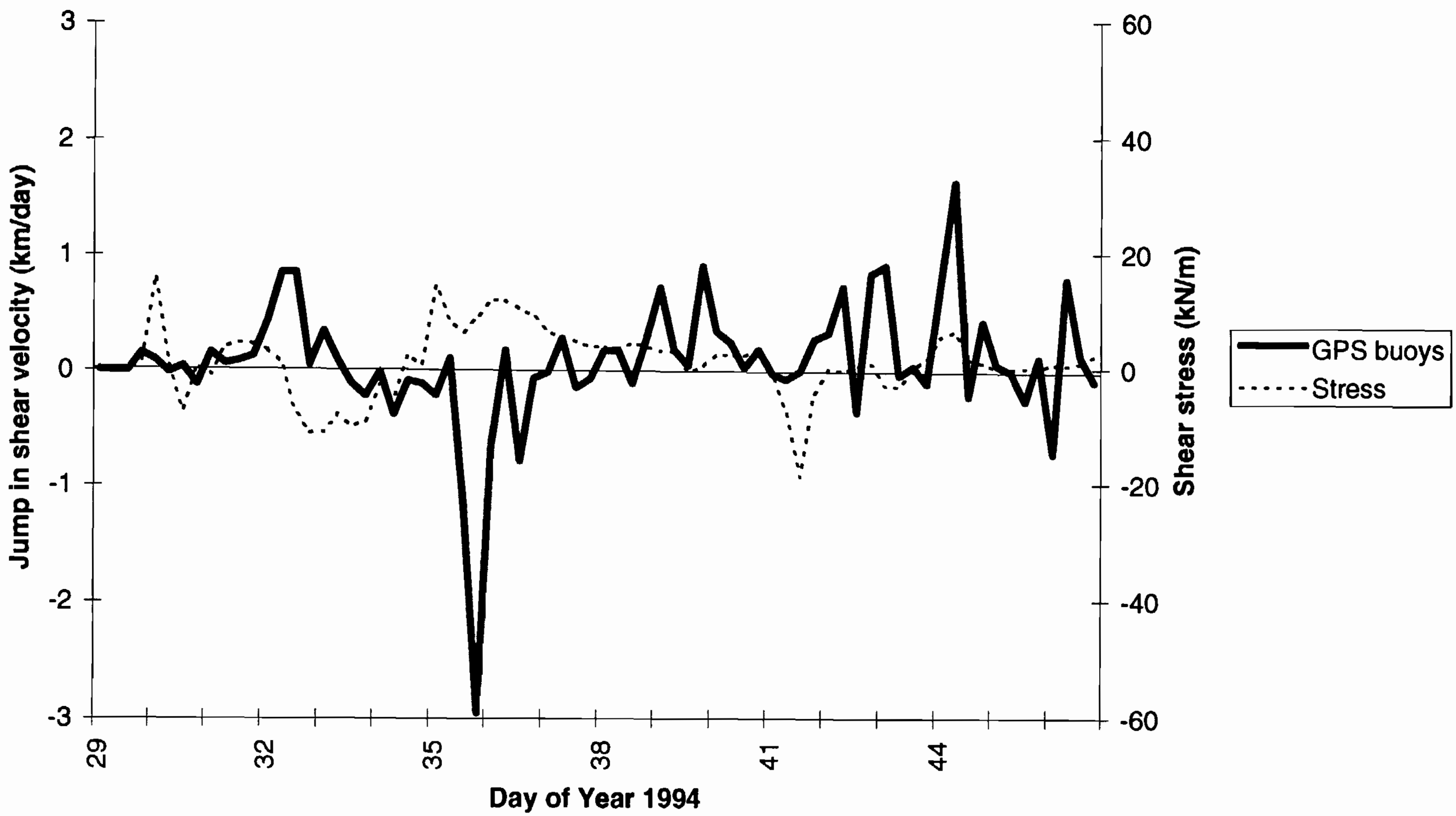
Normal Stress and Jump in Normal Velocity

The ice stress normal to the lead and the jump in ice velocity normal to the lead are plotted versus time. Positive motion is opening, and positive stress is tension. Ice stress normal to the lead plummets shortly before the lead opening is apparent in the ice motion data. The stress normal to the lead remained small (less than 20 kN/m) for the next 11 days.



Shear Stress and Jump in Shear Velocity

The ice shear stress and the jump in ice shear velocity are plotted versus time. During positive shear motion, the opposite side of the lead moves to the right. Positive shear stress has the same sense. The shear stress is generally small (less than 20 kN/m) for entire time period.



A Coupled Ice-Ocean-Atmosphere Model of the Bering Sea

Katherine Hedstrom
Institute of Marine and Coastal Sciences
Rutgers University

April 24, 1995

Abstract

Prof. Amanda Lynch and Mr. Bill Chapman have constructed a coupled atmosphere-ice model, consisting of the NCAR RegCM2 atmospheric model an an ice model with Flato-Hibler dynamics and Parkinson-Washington thermodynamics. Our goal has been to add an ocean model to this coupled system in order to determine what effect this will have on the model results.

Our approach has been to create a coupled ice-ocean system which can replace the ice component of the ice-atmosphere model. We are using the S-coordinate Primitive Equation ocean-circulation Model (SPEM 5.1) and the ice model mentioned above. This ice-ocean model is driven by daily ECMWF products or by the atmosphere fields from the coupled ice-atmosphere model. All of these runs are done as a hindcast of the year 1988 in the Bering Sea. The grid used has a uniform resolution of 63 km. Monthly means from the ice and ice-ocean models show that the inclusion of an active ocean does affect the results, although it is not clearly an improvement.

1 Introduction

A number of interesting processes are observed in the polar regions, many of which are poorly represented or completely left out of global climate simulations. Omitted processes which are believed to be important include atmospheric radiative processes involving ice crystals, ice-phase hydrology and permafrost, and sea ice dynamics and lead thermodynamics. Processes which would hopefully be improved with added resolution include the orographic effects and cloud distribution. The Arctic Region Climate System Model (ARCSyM) project is an attempt to determine which processes are required to accurately represent the polar climate. A regional coupled ice-atmosphere model has been constructed for sensitivity studies as described in Lynch et al. [6]. They evaluated the model response to addition of processes such as ice dynamics and ice phase physics in clouds.

The atmospheric component of the model is the NCAR RegCM2 (Giorgi et al. [2] and [3]) while the ice model has Flato-Hibler dynamics (Flato and Hibler [1]) and Parkinson-Washington thermodynamics (Parkinson and Washington [7]). The ice component contains a simple mixed-layer ocean for storing heat. The current project is to replace this simple ocean with the S-coordinate Primitive Equation ocean Model (SPEM; Haidvogel et al. [4]; Hedstrom [5]).

Our approach for coupling SPEM into ARCSyM is to take the ice component and create a coupled ice-ocean model. The ice model and the ice-ocean model were driven with ECMWF forcing fields prior to attempting a full ice-air-ocean coupling. These are the simulations which will be described here, using fields from the year 1988.

2 Ocean model configuration

The domain used in the atmospheric process study covers the Bering Sea. A resolution of 63 km was chosen to resolve the mesoscale atmospheric features. We used the same grid, although we have added seven grid points around the edge to accommodate the multigrid solver used by the ocean model. These edge points can also be used for sponge boundary conditions if necessary. The ETOPO5 topography on this grid is shown in Fig. 1. Notice that at this resolution there are jumps over over 1000 m between adjacent grid points. The ocean model is ill-behaved when these steep slopes are under-resolved so the bathymetry used was that shown in Fig. 2, which also shows the land mask.

The ocean model boundary conditions are a barotropic inflow of 10.8 Sverdrups on the eastern edge in the Gulf of Alaska (Reed et al. [8]), a barotropic outflow of 10 Sverdrups on the western edge south of Kamchatka Peninsula, and 0.8 Sverdrups going through Bering Strait and out the northern boundary. A strong boundary eddy developed at the western edge so a simple radiation condition was applied there to the temperature, salinity and the north-south component of velocity. The phase speed chosen was that of the largest (imposed) outflow velocity (Roberta Young, personal communication). A typical example of the barotropic streamfunction for the ocean model is shown in Fig. 3.

3 Ice-ocean coupling

3.1 Momentum coupling

The momentum coupling is of the traditional quadratic form with a turning angle of 25°:

$$\vec{\tau} = \rho_w C_d |\vec{v}_w - \vec{v}_i| \left[(\vec{v}_w - \vec{v}_i) \cos\theta + \mathbf{k} \times (\vec{v}_w - \vec{v}) \sin\theta \right] \quad (1)$$

Observationally, the drag coefficient C_d varies from 0.0011 for first year ice to 0.0055 for multiyear ice. We attempted to use a value of 0.0055, but the model developed an instability. We compromised on a value of 0.0022, for which the model ran stably for a year. The nature of the instability we observed is a strong local flow which is oscillating in time. We believe it to be exacerbated by the nonlinear stress, so that once the ice-ocean shear reaches a critical value, the stresses cause one or both velocities to reverse and the shear to be even larger in the opposite direction at the next timestep. It may be possible to design a time filter to damp these oscillations.

3.2 Salt flux

The ice model keeps track of the amount of ice grown or melted through thermodynamic processes (thermo_growth). This is used to find the surface salt flux into the ocean:

$$F_S = \frac{30.0 \text{thermo\_growth}}{dt} \quad (2)$$

where dt is the timestep and the factor of 30.0 comes about by the assumption that the salinity of the surface water is 30 parts per thousand and the salinity of the ice is 0.0.

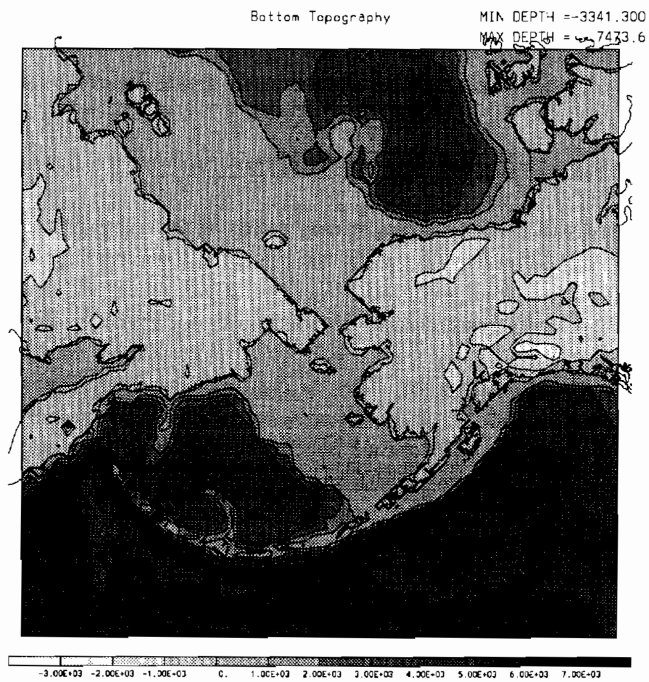


Figure 1: The ETOPO5 bathymetry on the Bering Sea grid.

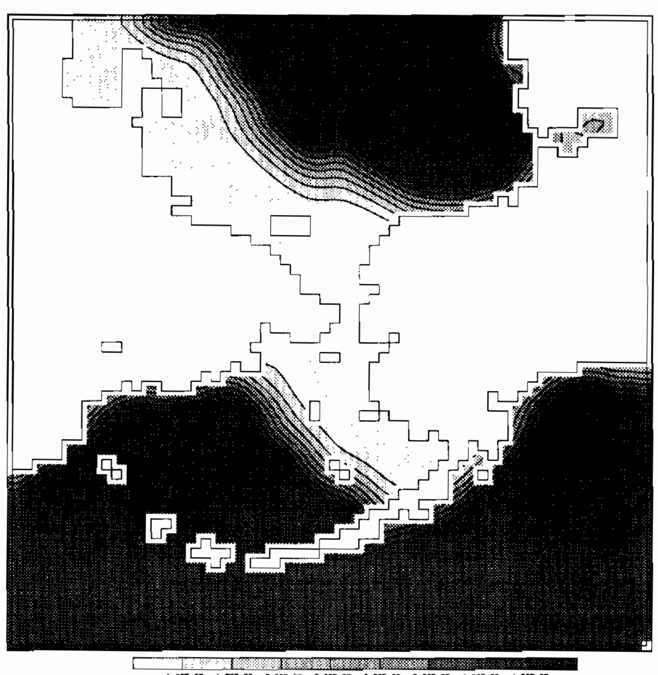


Figure 2: The smoothed bathymetry and the land mask for the Bering Sea grid.

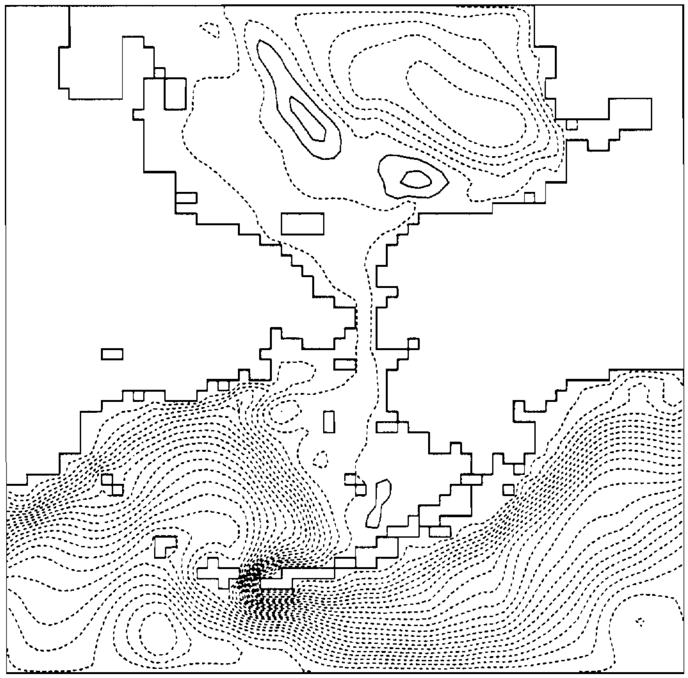


Figure 3: The barotropic streamfunction after one year of simulation.

3.3 Thermal coupling

The Parkinson-Washington thermodynamics separately treats the ice-covered portion and the ice-free portion of each grid cell, and includes two different ocean temperatures. In the coupled model, we have only one surface ocean temperature. For now we have kept the under-ice upward heat flux (F_w) at 2 W/m^2. The difference between this and the heat flux through the ice determines the change in thickness at the bottom of the ice.

The surface ocean heat budget is computed as the sum of the contributions from the ice-free and ice-covered portions. The flux into the water in ice-covered regions is $-F_w$ while the ice-free regions have a thermal balance given by:

$$Q = SH + LH + \epsilon_w \cdot LW + (1.0 - \alpha_w)SW - \epsilon_w \sigma T^4 \tag{3}$$

where SH is the sensible heat flux, LH is the latent heat flux, ϵ_w is the longwave emissivity of water, α_w is the shortwave albedo of water, σ is the Stefan-Boltzmann constant, and T is the surface temperature of the water in degrees Kelvin. The heat flux as seen by the ocean model is

$$F_T = \frac{(-AF_w + (1 - A)Q)}{HC} \tag{4}$$

where A is the fractional ice cover and $HC = 4.2 \times 10^6$ is the heat constant for water.

The ocean temperature is timestepped and then checked to see if it contains temperatures colder than freezing. If so, the temperature is set to freezing and the corresponding amount of ice is frozen. The surface waters are also checked for warm temperatures under ice in which case the ice would be melted.

4 Results

Both the ice model and the ice-ocean model were forced with geostrophic winds derived from the ECMWF surface pressure and the surface air temperature. The initial conditions were 2.0 m thickness of ice north of a "typical" ice edge just south of the Bering Strait. The ice concentration to the north was 95% to represent 5% leads. We assume that the model will find its own climatology and therefore the details of the initialization are not important.

The ice concentration and thickness averaged over the month of June are shown in Fig. 4 for both the ice model and the ice-ocean model. The large-scale features such as Arctic ice extent are similar between the two models, but the details differ. The coupled model exhibits a banded structure that is absent from the ice model. The coupled model is also lacking the ice in the Bering Sea. It is not clear in the figure, but the ice velocities are larger in the ice model than in the coupled model.

The corresponding plots for the month of December are shown in Fig. 5, in which the two models have diverged to a greater degree. In particular, the coupled model has a band of low ice concentration in the Arctic at a season in which one would expect almost complete ice coverage. Examination of the growth plots shows that the coupled model is slower to start growing ice in the fall, perhaps because of the added heat reservoir in the ocean component. The plots of the surface ocean temperature (Fig. 6) show that both models have a net warming throughout the year. The temperature started near the freezing point on January 1 and is substantially warmer in the southern half of the domain the following December. The ice model becomes warmer than the coupled model since the heat is trapped in a 30 m swamp ocean. In view of these large temperature drifts, we feel that the next step is to try more realistic forcing fields, both from the coupled ice-atmosphere model, and within a fully coupled ice-atmosphere-ocean model.

5 Discussion

We have coupled the ARCSyM ice model with the SPEM ocean model as a preliminary step in creating a fully coupled ice-air-ocean model. It is clear that the ocean modifies the results when using the ECMWF forcing, although both models exhibit a net warming throughout the year. There are deficiencies in the forcing used here; for instance, the clouds are represented by one value per month. We look forward to trying the fully coupled ice-air-ocean model.

6 Acknowledgments

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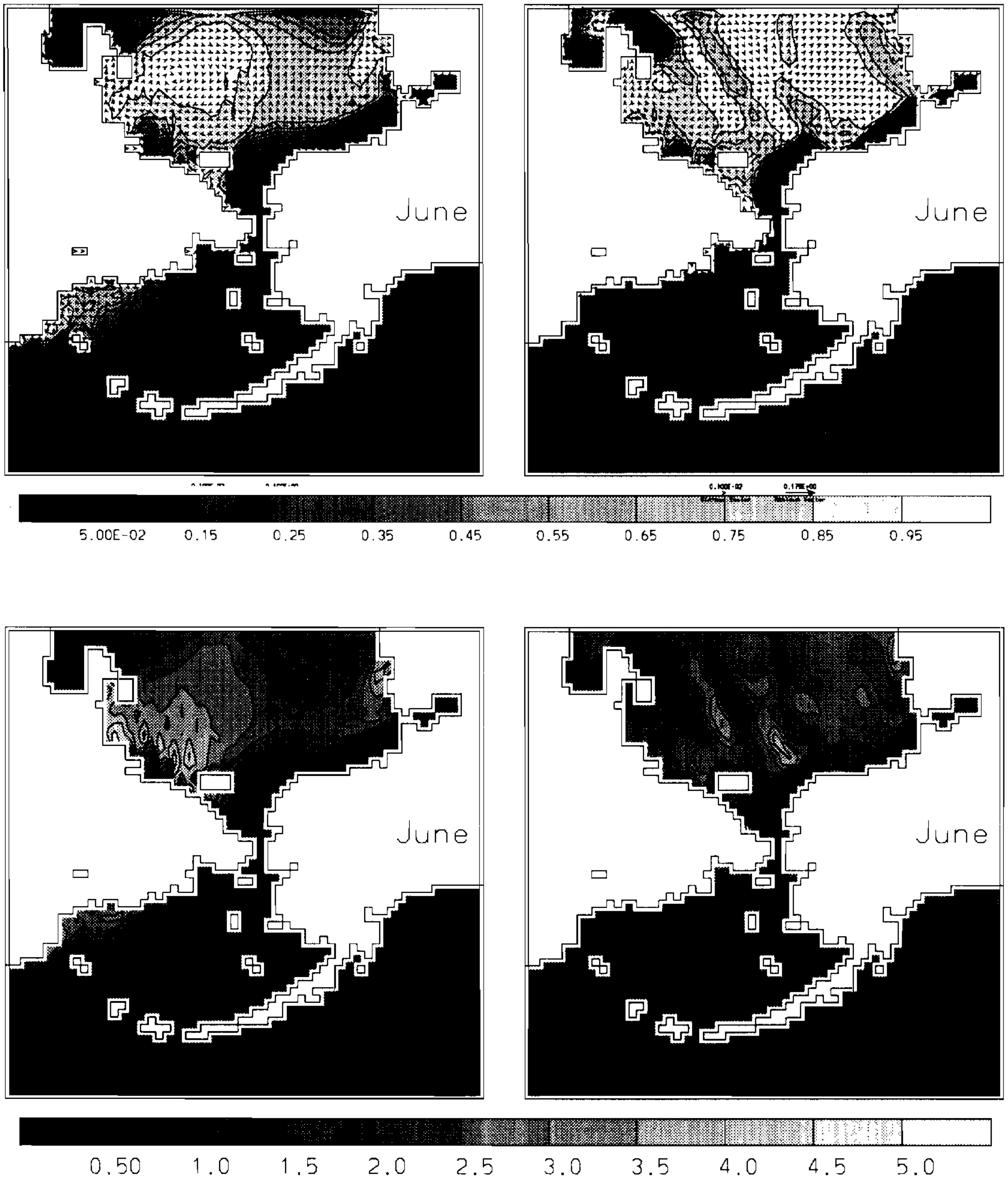

Figure 4: June monthly mean plots of the ice fields. The plots on the left are from the ice run and the plots on the right are from the ice-ocean run. The upper panel shows the ice concentration and the ice velocity. The maximum velocity for the ice simulation is 0.4 m/s while the maximum ice velocity of the ice-ocean simulation is 0.175 m/s. The lower panel shows the effective ice thickness $(h \cdot A)$.

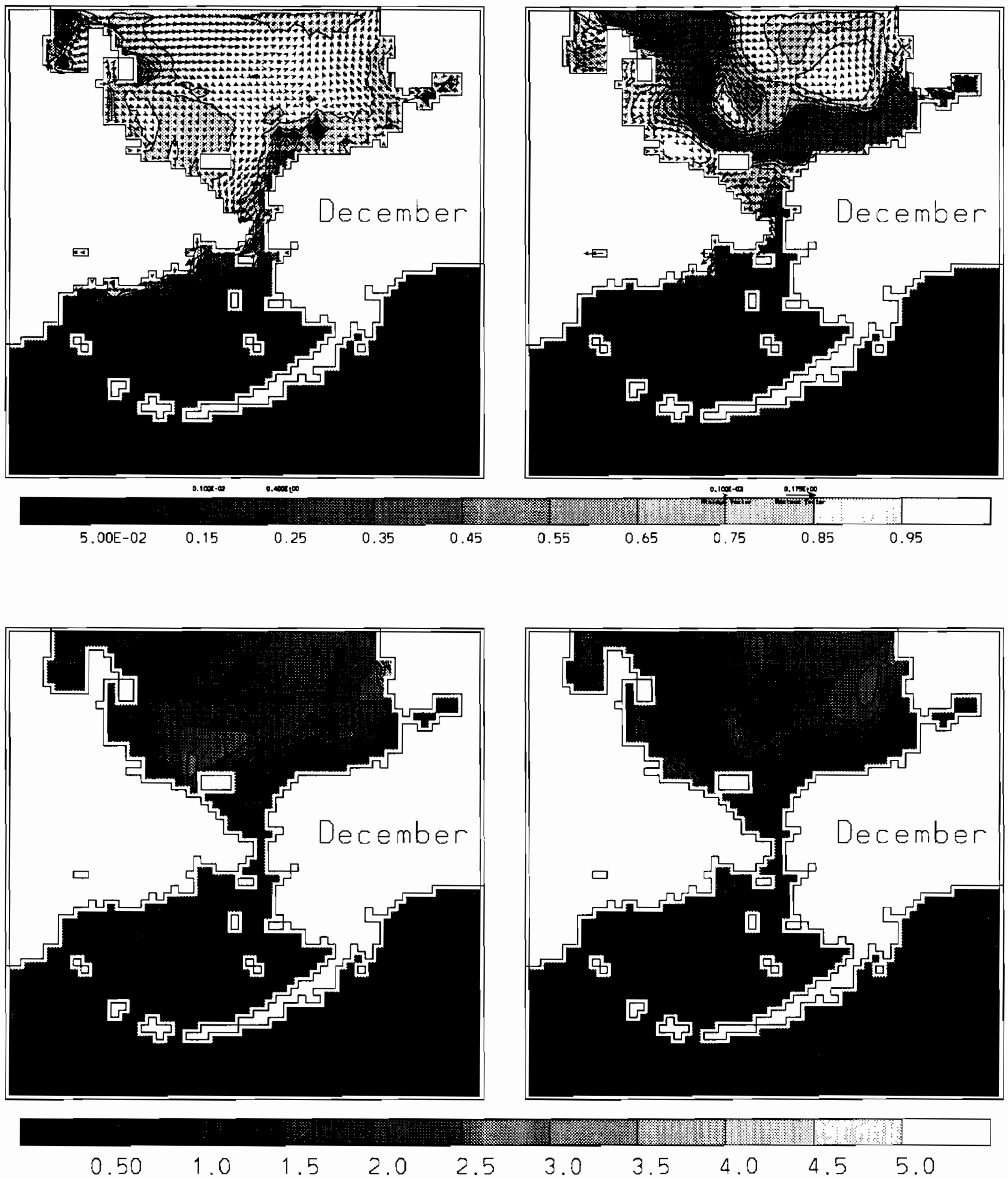

Figure 5: December monthly mean plots of the ice fields. The plots on the left are from the ice-only run and the plots on the right are from the ice-ocean run. The upper panel shows the ice concentration and the ice velocity. The maximum velocity for the ice simulation is 0.4 m/s while the maximum ice velocity of the ice-ocean simulation is 0.175 m/s. The lower panel shows the effective ice thickness $(h \cdot A)$.

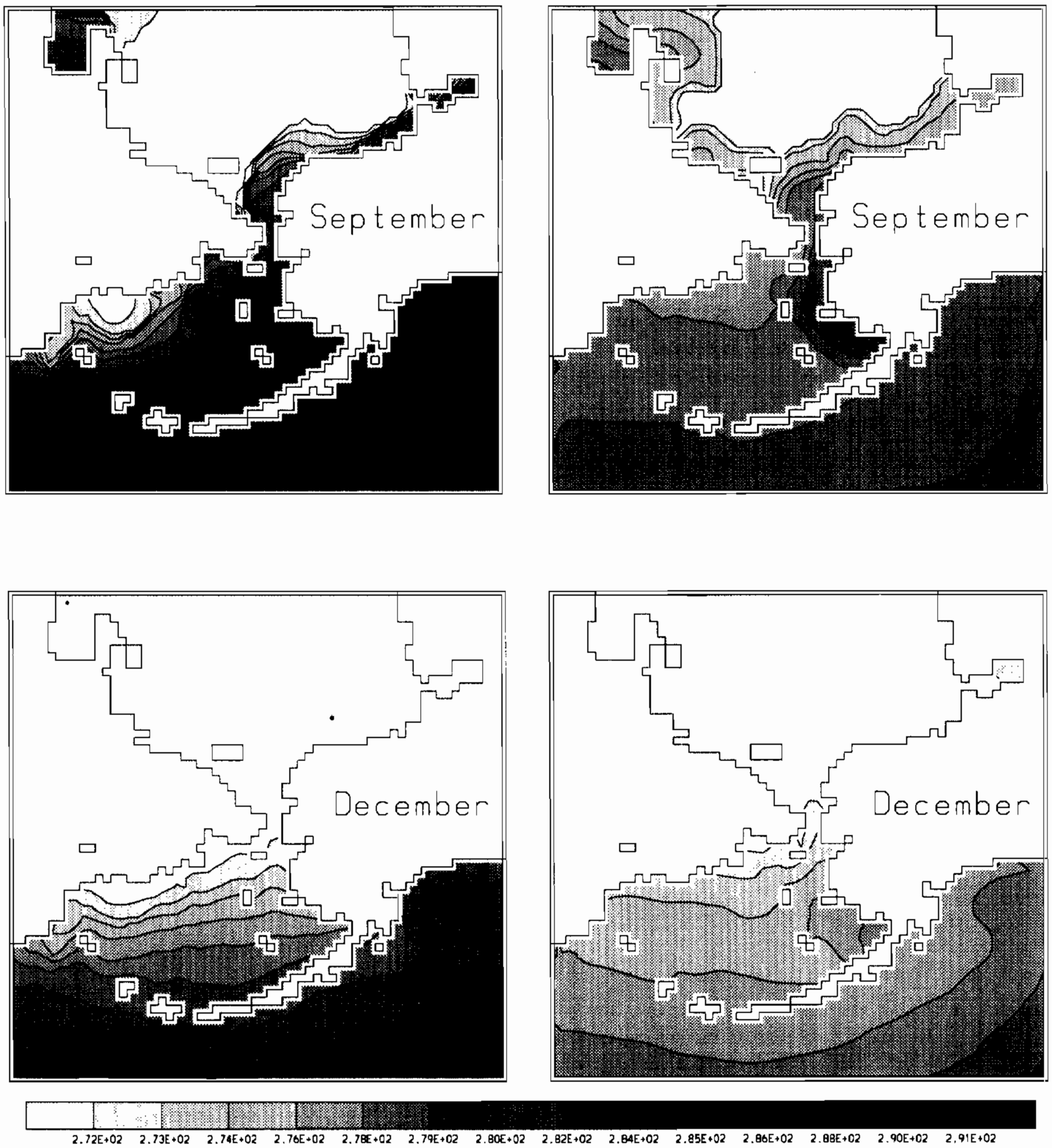

Figure 6: September and December monthly mean plots of the surface ocean temperature. The plots on the left are from the ice-only run and the plots on the right are from the ice-ocean run. The values are in degrees Kelvin.

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INFORMATION STATES IN SEA ICE IMAGERY

Constitutive Relationships for SAR Imagery

Bryan Kerman

Atmospheric Environment Service
Canada Centre for Inland Waters
Burlington Ontario Canada

OBJECTIVE:

Examine the information (entropy) inherent in SAR sea ice imagery in order to

1. Characterize and recognize ice type
2. Provide a bridge to stochastic micromechanics description of sea ice
3. Provide a bridge to applications (navigation, loads, fracture mechanics)
4. Develop an image compression algorithm based on inherent physical image structure.

BACKGROUND:

Consider an arbitrarily coloured image of a SAR image of sea ice.

Observe some obvious structures coded to colour but also overlap from one ice type to another.

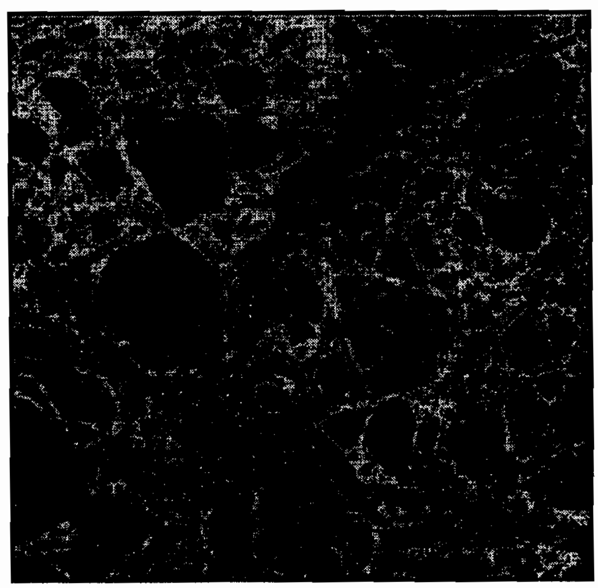

Figure 1 SAR image (L band HV polarization) of wintertime sea ice in the transitional zone between shorefast and off-shore pack ice fields in the Beaufort Sea.

Consider classical single point statistics, such as probability density functions (Fig. 2)

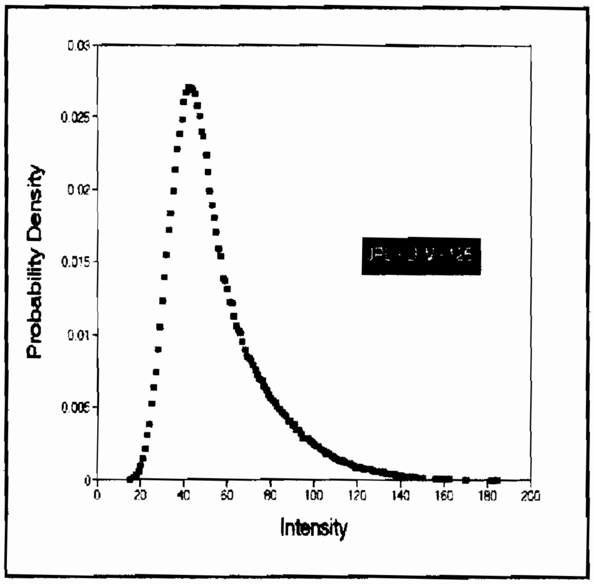

Figure 2 Probability density function corresponding to Figure 1.

Observe no obvious demarkation points with intensity

Expand consideration to nearest neighbours (defined as x=1)

Consider probability of a neighbour being larger than selected pixels at a given intensity (Fig. 3)

Observe that some indication of structure exists.

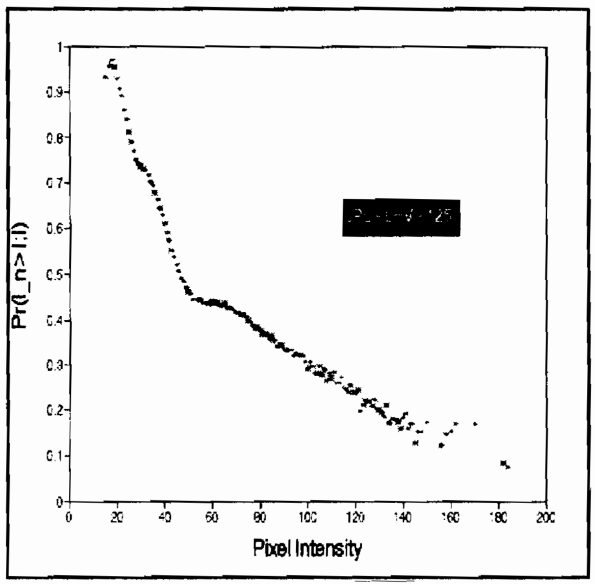

Figure 3 Probability that a pixel at intensity I will have a neighbour with a larger intensity.

Expand consideration to how the intensity differences above a given intensity are distributed

Observe (Fig. 4) a negative exponential form for the conditional probability given by

$$Pr_c = \frac{1}{Q}\exp(-\beta \Delta I) \qquad (1)$$

Consider how slope (β) and intercept (lnQ) vary with intensity (Fig. 5)

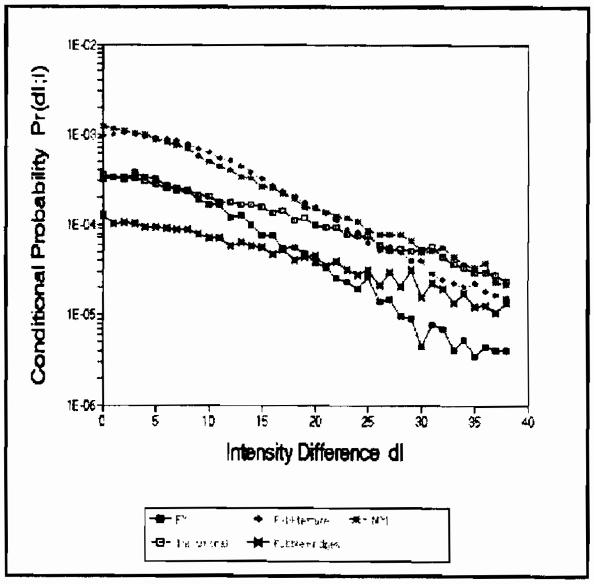

Figure 4 Probability of intensity differences dI occurring between pixels at a given intensity I, and those neighbours having a larger intensity, I+ΔI.

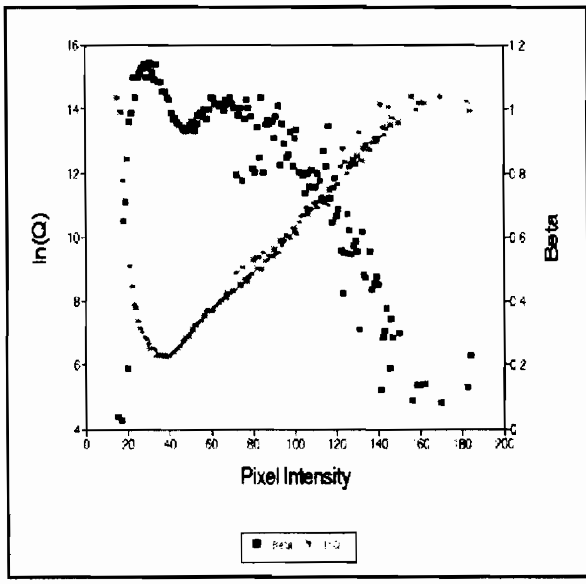

Figure 5 Variation of average textural and structural information as a function of image intensity.

Observe that generally β decreases monotonically with increasing intensity and that lnQ has a well-defined minimum

Consider how conditional probability varies for non-adjacent neighbours (x>1) (Fig.6)

Observe that β is invariant with separation distance. (Fig. 6 'Total')

Observe that lnQ is of the form x^{-m} (Fig. 7)

CONCLUDE: Overall description of conditional probability given by

$$Pr_c(\Delta I;I;x) = \frac{x^{-m}}{Q_1}\exp(-\beta \Delta I) \qquad (2)$$

INFORMATION DECOMPOSITION:

Consider expansion of conditional probability for nearest neighbours

$$-lnPr_c = lnQ + \beta \Delta I \qquad (3)$$

Recognize ***-lnPr*** as form of a 'surprisal', i.e. the basic element of 'Information'

Then what are ***lnQ*** and $\beta\Delta I$ in terms of 'Information'?

SEE COMPUTER DEMONSTRATION 1

Observe that a rarer event generates more surprise

Observe that the larger intensity differences generate more surprise

CONCLUDE:

$$dS = -lnPr_L = \beta \Delta I \qquad (4)$$

SEE COMPUTER DEMONSTRATION 2

Observe that surprise decreases as available dynamic range decreases

CONCLUDE: β decreases with intensity. See Figure 5.

CONCLUDE: $\beta\Delta I$ **represents local, textural 'Information'**

SEE COMPUTER DEMONSTRATION 3

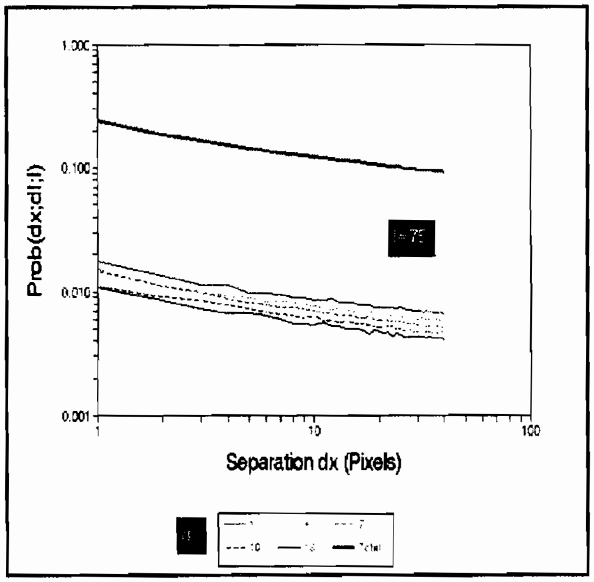

Figure 6 Conditional probability as a function of spatial separation for various intensity differences about pixels of a given intensity (75).

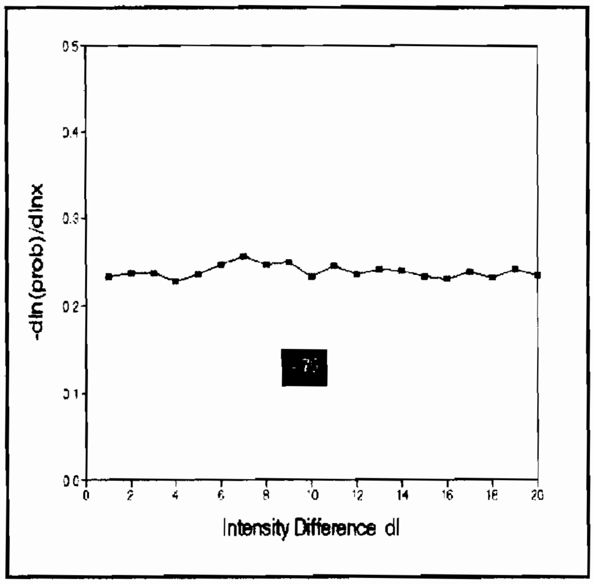

Figure 7 Best fit slope of power law relationship of Figure 6 for various intensity differences. Constant value indicates its invariance to ΔI.

Observe surprise increases with number of elements at a given intensity

Observe surprise increases with probability of larger intensity neighbours

Note: Sum of local occurrences (Equation 1) is given by $Q = \sum Pr_L$

CONCLUDE: *lnQ* represents non-local, structural 'Information'

$$Total\ info = Structural\ info + Textural\ info$$

$$-lnPr_c = lnQ + \beta \Delta I$$

INFORMATION CURVE = CONSTITUTIVE RELATIONSHIP:

Sea Ice Deformation

Observe regions of different material properties depending on size

CONCLUDE: Expect a mixture of ice types depending on time and space scales.

Statistical Mechanics Formulation of Perfect Gas Law

Observe *lnQ* is a constant, independent of β (Equilibrium).

CONCLUDE: *lnQ* as a function of β characterizes the material

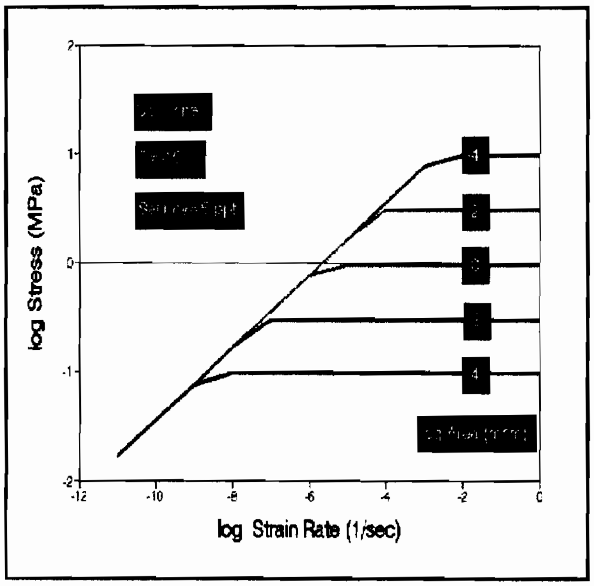

Figure 8 Constitutional relationship for sea ice in terms of the sustainable stress for a given rate of straining and the area over which it occurs.

Ice Imagery

L-HV, Beaufort, winter, JPL aircraft, 2 frequencies, 3 polarizations

Observe (Fig. 9) distinct subregions (material type)

Observe well-defined intersections ('phase-transitions')

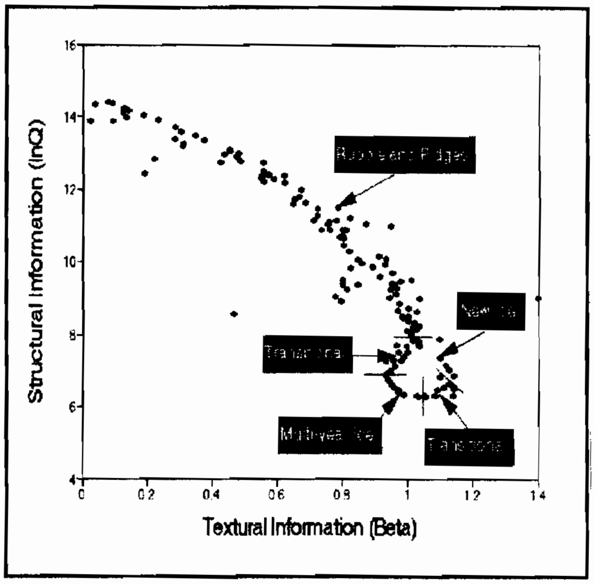

Figure 9 Information curve for sea ice imagery, consisting of a comparison of structural information in terms of textural information.

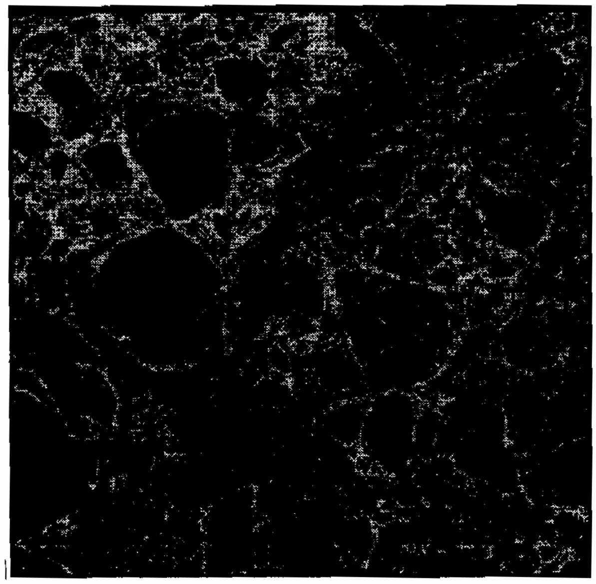

Figure 10 An ice image classified according to subsections of information curve as identified on Figure 9.

Observe 'phase-transitions' serve as critical identifiers of ice type boundaries

CONCLUDE: Joint behaviour of textural and structural informations characterize ice type (state)

What is the relationship between 'Information' in a 2-dimensional SAR image of sea ice and a 1-dimensional cut of its thickness?

Observe (Figs. 11 and 12) that the 'Information curve' for the two processes are parallel.

CONCLUDE: The 2 forms of measurement (imagery and ice thickness) are equivalent (i.e. identical under an affine transformation)

CONNECTEDNESS:

Consider intensity difference ΔI at scaled distance λ $(=2x/\delta x)$ away from a pixel of intensity I

Organize all such points by parameter $\alpha = \frac{\beta \Delta I}{\ln \lambda}$ into a given set of points

Count number of pixels in this set which occur at a given distance λ (Fig. 13).

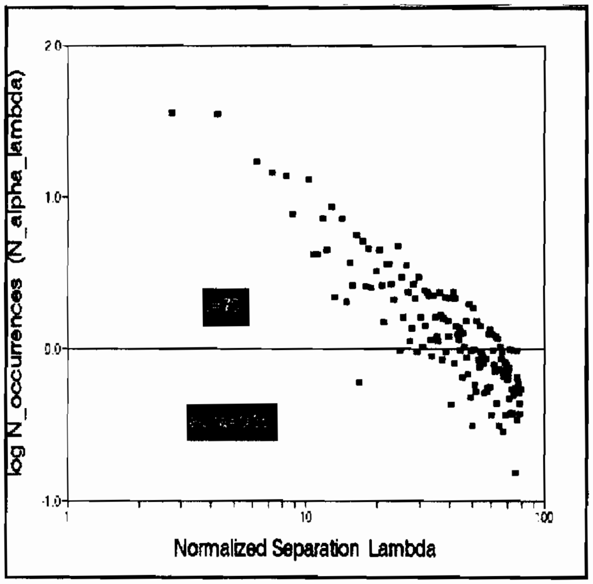

Figure 13 Number of connected pixels in a given similarity set as a function of scaled distance.

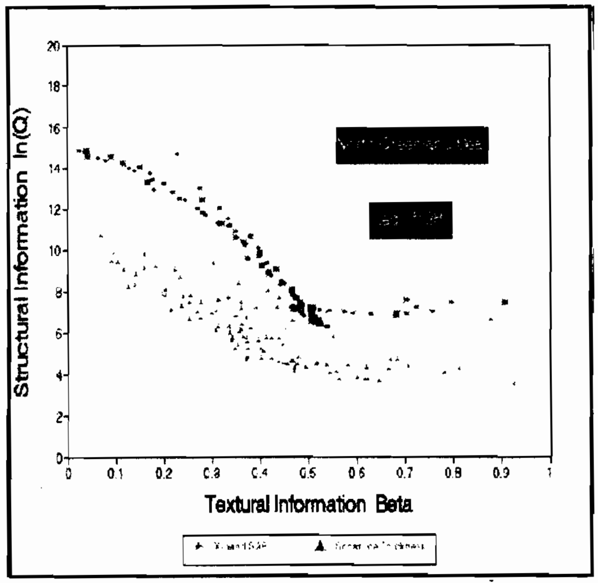

Figure 11 Information curves for an X-band SAR image of a pack ice region taken simultaneously with an ice thickness profile using a submarine-borne sonar.

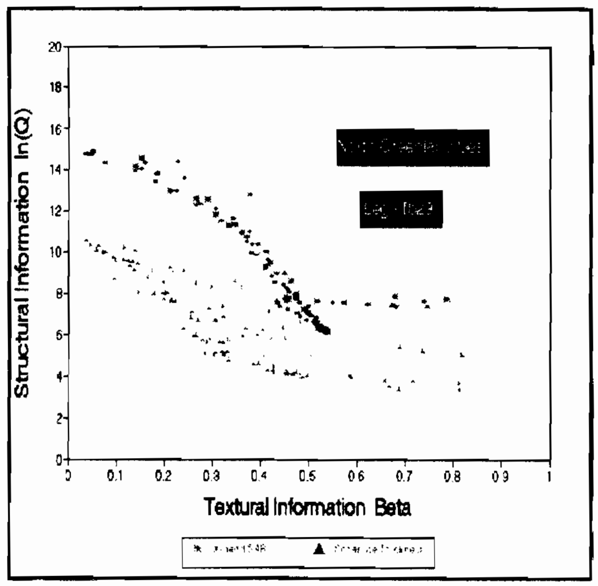

Figure 12 Same as Figure 11 except for another leg.

Observe number decreases with distance - $N_{\alpha_\lambda} \sim \lambda^{-D}$ i.e. the sets are FRACTAL.

Consider how the exponent D (fractal dimension) varies with α.

Observe (Fig. 14) that fractal dimension D is a function of the similarity parameter α i.e. the sets at a given intensity are MULTIFRACTAL.

Consider mixture of subsets about pixels of intensity I. Count size up to $\alpha'=\alpha$.

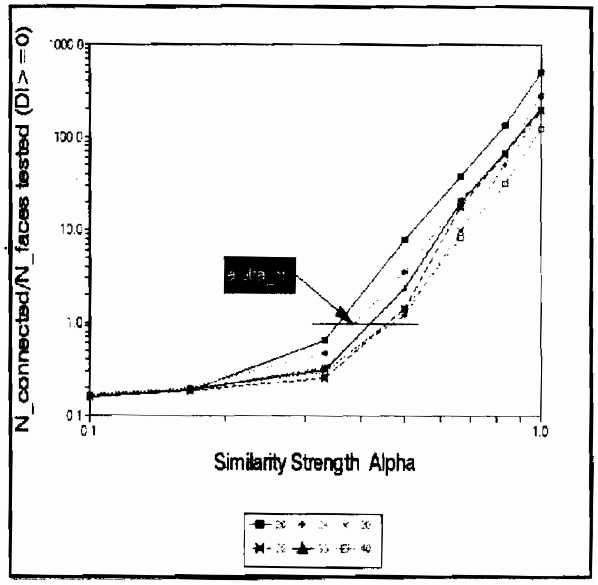

Figure 15 Number of pixels connected compared to number of faces of a given intensity where ΔI≥0, indicating a critical similarity set parameter, α, above which connectivity increases significantly.

Observe (Fig. 15) that there exists a critical value, α_{cr}, above which connection grows rapidly.

CONCLUDE: Dynamic process of 'nucleated fracture' has a counterpoint in imagery.

Consider spatial consequence of growth of similarity sets.

Observe that a connected cluster, spanning the entire image, exists for a critical value of local probability measure between nearest neighbours (Pr_L), or equivalently for the similarity parameter (α). (Figs. 16 and 17)

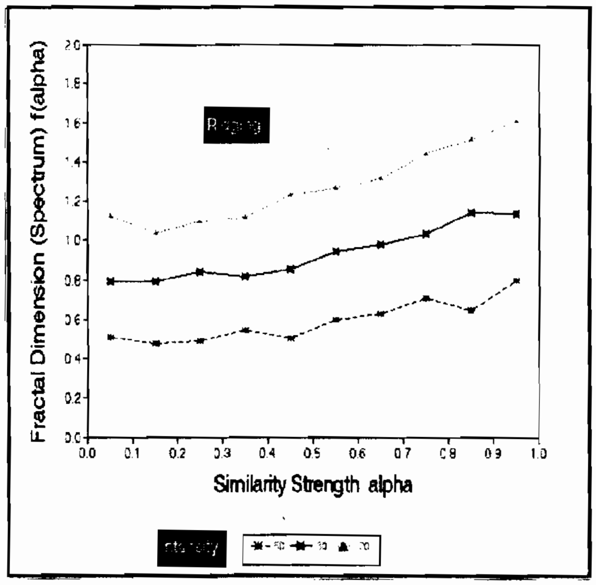

Figure 14 Fractal dimension of similarity sets for various intensities within the first-year ridging regime.

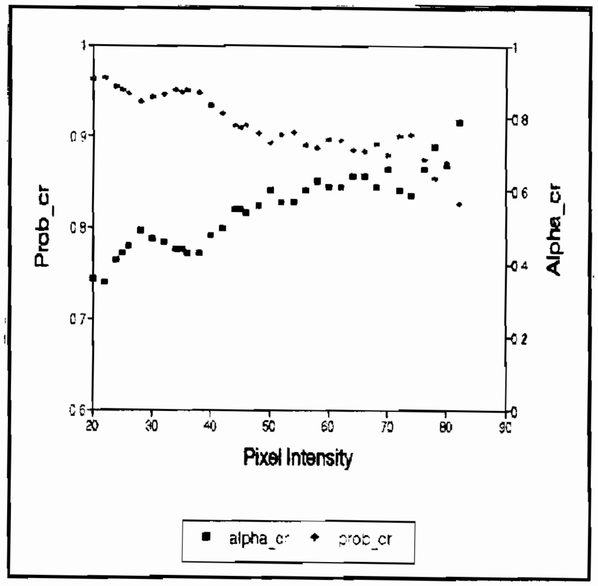

Figure 16 Critical values of similarity set parameter and probability associated with rapid change in connectivity in Figure 15.

CONCLUDE: Observed percolation relates to observed limiting stress of fractured ice under strain.

Other Applications of Percolation:

1. Detection of leads and multi-year ice floes.

2. Basis of an image compression technique for sea ice imagery because

   a. percolation cluster dominates information content of the image;

   b. it is a path, and so can be more efficiently stored.

3. Relationship to critical load-bearing in ice mechanics.

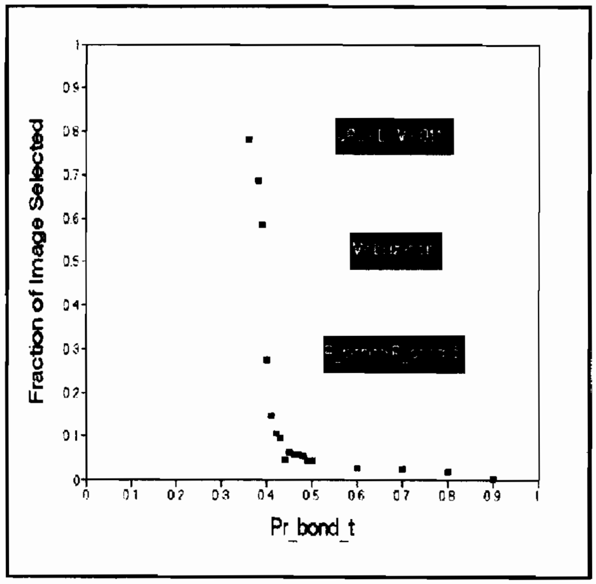

Figure 17 Example of percolation associated with the rapidly connecting fraction of the image as a threshold probability is approached.

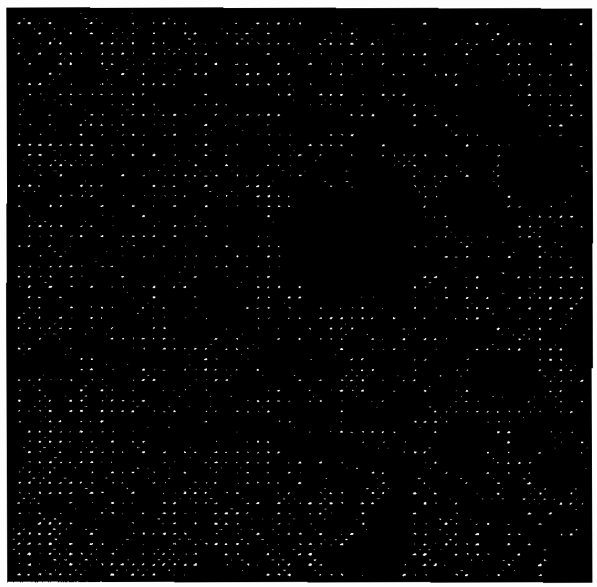

Figure 18 The resulting percolation cluster showing its property of outlining well-connected regions such as leads and multi-year floes.

SUMMARY:

1. Need (only) 2-point description to establish a characterization of sea ice imagery in terms of 'Information'.

2. There exists 2 types of 'Information' : (local=textural)and(global=structural).

3. Closure by comparing the 2 forms of 'Information' establishes a characteristic function form, the 'Information Curve', which distinguishes ice type.

4. The characteristic form of the 2 'Informations' for ice thickness is similar to that from the sea ice imagery.

5. There exist distinct and readily identifiable combinations of pixels, arranged under the parameter α, for a given intensity, which are multifractal.

6. Limited and unlimited forms of connection of the similarity sets can be identified with fracture nucleation and percolation (load-limiting).

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The Planned NSF/UNOLS Arctic Research Vessel for the United States Arctic Science Community

Poster #41

Dirk H. Kristensen, P.E., The Glosten Associates, Seattle, Washington
Dr. Vera Alexander, IMS, University of Alaska, Fairbanks
Dr. Thomas Royer, IMS, University of Alaska, Fairbanks
Dr. Robert Elsner, IMS, University of Alaska, Fairbanks

Prepared for

Sea Ice Mechanics and Arctic Modeling Workshop
Anchorage, Alaska
April 25 - 28, 1995

ABSTRACT

The new Arctic Research Vessel (ARV), the design of which was commissioned by the University National Oceanographic Laboratory System (UNOLS) under a grant from the National Science Foundation (NSF), will be required to support science missions in the Arctic well into the next century. The vessel is being designed primarily as an ice-breaking research vessel with modest open water capability.

At the preliminary design stage recently concluded, the ARV has grown to a size and capability that will make it the first U.S. academic research vessel able to provide access to the Arctic Ocean. This ship would open a vast arena for new studies in the least known of the world's seas. These studies promise to rank high in national priority because of the importance of the Arctic Ocean as a source of data relating to global climate change. Other issues that demand attention in the Arctic include its contributions to the world's heat budget, the climate history buried in its sediments, pollution monitoring, and the influence of arctic conditions on marine renewable resources.

INTRODUCTION

The design of a U.S. platform for arctic research has been a priority of the National Science Foundation since 1987. The Glosten Associates have been involved in the current design effort since 1990. This effort is being directed by the Arctic Research Vessel Subcommittee of the UNOLS Fleet Improvement Committee. The Subcommittee includes several representatives from the arctic science community, the U.S. Coast Guard, NOAA, and the National Science Foundation.

The Subcommittee, and the arctic science community that it represents, has provided clear guidance in their desire to have a highly capable ice-breaking research vessel able to meet current and anticipated future needs of the arctic research community. The vessel is to take advantage of the latest innovations in icebreaker design in order to obtain an efficient and economically viable platform for arctic research.

Numerous national reports and recommendations of recent years have attested to the urgency of the need for access to the marine Arctic (Polar Research Board, Arctic Research Commission, Committee on Polar Research of the National Science Board, and Arctic System Science [ARCSS] Ocean-Atmosphere-Ice Interactions). In the report of the ARCSS OAII Workshop at Lake Arrowhead, California, in March 1990, it is stated : "In the long haul, the U.S. needs an icebreaker built for and operated for arctic research. Research should be the primary mission of such a platform." The Arctic Research Commission recommends, in their annual report to the president and Congress of the United States for the period October 1, 1991-September 30, 1992, ". . . inclusion of a budget request by NSF for the construction of a dedicated arctic ice-capable research vessel . . ."

SCIENCE MISSION

In preparing its report, "Priorities in Arctic Marine Science" (1988), the Committee on Arctic Marine Science of the Polar Research Board (PRB), National Research Council, conducted a poll among users of research vessels in the Arctic. The responses showed three primary areas of interest: the Bering/Chukchi Seas, the Arctic Ocean Basin, and its marginal seas and the Greenland Sea/Fram Strait/Norwegian Sea/Barents Sea areas. Scientific plans included, among others, such activities as box coring in the Norwegian Sea, marine geology/geophysics in Baffin Bay, radiotracer studies in the Barents and Beaufort Seas and Fram Strait, and winter work in the Greenland Sea, all requiring significant ice breaking capability. Many individual respondents planned to work in multiple regions, such as the Barents, Greenland and Chukchi or Beaufort Seas - spanning both eastern and western arctic regions, other needed access to the Central Arctic Ocean Basin. A significant number planned to work in the eastern Arctic, which requires a platform with ice breaking capability. In compiling this information, it became evident that much work was simply not getting done due to the lack of a suitable U.S. vessel.

The timeliness and importance of the work identified in the PRB survey has increased, with high priority issues driving the development of arctic national research initiatives, for example global change and arctic pollution. The National Science Foundation has initiated the ten-year Arctic System Science program, with a multidisciplinary study of the Northeast Water polynya in the Greenland Sea among the first marine projects funded under this umbrella. However, the capability to support this program at sea is inadequate. This region is extremely important from the global point of view, since it is a dynamic region with exchange of water between the Atlantic and the Arctic Ocean, exhibiting strong fluxes of heat between the ocean and atmosphere, and also is active in the formation of subsurface water layers which affect large areas of the world oceans. On a regional basis, the polynya is important to the marine ecosystem. Access is difficult because the area is surrounded by heavy ice that moves southward from the Arctic Ocean via the East Greenland Current. The lack of a U.S. dedicated research vessel strongly affects our ability to understand the impact of these phenomena. In the western Arctic there is a need for research that spans the national boundaries between Russia and the U.S. and the U.S. and Canada. The most important process might occur during the ice-covered season.

Some specific research needs, for which the ARV is needed, will be addressed briefly:

Geological and geophysical studies of the Arctic Ocean Basin are needed if we are to fully understand climatic change. For example, nothing is known about the state of the polar oceans in Cretaceous times, a time of extraordinarily equable climate. There are inadequate numbers of sediment cores from the Arctic Ocean that penetrate the Cretaceous, and for those that do exist, context and correlation potential are unknown, as their sites are unsurveyed. Site survey for any future Arctic Ocean drilling program will be very demanding in time and effort, since there is no background or data base for geophysical studies in the region. This will require major ship time on a vessel suitable for arctic ice operations. Other geological/geophysical study needs include work on sedimentary processes in the Arctic Basin and at the continental margins, tectonics of the Arctic, and the interaction of the North American and Eurasian Plates. Finally, the opening of the western Arctic Ocean is a matter that remains unsettled along with continuing questions about the propagation of the Mid-Atlantic Ridge into the Arctic Ocean east and west of Greenland.

Physical Oceanographic studies in ice-covered waters are essential, since the permanent, dynamic ice cover significantly affects the Arctic Ocean on a number of scales. In particular, the Arctic Ocean plays a major role in the formation of cold, saline water layers overlain by low-salinity, low-density surface waters. Studies of large scale processes in the Arctic Ocean, including mixing, and generation of cold saline water, require access to regions of heavy ice, as does work on shelf/basin dynamics and structure. The Arctic Ocean is one of the few areas in which there is deep convection, ventilation of the deep ocean and production of the intermediate and bottom water masses of the global ocean. These studies must take place at times of the year with active ice formation and in locations that require a very ice capable research vessel.

There is a great deal of concern about the increasing **pollution of the Arctic** in general, most recently specifically with respect to radionuclides which have been introduced into high latitude Russian waters. Monitoring programs planned to address this problem and its broad effects will need to include physical oceanographic/circulation studies, sediment sampling and ecological work. This will be in addition to research underway or planned EMAP (Environmental Monitoring and Assessment Program - EPA) work.

Studies of **sea ice properties** and ground truth measurements in conjunction with satellite remote sensing using Synthetic Aperture Radar and other sensors, including the upcoming SeaWiFS, require access to ice covered regions.

Marine ecological work requires access to ice-covered regions, especially at the higher latitudes, where ice-related biological production and food chains become dominant. We currently lack information on the basis for the relatively high productivity of arctic waters, and therefore cannot estimate the impact of climate change on these systems. The long ice-covered season in polar seas does not necessarily result in biological dormancy, and critical biological activity may take place in extremely brief time periods early in the spring. Currently, lack of access beyond the marginal ice zone has precluded efforts to address this problems. Knowledge of the biological role of sea ice is particularly needed to allow prediction of the effects of variability in ice extent on marine species, including those that are commercially exploited or subject to subsistence utilization. Sampling must be expanded to earlier and later dates in the season than presently is possible.

Current Research Planning and the Evolution of the ARV

Perhaps the most important events in the chronology of the development of the arctic research vessel have been meetings of arctic scientists convened to define the outstanding research questions for the Arctic, with special reference to global change. One meeting, the Workshop on Arctic System Science (Moritz et al., 1990), identified a number of research problems related to interactions among the ocean, atmosphere and ice of the arctic region; while another meeting, a workshop on The Arctic Ocean Record: Key to Global Change (Thiede et al., 1992), identified a series of investigations needed to understand climate history and evolution of the basins and shelves of the Arctic Ocean. Fundamental to any scientific discussion of the Arctic Ocean and its marginal and adjacent seas, its atmosphere and seabed, is the suggestion in presently available global climate models that the Arctic contains many powerful processes and feed-back mechanisms that distribute its climatic influence world-wide and that the Arctic will be dramatically affected by presently predicted climate change. Since our knowledge of past climate change in the Arctic is practically nil (Thiede et al., 1992), and our understanding of critical state variables of the system is similarly quite small (Mortiz et al., 1990), it is clear that a wide variety of observational information is needed immediately. The realization in the scientific community that our understanding cannot improve without the platforms to investigate the Arctic has led to a unified and determined effort to obtain the appropriate research vessel needed for the wide variety of investigations that have been identified as necessary to achieve adequate understanding.

Through several years of the arctic research vessel design process it is clear that arctic marine scientists feel the need for a vessel that has the capability to support research under quite severe ice conditions in the Arctic Ocean. The United States currently has very limited capability to support shipborne science in the Arctic, apart from open water and ice margins, and the U.S. scientific interests in the Arctic now clearly require such support. Without question, a vessel of A3 ice classification will greatly enhance our ability to operate in the Arctic, and will increase the number of users when compared with a smaller, less capable vessel. The evolution of the Scientific Mission Requirements has determined the proposed size and capability in accordance with their needs.

VESSEL DESIGN

The development of the vessel's mission requirements has been focused on providing a platform for operations in ice covered waters. Open water performance was identified as secondary to ice capability. The following is a summary of the ice capability outlined in the Science Mission Requirements.

- The ship shall be able to operate continuously in Arctic first year ice, shall be capable of limited operations in multi-year ice and shall be able to transit 7 foot ridges by ramming. Continuous operation is defined as maintaining a minimum speed of 3 knots in 3.5 to 4.0 feet of consolidated level ice. Limited operation is defined as controlled ramming with avoidance of ice features whenever practical.

  The vessel is to be capable of independent, short term, short distance entries into the Central Arctic Basin (multi-year ice), normally in the summer, from July through September and of operations in the Arctic offshore shelf from July through December. When escorted by an icebreaker, it is to be capable of a broader range of Arctic operations.

  The required operating profile of the vessel generally falls within the operating areas and seasons described for ice class A3 in the American Bureau of Shipping's guide to ice classification or to those associated with an Icebreaker Polar 10 classification from Det Norske Veritas. Note that the vessel's actual range of operations will depend heavily on seasonal and local conditions.

- In addition to the regulatory requirements stated above, the vessel must meet the requirements of the proposed new Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR), specifically Canadian Arctic Class 2 (CAC-2). Included in these regulations are requirements for double bottoms and/or cofferdams between shell plating and all tanks containing polluting liquids.

- The vessel is to have excellent maneuvering characteristics in order to enhance ice trafficability and science operations. In this respect, maneuvering characteristics similar to the latest generation of modern icebreakers, such as the Swedish icebreaker *Oden*, is desired. Optimum maneuvering characteristics are to be achieved through hull design, high performance rudders, rapid heeling system and hull lubrication.

- The required mission profile of the vessel will emphasize operations in ice, dictating that the hull form be optimized around ice transiting performance. In addition, the required endurance of the vessel, 90 days, makes the propulsion efficiency for high thrust, low speed operations (those typically associated with ice navigation) a key feature of the vessel's design.

These relatively stringent requirements have made the design of this vessel a challenge. The ship's size, in particular, is directly affected by the specified ice capability and endurance.

The space requirements identified for science also played a key role in development of the design. These requirements were based on UNOLS standards for a large, high endurance, oceanographic research vessel.

Size has been driven throughout the design by the large power demands for operation in ice and by the identified endurance of 90 days. The required double skin construction in way of all fuel and waste water tanks has also had a significant impact on the vessel's size.

Sea ice, the overriding marine navigational concern in the polar regions, presents a more severe obstacle in the Arctic than in the Antarctic, because of its largely multi-year nature. Arctic Ocean ice is therefore less saline, stronger, and more massive than seasonal ice of peripheral seas. Despite these formidable barriers, the dynamic nature of the sea ice provides frequent open leads and relatively week refrozen leads that can be used by a sufficiently maneuverable ship. A strong ship having superior maneuverability, minimum resistance to progress in ice, and long endurance is required. The pursuit of practical and safe arctic oceanography will also require that the research vessel be accompanied on some occasions by an escorting icebreaker. Such two-ship operations have been found to be prudent in recent arctic expeditions.

The design philosophy has been based upon an appreciation that the operational ship should closely match the navigational features of the Arctic Ocean and should take full advantage of the experience of modern icebreaker technology and the recent arctic transportation successes. Consequently, we have analyzed the operational requirements for this research vessel and the logistic demands that result from operations at great distance from suitable bases of supply and repair.

The conceptual and preliminary designs, including arrangements, engineering and model testing, have been developed in partnership with The Glosten Associates. Consultants participated in a comparative study of hull forms and an examination of the optimal design to satisfy the requirements. Consultants Dr. Karl-Heinz Rupp of HSVA (Hamburgishe Shiffbau-Versuchsanstalt GmbH/The Hamburg Ship Model Basin) and Dr. Arno Keinonen of Calgary, Alberta, contributed to the design and to the evaluation of hull forms. Rupp and his colleagues have a very wide background of experience in the design and testing of icebreakers, and Keinonen has been associated with the successful recent Canadian, Swedish and Finnish icebreaker designs. The combined efforts of naval architects and consultants have produced a design that will provide a practical and realistic solution to the requirements for scientific operations in the Arctic Basin and its peripheral seas.

The ARV hull design takes into account the physical properties of sea ice – that is, it breaks ice primarily in a bending mode which offers less resistance than the more characteristic crushing mode of conventional icebreakers. Emphasis was also placed on an appropriate displacement of the ice to avoid or reduce impacts with the propellers. Incorporation of bow reamers and the additional forward beam associated with them, reduces ice friction along the hull and improves turning facility. A rapid heeling system will permit easier passage through consolidated ice pack and ridges. The bow forms of modern icebreakers have been shown to improve the ship's progress through ice at reduced power levels. In so doing, vessels are more economical to operate, and less subject to the uncomfortable roll motions in open seas. However, the higher cost of increased open water resistance can amount to as much as a 20 percent greater fuel consumption than is experienced with more conventional hulls. Therefore, the choice of design hinges on the specific operational requirements for enhanced and economical operations in sea ice.

The size of the ARV has been dictated by both scientific and operational conditions. The primary consideration, vessel integrity and safety, requires a protective hull adequate for encounters with heavy ice. Navigational progress in Arctic Ocean conditions requires a minimum mass for efficient ice breaking. The power requirements, long distances involved, and safe margins for unanticipated delays require long endurance. Effective scientific operations demand a large complement of personnel and extensive outfitting with modern equipment.

Model testing of the hull was carried out at HSVA in Hamburg. The vessel performance was excellent, meeting or exceeding all requirements. The design performed flawlessly in level ice breaking and ridge transiting efficiency. Ice was diverted from the propellers while going ahead in the equivalent of 3 to 4.5 feet of level ice. Maneuvering capability in level ice and ice floes (9/10 cover) was exceptional, and open water performance exceeded expectations.

The ARV is estimated to have good performance characteristics in sea ice and open water. Expectations for the ARV's ice operations suggest that it will represent a step forward in icebreaker technology from its derivative ship designs. Good open water capability is also expected. Bow shape has been designed to provide for easy extraction from ice ridges. Hull shape has been refined to the point where propeller collisions with ice fragments, a major source of increased icebreaker operation costs in both propeller inefficiency and repairs, have been eliminated or greatly reduced. The strategically located ice wedge and slight dead rise of the ship's underbody were shown by the model tests to provide excellent clearance of ice from beneath the hull and its displacement to the side, leaving a clear channel astern. Good ice breaking in the reverse direction is indicated. Hull lubrication, efficient independently operated rudders and a rapid heeling system are additional features that will improve maneuverability and ice transit.

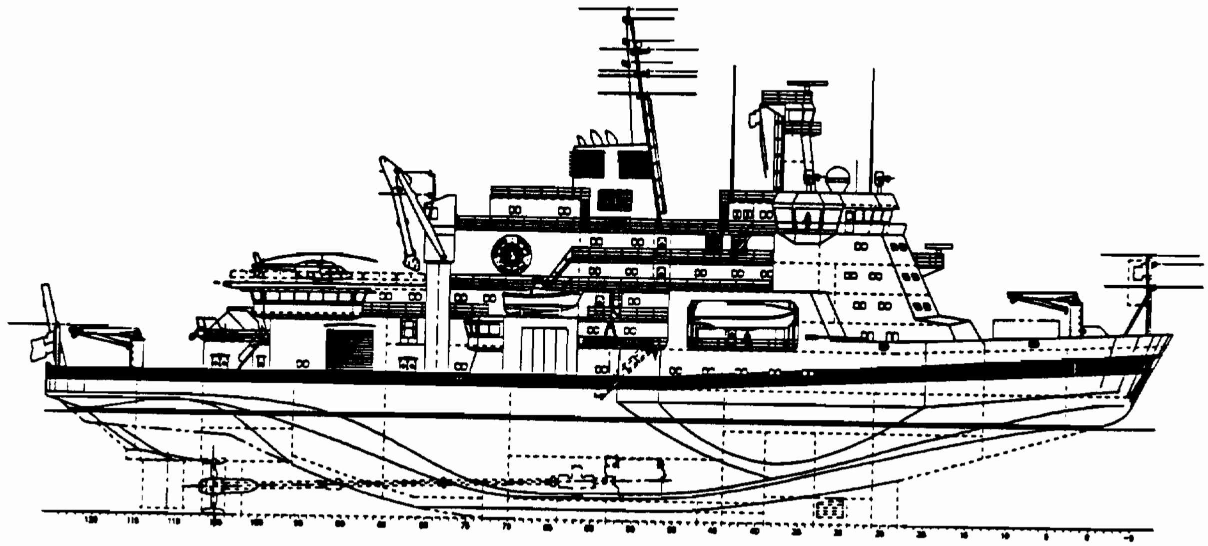
The ARV will equal or exceed UNOLS mission requirements for long-range, high endurance research vessels. Concurrently with the hull design work, the arctic oceanographic community was providing input into the deck arrangements of the vessel. These arrangements, as they exist at the conclusion of the preliminary design cycle, reflect the continual review of the ARV subcommittee and other interested individuals within the arctic research community. The general arrangements are appendices to this report. The principal characteristics of the vessel are shown in Table 1. Detailed descriptions of these and other features are included in the preliminary design report (Ref. 7).

Presentations of the design have been made at several national conferences, including the fall American Geophysical Union (AGU) meetings (1992 and 1993), the Polar Research Board of the National Research Council, the Arctic Research Commission, the Oceanography Society, the AGU Ocean Sciences meeting (February 1994) and the 1993 Marine Technology Society meeting (Springer, Kristensen and Laible, 1993). A paper on the design and predicted ice breaking and open water performance of the ARV, written by members of the design team, was presented at the Arctic Section of the Society of Naval Architects and Marine Engineers (SNAME) 5th International ICETECH Symposium on Icebreaker Technology, held in Calgary, Alberta, in March 1994 (Kristensen et al., 1994). A publication in *EOS, Transactions of the AGU*, described in the design history and scientific prospects (Elsner and Kristensen, 1993). Through these various mechanisms, arctic oceanographers and the polar ship design community have been kept informed and given an opportunity to comment and to contribute to the project.

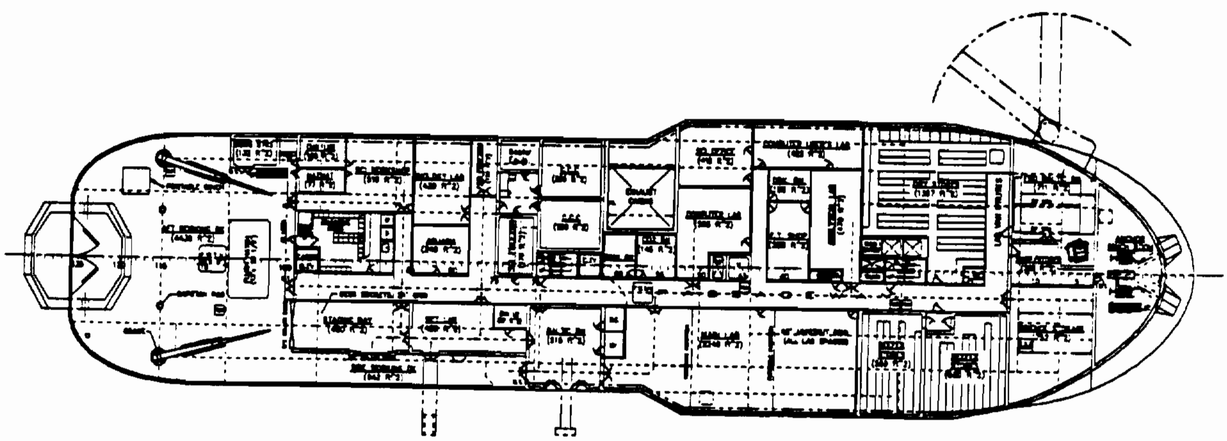
Table 1

Arctic Research Vessel Characteristics

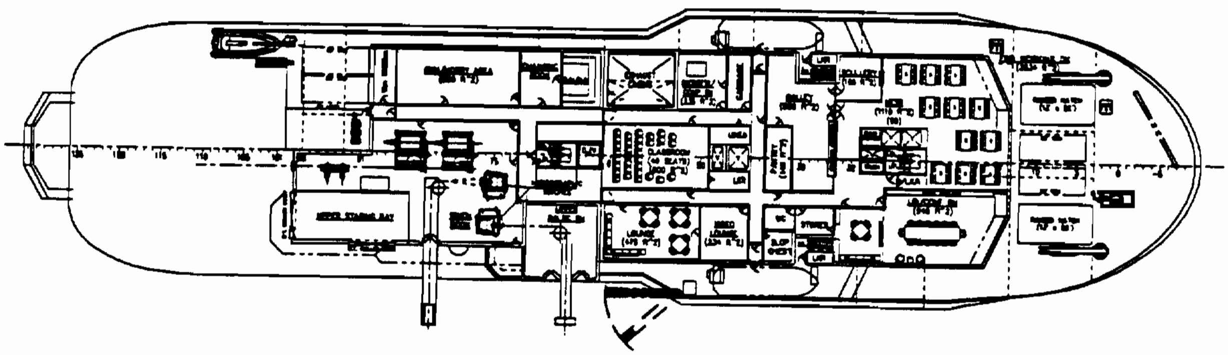
Dimensions	
Length overall, ft	340
Length waterline, ft	308
Beam reamer, ft	89
Beam amidships, ft	76
Draft, ft	30
Displacement, L tons	11,500
Propulsive HP	20,000
Propellers	Two CP in nozzles
Endurance, days	90
Accommodations	
Scientists	34-36
Crew	26
Laboratories, sq ft	6120
Science storage, sq ft	2460
Science common area, sq ft	1540
Science working decks	
Covered, sq ft	1716
Exterior, sq ft	5080
ABS ice classification	A3



OUTBOARD PROFILE



MAIN DECK



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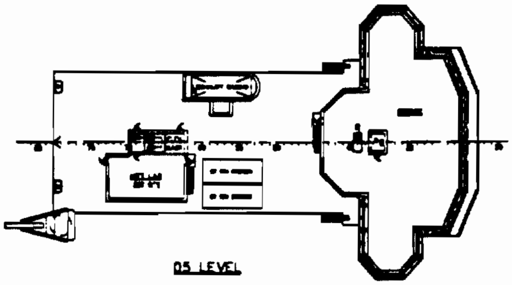

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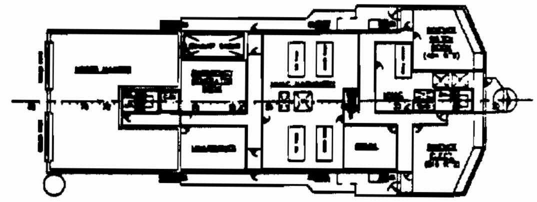

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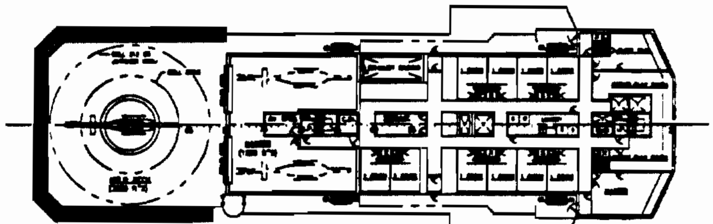

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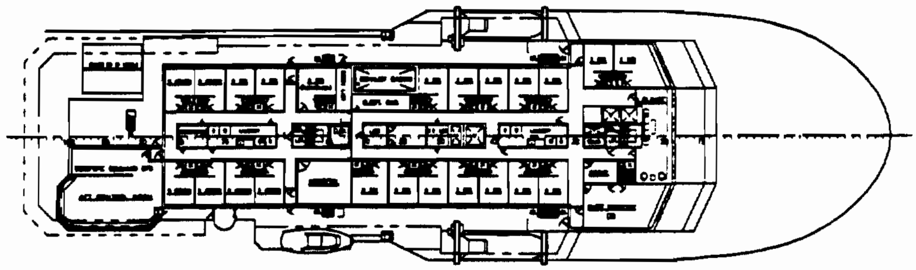

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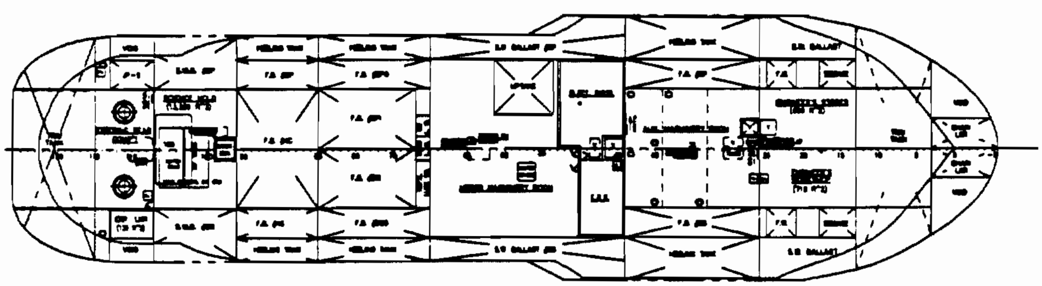
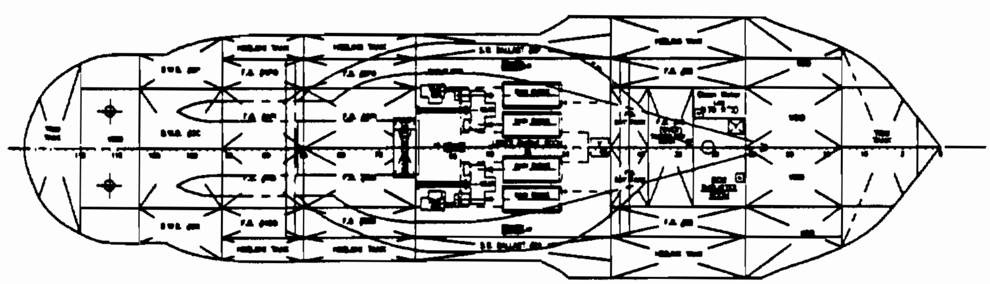


1st PLATFORM



HOLD PLAN

STATUS

There is a long history of operational support to American oceanographers by the U.S. Coast Guard. We presently have occasional use of the two U.S. Coast Guard icebreakers, *Polar Sea* and *Polar Star*. These ships have contributed importantly to arctic oceanography by providing a base for operations that would otherwise be unavailable. However, their performance has been less than ideal for several reasons. Both have been plagued by disabling breakdowns. The Coast Guard, as a military organization, has missions other than science, and their icebreakers have heavy manning and training requirements and rapid personnel turnover. Long-range continuity is lacking, and therefore it has been difficult to build intensive, multi-year, multi-investigator programs. Furthermore, administrative and shipboard arrangements for science are limited and of lesser priority. Larger laboratories, more accommodations for scientists, and more deck space are needed for modern research initiatives. The next generation of arctic science will require extensive planning with new facilities construction, new equipment, technical support, and scheduling. The two Polar class icebreakers are now more than twenty years old, well along in their anticipated life spans.

The Coast Guard anticipates construction of a new icebreaker that will have better science facilities than are now available on the Polar class ships. Nevertheless, its plans and mode of operation will make it very difficult to meet the high level of research capability customary on UNOLS ships. Coast Guard ship and air operations are expensive and complex. Personnel rotation leads to decreased experience and corporate memory and the related dedicated science operations, technician programs, and shared equipment characteristic of UNOLS operations. The Coast Guard vessels lack the extensive infrastructure and technical and equipment support that is available to UNOLS operators and users. Deficiency in this type of support is also a serious weakness on the *R/V Nathaniel B. Palmer* and the *Polar Duke*, which are non-UNOLS vessels operated by the National Science Foundation on a lease basis in the Antarctic.

In the summer of 1993, an arctic science cruise took place on the *USS Pargo*, a nuclear powered U.S. Navy submarine. Five scientists were able to sample throughout the Arctic on a forty-five day cruise. This approach to research in the Arctic Ocean is promising for some measurements such as gravimetry, acoustics, bathymetry and some water column measurements. Nuclear submarines can provide unique sampling opportunities, but they cannot begin to satisfy the broader scientific requirements of the arctic community. A dedicated modern research vessel is required; in many instances it and a submarine can advantageously work cooperatively.

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Minerals Management Service Environmental Studies Program and Oil Spill Risk Analysis for the Beaufort Sea

Ronald J. Lai and Walter J. Johnson
Minerals Management Service

The Environmental Studies Program (ESP) is a small, highly focused research program that provides information to decisionmakers in the Outer Continental Shelf (OCS) natural gas and oil program of the Department of the Interior. Because the EPS is designed to be flexible and responsive to changing OCS program needs, its focus has shifted over the years, tracking relevant issues and concerns of both the program and the participating States. The research sponsored by the ESP covers a broad range of topics, including the following: (1) physical oceanography and pollutant transport, (2) water quality, (3) air quality, (4) protected species, (5) fisheries resources, (6) coastal and marine birds, (7) archaeology, (8) ecological monitoring, (9) geology, and (10) socioeconomics.

The ESP has contributed substantially to coastal and marine science. It has (1) participated in marine mammals research, (2) has made great strides in better understanding fisheries populations in several of the OCS regions, (3) has provided the most comprehensive research program to date in Alaska. Currently, the ESP is undertaking several large, long-term physical oceanography studies, which will vastly improve our ability to model potential paths of oil spills in offshore waters.

A recent study has used coupled ice/ocean modeling to simulate the behavior of the pack ice and ocean currents in the Western Arctic Ocean. The coupled system used the semi-spectral primitive equation ocean model (SPEM) and the Hibler sea-ice model, and was forced with daily surface geostrophic winds and monthly thermodynamic fluxes. The simulation reproduced the Beaufort gyre and its seasonal variation, as well as the bulk properties of the sea-ice distribution. Results from this model simulation will be used to estimate the risk to environmental resources from potential oil spills that could occur as a result of an OCS lease sale in the Beaufort Sea.

MICROMECHANICALLY BASED CONSTITUTIVE LAWS FOR ICE FIELDS

M. Ostoja-Starzewski
Department of Materials Science and Mechanics
Michigan State University

We present several methods suited for modelling effective mechanical response of ice fields depending on the type of response: elastic, plastic, or crack-forming. It is assumed from the outset that ice fields have a random granular microstructure, where an ice floe is identified as a grain.

In case of elastic ice fields - a generic case - we set up a hierarchy of stochastic models [1, 2]:
- a granular medium, i.e. a random field of physical properties assigned to a 'mosaic' of ice floes,
- two continuum random (tensor) field approximations at the mesoscale,
- solution of the governing stochastic field equations via a probabilistic finite element, or finite difference, approximation of these two random fields.

These concepts may also be adapted to ice fields having a predominantly rigid-plastic response of, say, cohesive Mohr-Coulomb type with a spatial random variability of the material parameters. This method leads to solutions in terms of stochastic slip-line networks [3].

Problems of strength and crack propagation require special attention. Namely, it is at transitions in types of constitutive response (elastic to brittle) that very strongly scale-dependent features - such as fractals - may be formed [4]. Here we outline new techniques borrowed from recent studies of fracture phenomena in polycrystals and composites [5, a video tape of computer simulation].

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THE POLAR ICE PREDICTION SYSTEM AT FLEET NUMERICAL METEOROLOGY AND OCEANOGRAPHY CENTER (FLENUMMETOCCEN)

Thomas Thang Pham
Models Department
Fleet Numerical Meteorology and
Oceanography Center
Monterey, CA 93943-5501

There are three different resolution dynamic/thermodynamic sea-ice forecast models running operationally at the FLENUMMETOCCEN. The Arctic basin model forecasts ice motion and ice properties in the Arctic region at 127 km resolution, the Barents Sea model covers the Barents Sea and the Kara Sea at 25 km resolution; and the Greenland Sea model at 20 km resolution.

These models are using 3 hrs or 6 hrs atmospheric forecast fields from daily outputs of the Navy Operational Global Atmospheric Prediction System (NOGAPS) as inputs. The ocean inputs, ocean currents and heat fluxes, are derived from the Hibler-Bryan coupled ice-ocean model. Once a week the ice models are updated by observed ice concentration data produced by the Naval Ice Center (NIC).

Output of these ice models, sent daily to the NIC, are the forecasting fields up to 120 hrs, of the ice concentration, thickness, drift, stress and growth in these polar regions.

THE ARCTIC OCEAN ICE AND WATER TRANSPORT DURING 1946-1988

Andrey Proshutinsky and Mark Johnson

(Institute of Marine Sciences, University of Alaska Fairbanks)

A two-dimensional barotropic, coupled, ocean-ice model with spatial resolution of 55.5 km has been driven by observed atmospheric winds, and with prescribed river input and sea level slope between the Pacific and the Atlantic Oceans, to simulate the vertically averaged currents and ice drift in the Arctic Ocean between 1946 and 1988. Numerical simulations have been completed with different versions of the model to assess the effects of different forcing. For example, Figure 1 shows the surface circulation in the Arctic Ocean under the influence of prescribed river run-off and sea slope between the Pacific and Atlantic Oceans. Figure 1 demonstrate that the sea slope between the Pacific and the Atlantic Oceans, and the river run-off, drive the well-known, quasi-permanent circulation in the northern Bering Sea, Bering Strait, Chukchi Sea, Laptev, and Kara Seas. They also indicate the location of the core of Trans-Arctic and East-Greenland currents.

Figure 2 shows sea level elevations and the thermohaline circulation for surface flow in the Arctic Ocean in winter. This result are from simulations of I. Polyakov [1994, personal communication] using the Mellor-Blumberg 3-d model and multi-year averages of seasonal fields of temperature and salinity distribution obtained by the Arctic and Antarctic Research Institute, Russia. The surface thermohaline circulation is in general agreement with the observed anti-cyclonic circulation in the Canadian Arctic Basin, and cyclonic circulation in the European Basin, and the coastal currents in the East-Siberian, Trans-Arctic, East-Greenland, and Nord-Cap regions. However this thermohaline circulation does not explain the observed circulation in the Chukchi Sea.

Both the ocean and ice models were initialized from rest on January 1, 1946 and run for 43 years until December 31, 1988, using the NCAR daily surface atmospheric pressure and the simulated surface winds computed from the pressure data. Results from the numerical simulations include long time series of the ice transport, ocean currents, and sea level variations. Ice and water parcel trajectories were also determined for parcels released in Bering Strait, at the mouths of the Mackenzie, Kolyma, Indigirka, Lena, Khatanga, Yenisei, Ob, and Pechora rivers.

Year-to-year variability

Our analysis demonstrates that wind as a principal factor is responsible for the year-to-year variability in the circulation of ice and surface water. There are two major types of barotropic water and ice circulation in the Arctic Ocean. One is an anti-cyclonic circulation observed in the Arctic Ocean during 1946-1952, 1958-1964, 1972-1979 (Figures 3 and 5). The other type is cyclonic circulation observed during 1952-1957, 1964-1971 and 1980-1986 (Figures 4 and 6). The alternating pattern between cyclonic and anti-cyclonic has a 5-8 year periodicity (Figure 7). Figure 7 is a time-series of sea level slope at the center of the Arctic Basin and is a measure of cyclonicity. Positive gradient corresponds to a domed

(Figure 3) sea surface and anti-cyclonic ice and water circulation (Figure 5). Negative sea level gradients in the center of the Arctic Basin (Figure 4) correspond to cyclonic ice and water circulation (Figure 6). The absolute value of the sea level gradient in the center of the Arctic Basin may serve as an index of the circulation intensity (higher values correspond to a higher velocities in cyclonic or anti-cyclonic circulation of the ice and surface water). In the Greenland and Norwegian Seas one can see permanent cyclonic circulation.

In the years with anti-cyclonic ice and water circulation (Figures 3 and 5), the core of the Trans-Arctic current is intensified and shifted toward Siberia. This enhances the outflow of ice from the Laptev, East Siberian and Kara Seas. The ice transported through Fram Strait has to be thinner because it has its origin in these coastal seas (transport of fresh water into the Greenland Sea decreases). In the years with cyclonic circulation (Figures 4 and 6) the core of the Trans-Arctic current is shifted toward Canada and Greenland, enhancing the inflow of old ice into the Laptev, East Siberian and Chukchi Seas and, as a rule, makes navigation difficult along the Northern Sea Route. According to this ice circulation, the transport of ice and fresh water through Fram Strait at this time is greater because the ice transported from the Canadian sector of the Arctic is at least two times thicker than in the Siberian Seas. The navigation conditions in the Kara Sea are likely to be better in the years with anti-cyclonic type of circulation and worse in the cyclonic years when ice tends to block the Vilkitskogo Strait.

Seasonal variability

Analysis of model results of monthly averages of each regime demonstrate that the anti-cyclonic circulation of ice and surface water prevails in the winter. In the summer, the anti-cyclonic wind driven circulation weakens, or even weak cyclonic circulation is generated by atmospheric forcing. The East Greenland Current and ice transport through the Fram Strait have a maximum in winter and a minimum in summer. Conversely, the seasonal variation in flow through the Bering Strait is characterized by maximum inflow of Pacific water in summer and minimum inflow in winter. Sea level heights can serve as an index of the circulation. In the years with an anti-cyclonic regime, winter processes (anti-cyclonic) prevail and in the years with a cyclonic type of circulation the summer processes (cyclonic) prevail.

Pollutant transport

Our results are useful for investigating the temporal and spatial variability of ice, water and pollutant transport in the Arctic Ocean. For example, in Figures 8 we present for the period 1946-1986 the trajectories of water markers released in 1946 (every month one new marker was released) at the different regions. Water markers moving with vertically averaged velocities have more or less stable trajectories following bottom topography features and following the two types of circulation. One can see that markers from the Bering Strait have tracks with cyclonic and anti-cyclonic rotation. Eighty percent reach Fram Strait and 20% were entrained into the circulation of the central Arctic Basin. Markers with their origin in the Siberian rivers move to the east along the coastline under the influence of gradients of sea level and the Coriolis force. Wind driven circulation during years with cyclonic circulation supports motion from the west to east. Only 20% of water markers released at the Yenisei mouth in 1946 reached Fram Strait and 80% of them were entered in to the Arctic Basin circulation.

Ice markers have more chaotic trajectories because of the direct influence of wind conditions. Tracks of the ice motion can be found everywhere with a maximum concentration in the Beaufort Sea and along the core of the Trans-Arctic Current. Ice markers from the Ob and Yenisei rivers are directed mostly into the Fram Strait according to prevailing atmospheric circulation.

Conclusions

1. Two wind-driven circulation regimes are possible in the Arctic, a cyclonic and an anti-cyclonic circulation. These appear to alternate at intervals of 5 to 7 years. It is important to pollution studies to understand which circulation regime prevails. It is anticipated that we are now in a cyclonic regime, and during this phase, pollutants can indeed reach the Alaskan shelf.
2. Massive measurements of temperature and salinity distribution were done in the Arctic Ocean during the anti-cyclonic circulation regime (1972-1978). These data were used for a formation of Levitus data base and for modeling of the thermohaline Arctic Ocean circulation by many scientists. Therefore our knowledge about the Arctic Ocean anti-cyclonic circulation is based only on the data for the years with prevailing anti-cyclonic atmosphere regime. I. Polyakov (personal communication) obtained cyclonic thermohaline circulation in the Arctic Ocean using temperature and salinity distribution for 1979. We assume that wind-driven circulation and distribution of water density have to be adjusted and therefore temperature and salinity structures have to reflect the present cyclonic type of circulation.
3. The seasonal circulation has two regimes as well. During winter the anti-cyclonic regime prevails and during summer the anti-cyclonic circulation weakens or cyclonic circulation prevails.
4. This research will be continued to include into simulation the atmospheric conditions for 1989-1994. At the second stage, we plan to use a 3-D model for simulation of the Arctic Ocean circulation including the thermohaline effects and ice thermodynamics.

The regime shifts demonstrated in this paper are fundamentally important to understanding the Arctic's general circulation and particularly for estimating pollution transport. But because the majority of Arctic data reflect the anti-cyclonic (1972-1978) regime, and because the recent trans-Arctic effort may have sampled during an anti-cyclonic regime as well, it is central to Arctic science that this modeling work be fully tested and a major future field effort sample during the next cyclonic regime (1995-1999).

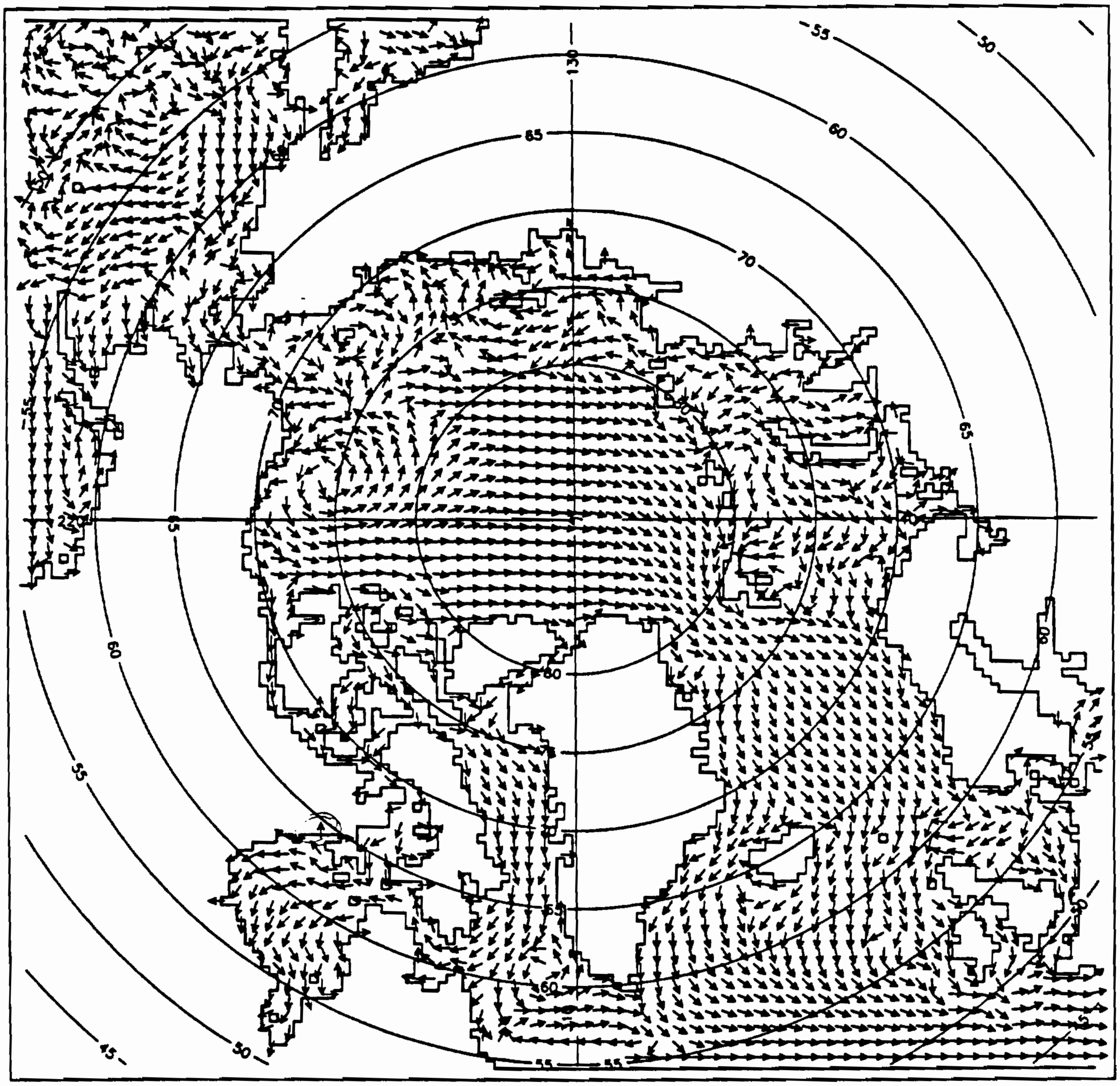

Figure 1. Surface currents from the barotropic model with prescribed river run-off and sea level slope between the Pacific and Atlantic Oceans.

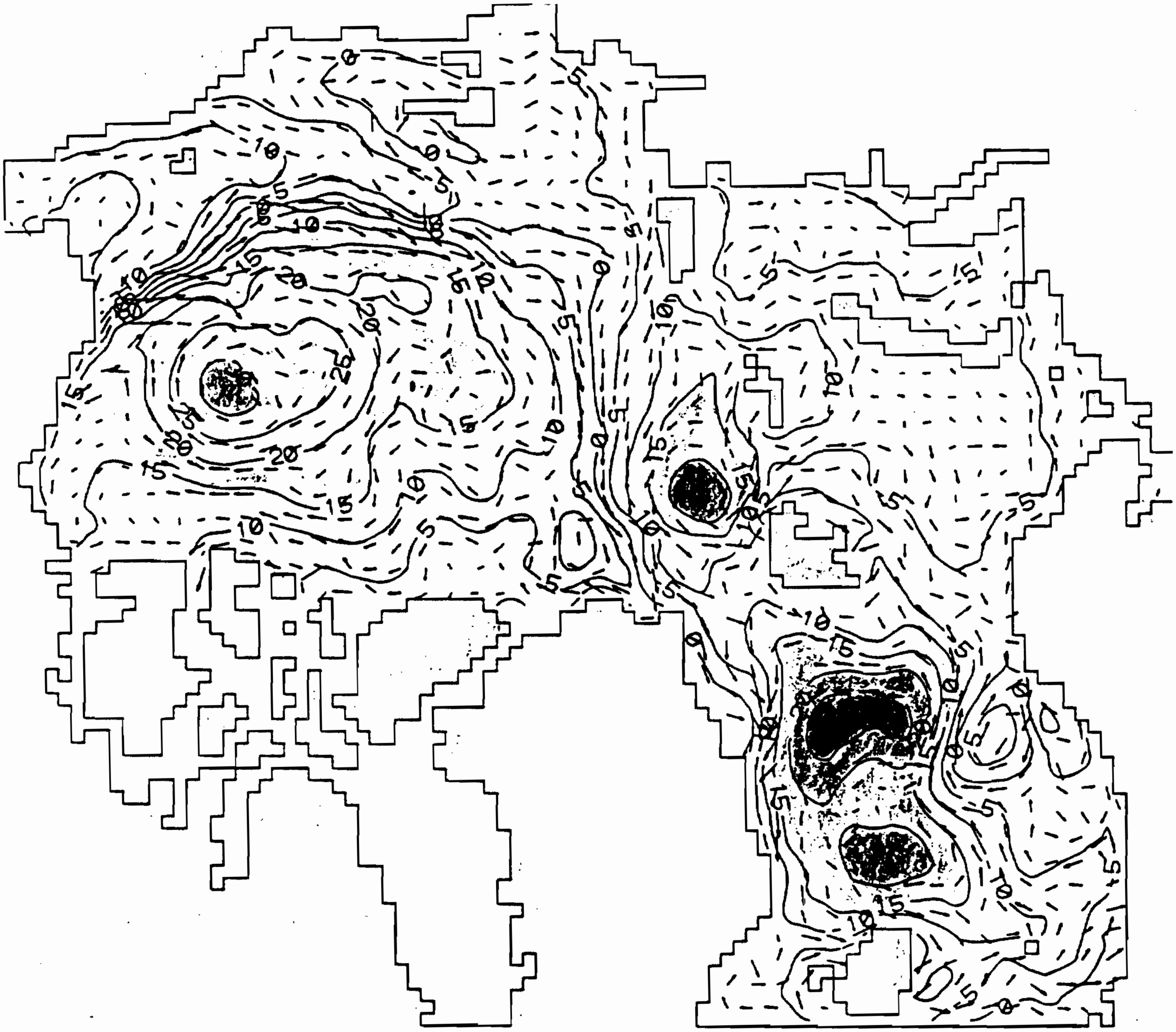

Figure 2. Sea level elevations and the thermohaline circulation for surface flow in winter.

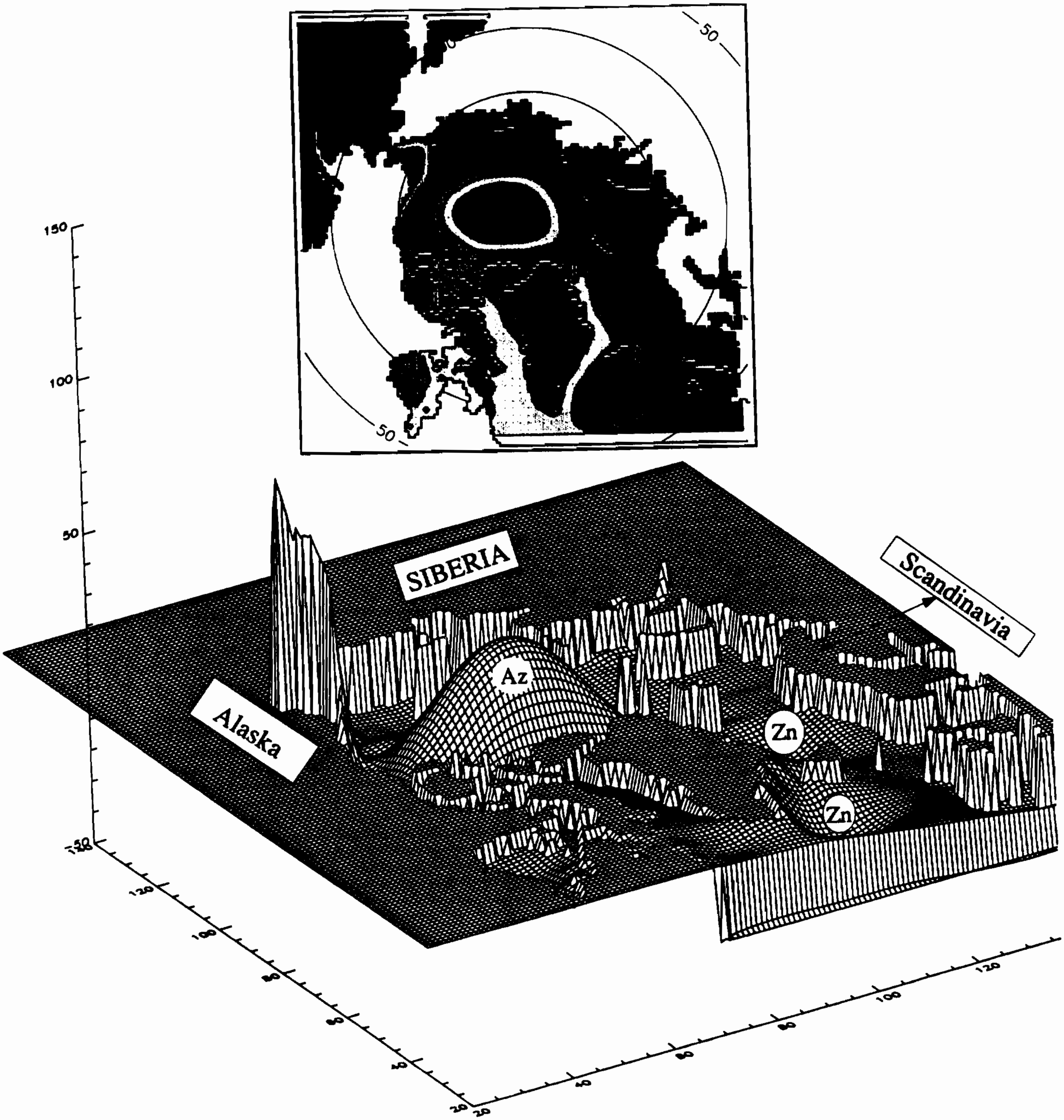

Figure 3. Sea level heights in the Arctic Ocean corresponding to the anticyclonic type of circulation. Az and Zn are centers of anticyclonic and cyclonic rotations respectively.

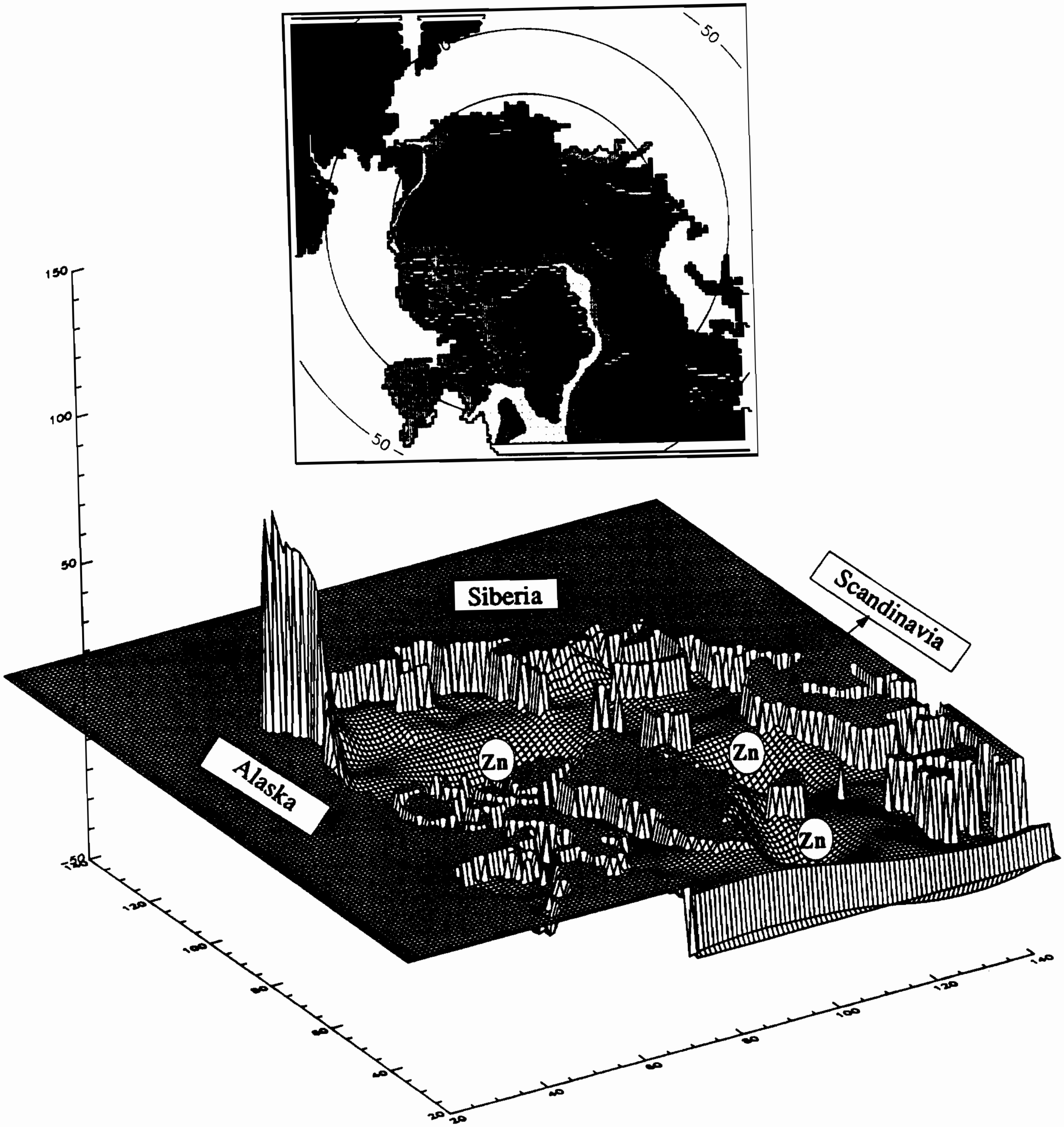

Figure 4. Sea level heights in the Arctic Ocean corresponding to the cyclonic type of circulation.

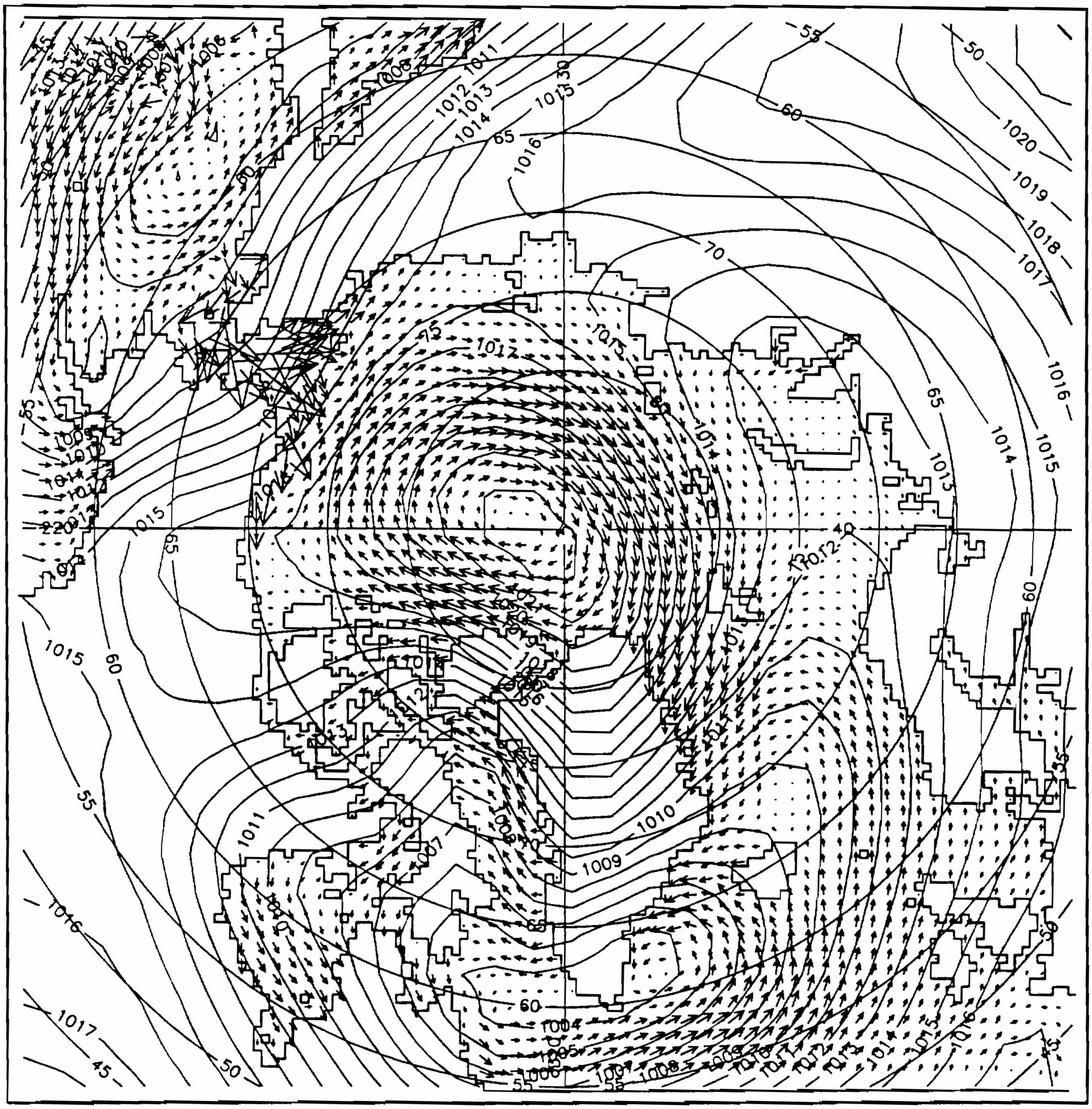

Figure 5. Surface currents and surface atmospheric pressure for the typical year with anticyclonic circulation.

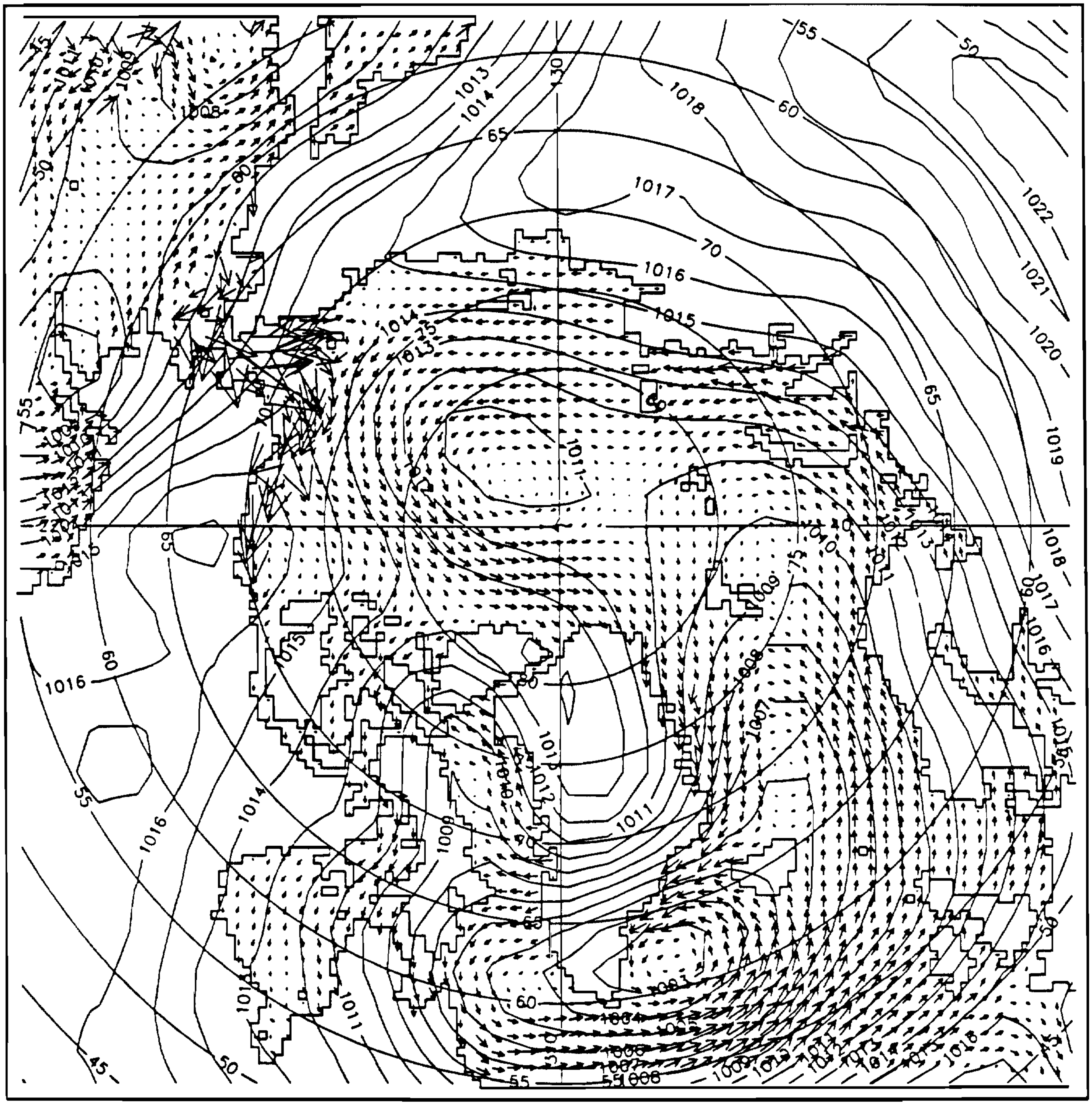

Figure 6. Surface currents and surface atmospheric pressure for the typical year with cyclonic circulation.

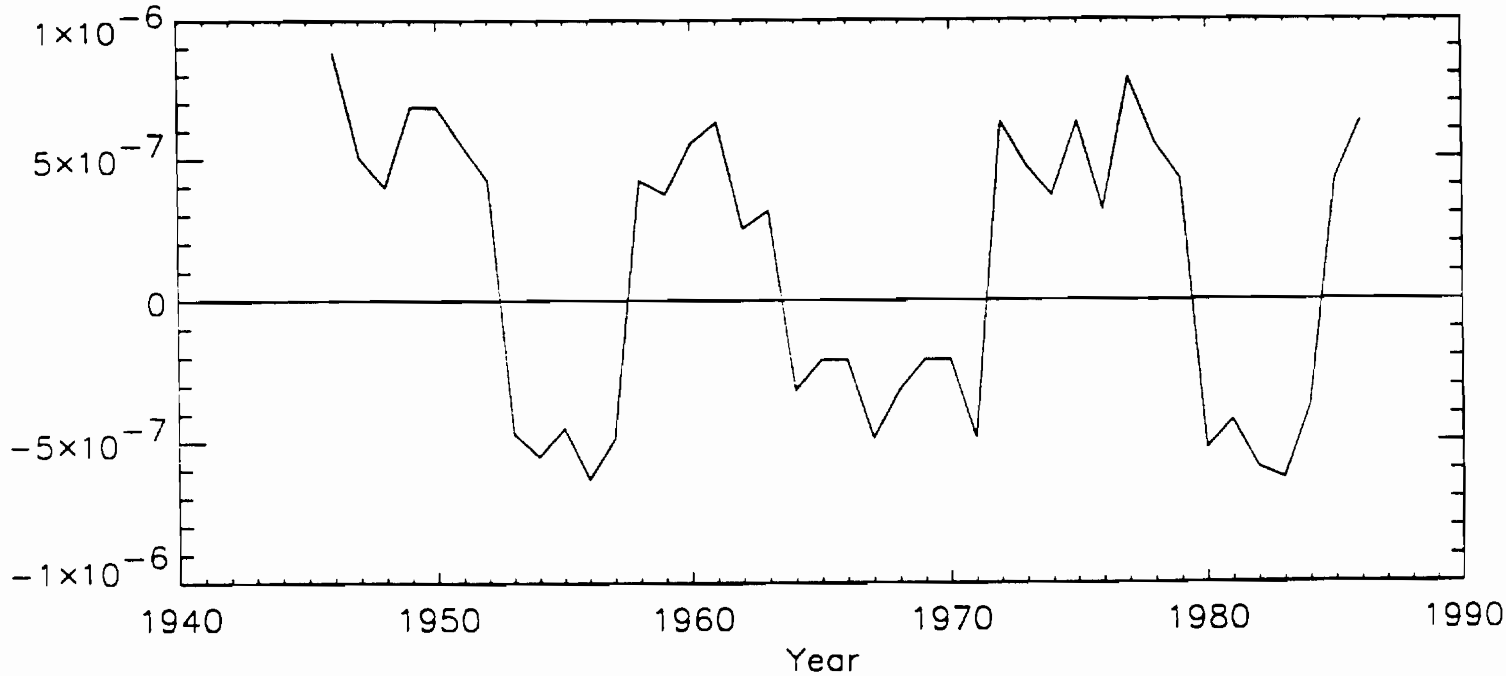

Figure 7. Gradients of sea level in the central Arctic Basin. Positive gradients indicate anticyclonic circulation and negative gradients indicate cyclonic circulation. In 1995-1999 we expect a cyclonic regime to prevail.

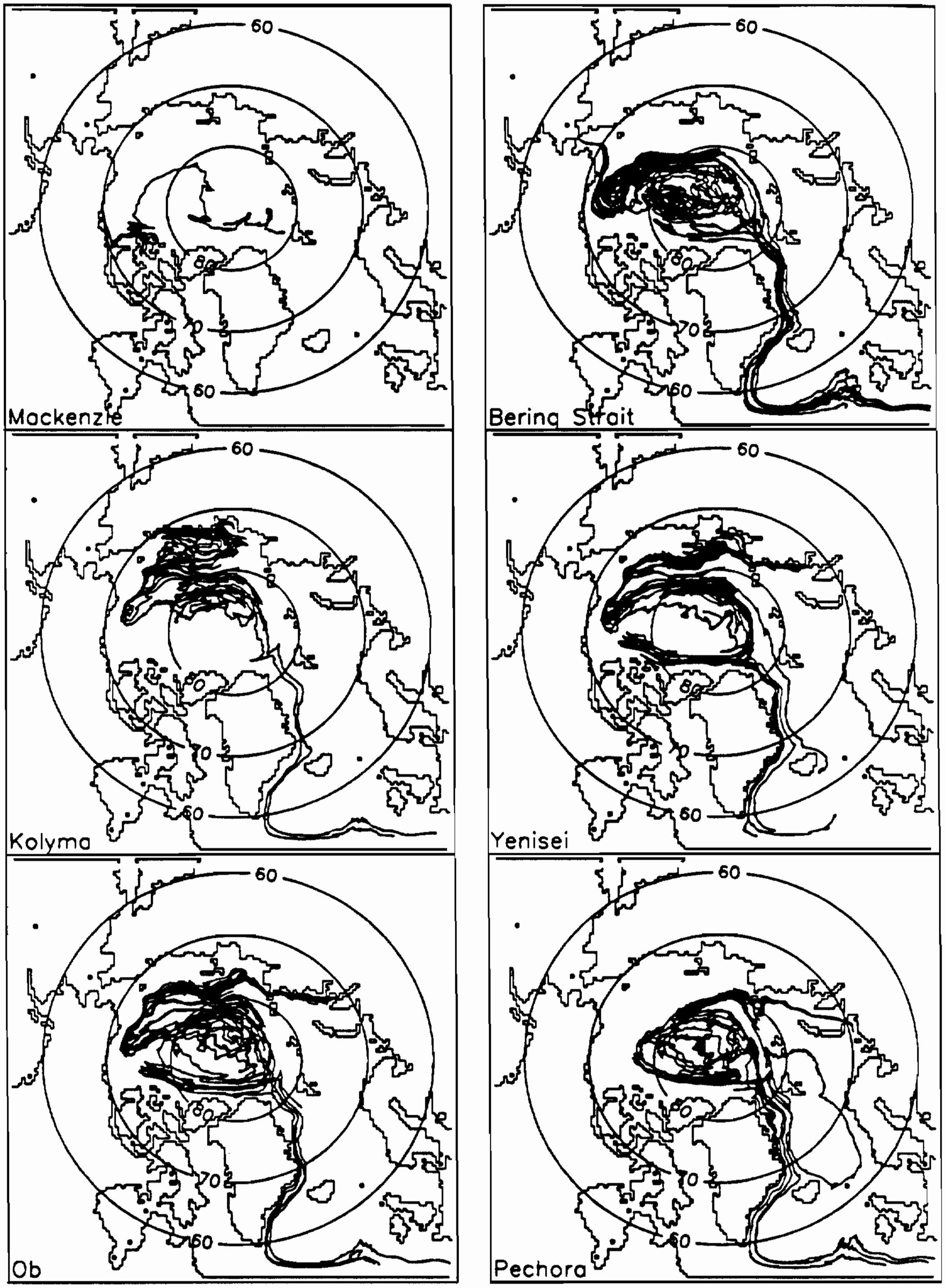

Figure 8.Trajectories of water parcels released from different regions in 1946.

Marine Ice Bottom Gouging: Some Mechanisms and an Approach to Depth Evaluation

Vladimir E. Ryabinin*, Alexander I. Danilov, Vladimir V. Elisov, Alexander V. Klepikov, Vladimir A. Kurdumov, Valery N. Malek, Victor N. Smirnov, Igor N. Stepanov, Oleg Ya. Timofeev
(Eco-System Ltd., Moscow)

Sea floor gouging by marine ice is an issue which is of crucial importance for feasibility assessment and design of underwater gas pipelines in polar seas. A framework for provision of corresponding information has been developed by Eco-System Ltd., Moscow, in the course of a project on gas pipeline construction across the Baydaratskaya Bay in the Kara Sea, Russia.

Among the mechanisms considered were:

- penetration of an iceberg from Kara Sea to the pipeline crossing area, which is likely to be catastrophic for the construction because of the strength of fresh iceberg ice;
- gouging by floating pressure ridges and previously grounded hummocks;
- bottom gouging by various motions of grounded hummocks.

In addition to that, some results have been obtained on other ice-related phenomena likely important for the project during both construction and exploitation phases. They included:

- ice storm;
- ice impact on the shore;
- sea floor erosion under intensification of tidal currents below pressure ridges;
- impact of ice on bottom during events of anomalous detachment of fast ice from the shore;
- penetration of multi-year ice from the Kara Sea to the bay, which usually is covered by a first year ice;
- late disappearance of ice cover in the bay;
- early freezing of the bay.

Fig. 1 shows a fragment of echolocation record revealing three deep gouges in the crossing zone. The width of each gouge was some tens of meters. The depth was slightly more than 1 meter. Similar gouges were observed in five spots likely located along one path in the deepest part of the region. It is shown in Fig. 2. Historical information on

*(PI). The corresponding author's address is: Dr. V.E. Ryabinin, State Oceanographic Institute, 6, Kropotkinsky Per., Moscow, 119838, Russia. Tel./fax +7 095 246 3970

observed tracks of icebergs in the Kara Sea illustrated in Fig. 3 may not exclude completely an event of an iceberg penetration into the bay.

The most important feature of the bay water dynamics is dominance of a semidiurnal tide. Accordingly, motion of an iceberg driven by wind and current from the North-West superimposed on tidal circulation was considered. The model was similar to one by E.G. Banke and S.D. Smith (1984). However, the set of forces taken into account was complemented by a bottom soil resistance. Melting of all iceberg sides was specified, too. The results are shown in Fig. 4(a-f). Fig. 4a shows total distance of iceberg drift during a four months long run. An increased part of the picture corresponding to the first 5 days of the run is given in Fig. 4b. It turned out that reversible motion of the iceberg with both positive (towards the bay) and negative velocities seen in Fig. 4e was possible during a part of the first month of the experiment only. When gouge depth exceeds approximately ten centimeters, the iceberg motion becomes unidirectional, and the iceberg starts to "jump" periodically towards the bay during rising tide and high water phases. Despite the decrease in iceberg draught (Fig. 4c) and mass (Fig. 4d) the gouge depth increases along the path, which corresponds fairly well to the results of field measurements. Hence combined effect of tidal and wind drift and of floor resistance acts somewhat like a semiconductor or a trap allowing iceberg propagation towards the bay only.

While iceberg gouging in the crossing zone must be excluded, special measures should be undertaken to monitor icebergs in Kara Sea to make this certain. Gouging by bodies made of broken ice is to be avoided by burying the pipe. A framework of three steps has been developed to provide quantitative information on gouging depth for decision makers.

The aim of the first step is the determination of statistics on all parameters to be taken into account. They include data on pressure ridges and grounded hummocks including: geometry, composition, ice strength, degree of ice consolidation, and amounts of water and air inclusions. The information is to be obtained from air reconnaissance, satellite data, core probing, topographic surveys, and from all other existing sources. Fine scale data for ice body drift velocity vectors should be collected as well. A directional distribution may be generated by a model. Supporting field measurements are of importance too. The procedure envisages determination of best statistical distribution estimates for each listed parameter with the most important correlations between some of them. Using specially developed methods, the procedure then generates a series of hummock parameters which, in statistical sense, are similar to those observed in the field near the area of interest. An example of simulated vertical profiles of the upper part of two pressure ridges is shown in Fig. 5.

The next step is the determination of gouge depth corresponding to each combination of parameters generated by the stochastic procedure at the previous step. It is done by using a gouging model, which generalizes the well known approach by T.R. Chari (1979). The input information for it includes a set of stochastically generated parameters on hummocks and a set of site specific parameters. They comprise data on soil composition, which makes computation of resistance possible, information on bottom relief, and the distribution of current vectors. The model is capable of considering the resistance of various types of soil including cases where: a gouge goes across two vertical layers with different soil properties; starts gouging at an intermediate point of a grid interval; or comes out of the soil at a point (see Fig. 6 a,b). It is a two-dimensional model. The model output is the gouge depth predicted for a given set of output parameters at a given point along the pipe. This process is repeated many times thereby generating a series of bottom gouging depth, which is specific for this point.

Fig. 7a-c shows comparison of observed (a) and predicted (b) gouge distribution at a point along the pipeline located nearly twenty kilometers from the Yamal Peninsula coast. A number of gouges was taken from side scan sonar survey, and all other information was specific for the point. Gaussian approximation of observed and simulated distributions revealed that differences of mean values and standard deviations were both equal to one centimeter. These first verifications were successful; however, in the future, they should be conducted on a much wider scale.

The purpose of the final step is the evaluation of the maximum gouge depth possible in *N* years of pipeline use with an *a priori* given probability. This is to be done for all points along the pipe. To make this calculation one should have a gouge depth series, which is the result of step 2 of the procedure. Besides one should know the total number of gouging events to occur at each point of the crossing. Thus detection of gouging becomes important. In principle, it is possible to detect gouging by frequency filtering of seismic noise arriving at special sensors installed in the area. Fig. 8 shows some results of corresponding studies. The method may also be very useful for locating places with minimal gouging to aid the selection of the crossing line. However, at present other considerations are being used to determine the number of gouging events.

The final output is represented by curves of maximum gouging depth possible in a given return interval for a given range of probabilities. An example is shown in Fig. 9. The results, however, happen to be very sensitive to input information on soil properties (composition and resistance).

An extension of this study is presently underway. Attention is now drawn to other ways of ice impact on a pipeline. For example, loads are being studied, which may be applied to several types of motions of a grounded hummock (see Fig. 10). A numerical finite element model for loads on a pipeline due to soil deformation and the direct contact of ice with the pipe has been developed (see Fig. 11).

The framework worked out along the above described lines makes it possible to evaluate a pipeline burying depth curve, which would lead to a minimal total damage risk (for the whole length of the pipe) due to gouging for a given set of pre-specified conditions. One of them is the cost of the soil work since pipeline burying is the most expensive part of such projects. This study, along with an account of permafrost-related problems, provides a background for the design of cost-efficient underwater pipelines in polar seas.

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Banke, E.G. and S.D. Smith (1984), "A hindcast study of iceberg drift off the Labrador coast," Can. Tech. Rep. Hydrogr. Ocean Sci.

Chari, T.R. (1979), "Geotechnical aspects of iceberg scours on ocean floor", Canadian Geotechnical Journ.

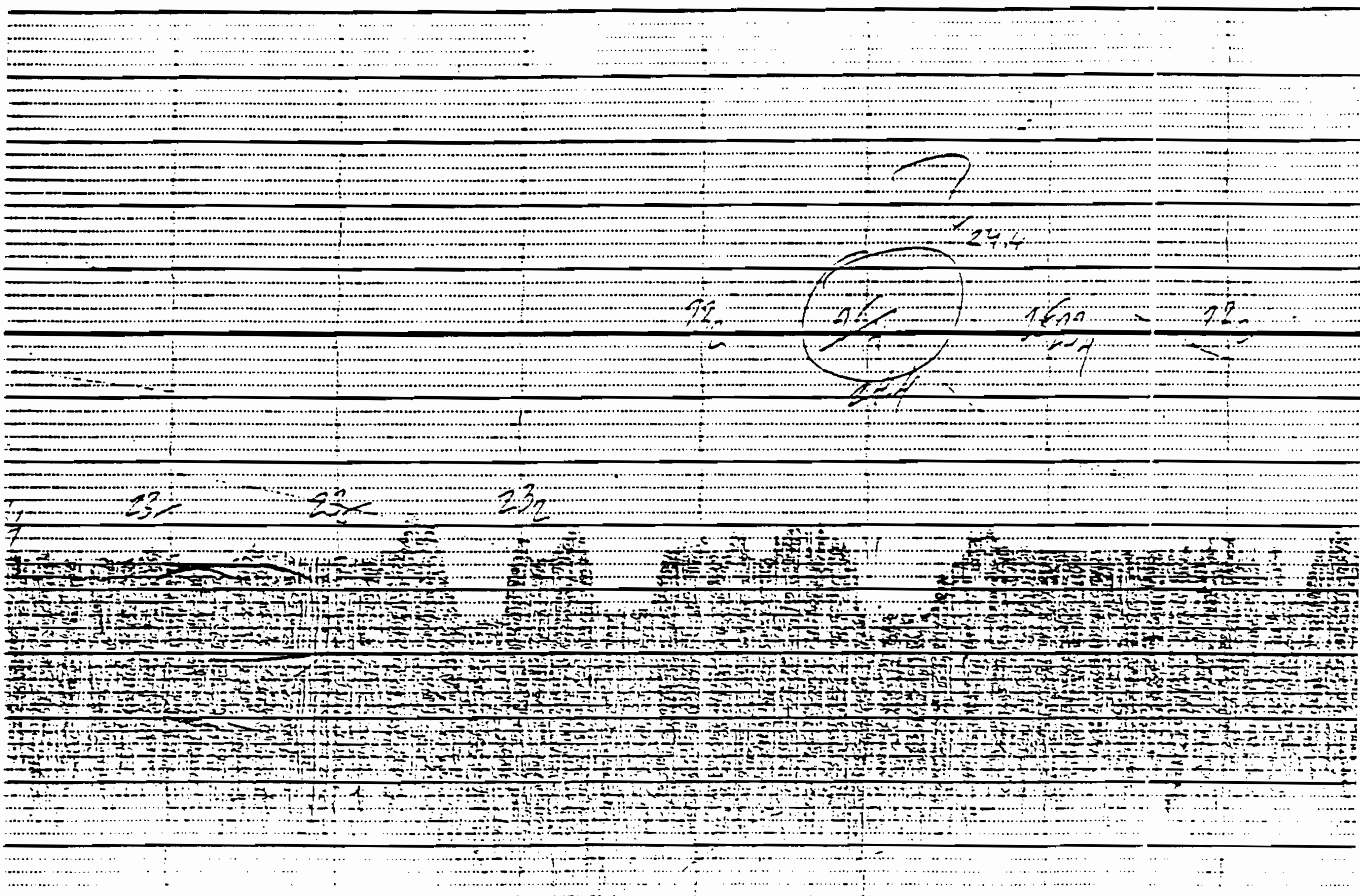


Figure 1. A part of echolocation record revealing three deep gouges probably left by an iceberg (pipeline crossing area).

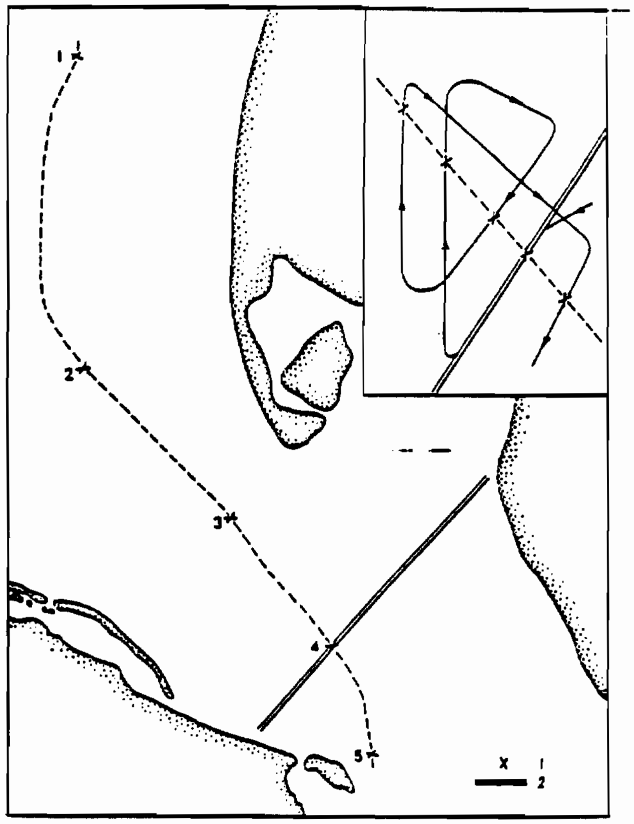


Figure 2. Spots where deep gouges were detected in 1992 and corresponding ship route.

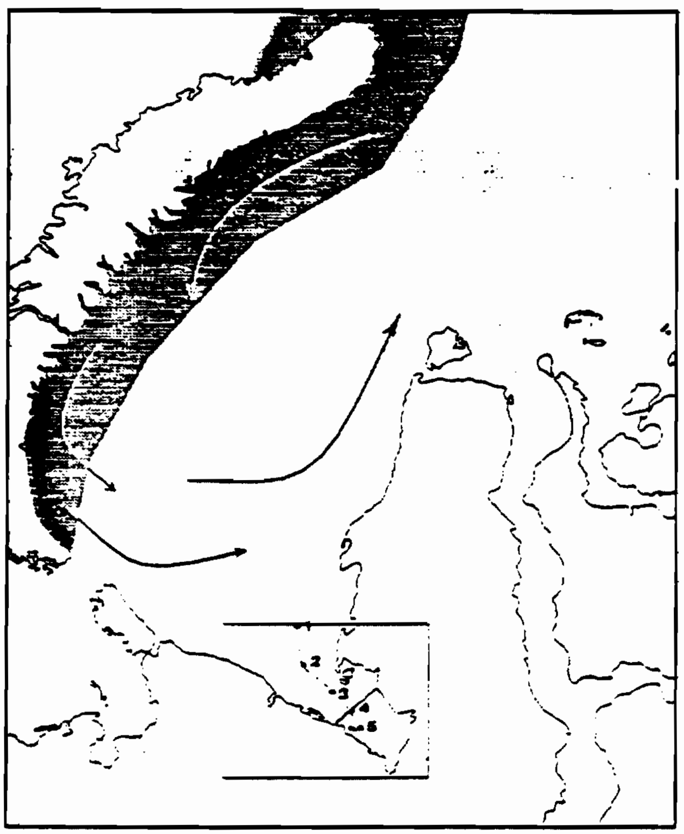


Figure 3. Dominant tracks of icebergs in Kara Sea dark area showing the region of iceberg maximal occurrence.

Iceberg motion simulation:

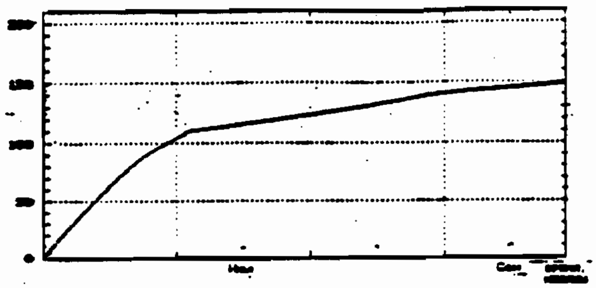


Figure 4a. Distance covered in 4 months time.

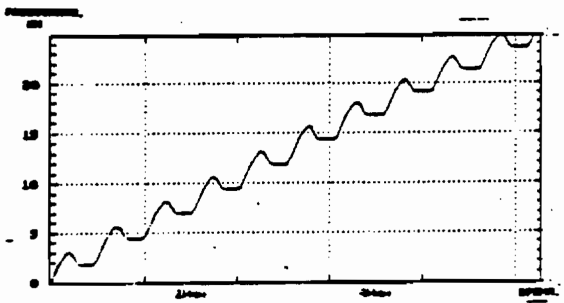


Figure 4b. Increased portion of the above picture for first 5 days of the run.

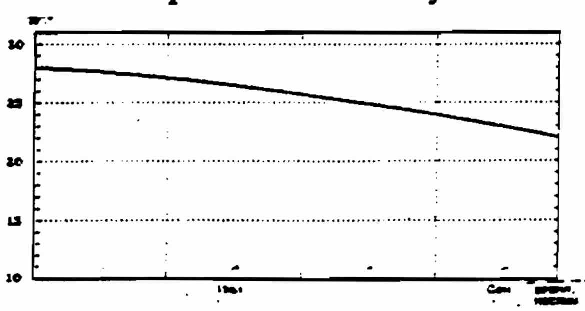


Figure 4c. Iceberg draught against time.

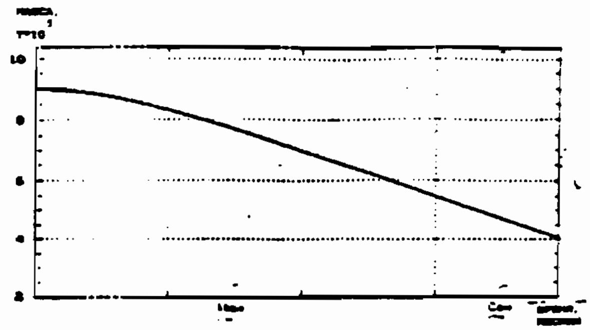


Figure 4d. Iceberg mass.

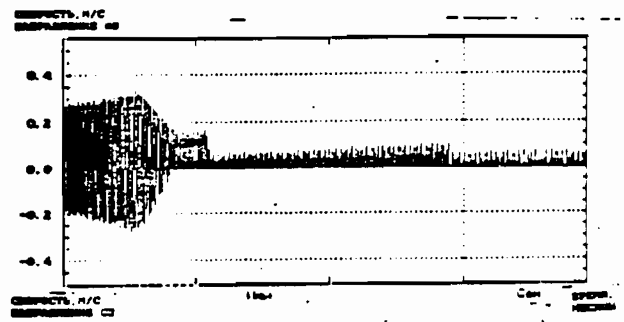


Figure 4e. Speed and direction of iceberg propagation.

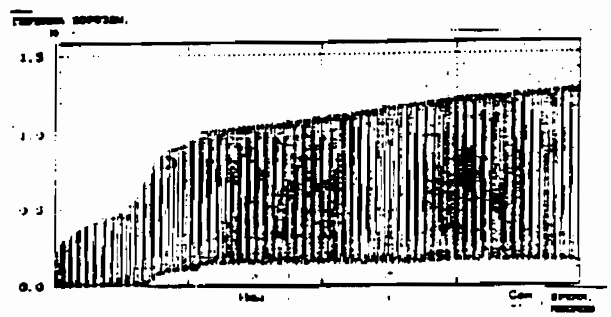


Figure 4f. Corresponding gouge depth.

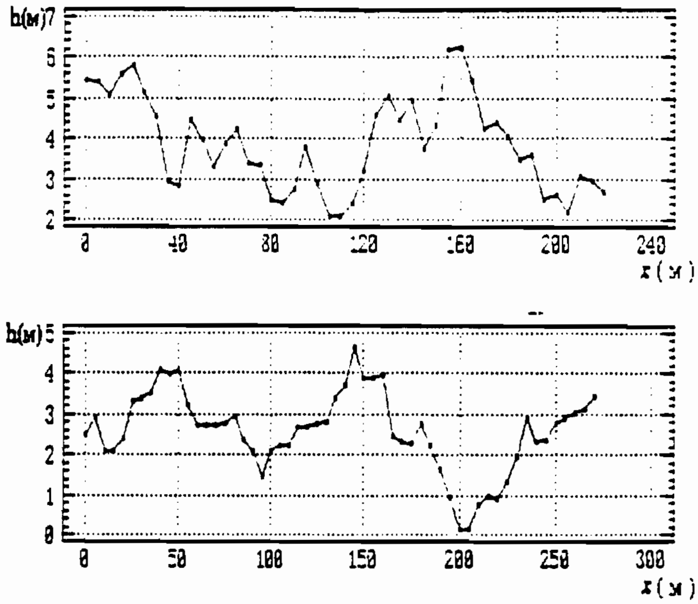


Figure 5. Simulated profiles of pressure ridges height in Baydaratskaya Bay using random number generator.

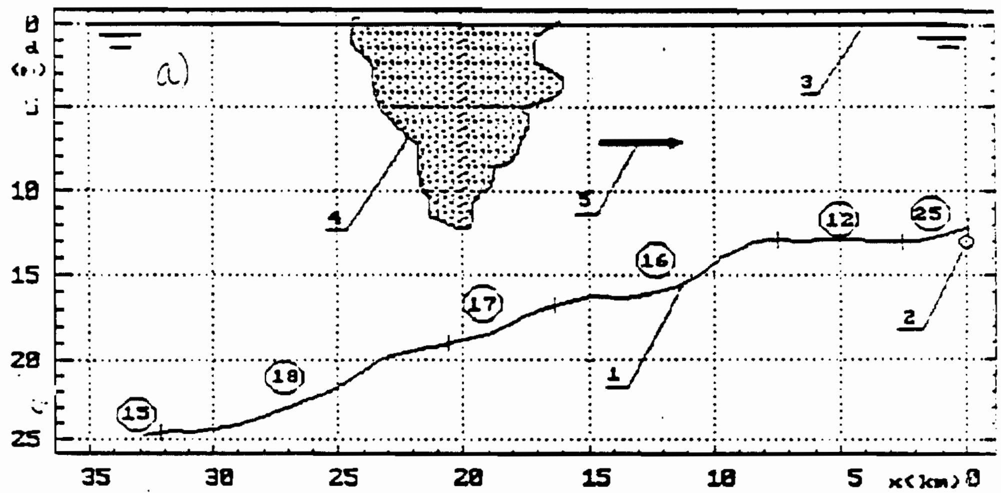


Figure 6a. Gouging simulation. Numbers in circules indicate soil type. The distance from the pipeline is given in kilometers. 1 - bottom profile, 2 - pipeline, 3 - water surface, 4 - pressure ridge underwater part, 5 - direction of its motion.

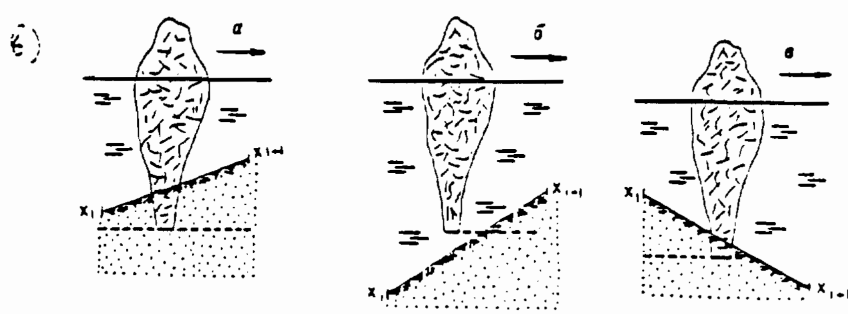


Figure 6b. Three possible schemes of hummock - floor interaction considered in the course of simulations.

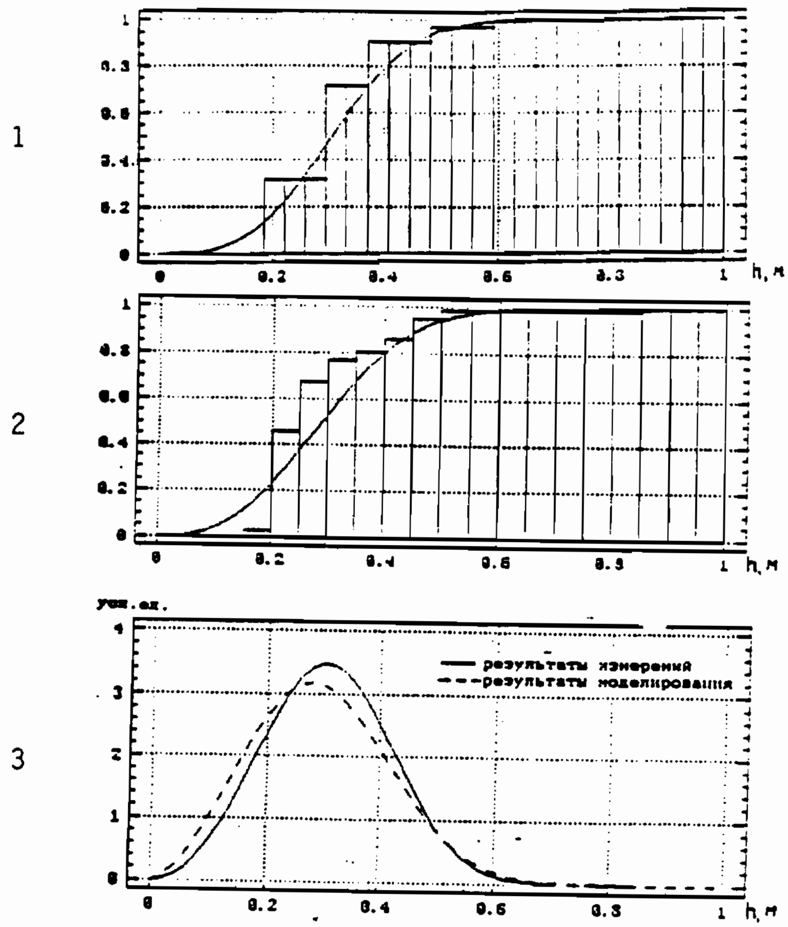


Figure 7. Test comparisons of gouge depth simulation against sonar data for small region closer to the eastern coast of Baydaratskaya Bay: 1 - distribution of measured depth, 2 - simulated depth distribution, 3 - their approximation of Gaussian hump (means and standard deviation differences were both equal to 1 cm).

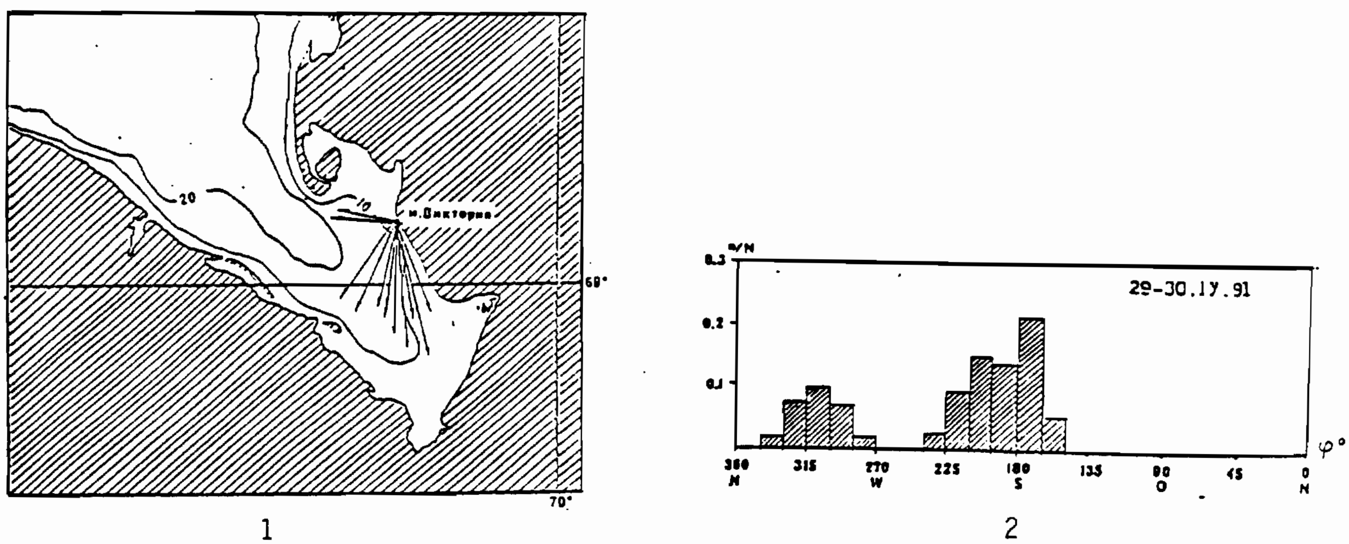


Figure 8. Seismic-acoustic detection of gouging: 1 - arrows pointing at seismic signals from point Victoria, 2 - relative numbers of gouging acts for various directions as seen from point Victoria.

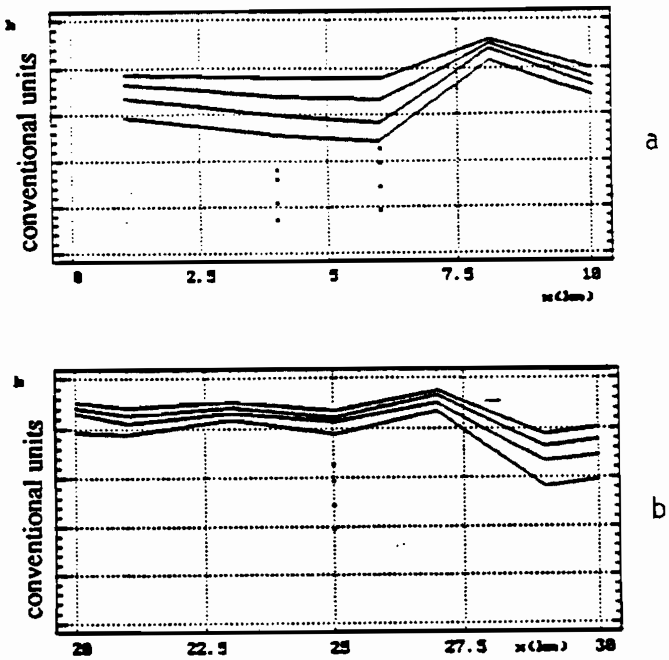


Figure 9. Gouge depth distribution prediction for two points along the crossing with four different probabilities (depth possible once in 30 years). Small black points show the results obtained before correction to information on soil properties was inserted.

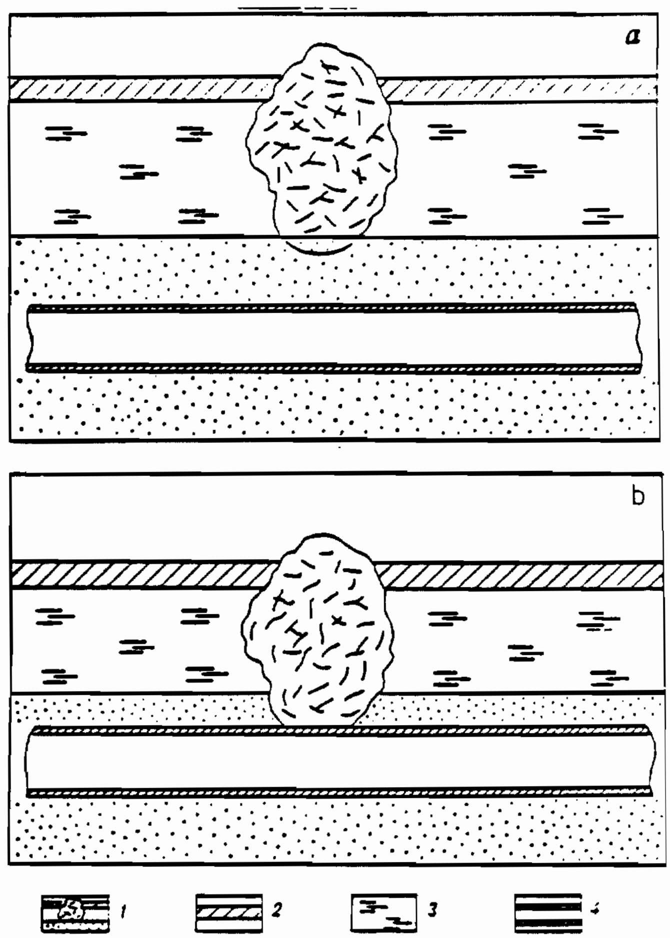
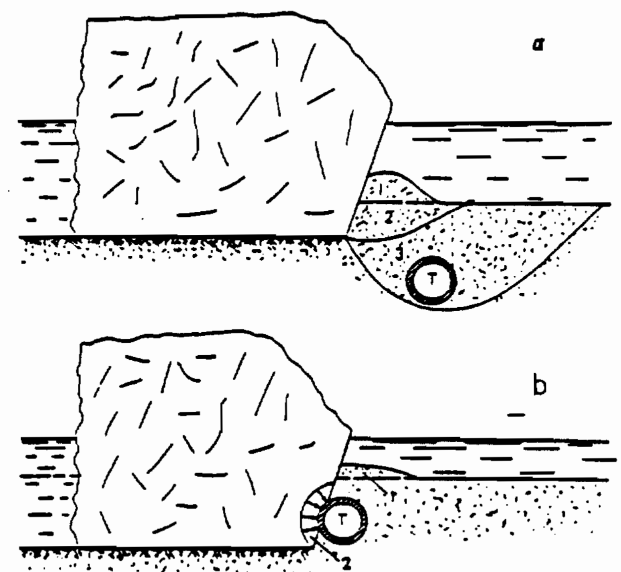


Figure 10. Two considered ways of grounded hummock interaction with pipeline (without and with direct contact).



Figures 11a and b. Two ways of ice impact on a pipeline. Figure a depicts the impact without direct contact. 1 - removed ground, 2 - zone of dangerous deformations, 3 - safe zone. Figure b depicts the impact with direct contact. 1 - removed ground, 2 - zone of plastic ice deformation.

An Improved Fuzzy Logic Segmentation of Sea Ice, Clouds and Ocean in Remotely Sensed Arctic Imagery

by

J.J. Simpson and R. H. Keller
Digital Image Analysis Laboratory
Scripps Institution of Oceanography
La Jolla, CA 92093 - 0237

Abstract

The accurate segmentation of sea ice from cloud and from cloud-free ocean in polar AVHRR imagery is important for many scientific applications (e.g., sea ice - albedo feedback mechanisms, heat exchange between ocean and atmosphere in polar regions; studies of the stability of surface water in polar regions). Unfortunately, it is a difficult task complicated by the common visible reflectance characteristics of sea ice and cloud. Moreover, AVHRR channel 3 data historically have been contaminated by highly variable sensor noise which generally has hampered their use in the classification of polar scenes. Likewise, polar scenes often contain pixels with mixed classes (e.g., sea ice and cloud). This paper uses a combination of fuzzy logic classification methods, noise reduction in AVHRR channel 3 data using Wiener filtering methods (Simpson and Yhann, 1994), and a physically motivated rule base which makes effective use of the Wiener filtered channel 3 data to more accurately segment polar imagery. The new method's improved classification skill compared to more traditional methods, as well as its regional independence, is demonstrated. The algorithm is computationally efficient and hence is suitable for analyzing the large volumes of polar imagery needed in many global change studies.

Accurate Segmentation of Complex Satellite Scenes

James J. Simpson and Robert H. Keller

Digital Image Analysis Laboratory
Scripps Institute of Oceanography
University California San Diego
Mail Stop 0237
9500 Gilman Drive
La Jolla, CA 92093-0237

ABSTRACT

Accurate cloud detection in Advanced Very High Resolution Radiometer (AVHRR) data over land is a difficult task complicated by spatially and temporally varying land surface reflectances and emissivities. The AVHRR Split-and-Merge Clustering (ASMC) algorithm for cloud detection in AVHRR scenes over land provides a computationally efficient, scene specific, objective way to circumvent these difficulties. The algorithm consists of two steps: 1) a split-and-merge clustering of the input data (calibrated channel 2 reflectance, calibrated channel 4 temperature, and a channel 3 - channel 4 temperature difference) which segments the scene into its natural groupings; and 2) a cluster labeling procedure which uses scene specific joint three-dimensional adaptive thresholds (as opposed to constant static thresholds) to label the clusters as either cloud, cloud-free land, or uncertain. The uncertain class is used for those pixels whose signature is not clearly cloud-free land or clouds (e.g., pixels at cloud boundaries which often contain subpixel cloud and land information which has been averaged together by the integrating aperture function of the AVHRR instrument). Results show that the ASMC algorithm is neither regionally nor temporally specific and can be used over a large range of solar altitudes. Sensitivity of the segmentation and labeling steps to the choice of input variables also was studied. Results obtained with the ASMC algorithm also compare favorably with those obtained from a wide range of currently used algorithms to detect cloud over land in AVHRR data. Moreover, the ASMC algorithm can be adopted for use with data to be taken by the Moderate Resolution Imaging Spectrometer-Nadir (MODIS-N).

Physical processes in ice cover

V. Smirnov and V. Korostelev

Arctic and Antarctic Research Institute, St. Petersburg, Russia

A description of the mechanical processes in sea ice cover is given. The stress releases, concentration and relaxations of stress, self-excited oscillations by compression and hummocking are observed. The periodical character of the destruction mechanism creates preconditions for occurrence of the cyclic ice loads. Self-oscillations in drifting sea ice floes are considered. Periodic flexural fluctuations of ice floes are concurred by generation of a wide spectrum of elastic and surface gravitation waves revealing features of hummocking mechanisms. Self-excited oscillations in the system "iceberg-pack ice" are considered. The dynamic response of an iceberg at interaction with ice fields are showed.

1. INTRODUCTION

A physical description of the interactions between sea ice floes is a complicated scientific problem. This is important both for proper understanding geophysical large-scale processes and for solutions of a number of engineering problems. Ice floes have different shapes and different drift velocities, that is why cracks and leads being formed. Ice hammoking can happen both due to local external forces and to influence of adjacent and remote ice floes. Spreading of a "compression wave" in the ice cover was found in some reports.

Images from satellites and aircrafts have made obvious a presence of hummock ranges of different forms and scales. A rectilinear structure of these ranges with mosaic and diamond shaped formations is observed sometimes (Kupetsky, 1974). It should be noted that similar cress-cross lead patterns are formed both in small specimen ice pieces and in large-scale ice cover; this confirms an existence of a scale effect in continuous media (Fig. 1).

It indicates also a probability of relatively rapid strain rates in vast areas of the Arctic Ocean being under external forces (Marko and Thompson, 1979). Shearing motions of ice floes are the major energy sink. So it is necessary to know the distribution of stresses which is able to form the regular structure.

2. RESULTS

A few examples of interactions between ice floes under the action of external forces follow. A major attention is devoted to determination of space-time scales of these phenomena; by other words to what extent these processes are responsible for large-scale structure of the sea ice.

1. Figure 2^a presents a record of a seismo-tiltmeter installed on the edge of a drifting Arctic iceberg, an ice island with dimensions 2.5x5 km and thickness of 28 m. For several minutes it was responding to an impact of adjoining solid ice floe with a thickness between 3 and 5 m. Before this event oscillations of the iceberg's tilt did not exceed 0.1 mcrad. The

iceberg can be considered to accelerate or to decelerate (as well as to tilt) for the periods t1-t2, t5-t6 and t7-t8.

In the case of impact the estimates made by Weber's technique (1972) showed that the iceberg could change its velocity during one event of interaction 0.1-1.0 cm/s.

In the case of the tilt the picture is as follows. The iceberg started to tilt at the moment t; the tilt was rising gradually until the moment t1, when a sharp shake up to 5 mkrad during 10 c occured. Right this moment the edge of the iceberg began to return to its initial position.

Altogether 3 events of interaction took place; they could be used for a description of the picture of destruction and hammoking of the pack ice on the basis of existing models. Periods between destruction events amounted to 3 min and 2 min. The period of destruction by a flexure is about 10 s. The residual iceberg's tilt was 2 mkrad.

The ice-floe's destructive process lasted about 10 s, the shape of the record permits us to propose that the destruction was caused by ice floe buckling in the iceberg's vicinity. A few parallel crack 50 m apart one from another have been noticed visually.

2. It is interesting to consider data on an interaction between the drifting ice cover and an iceberg of 200x300m in dimensions with the height of the surface part about 50 m. Such an iceberg could be regarded as a model of a wide floating engineering structure.

The measurements were carried out by instruments installed on the drifting ice and on the iceberg. A typical record of the pendulum tiltmeter is presented in Figure 2b.

3. A tilt record of an ice floe with thickness of 3-4 m is drawn in Figure 3. No signs of local processes took place in this event. There were periods between 70 and 160 s in the oscillation spectrum. Oscillation processes were accompanied by a friction on the walls of through cracks; these generated elastic and gravity waves in period range from 0.3 to 6 s. In turn these waves could be subdivided into elastic horizontally polarized ones with periods of 0.3-3 s (self excited oscillations) and flexural-gravity waves with periods 1-6 s. The pattern of the event was a follows obviously. A pulse group with a duration of an hour generated strains in the ice floe, on the cracks' walls and in the boundary surface between two floes. As a result a collapse occured in the moment t2. The wave length in the group could amount to dozens of kilometers, a trace in the form of cracks and small ranges of hummocks could remain after the wave train passage.

Example presented is the illustrations of ice floes' deformations when long-period oscillations provoke the ice destruction. The space scale of the phenomenon taking into account long waves could amount to dozens of kilometers.

4. As a result of ice-floe interaction a self excited oscillation arises which is accompanied by periodical buckling of ice floes and a generation of elastic waves. Two hypotheses are proposed to explain this phenomena (Smirnov et al., 1993).

A displacement of the ice-floe's part causes its buckling and gradual increase of compression stress inside the contact area. At a moment the ice inside the boundary zone being destroyed and a clearance between the parts of the ice is appearing. The flat shape of the ice is restoring and a sliding in the longitudinal direction is going on due to decrease of the friction between the sides of the crack.

A "period" of these deformations amounts to 30 s. A record of relative deformations or tilts of the ice is saw-like. If the ice inside the interface area is not destroyed the ice floe may be wave-shaped. In accordance with the elasticity theory a fixed rectangular ice plate compressed from two opposite sides loses its stability when force of compression reaches the value N=kD/b, where k is hardness of the underlay (here this is a sea water); D-Eh/12(1-m); E- elastic modulus; h is ice plate thickness; m - Poisson coefficient; b - ice plate width. The form of buckled plate in the direction of the compression force has a damping sinusoid shape. The amplitudes of further periods of the sinusoid are rising and flattening out with the increase of the force. In the perpendicular direction there is only one half-wave of the sinusoid.

In the case of weak interaction a destruction of the ice is going on at the boundary area and the former shape of the ice floe being restored. The process is recurring many times until the final ice destruction. The period of this self-excited process is determined mainly by physical-mechanical properties of the ice and by area of interaction.

An alternative explanation is based on the phenomenon of self-excited oscillations arising due to non-linear dependence of friction upon the velocity. The velocity of one part of the floe relative to another part remains zero until static friction is larger that elastic deformation forces. As the elastic force begins to exceed the static friction, the sliding starts. The ice floe slides for some period of time and stops. Then again it is held by static friction for some time.

According to the second hypotheses a friction pair arises at the interface between two floes and it generates self excited elastic horizontally polarized waves in narrow frequency band (0.3 to 3 Hz). A duration of such type of oscillations can reach dozens of minutes: it is reasonable to assume that the compression force and the velocity of sliding with friction are more or less constant for a long time.

Therefore self excited oscillations indicate a development of shears with friction caused by a compression. There were cases when oscillations were observed be wave trains with intervals between them. For example, wave trains with frequency 0.8 Hz were observed a few hours in the drifting ice of 0.5 m thickness. A duration of a train was about 2 or 3 minutes. It is difficult to determine what was an area of this phenomenon. Anyway the scale is not less than 5 km (the distance between our detectors). Ice compression occurred once a period of 10 or 20 minutes, and was observed during several hours. But there is no idea still what is the cause of this periodicity.

The Antarctic measurements were made at the mesopolygon relative to the drift of five icebergs, located near a ship at a distance of 4-6 km. According to data, the periods of iceberg convergence coincide with the periods of appearance of self-exited oscillations. For example, on 13-14 October the most intensive self-excited oscillations were observed, while the area of the triangle, made by two icebergs and the ship decreased during the same period by 10 km^2. (Figure 4).

The similar case is shown on Figure 5. The data obtained on measuring Ice Dynamics by Russian-American drifting station "Weddel-1" operating in the Weddel Sea allow to determine the connection between ice compression velocity and self-oscillations. This connection is observed on the scale of several tens of kilometers.

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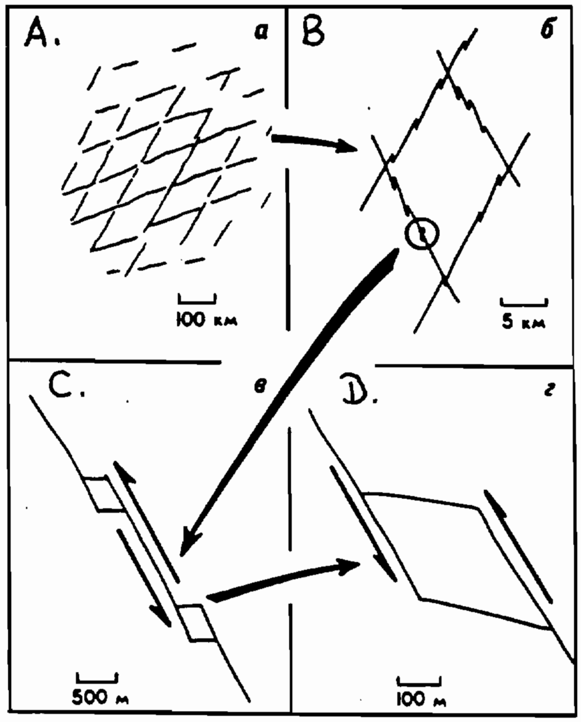


Figure 1. Shearing deformation in sea ice.
Scales: a,b -satellite; c,d - craft.

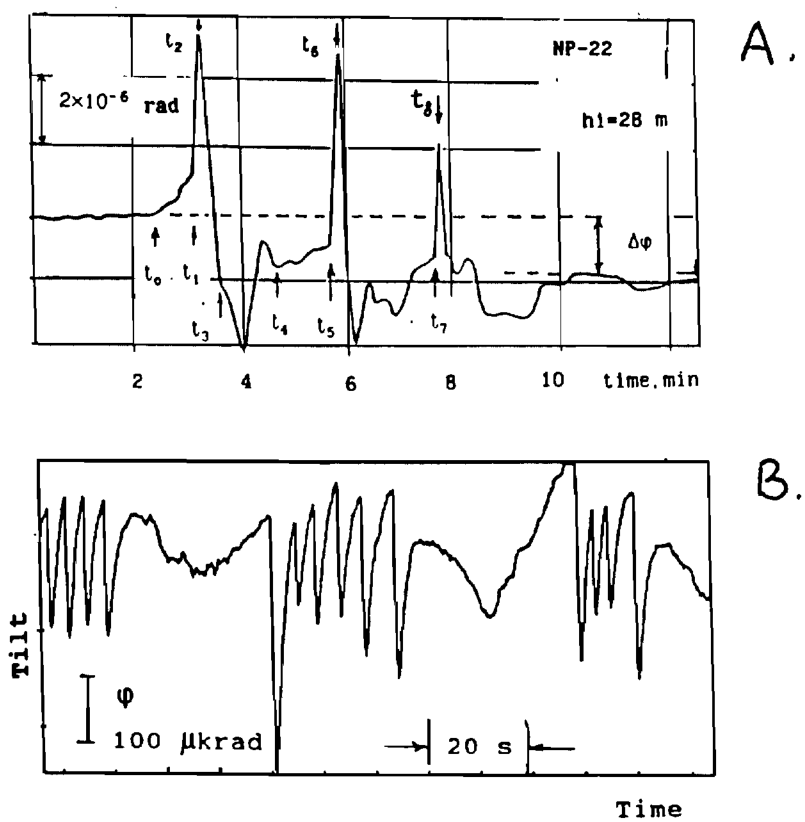


Figure 2. Dynamical response of drifting ice island
and iceberg to their interaction with ice fields.
a - tilt and acceleration of ice iceland;
b - tilt of iceberg.

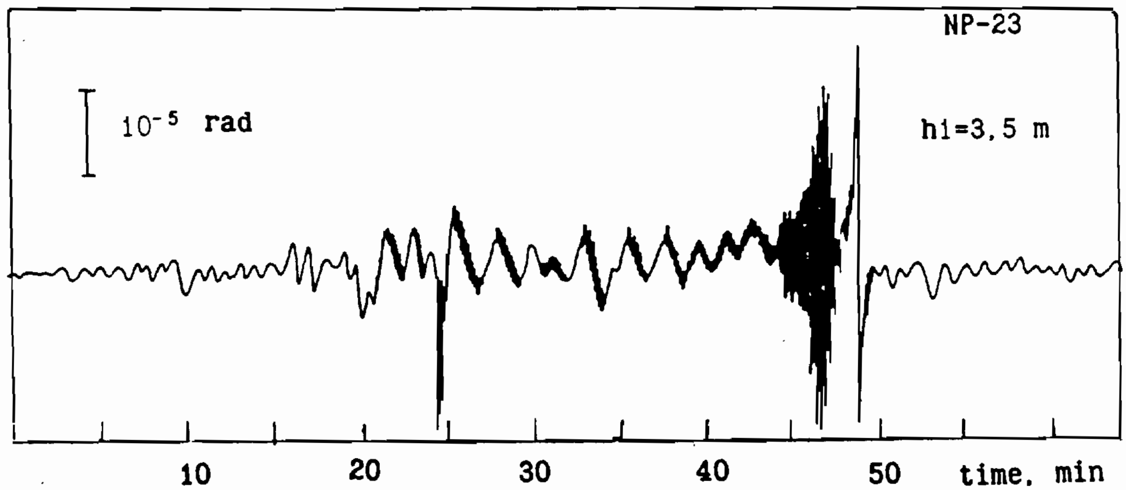


Figure 3. Oscillation and waves in ice field
(the recorder from tiltmeter).

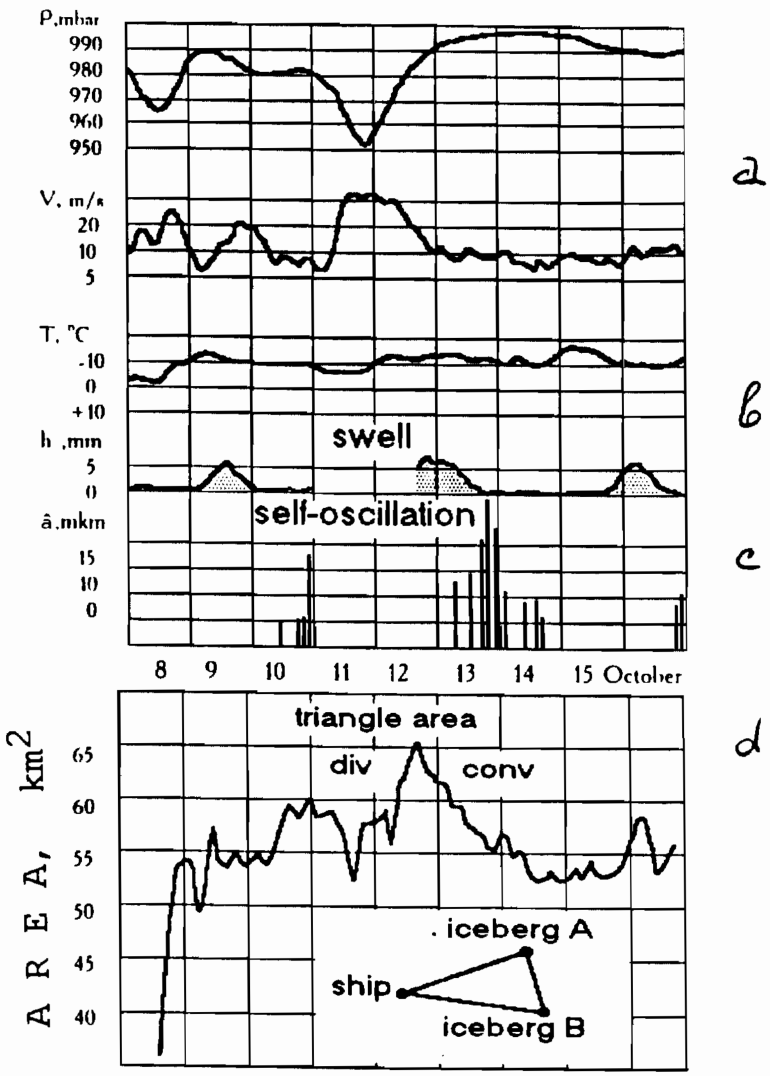


Figure 4. The swell and self-excited oscillation in the ice of the Weddell Sea under compression
a - meteoparameters; b - swell;
c - self-oscillations; d - area of triangle:
iceberg A-ship-iceberg B.

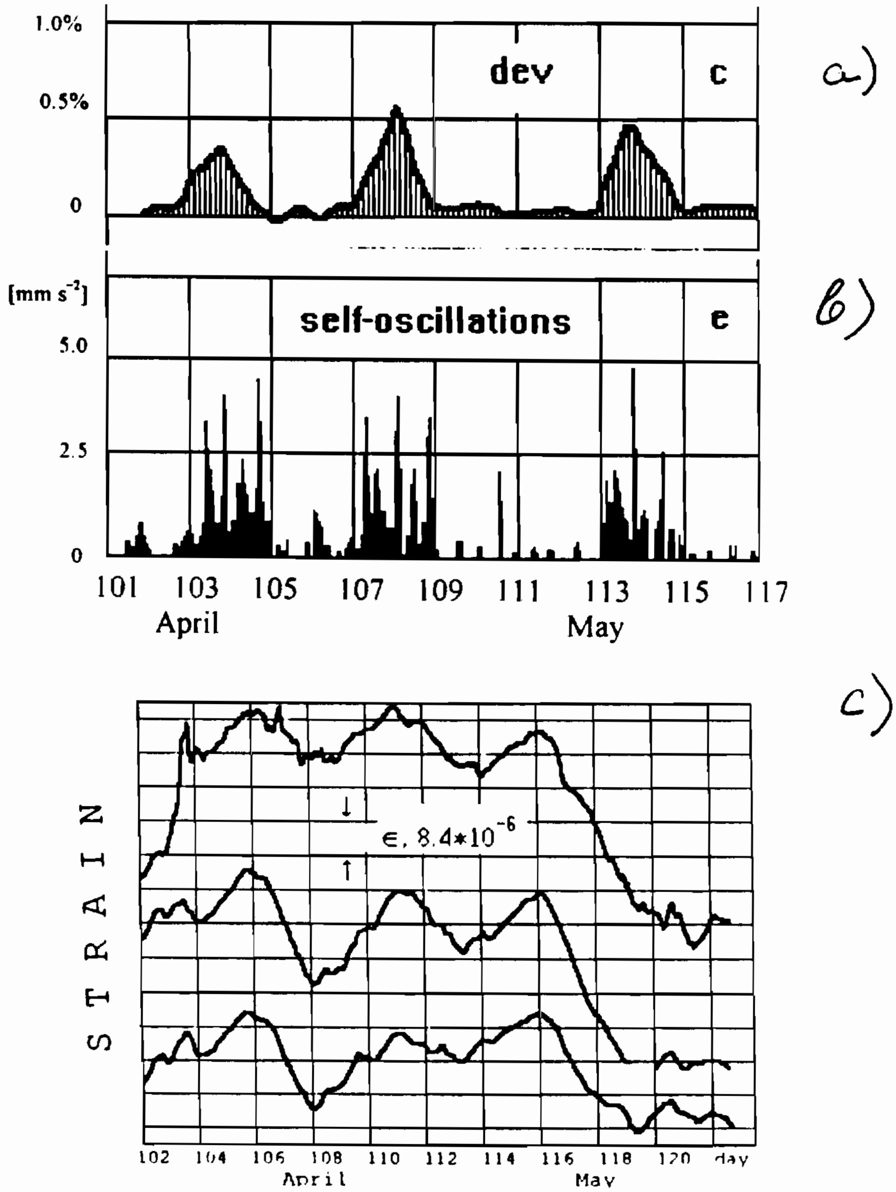


Figure 5. The results of observations of sea ice dynamics and mechanisms of ice interaction in the Weddell Sea.

a) Ice Deformation deviators for large and small scales measured with laser geodimeter;

b) Self-oscillation measured with three seismometers;

c) Relative ice strain recorded by three strain-meters installed in one point.

ICE STUDIES ON THE NORTHERN SAKHALIN OFFSHORE

Truskov P.A., Polomoshnov A.M.
Sakhalin Oil & Gas Institute

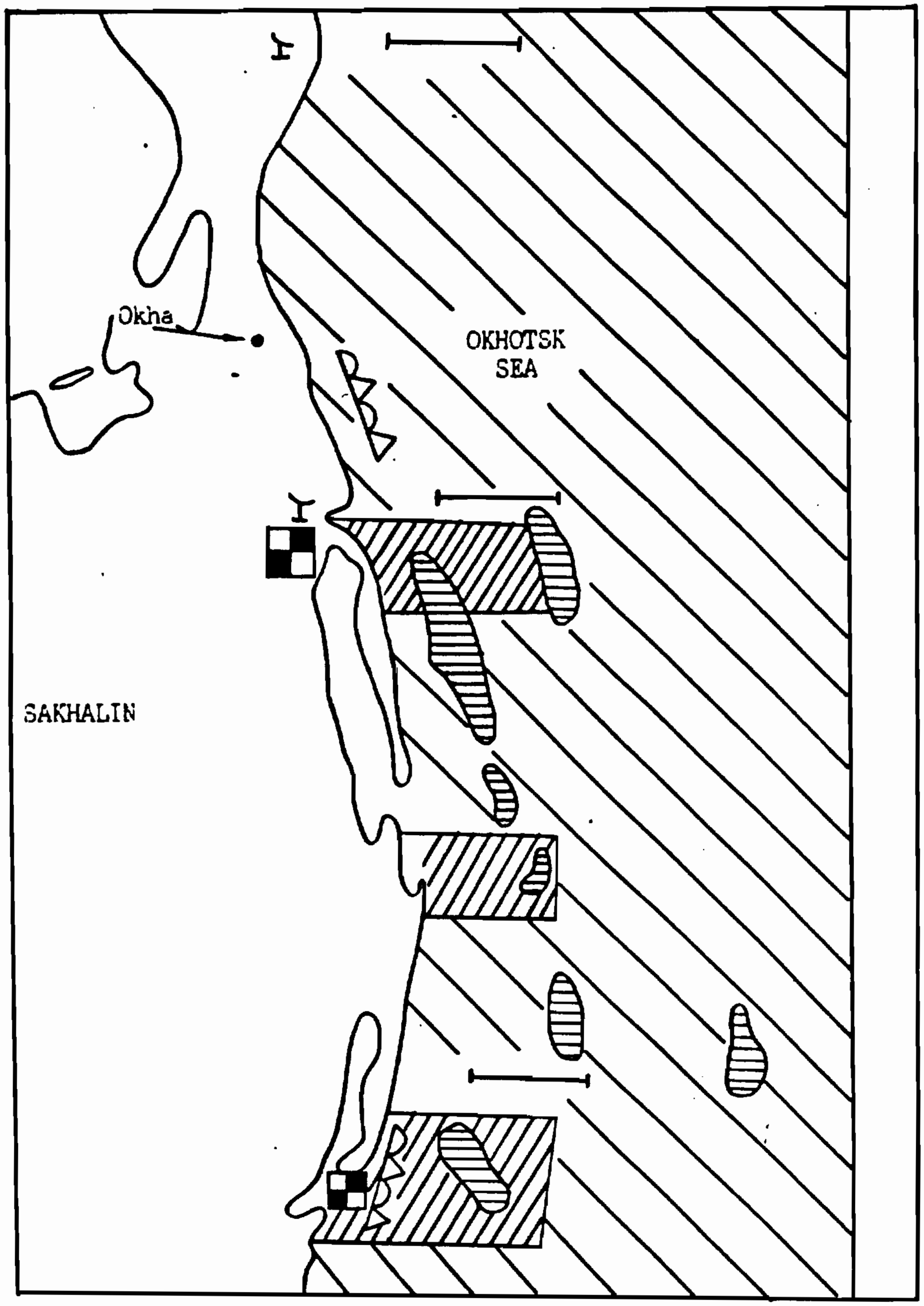
Ice studies on the northern Sakhalin offshore have been carried out since early 80-es. As a result of ice-breaker and helicopter expeditions, RLS based observations of ice drift, analysis of multi-year satellite images and aerial reconnaissances, the following basic data were obtained:

- phisico-mechanical properties of drift ice and fast ice;
- characteristics of grounded hummocks (stamukhas) and gouges left by stamukhas on the sea floor;
- ice drift parameters;
- mega- and mesoscale variability of ice cover;
- interaction parameters for the "atmosphere- ice-water" system;
- horizontal and vertical sizes of drift ice and fast ice.

In addition, the following methods were developed and used in the studies:

- polygon method for studying heterogeneity of physico-mechanical properties of ice;
- complex method for studying stamukhas;
- radar method for studying ice drift parameters.

The obtained data are successfully used for designing oil and gas field facilities on the northern Sakhalin offshore.



- standard ice survey profile
- stamukha's investigation region by mechanical characteristics
- field survey of sea ice mechanical characteristics
- region of air-photography and helicopter landings work
- region of detailed aircraft ice reconnaissance
-perspective for oil and gas structure
- radar station

Fig. 1 Scheme of sea ice regime complex investigation
on Sakhalin eastern coast

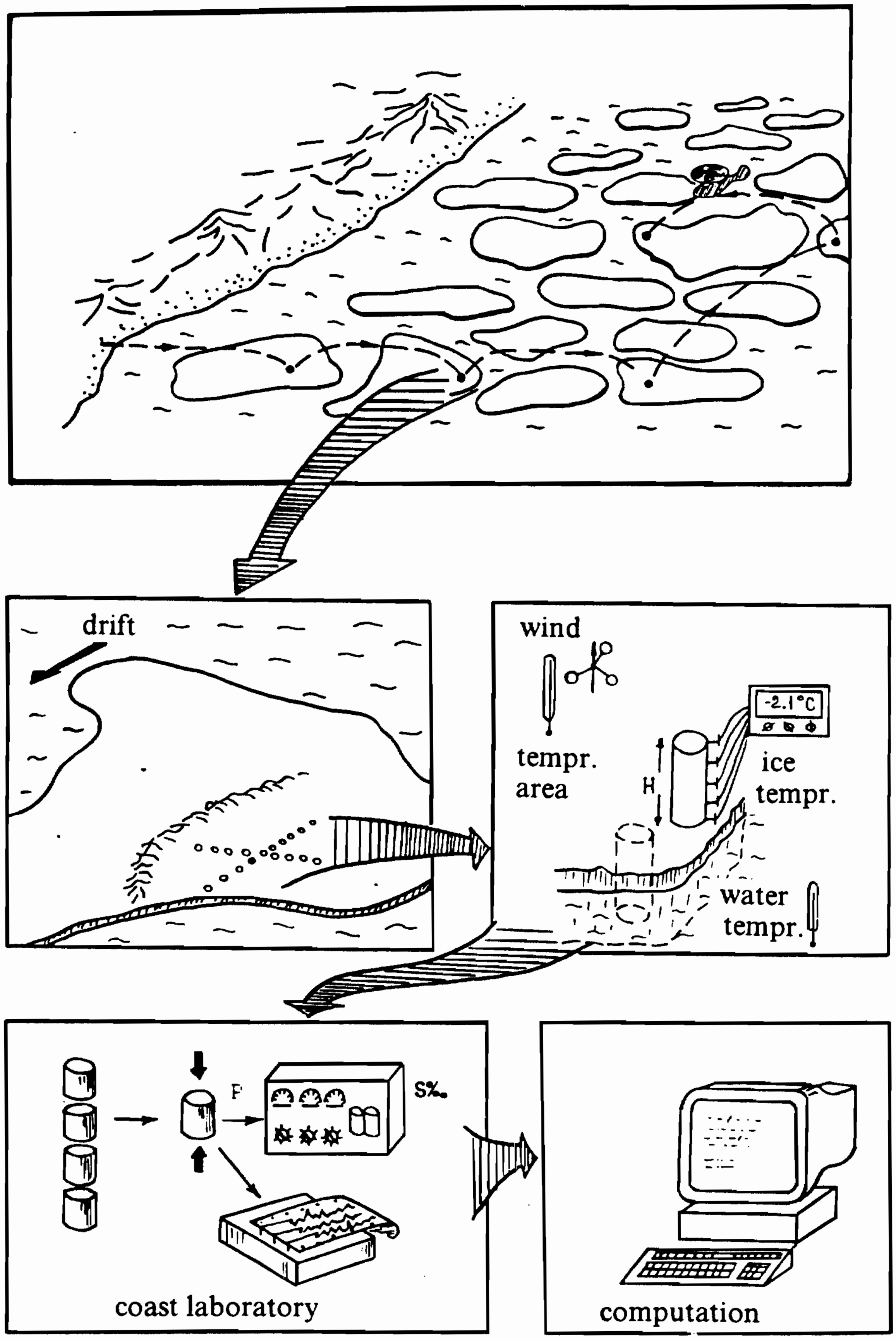


Fig.2 Block-scheme investigation by method of helicopter landing work

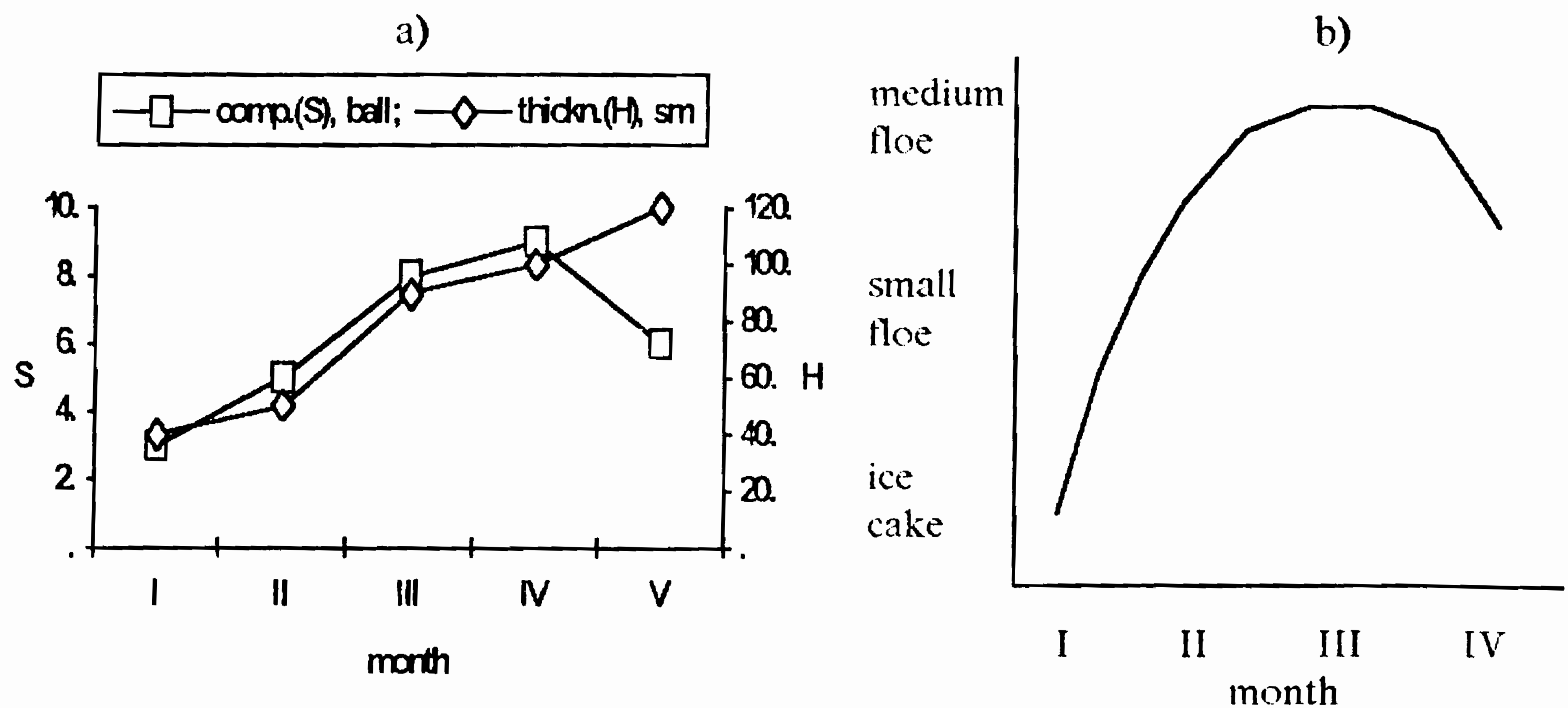


Fig. 3 Seasonal variation of average values of compactness, thickness (a) and form (b) of the drifting ice

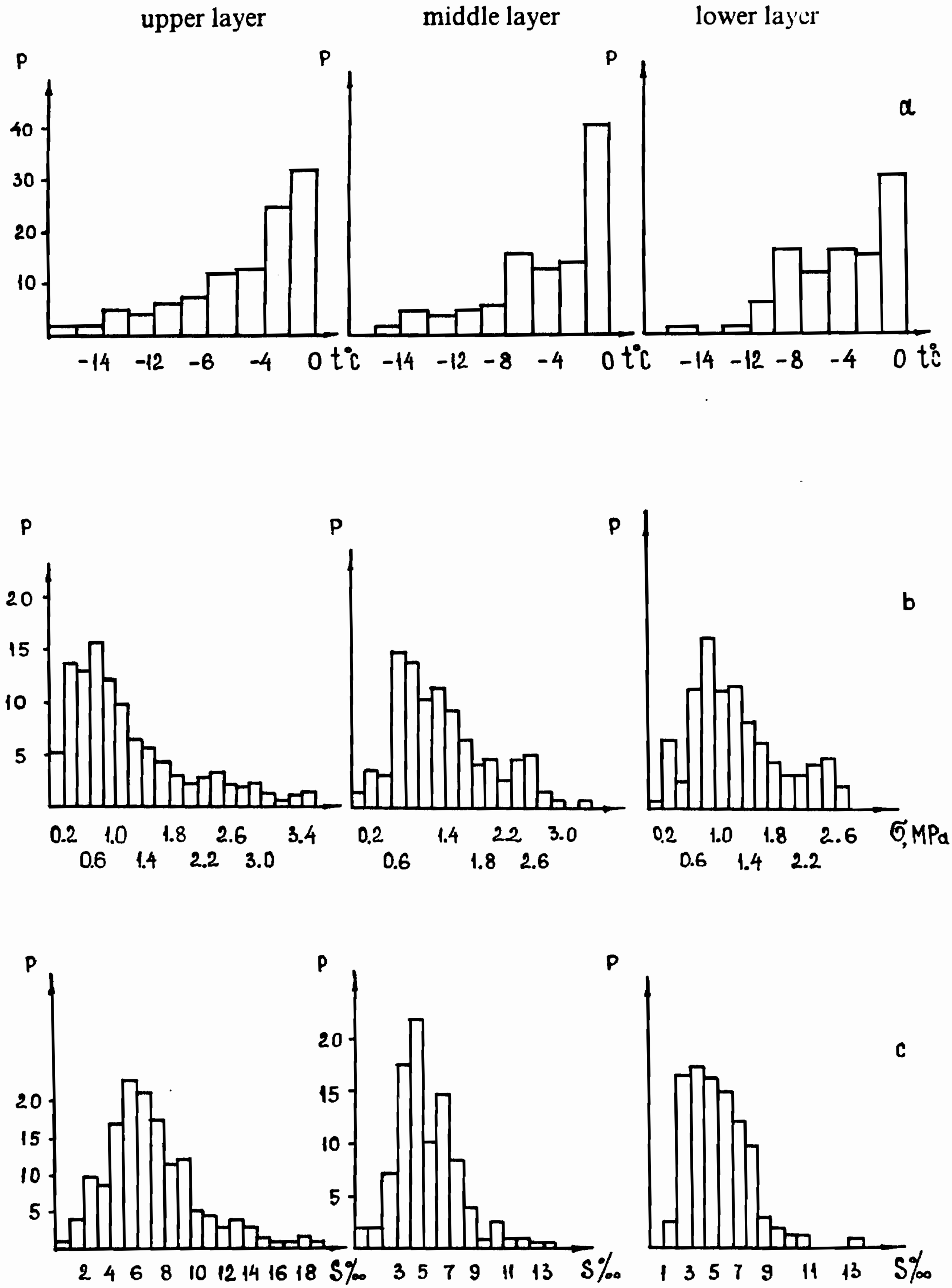


Fig.4 Histograms of multiyear averages for temperature (a), strength (b) and salinity (c) of various sea ice layers.

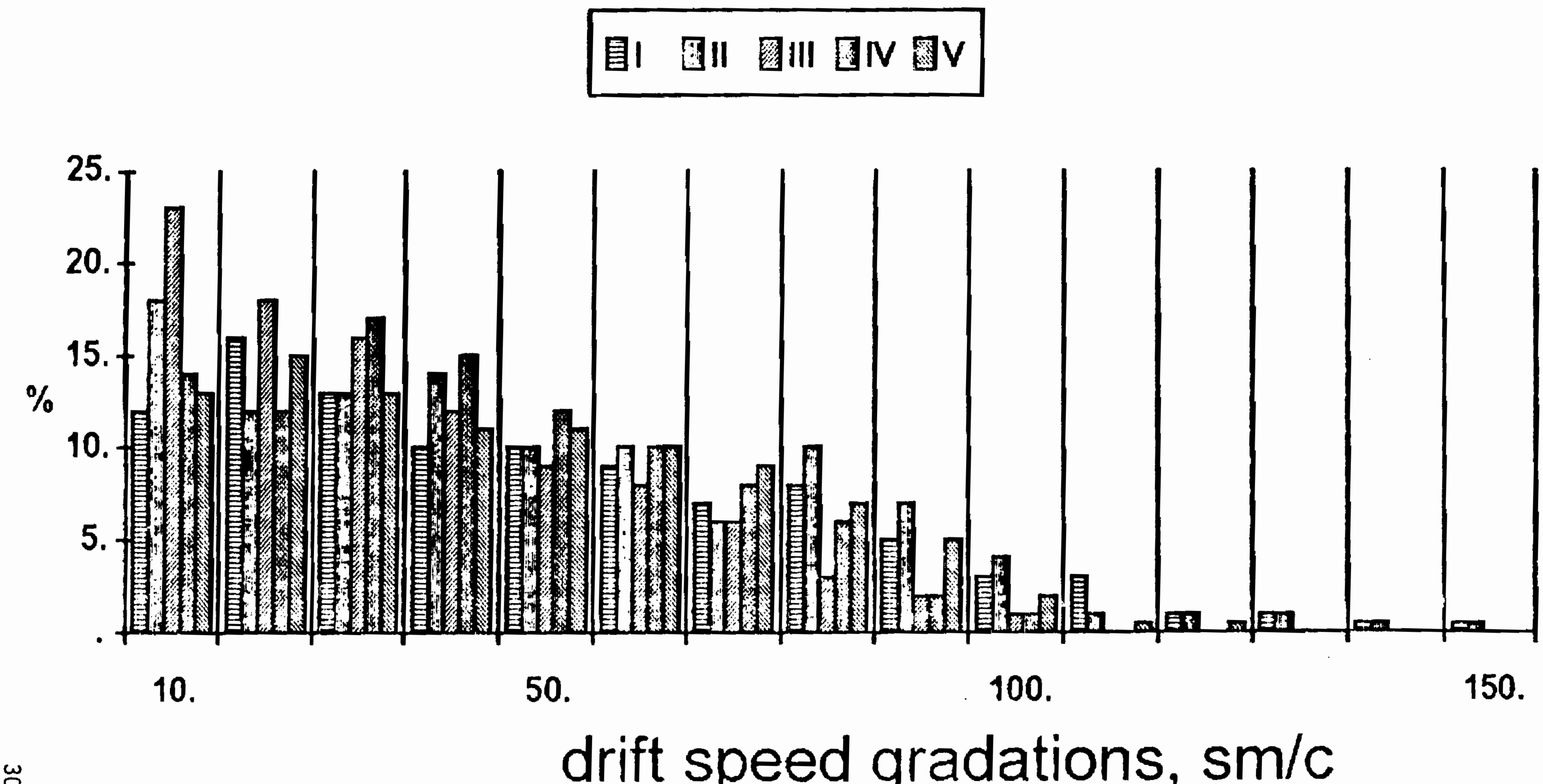


Fig. 5 Seasonal variability of distribution of an ice drift speed on gradations

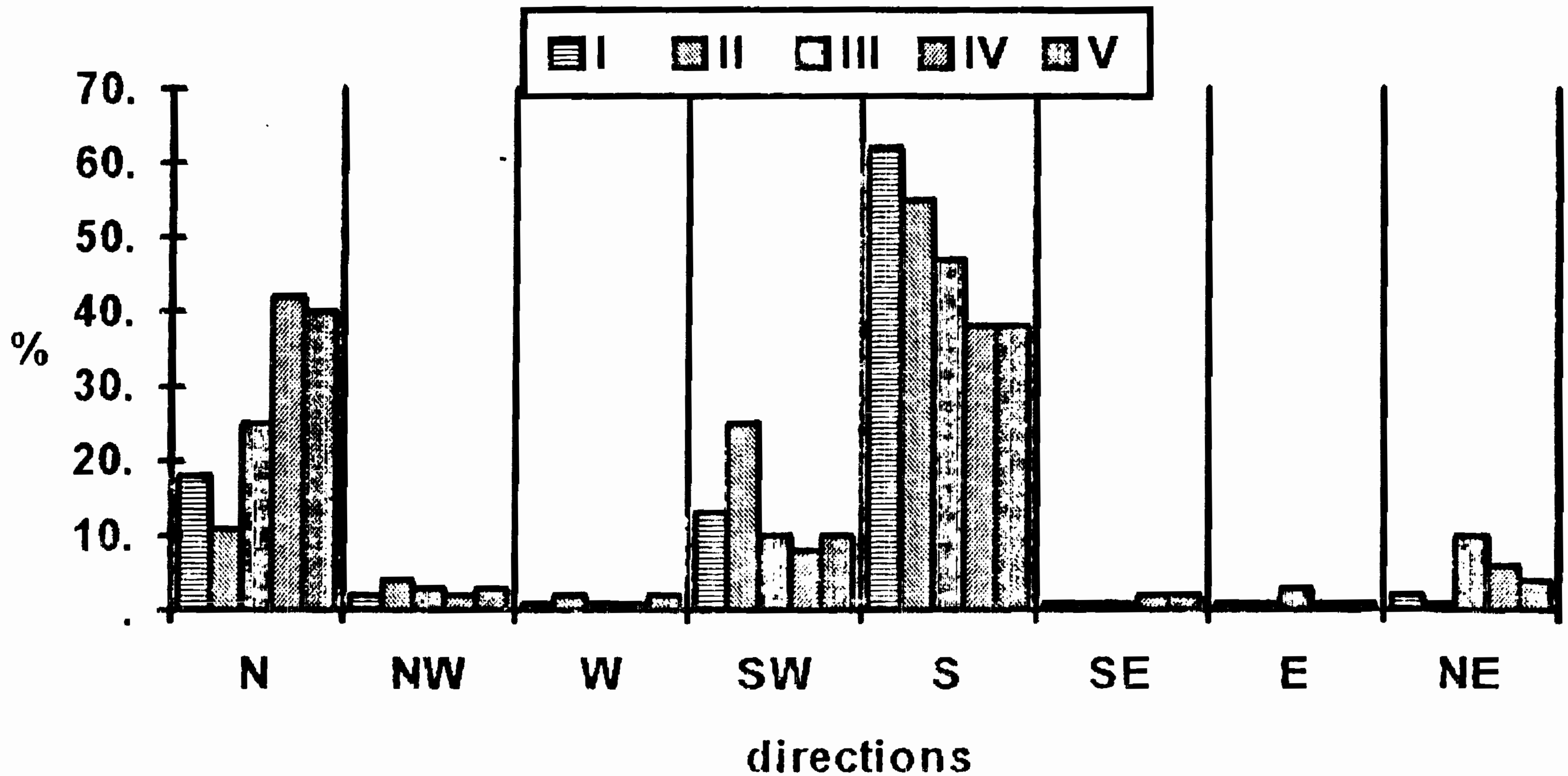


Fig. 6 Seasonal variability of distribution of direction of an ice drift on directions

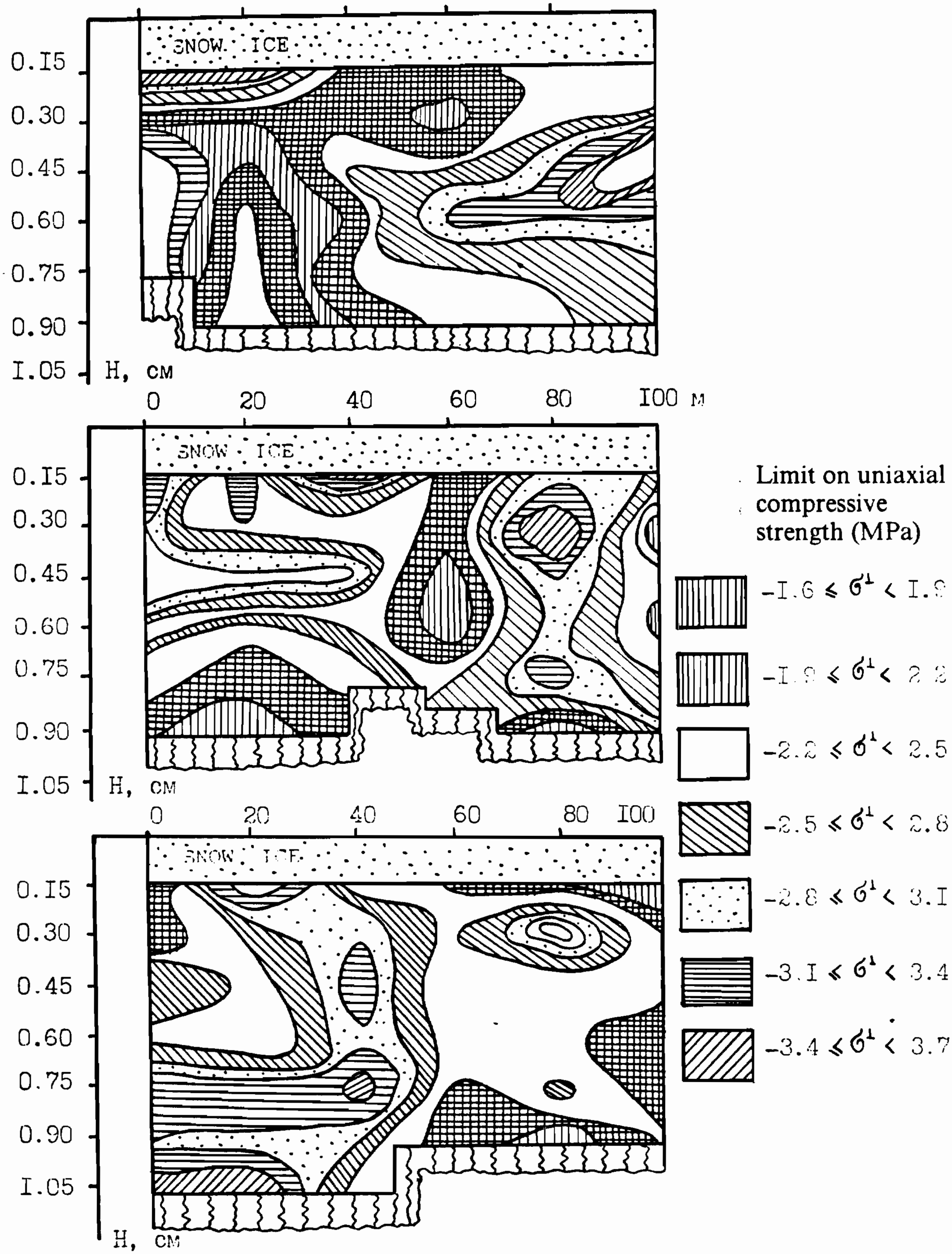


Fig.7 Typical scheme of spatial heterogeneity of sea ice mechanical characteristics

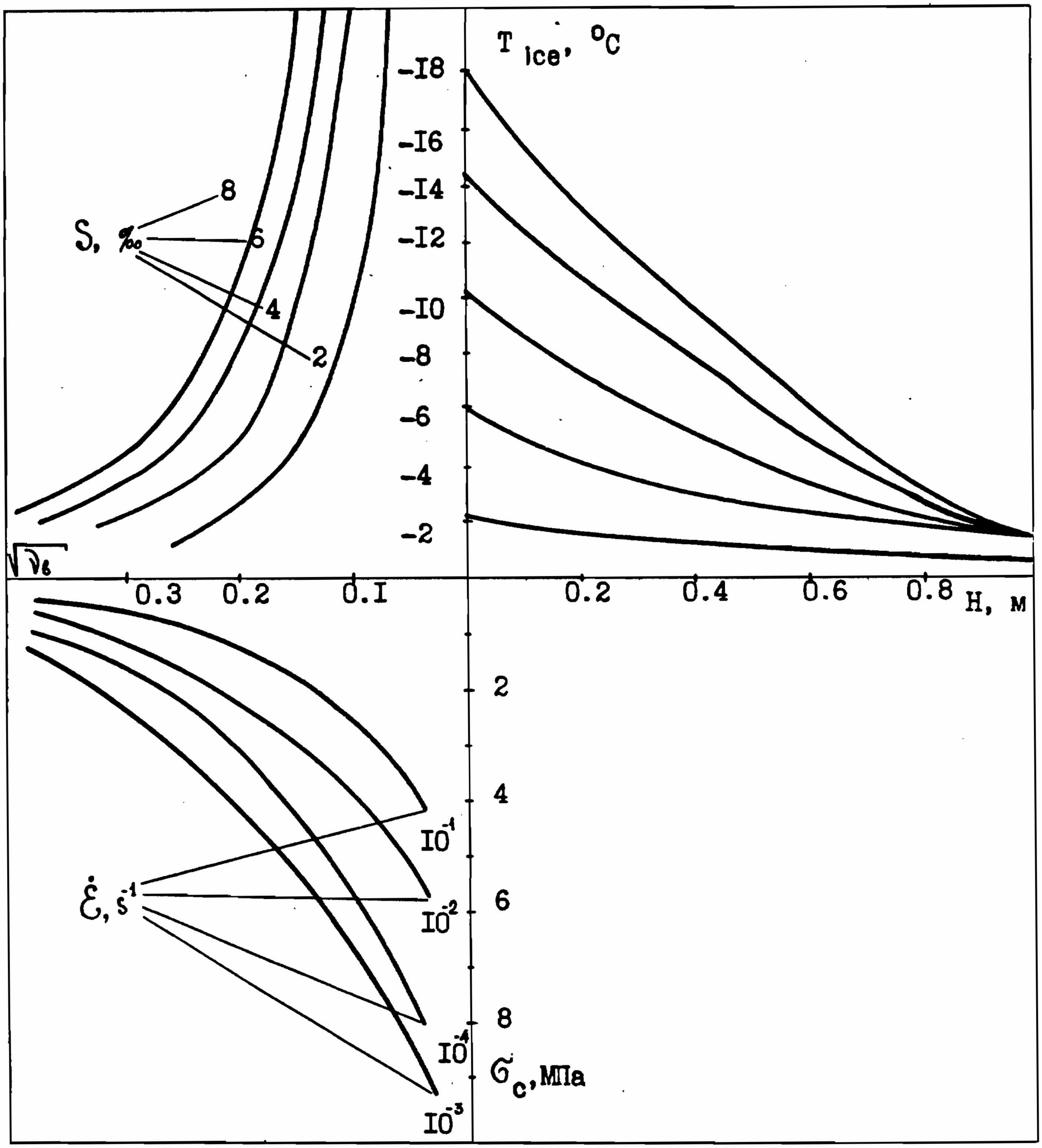


Fig.8 Nomogram to determine sea ice uniaxial compressive strength.

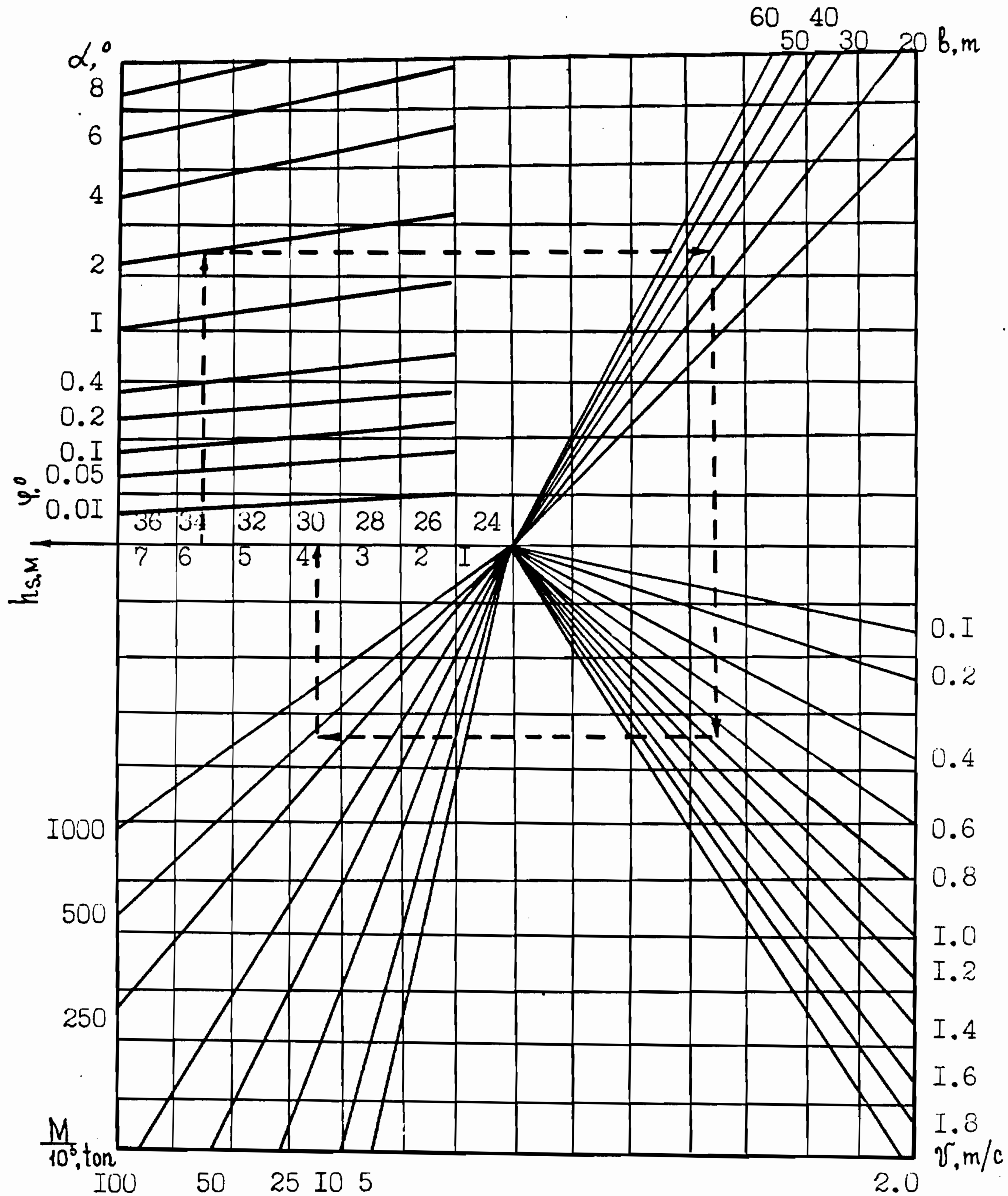


Fig. 9 **Nomogramm for determination of scour depth in the result of iceridge impact on sea bottom.**

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PRISE - the Pressure Ridge Ice Scour Experiment:
Preliminary Verification of Ice Keel Scour Centrifuge Model Results Against Field Data

C.M.T. Woodworth-Lynas, R. Phillips, J.I. Clark, R. Meaney, F. Hynes and X. Xiao
C-CORE - Centre for Cold Ocean Resources Engineering
Memorial University of Newfoundland, St. John's, NF, Canada A1B 3X5

Centrifuge model data are shown to replicate the general morphology and structure of naturally-occurring scour marks at equivalent prototype scale. Such verification is vitally important because it indicates that the centrifuge models reproduce soil deformations observed in the field, and thus that there is confidence that the models are accurate predictors of the scouring phenomenon. Four classes of soil deformation structures have been observed in the PRISE centrifuge models that correlate well with similar structures observed in the field. These structures include: lateral berm piles; sand boils; sub-scour bearing capacity-type failures; low angle thrusts.

In the field, the best examples of berms are associated with modern marine scour marks where surface structures are exposed to observation by both sidescan sonar and from submersibles. Small-scale variability of berm structure is observed in examples of both modern marine and PRISE model scour marks. Field and model examples show development of both structureless piles and regions where apparent tension fractures create block-like topography, probably indicative of remoulding caused by bulldozing and of local seabed upheaval respectively.

Conical mounds, approximately 50 cm high and 80-100 cm diameter, were observed in the trough of a new scour mark on Makkovik Bank, Labrador Sea in 1985. Combined visual evidence suggests that the mounds were extrusive in origin, and were the result of sub-scour liquefaction. Sand boils were observed in one of the PRISE models of clay (approximately 2.7 m thick) over dense sand. The scour event removed all but approximately 0.3 m of clay in the scour mark trough, and it was in the trough that the boils developed. The boils consisted entirely of sand that had been mobilized after the scour event from below the clay layer.

Bearing capacity failure surfaces were identified and mapped beneath relic scour marks exposed at surface in southeastern Manitoba. Some of these failure surfaces extended more than 5.5 m below the scour mark cut depth and one showed relative offset movement of 3.5 m. Bearing capacity failures were evident in some of the PRISE clay tests, although discrete failure surfaces could not be discerned. This failure mechanism correlates with that hypothesized for the Manitoba scour marks. With one exception bearing capacity failures did not develop beneath any of the sand tests.

Thrust faults were observed only beneath two relic Manitoba scour marks. Similar, well-developed low-angle thrust faults were observed in sub-scour sediments of one PRISE centrifuge model test. This test modelled a simple stratigraphy of sand over clay, and the keel did not penetrate through the sand to the clay. After the test, removal of the sand layer within the scour mark trough revealed that the buried, originally flat clay surface had been deformed into a series of imbricately-stacked thrust slabs, each approximately 0.75 m thick. Movement of the scouring keel caused shear dragging of the sand forward beneath it and detachment of thin slabs of clay in the zone immediately below the sand/clay contact. Stratigraphic conditions for the model test (sand over clay) were broadly similar to those for the Manitoba scour marks (silt over clay) in that coarse soils overlay fine soils.

INSTRUMENTS FOR CORING, STRUCTURE AND COMPOSITION ANALYSIS AND MONITORING SEA ICE

V. Zagorodnov and J.J. Kelley

Arctic Center for Applied Research
University of Alaska Fairbanks
Fairbanks, AK 99775

Industrial and research activities in Arctic regions often require the penetration and coring of sea, lake or river ice and the analysis of recovered ice cores. It is desirable to acquire ice samples or perform *in situ* analyses with minimum logistics support cost. A few new ice coring and analytical instruments have been developed at the University of Alaska Fairbanks.

A new ice coring auger is capable of producing a 100 mm diameter ice core and 125 mm diameter bore hole. Drilling efficiency of the auger is expected to be two-fold that of existing drills. Durability and ease of operation of the drill is high.

The unique capability of making round, triangle, rectangular or any other shape holes and ice cores are provided by thermal drills. Thermal drills also provide smooth surface ice cores and bore hole walls. Incline holes can also be made with portable thermal drills. Hot water, steam and electricity powered open hole and coring drills have been tested. A new version of a thermal electric drill has a capability to core in ice with 60-70 % volume concentration of sand. Thermal drills are capable of being air dropped for through-ice sampling and remote installation of monitoring apparatus.

Great care must be taken in the research of fresh and salt water ice cores. Chemical and physical analysis of the cores should be accomplished as soon as possible after core recovery because some of the constituents may be altered. This is especially true of sea ice. In order to provide more rapid analysis of ice cores, two methods can be considered: (1) An Ice core Analytical System (ICAS), and (2) Thermal Probe (TP). ICAS provides for continuous solid and liquid state analysis and/or melt water sampling of an ice core. A TP is a device which penetrates the ice cover and conducts measurements and/or sampling of melt water during penetration. It also allows for the measurement of structural parameters of the ice.

An acoustical device used for about one year during an experiment under the Ross Ice Shelf in Antarctica allowed for a high resolution monitoring of mass balance at the ice-sea water interface. Such sensors can be installed under sea ice through a small hole. Observations such as temperature, salinity, relative current and basal mass balance can be transmitted via the "Argos" satellite system.

New improved hand operated ice coring auger

The study of sea ice, lake and rivers ice, glaciers, and permafrost often need ice cores from depth of 1-40 m. Because the specific energy of ice cutting is low, and penetration depth usually less then 40 m, hand powered drills are commonly used. Typical hand operated ice core auger (Figure 1), has an annular drilling head equipped with two or more cutters, two core catchers, and core barrel with two spiral flights. In order to drill a holes of a few meters depth, extension rods are used.

The SIPRE ice auger was a common instrument for glacier and sea ice investigations during 1948-80. This drill provided an ice core of 76 mm in diameter and produced approximately a 112 mm diameter access hole. By using a hand brace a drilling rate of 4-6 mm/sec have been achieved; with a gasoline and electric drive the maximum drilling rate of 18 mm/sec and 28 mm/sec has been reached. The drill utilized a coring head with two drag type cutters. The annulus of the drilling head has a conical shape which allows an ice core to be jammed by the cutting when the drill moves up. The stainless steel core barrel is equipped

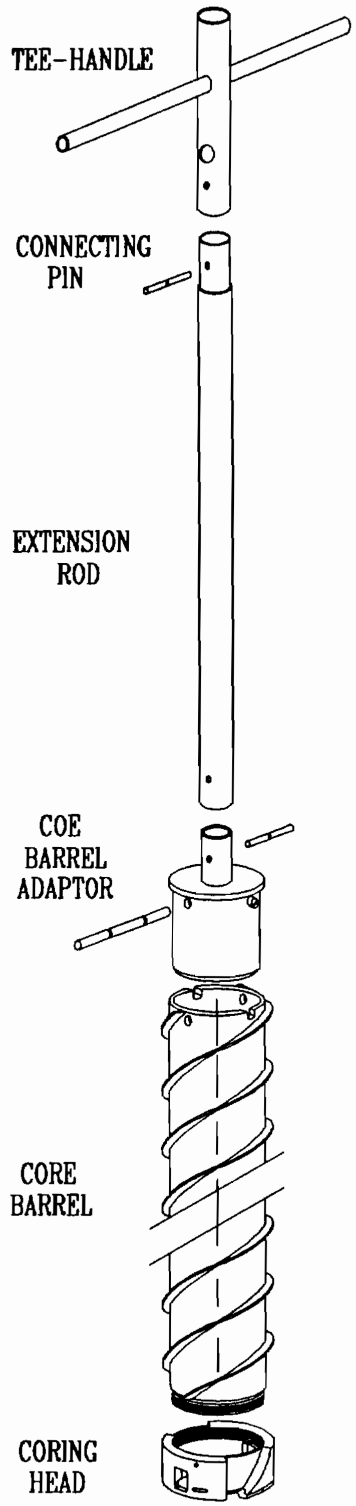

Figure 1. Ice coring hand auger.

with two flights for chip removal. Ice core and chips remove from the bore hole every 0.5 m of drilling run (Annonimus, 1957, Mellor and Sellmann, 1976).

A new design ice coring auger was made in PICO by B.Koci (1984). The concept of the drill does not differ from the SIPRE prototype. But, application of glass epoxy composites has made it possible to build a drill with 10-m extension pipes and a weight of 10 kg. The coring head has a two drag cutters and two core catchers. The drill produces an ice core of 76 mm in diameter and a bore hole of 110 mm in diameter. It was successfully tested with 250 W electric drive with solar power panels. The drilling rate of 10 mm/sec has been reached at 40 m depth bore hole. A practical drilling rate of 10-m depth bore hole is about 2 m/hr. With a tripod system the drill can take ice core up to 50 m depth (Benson, 1984). The use of PICO-epoxy hand auger shows the following drawbacks: small ice core diameter, fast erosion of the plastic flights, inconvenient coupling of the extension rods.

These drawbacks were eliminated in ice core auger developed in Institute Geography of the Russian Academy of Sciences (IGRAS) by V. Zagorodnov. This drill produces of ice core of 100 mm in diameter and access hole of 125 mm in diameter. The weight of IGRAS drill does not exceed that of the PICO-epoxy drill. The core barrel and flights are made of aluminum and therefore the life time of the drill is significantly longer, compared to the PICO-epoxy drill. Aluminum thin wall extension rods are coupled by simple and reliable pin device. Because the drill makes a narrow cut, the ratio of the volumes of the ice core and cutting is 3-4 times larger than that of the SIPRE and PICO-epoxy drills. Thus the IGRAS drill permits ice core recovery with about twice less hoisting operations than other drills. The IGRAS drill was successfully tested under a wide variety of conditions: in cold Antarctic firn and ice, in Arctic polar and subpolar glaciers and in mountains temperate glaciers. Good performance could also be expected for coring of sea ice.

Thermal drills.

Thermal drilling is the simplest method of ice penetration and obtaining cores (Figure 2). Electricity, hot water or steam powered drilling heads are capable of making round, triangular, rectangular or any other shape holes. Thermal drills also provide smooth surface ice cores

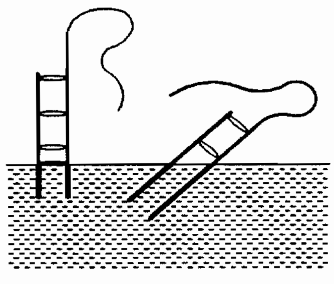

Figure 2. Thermal coring devices

and bore hole walls. That makes them more suitable for the optical and acoustical investigations. Inclined holes can also be made with portable thermal drills. Because thermal drilling does not require antitorque reaction the setup for thermal directional drilling is much lighter than for electromechanical drilling. Moreover, thermal drilling systems can be operated remotely. Therefore, they are capable of being air dropped for through-ice remote installation of monitoring apparatus. In general, thermal ice drilling systems are from 2 to 5 times smaller than electromechanical ones.

Environmentally safe, intermediate depth portable thermal ice core drill

Figure 3. Antifreeze Thermal Electric Drill (ATED): 1 -drilling head; 2- core catchers; 3 - piston; 4 - cable.

For over 20 years, the Antifreeze Thermal Electrical Drill (ATED) (Figure 3), invented by V.A. Morev (1972) (Arctic and Antarctic Research Institute, Russia) has been used on various glaciers: from high altitude mountain temperate glaciers to Central Antarctica. Twenty six holes of average depth of 430 m were drilled. Each coring operation was conducted during one field season. A team of 4-6 persons operated the drill and conducted field ice core investigations and data gathering. This experience allows us to evaluate the following advantages of the ethanol thermal electrical drilling method: environmentally and personally safe drilling fluid (ethanol), portable (500 m drill depth setup weight is about 400 kg, high penetration rate 420-500 m/week, short set-up time (5-12 hours), small drilling crew (1 driller and 1 technician), low drilling fluid requirements (500 kg of ethanol at ice temperature of -10°C for a 500 m borehole), drill is suitable for directional drilling and extra core recovery from previously drilled hole, drill is suitable for mixed ice/particulate drilling, low construction cost ($15-20 K for the drill) ($20-25 K for the surface equipment). The following drawbacks were also found: ice core may fracture when the ice temperature is below -15°C, drill descent rate decreases when the ice temperature is below -25°C, small ice core diameter (maximum diameter is about 80 mm).

The major drawback of the thermal ice coring method is thermal-elastic stresses (or thermal shock) which appears in the ice core during drilling cold ice (below -15°C). Based on results of mathematical modeling, a short (48 cm long) version of a new antifreeze drill called m-ATED was built and tested. Tests and mathematical modeling showed that the above drawbacks could be eliminated (Zagorodnov et al, 1994). With the same advantages as the ATED, the m-ATED is expected to provide the following improvements: the thermal shock decreased by a factor of 5 (eliminate core fracture), drill descent rate increased by a factor of 2, and larger ice core diameter (up to 100 mm) can be recovered.

The m-ATED ice coring system also has the following options: ice coring can be accomplished by a small team (2 person per drilling shift), small drilling fluid requirements and light weight, portable drilling equipment allow transportation by small aircraft (Twin Otter) or helicopter (total weight of equipment and drilling fluid is from 5 to 10 times less than that needed for other methods of drilling for the same depth), capable of penetrating extremely dirty ice (sand concentration 70 % by volume).

Analytical instruments

Study of the fresh or salt water ice cover is associated with time consuming work for the preparation of ice specimens. Structure, chemical and isotope composition investigations of the ice samples also involve much human labor (HAMMER et al, 1985; HAMMER, 1989). After recovery, especially during ice core storage some ice parameters are changed (COX and WEEKS, 1986). In order to speed up the process of data recovery two concepts have been developed: (1) Ice Core Analytical Systems (ICAS) (ZAGORODNOV et al, 1991; ZAGORODNOV et al, 1993) and (2) thermal probe (TP) (AAMOT, 1968; PHILBERT, 1976). Liquid state Ice Core Analytical Systems were developed by B.STAUFFER et al (1988) and C.HAMMER (1989). Continuous analysis of an ice core has several advantages: multiple continuous profiles can be obtained, data processing speed is increased, and only small portion (3-5 %) of an ice core is wasted.

Solid state ice core analysis

The solid state ICAS (Figure 4) consists of a rail system for carrying an ice core segment past the analytical instruments. The instrument package includes the cutting tools (mills) and sensors (electrodes and laser sensors). The system permits the following parameters of an ice core to be continuously measured: electrical conductivity (ECM); optical density and stratigraphy, ice crystal lineal dimensions. Optical sensors permit a high spatial resolution profiles (density, air bubbles or brines concentration and size distribution). The electrical conductivity of ice is associated with soluble inclusion concentration. Positive results have been obtained for measurement of C-axis orientation of individual crystals during single plane angular

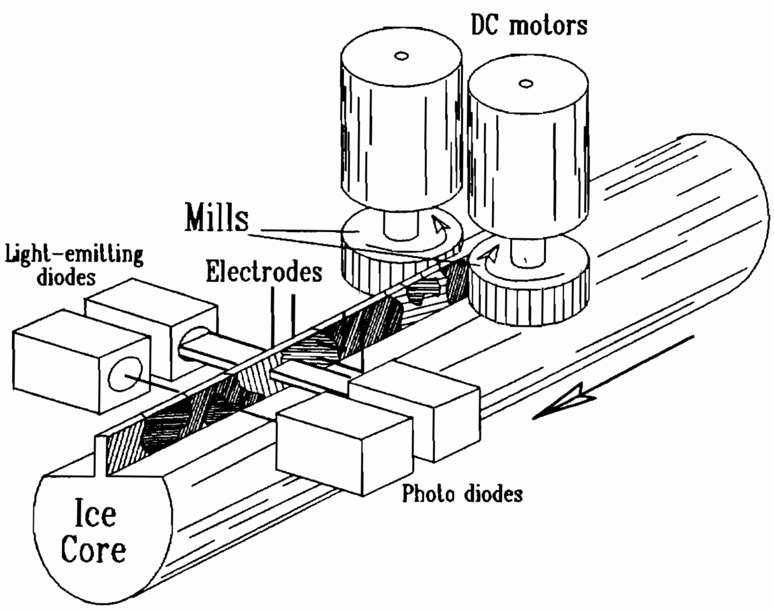

Figure 4. Schematic of solid state Ice Core Analitical System

scanning. The speed of thin section formation of about 6 mm/s was achieved on the fresh Greenland ice core. The estimated productivity of multi parameter ice core analysis by solid state ICAS is about 1 m/hr.

Liquid state ice core analysis

The ice core analytical system for liquid state analysis and sampling (Figure 5) includes a rail system for vertical motion of an ice core, the melter-collector and the vacuum water aspiration circuit. The ICAS melts the ice core only along a limited part of an ice core section and along the direction parallel to the core axis by the heated head. This funnel-shaped head can be heated by an electrical element or by water or steam circulation inside. The melt water makes contact with only a Teflon covered funnel and passes through the Teflon tubing. This mechanism is expected to be effective to avoid contamination from surrounding air and from the system materials. The method for the continuous melt water sampling and continuous water flow (1 ml/min) analysis of the microparticles (radius 0.1-4 μ m) concentration and size distribution has been successfully tested with an antarctic ice core. Maximum speed of the sampling device during melting of the ice core was 5 mm/s. The advantage of the method is that this system made it possible to avoid cutting of an ice core into small pieces as well as other time consuming manipulations with the ice samples.

The system has two circuits: (1) gas circuit, and (2) water circuit. First the water is subjected for degassing and gas can be sampled in separate bottles. The automatically operated solenoid valves permit gas sampling from the different parts of the ice core. Then the water is drawn into its the fraction collector. The pressure in the fraction collector is lower than in the gas circuit. There are multiple water tubes to sample the water. For simplicity in Figure 2 only two lines are shown. The water samples directly pass to the fraction collector and are reserved for further chemical analyses. Other water loops pass through the analytical cells and can be subjected for the following on-line continuous analyses:

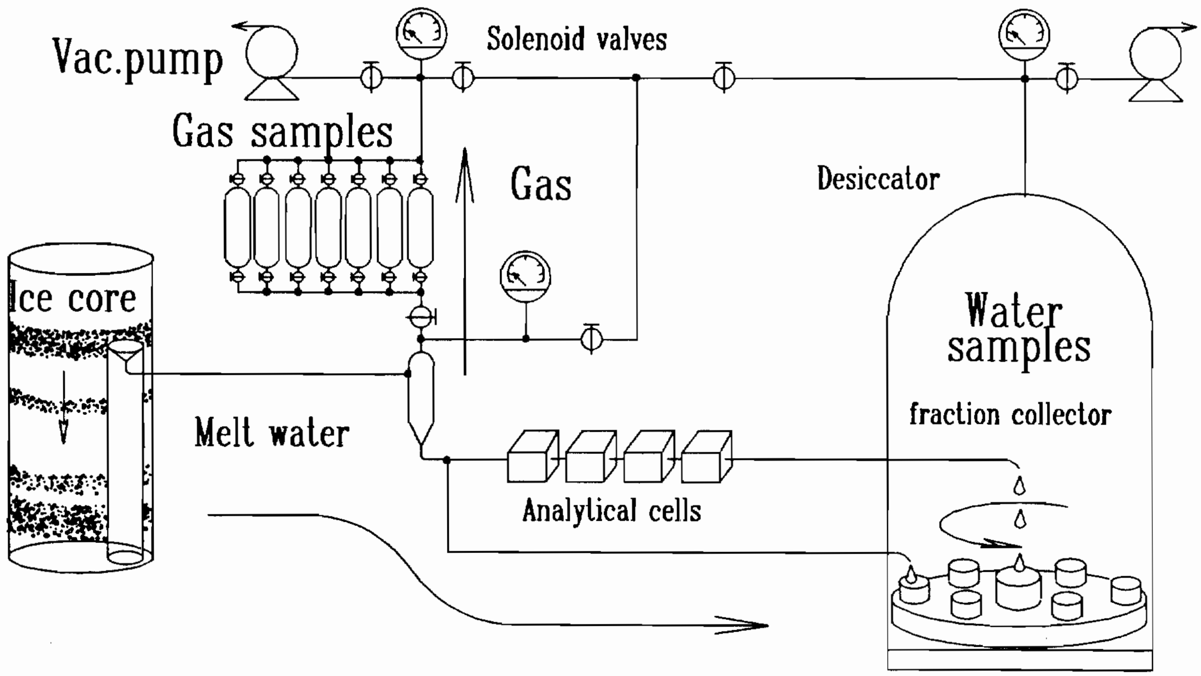

Figure 5. Schematic of liquid state Ice Core Analytical System.

(1) electrical conductivity, without water contamination;

(2) pH;

(3) ion composition of the melt water can be done by application of ion-selective electrodes (ammonium, calcium, carbon dioxide, chloride, chlorine, iodide, lead, nitrate, potassium, sodium et al.); these are not usable for glacier ice cores because they have a sensitivity of 10^{-5} mole/l or 1 ppm (assuming molecular weight at 100), but for sea ice they can be reliable.

(4) the Millipore filters; can also be applied for collecting the insoluble inclusions.

Ion chromatography and Inductively Coupled Plasma (ICP) method, can be utilized, with slight complication and apparatus modification.

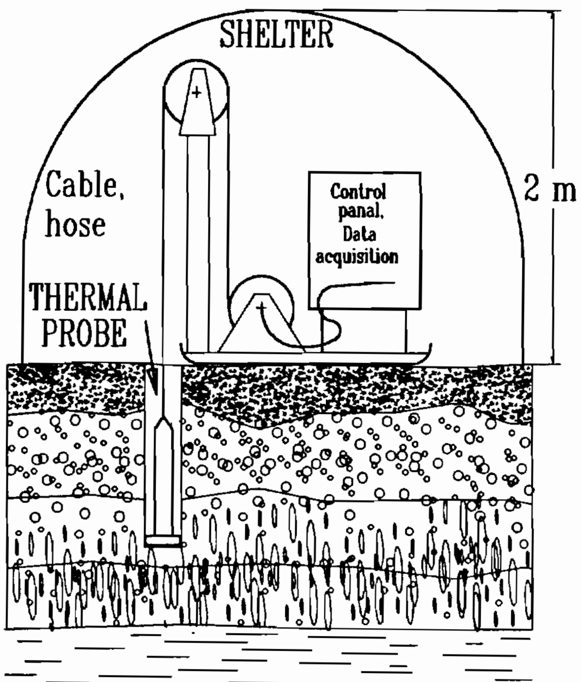

Figure 6. Schematic of the Thermal Probe setup.

Thermal probe

The collection of ice cores especially from glaciers, involves considerable equipment and labor. A thermal probe (TP) concept can be utilized for sea, lake or river ice cover for rapid field observations (Figure 6). The system includes: thermal probe, mast, winch, control panel, computer data acquisition system, power generator (2-3 kW) and shelter. A thermal probe is a device which combines the functions of a thermal drill, sampling head, and a carrier of the sensor array. The TP is connected with the water aspiration system and power source at the surface by an electrical cable and Teflon tubing. The bottom portion of the device has an electrically heated funnel shaped bit. The Teflon covered bit could provide a penetration rate of about 1 mm/s. The bit may also form a thin section facing to the center of the borehole. The section(s) could be analyzed by a laser sensor for air, brine and crystal concentration and morphology. The melt water drawn to the liquid state ICAS is similar to the arrangement shown in Figure 5. By placing the ion selective electrodes above the head, water can be analyzed during penetration. In this manner sampling shouldonly be done on the surface. The total weight of the system is estimated to be about 400 kg. The operation speed is estimated to be 1 mm/s.

Acoustic monitoring of mass balance on sea ice base.

Several different methods can be used to measure mass balance at the sea ice-water interface. The acoustic up-looking high frequency sonar system makes it possible to determine accumulation or ablation of ice with high resolution. The schematic of an acoustic device for the measurement of ablation or accumulation at the bottom of floating ice is shown in Figure 7. The method is based on echo sounding measurements of the thickness of the seawater layer between the acoustic transducer and the bottom of the ice; the transducer is securely attached to the ice cover through the borehole. If the sound speed in the seawater is known. Then: $\Delta d = 0.5\ c\left(\tau_1 - \tau_2\right)$, where Δd is the thickness of ice growth or ice melt at the ice-water interface; c is the speed of sound in sea water; τ_1 and τ_2 are acoustic impulse travel times at the first and second observation. Because the antenna is attached to the ice and immovable, the freezing or melting of ice will change the distance between the transducer and ice-seawater interface.

Previous under-glacier measurements show that high frequency (0.5 to 2 MHz) echo sounding can provide spatial resolution greater than 0.2 mm

The system shown in Figure 7 can be installed under sea ice through a small hole. Observations such as temperature, salinity, relative current and basal mass balance can be transmitted via the "Argos" satellite system. This proposed system could be very advatageous during remote monitoring of very early stages of sea ice formation.

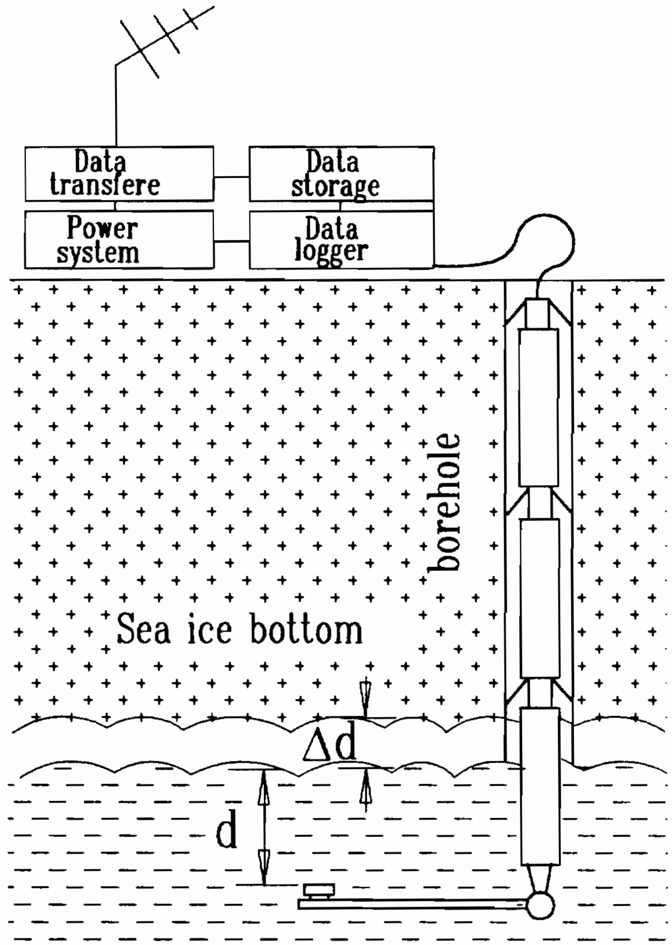

Figure 7. Schematic of basal sea icre mass balance measurements.

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Appendix A - Errata to Volume 1

1. On page 82 of Vol. 1, in the paper "Effect of Size on Distributed Damage and Fracture of Sea Ice," by Prof. Zdeněk P. Bažant (P.I.), Dr. Ying-Neng Li, Dr. Milan Jirásek, Zhengzhi Li, and Jay-Jang Kim of Northwestern University, Figure 7 should read as "Histories of calculated contact force for Fig. 6 ..." not "Fig. 1".

2. On page 160 of Vol. 1,in the paper "SIMI GPS Position and CTD Cast Data" by Suzanne O'Hara and Jose Ardai Jr., the bad conductivity data in the SIMI spring data set was caused by a leaking pressure sensor, not a cracked conductivity Cell as originally reported.

Appendix B - Author, Speaker, and Panel Member Index

This section contains an alphabetical listing of authors, speakers, and panel members, followed by the volume and pages on which their contributions begin.

Appendix C - List of Workshop Participants

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Attendees - See Ice Mechanics and Arctic Modeling Workshop - April 25-28, 1995

Anderson, Robert	NUWC Arctic Submarine Lab	49250 Fleming Road San Diego, CA 92152-7210	619-553-0190 619-553-0972	robert@manta,nosc,navy.mil
Appel, Igor	Fairweather Forecasting	715 L Street, #1 Anchorage, AK 99501	907-258-9165 907-258-9167	72053.1734@compuserve.com
Ardai, Jay	Lamont Doherty Earth Observatory	RT 9W Palisades, NY 10964	914-365-8436 914-359-6940	jay@ldeo.columbia.edu
Bailey, Cynthia	BP Exploration	P.O. Box 196612 Anchorage, AK 99519-6612	907-564-5537 907-564-4124	
Barter, Paul	Kinnetic Lab., Inc.	403 W 8th Ave. Anchorage, AK 99501	907-276-6178 907-278-6881	kinnetic@alaska.net
Bazant, Zdenek	Northwestern University	Dept. of Civil Engineering Evanston, IL 60208	708-491-4025 708-467-1078	z-bazant@nwu.edu
Becker, Marie	CIRCAC	11355 Frontage Rd., Suite 228 Kenai, AK 99611	907-776-7650 907-776-7068	
Bekker, Alexander	Far-Eastern State Technical Univ. Civil Engineering Institute	10, Pushkinskaya str. 690600, Vladivostok, Russia	4232-259-202 4232-266-988	
Bentley, Diane	NUWC Arctic Submarine Lab	49250 Fleming Road San Diego, CA 92152-7210	619-553-0190 619-553-0972	dbentley@cod.nosc.navy.mil
Bugno, Walter	Chevron Petroleum Tech. Co.	6001 Bollinger Canyon Rd. San Ramon, CA 94582-0945	510-842-8650 510-842-8626	wtbu@chevron.com
Campbell, Gary	BP Exploration	P.O. Box 196612 Anchorage, AK 99519-6612	907-564-4275 907-564-4680	
Cole, David	USA CRREL	72 Lyme Rd. Hanover, NH 03755	603-646-4217 603-646-4640	dmcole@crrel.usace.army.mil
Conley, Judy	NSWC	Carderock Div., Code 654 Bethesda, MD 22080	301-227-1658 301-227-1230	conleyj@oasys.dt.navy.mil
Connor, Jerome	MIT	Rm 1-238 Cambridge, MA 02139	617-253-8435 617-253-6324	jjconnor@mit.edu
Coon, Max	Northwest Research Assoc., Inc.	P.O. Box 3027 Bellevue, WA 98009	206-453-8141 x332 206-646-9123	max@nwra.com
Cox, Chris	BP Exploration	P.O. Box 196612 Anchorage, AK 99519-6612	907-564-5237 907-564-4680	
Cox, Gordon	Amoco Eurasia	P.O. Box 3092 Houston, TX 77253	713-366-2965 713-366-2746	gcox@amoco.com
Crossdale, Ken	K. R. Crossdale & Assoc.	334, 40th Ave. SW Calgary, AB T2S 0X4	403-243-7787 403-287-7889	
Curtin, Thomas	Office of Naval Research Code 322	800 N. Quincy St. Arlington,VA 22217-5600	703-696-4119 703-696-2710	curtint@onrhq.onr.navy.mil
Daley, Claude	Memorial Univ. of Newfoundland	Faculty of Eng. and Applied Sci. St. Johns, Newfoundland A1B 3X5	709-737-4058 709-737-4042	cdaley@engr.mun.ca

Danielewicz, Ben	Canmar	Calgary, AB T2P 2H8	403-298-2813 403-298-3532	
Dempsey, John	Clarkson University	Dept. of Civil and Environmental Eng. Potsdam, NY 13699-5710	315-268-6517 315-268-7985	john@jpdnz.cee.clarkson.edu
Denbo, Donald	Pacific Northwest Lab	1529 West Sequim Bay Road Sequim, WA 98382	360-681-3614 360-681-3699	dwd@elwha.pnl.gov
Echert, Skip	Northwest Research Assoc., Inc.	P.O. Box 3027 Bellevue, WA 98009	206-453-8141 x330 206-646-9123	skip@nwra.com
Elder, Bruce	USA-CRREL	72 Lyme Road Hanover, NH 03755	603-646-4637 603-646-4644	belder@crrel41.crrel. usace.army.mil
Eldred, John	ARCO, AK	P.O. Box 100360 Anchorage, AK 99516	907-263-4347 907-265-1515	johne@arco.com
Elvin, Alex	MIT, Room 5-330a	77 Massachusetts Ave Cambridge, MA 02139	617-253-3021 617-253-6044	arrow@mit.edu
Farmer, David	Inst. of Ocean Sciences	9860 West Saanich Road Sidney, BC V8L 4B2	604-363-6591 604-363-6798	dmf@ios.bc.ca
Fremouw, Edward	Northwest Research Assoc., Inc.	P.O. Box 3027 Bellevue, WA 98009	206-453-8141 x310 206-646-9123	ed@nwra.com
Gantz, Marina		6738 Lunar Drive Anchorage, AK 99504-4574	907-333-1893	
Goldstein, Robert	Institute for Problems in Mech. Russian Academy of Science	Prospect of Vernadskogo, 101 Moscow, 117526, Russia	7-095-434-4341 7-095-938-2048	
Gottlieb, Judith	Minerals Management Service	949 East 36th Avenue Anchorage, AK 99508-4302	907-271-6010 907-271-6805	
Hansen, James	Alaska Dept. of Natural Resources	P.O. Box 107034 Anchorage, AK 99510-7034	907-762-2588 907-562-3852	
Harrison, W.	University of Alaska Fairbanks	Geophysical Institute Fairbanks, AK 99775-7320	907-474-7706 907-474-7290	harrison@gi.alaska.edu
Hedstrom, Kate	Rutgers University IMCS	P.O. Box 231 New Brunswick, NJ 08903	908-932-6555 x258 908-932-8578	
Hewett, Karen	Northwest Research Associates	P.O. Box 3027 Bellevue, WA 98009	206-453-8141 x322 206-646-9123	karen@nwra.com
Hopkins, Mark	USA CRREL	72 Lyme Rd. Hanover, NH 03755	603-646-4249	hopkins@crrel.usace.army. mil
Johnson, Walter	Minerals Management Service	381 Elden Street, MS 4360 Herndon, VA 22070	703-787-1642 703-787-1010	johnsonw@smtp.mms.gov
Jones, Doug	Cook Inlet RCAC	910 Highland Ave. Kenai, AK 99611	907-283-7222 907-283-6102	
Kerman, Bryan	Atmospheric Environment Service Canada Centre for Inland Waters	867 Lakeshore Rd. Burlington, Ontario L7R 4A6	905-336-4798 905-336-4797	bryan.kerman@cciw.ca

Knoke, Stu	Northwest Research Assoc., Inc.	P.O. Box 3027 Bellevue, WA 98009	206-453-8141 x333 206-646-9123	stu@nwra.com
Konuk, Ibrahim	National Energy Board	311 6th Avenue S.W. Calgary, Alberta T2P 3H2	403-292-6911 403-292-5876	75144.1015@compuserve.com
Kristensen, Dirk	The Glosten Assoc.	605 First Avenue, Suite 600 Seattle, WA 98119	206-624-7850 206-682-9117	
Lai, Ronald	EPPD/MMS	381 Elden Street Herndon, VA 22070	703-787-1714 703-787-1010	ronald_j._lai@smtp.mms.gov
Lewis, James	BPX (Alaska)	700 G St., ATO-1838 Anchorage, AK 99510-0360	907-263-4895 907-265-1468	lewis#m#_james_c@msmail. aai.arco.com
Lewis, James	Ocean Physics R&D	207 S. Seashore Ave Long Beach, MS 39560	601-865-0059 601-864-3268	ocnphys@dol.com
Markham, Burton	NUWC Arctic Submarine Lab	49250 Fleming Road San Diego, CA 92152-7210	619-553-0190 619-553-0972	markham@cod.nosc.navy.mil
McNamara, Mary Lou	NSWC	Carderock Div., Code 654 Bethesda, MD 22080	301-227-1650 301-227-1230	mimcnama@oasys.dt.navy.mil
McNutt, Lyn	University of Alaska Fairbanks	Geophysical Institute, Box 7320 Fairbanks, AK 99775-7320	907-474-6077 907-474-7290	lyn@dino.gi.alaska.edu
Monkelien, Kyle	Minerals Management Service	949 E. 36th Avenue Anchorage, AK 99508	907-271-6431 907-271-6504	
Murrell, Tom	Minerals Management Service	949 E. 36th Ave., Room 110 Anchorage, AK 99508	907-271-6503 907-271-6805	
Ostoja, Martin	Michigan State University	Dept. of Materials Sci. & Mech. E. Lansing, MI 48864	517-432-2181 517-353-9842	ostoja@egr.msu.edu
Overland, Jim	PMEL/NOAA	7600 Sand Point Way, NE Seattle, WA 98115	206-526-6795 206-526-6485	overland@pmel.noaa.gov
Petrenko, Victor	Dartmouth College	HB 8000, Thayer School of Eng. Hanover, NH 03755	603-646-3526 603-646-3856	victor.f.petrenko@mac. dartmouth.edu
Pham, Thomas	FLENUMMETOCCEN	7 Grace Hopper Ave, STOP 1 Monterey, CA 93943-5501	408-656-4519 408-656-4489	
Polomoshnov, Anatoly	Sakhalin Oil & Gas Institute	18 K. Marx St.,Okha Sakhalin Island, Russia	878-682-500-034	
Post, Ruth	Cook Inlet RCAC	910 Highland Ave. Kenai, AK 99611	907-283-7222 907-283-6102	
Prentki, Richard	Minerals Management Service	949 E. 36th Avenue Anchorage, AK 99508	907-271-6599 907-271-6805	
Preller, Ruth	Naval Research Laboratory	NRL, Code 7322 Stennis Space Center, MS 39529	601-688-5444 601-688-4759	preller@nrlssc.navy.mil
Pritchard, Robert	Ice Casting, Inc.	11042 Sand Point Way NE Seattle, WA 98125-5846	206-363-3394 206-363-3394	rsp@halcyon.com
Proshutinsky, Andrey	Inst. of Marine Science, UAF 200 O'Neill Bldg.	P.O. Box 757220 Fairbanks, AK 99775-7220	907-474-7204	prosh@ims.alaska.edu

Rajan, Subramaniam	WHOI	Woods Hole, MA 02543	508-457-2000 x2317 508-457-2194	rajan@avcac.whoi.edu
Rajapakse, Yapa	Office of Naval Research	Ship Structures Division (ONR 334) Arlington, VA 22217-5660	703-696-4405 703-696-0308	rajapay@onrhq.onr.navy.mil
Richter-Menge, Jackie	US Army CRREL	72 Lyme Road Hanover, NH 03755	603-646-4266 603-646-4644	jrichtermenge@crrel.usace. army.mil
Ryabinin, Vladimir	Hydrometcentre of Russia	9-13 Bol. Predtechensky 123242 Moscow, Russia	7-095-255-2178 7-095-246-3970	c/o State Oceanographic Inst.
Schmidt, Henrik	MIT, Ocean Eng. Dept. Rm. 5-204	77 Massachusetts Ave Cambridge, MA 02139	617-253-5727 617-253-2350	henrik@keel.mit.edu
Schulson, Erland	Dartmouth College	Thayer School of Engineering Hanover, NH 03755	603-646-2888 603-646-3856	erland.schulson@dartmouth. edu
Shapiro, Lew	Univ. of Alaska Fairbanks	Geophysical Institute Fairbanks, AK	907-474-7190 907-474-7290	lew_shapiro@asfgm.imdges. alaska.edu
Shen, Hung Tao	Clarkson University CEE Dept.	Box 5710 Potsdam, NY 13699-5710		
Simpson, James	Scripps Oceanographer	9500 Gilman Drive / MS 0237 San Diego, CA 92122	619-534-5426 619-534-5602	jsimpson@ucsd.edu
Smirnov, Victor	Laboratory of Ice Physics Arctic & Antarctic Res. Inst.	38 Bering St. St. Petersburg, 199397, Russia	7-812-352-2688 7-812-352-2688	earicoop@sovam.com
Smith, Charles	Minerals Management Service	381 Elden St., MS 4700 Herndon, VA 22070-4817	703-787-1559 703-787-1115	smitc@smtp.mms.gov
Smith, Robert	Arco Exploration & Prod. Tech. D1225	2300 West Plano Pkw. Plano, TX 75075	214-509-3072 214-509-3920	
Stein, Peter	Scientific Solutions, Inc	18 Clinton Drive Hollis, NH 03049	603-880-3784 603-598-1803	pstein@world.std.com
Stringfellow, Robert	Minerals Management Service	949 East 36th, Suite 614 Anchorage, AK 99510	907-271-6505 907-271-6805	
Swean, Tom	Office of Naval Research Code 3210E	800 N. Quincy St. Arlington, VA 22217	703-696-4025 703-696-2710	sweant@onrhq.onr.navy.mil
Thomas, Graham	BP International Ltd Research & Engineering Centre	Chertsey Road, Sunbury-on-Thames Middlesex TW16 7LN UK	44-1932-764305 44-1932-764077	thomasg@txpcap.hou.xwh.bp. com
Toimil, Larry	Harding Lawson Assoc.	1325 Fourth Avenue, Suite 1800 Seattle, WA 98101	206-622-0812 206-292-8619	
Tuhkuri, Jukka	Helsinki Univ. of Tech. Ship Laboratory	Otakaari 4 02150 Espoo, Finland	358-0-451-3509 358-0-451-3419	jukka.tuhkuri@hut.fi
Tyagi, Rishi	Minerals Management Service	770 Paseo Camarillo Camarillo, CA 93010	805-389-7775 805-389-7784	
Truskov, Pavel	Sakhalin Oil & Gas Institute	18 K. Marx St., Okha Sakhalin Island, Russia	878-682-500-034	

Van Woert, Michael	Office of Naval Research Code 322	800 N. Quincy St. Arlington, VA 22217	703-696-4720 703-696-2710	vanwoem@hornet.onr.navy.mil
Vaudrey, Kennon	Vaudrey & Assoc., Inc.	1540 Marsh St. - Suite 105 San Luis Obispo, CA 93401	805-544-0940 805-544-0940	74733.2666@compuserve.com
Wadhams, Peter	Scott Polar Res. Inst.	Lensfield Road Cambridge, UK CB2 1ER	44-223-336562 44-223-336569	pw11@cum.sc.uk
Walker, Jeff	Minerals Management Service	949 E. 36th Avenue Anchorage, AK 99508	907-271-6188 907-271-6805	
Walter, Bernard	SAIC	13400B Northup Way, Suite 36 Bellevue, WA 98005	206-747-7152 206-747-9211	walter@salty.nw.saic.com
Wang, Albert	Exxon	P.O. Box 2189 Houston, TX 77252-2189	713-973-3082 713-973-3340	
Watt, James	Union Texas Petroleum	P.O. Box 2120 Houston, Texas	713-968-2604 713-968-2623	
Weeks, Willy	GI/UAF	P.O. Box 757320 Anchorage, AK 99775-7320	907-474-7280 907-474-7290	willy@dino.gi.alaska.edu
Whitney, John	NOAA Hazmat	510 L St., #100 Anchorage, AK 99501	907-271-3593 907-271-3139	whitney@hazmat.noaa.gov
Woodworth-Lynas, C.	C-CORE, Bartlett Bldg.	Memorial Univ. of Newfoundland St. John's, NF A1B 3X5	709-737-8368 709-737-4706	chriswl@kean.ucs.mun.ca
WU, Mao	Univ. of Nebraska-Lincoln	212 Bancroft Hall Lincoln, NE 68588-0347	402-472-2385 402-472-8292	wu@emwu.unl.edu
Zagorodnov, Victor	Inst. of Marine Science, UAF	P.O. Box 757220 Fairbanks, AK 99775-7220	907-474-5585 907-474-5582	
Xie, Yunbo	Inst. of Ocean Sciences	9860 West Saanich Road Sidney, BC V8L 4B2	604-363-6339 604-363-6798	yunbo@ios.bc.ca